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Foreword

The papers in this volume address energy, environmental concerns, and natural resources. Car scrappage rates and their effects on fleet fuel efficiency in the United States between 1966 and 1992 are described. Transportation energy consumption and energy intensity from 1972 to 1992 are reviewed. Pavement damage caused by buses fueled by compressed natural gas is assessed, and the market for electric vehicles is reexamined. Another paper reports on studies to evaluate the costs and benefits associated with technologies for reducing vehicle emissions.

Among the papers on environmental concerns, one suggests techniques for accelerating the remediation of a hazardous waste site, and another explores the integration of the environmental review process and the new planning process known as major metropolitan transportation investment studies.

Four papers consider noise generated by transportation: issues include noise generated by high-speed tracked vehicles, airport noise contours, the perceptions of helicopter noise in rural communities, and vibration-attenuating rail fasteners.

The papers that address waste management discuss Superfund site cleanup efforts, control of groundwater contamination plumes during highway construction, large-scale groundwater remediation of a contaminated storm water runoff construction pond, and gas sampling and analysis of petroleum-contaminated soils.

The final two papers describe wetland function and value assessment using computer-aided drafting and design and geographic information system techniques, and the mitigation of adverse impacts on natural resources and fragmentation of vertebrate habitats.

PART 1

Energy and Alternative Fuels

Factors Associated with Aggregate Car Scrappage Rate in the United States: 1966–1992

SHAW-PIN MIAOU

Vehicle scrappage or survival models provide estimates of the fraction of vehicles of each model year that survive to each later year. Earlier studies have suggested that many socioeconomic factors are associated with vehicle scrappage decisions, such as vehicle age, new vehicle price, household income, unemployment rate, used vehicle price, vehicle maintenance and repair cost, and interest rate for new car loans. However, most of the vehicle scrappage models used so far have been quite simple, using either vehicle age or new car price as determinants. The objectives of the research presented were to (*a*) develop a statistical vehicle scrappage model capable of describing the association between vehicle scrappage rate and a number of potential determinants such as those just suggested, (*b*) use the developed model to identify socioeconomic factors that may be associated with aggregate car scrappage rate in the United States using historical data and infer a car scrappage model for prediction purposes, and (*c*) illustrate how the suggested scrappage model can be used to predict car scrappage and survival rates.

The proportion of older cars in the U.S. car fleet has increased significantly in the past 18 years. This can be seen from Figure 1, which shows that the percentage of cars 15 years or older in the registered car fleet rose from about 2.3 percent during 1962–1974 to about 11 percent in 1992 (*1*). This aging car fleet has raised considerable concerns as to whether federally mandated legislation on, for example, the use of alternative fuel vehicles and new car fuel economy and emission standards could meet the desired goals of reducing motor fuel consumption and improving air quality, and whether other programs aimed at accelerating vehicle scrappage would be necessary to help achieve such goals (*2*).

Because of the long life span of cars and trucks (about 10 to 15 years), vehicle stock turnover is a slow process. The vehicles purchased now and in recent past will have long-term effects on vehicle stock composition and, therefore, on motor fuel consumption and vehicle emissions (*3–5*). To address properly the aforementioned concerns, one must be able to make a good prediction of vehicle stock compositions.

For many years, vehicle stock dynamic models have been developed for making such predictions. These models have also been included as a major submodel in many energy and environmental analysis models designed to analyze the impact of various regulatory policies on fuel consumption and air quality. Some examples are the alternative motor fuel use (AMFU) model (*6*), the ideas model (*7*), and DRI/McGraw-Hill's transportation model (*2*). The vehicle stock dynamic model usually includes a new vehicle sales model and a vehicle scrappage (or survival) model. Depending on applications, these models may be disaggregated by the type of vehicle or fuel.

The vehicle scrappage model provides estimates on the fraction of vehicles of each model year that survive to each later year. Earlier studies have suggested that many socioeconomic factors are associated with vehicle scrappage decisions, for example, vehicle age, new vehicle price, household income, unemployment rate (or job security), used vehicle price, vehicle maintenance and repair cost, and interest rate for new car loans (*4,8,9*). However, most of the vehicle scrappage models used so far have been quite simple. For example, many have adopted the age-specific scrappage model that uses vehicle age as the only determinant, and Greene's AMFU model uses two determinants: vehicle age and new car price (*6*).

The first objective of the research presented in this paper was to develop a statistical vehicle scrappage model capable of describing the association between vehicle scrappage rate (or probability) and a number of potential determinants such as those socioeconomic factors just suggested. The second objective was to use the developed model to identify socioeconomic factors that may be associated with the aggregate car scrappage rate in the United States using historical data and infer a car scrappage model for prediction purposes. The third objective was to illustrate how the developed scrappage model can be used to estimate and predict aggregate car scrappage and survival rates for future years using predicted values of the identified socioeconomic factors.

STATISTICAL MODEL

Suppose that $N_{t,m}$ vehicles of model year m are in operation at the beginning of calendar year t. Typically, model year m vehicles are introduced in the fall of year $m - 1$. Thus, model year m vehicles are in operation in years $t = m - 1, m, m + 1, m + 2, \ldots$; conversely, in year t vehicles of model years $m = t + 1, t, t - 1, t - 2, t - 3, \ldots$ are in operation. Let $Z_{t,m,i}$, where $i = 1, 2, \ldots, N_{t,m}$, be an indicator variable of 1 or 0 indicating that the ith vehicle of model year m is either scrapped (= 1) or survived (= 0) during year t. Further, assume that the scrappage decision is made independently for each individual vehicle in each year, that is, variables $Z_{t,m,i}$ are independent for all t, m, and i. The probability that the ith vehicle of model year m will be scrapped in year t is postulated to be associated with a set of k socioeconomic and vehicle age variables $x_{t,m,j}$, $j = 1, 2, \ldots k$, by a modified logit model as follows:

$$P(Z_{t,m,i} = 1) = q_{t,m}(\theta) = \frac{1}{\alpha + \exp\left(\beta + \sum_{j=1}^{k} x_{t,m,j}\gamma_j\right)} \qquad i = 1, 2, 3, \ldots N_{t,m} \qquad (1)$$

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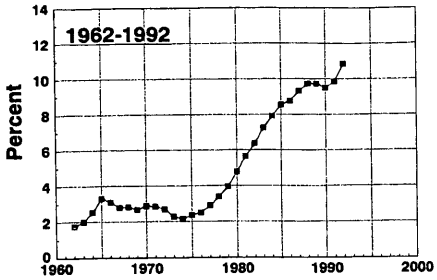

FIGURE 1 Percentage of cars in operation 15 years or older, 1962–1992.

where α (≥ 1), β, and γ_j, $j = 1, 2, \ldots, k$, are unknown parameters to be estimated from the data; and $\theta = (\alpha, \beta, \gamma_1, \gamma_2, \ldots, \gamma_k)^T$ is a column parameter vector. Note that in a conventional logit model, α is set equal to 1, and that in this paper superscript T is used to denote the transpose of a vector or matrix. Given the covariates $x_{t,m,j}$, $j = 1, 2, \ldots k$, the model assumes that $Z_{t,m,i}$ is a Bernoulli random variable with probability $q_{t,m}(\theta)$ of being equal to 1 and with probability $[1 - q_{t,m}(\theta)]$ of being equal to 0. The mean and variance of $Z_{t,m,i}$, which are conditional on the covariates and are denoted by $E(Z_{t,m,i})$ and $\text{var}(Z_{t,m,i})$, are $q_{t,m}(\theta)$ and $q_{t,m}(\theta)[1 - q_{t,m}(\theta)]$, respectively. The covariates $x_{t,m,j}$ could be specific to model year or to year. The former varies only by model year m (e.g., new car price), whereas the latter varies only by year t (e.g., unemployment rate). These two types of covariates will be denoted by $x_{m,j}$ and $x_{t,j}$, respectively, instead of $x_{t,m,j}$. Note that when appropriate, higher-order and interactive terms of covariates can be included in Equation 1 without difficulty.

Equation 1 can be rewritten as

$$Z_{t,m,i} = q_{t,m}(\theta) + u_{t,m,i} \qquad i = 1, 2, \ldots, N_{t,m} \tag{2}$$

where $u_{t,m,i}$, $i = 1, 2, \ldots, N_{t,m}$, are independent random variables for all t, m, and i and have zero mean and variance of $q_{t,m}(\theta)[1 - q_{t,m}(\theta)]$. Summing $Z_{t,m,i}$ over individual vehicles gives

$$\sum_{i=1}^{N_{t,m}} Z_{t,m,i} = N_{t,m} q_{t,m}(\theta) + \sum_{i=1}^{N_{t,m}} u_{t,m,i} \tag{3}$$

or

$$\frac{1}{N_{t,m}}\left(\sum_{i=1}^{N_{t,m}} Z_{t,m,i}\right) = q_{t,m}(\theta) + \frac{1}{N_{t,m}}\left(\sum_{i=1}^{N_{t,m}} u_{t,m,i}\right) \tag{4}$$

Letting

$$Y_{t,m} = \frac{1}{N_{t,m}}\left(\sum_{i=1}^{N_{t,m}} Z_{t,m,i}\right)$$

and

$$e_{t,m} = \frac{1}{N_{t,m}}\left(\sum_{i=1}^{N_{t,m}} u_{t,m,i}\right) \tag{5}$$

gives

$$Y_{t,m} = q_{t,m}(\theta) + e_{t,m} \tag{6}$$

where $q_{t,m}(\theta)$ is expressed in Equation 1. Variable $Y_{t,m}$ on the left side of Equation 6 represents the proportion of model year m vehicles scrapped in year t, the observation of which will be denoted as $y_{t,m}$ and typically is calculated as $(N_{t,m} - N_{t+1,m})/N_{t,m}$. Model residuals $e_{t,m}$ are independent random variables with zero mean and nonconstant variance of $q_{t,m}(\theta)[1 - q_{t,m}(\theta)]/N_{t,m}$.

The modified logit model presented in Equation 6 is quite general. Most of the vehicle scrappage models used in previous studies can be regarded as special cases of this general model. For example, the logit model of Parks (*9*) is when the parameter α in $q_{t,m}(\theta)$ is set equal to 1, and the age-specific logistic model of Greene and Chen (*3*) is when vehicle age is included as the only covariate in the model [also see the work by Feeney and Cardebring (*10*)].

Even though vehicle age is the only factor considered in the age-specific logistic model, the model has been found to explain the vehicle scrappage rate pattern quite well (*3,10*). The model has the following form:

$$Y_{t,m} = q_{t,m}(\theta) + e_{t,m} = \frac{1}{\alpha + \exp(\beta + \gamma \cdot \text{AGE}_{t,m})} + e_{t,m} \tag{7}$$

where α (≥ 1), β, and γ (<0) are model parameters, and $\text{AGE}_{t,m}$ is the average age of model year m vehicles in operation during calendar year t. The parameters of this model are easy to interpret. For example, $1/\alpha$ is the asymptotic scrappage rate (i.e., rate of scrappage for vehicles of infinite age), β determines the scrappage rate of vehicles at age 0, and γ is the shape parameter that determines the increase in vehicle scrappage rate as vehicle age increases. Figure 2 shows some example vehicle scrappage rate–age relationships from the logistic model when $\alpha = 4$, $\beta = 6$, and $\gamma = -0.8$, -0.6, and -0.4. As γ increases from -0.8 to -0.4, vehicle scrappage rates decrease at all vehicle ages. Feeney and Cardebring have pointed out (*10*) that as vehicles age, observed scrappage rates tend to increase to a maximum and then either decline or stabilize. This favors the choice of the logistic type of models over other sigmoidal growth models such as the Gompertz and Weibull models. Work by Ratkowsky (*11*) is a good source for the statistical properties of many sigmoidal growth models.

The specific model considered in this paper is a variation of the age-specific logistic model in Equation 7, in which parameter γ is assumed to depend on a set of covariates and, therefore, is allowed

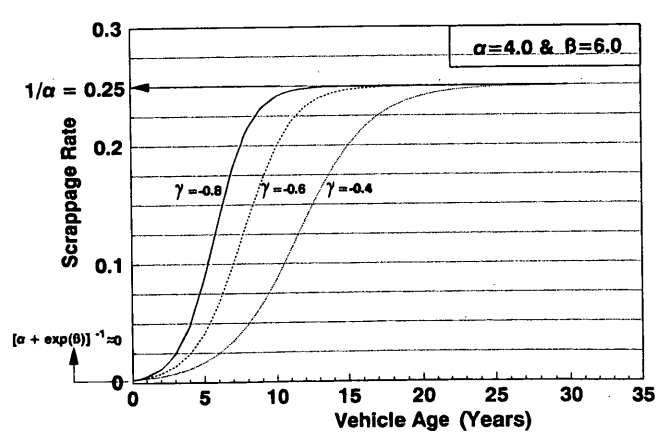

FIGURE 2 Example scrappage rate–vehicle age relationships using logistic models.

to vary over the year and model year. The model has the following form:

$$Y_{t,m} = q_{t,m}(\theta) + e_{t,m}$$
$$= \frac{1}{\alpha + \exp[\beta + (\gamma_1 + \gamma_2 x_{t,m,2} + \gamma_3 x_{t,m,3} + \ldots + \gamma_k x_{t,m,k})\cdot \mathrm{AGE}_{t,m}]} + e_{t,m} \quad (8)$$

where $\gamma_1, \gamma_2, \gamma_3, \ldots, \gamma_k$ are parameters associated with covariates $[\mathrm{AGE}_{t,m}]$, $[x_{t,m,2}\ \mathrm{AGE}_{t,m}]$, $[x_{t,m,3}\ \mathrm{AGE}_{t,m}], \ldots, [x_{t,m,k}\ \mathrm{AGE}_{t,m}]$. The model can be seen to be a special model of the modified logit model in Equation 6 where only vehicle age and interactive terms of vehicle age and other covariates are included. This particular model implies that the effect of socioeconomic variables x's on vehicle scrapping decisions is dependent on the age of vehicles. Other variations of Equation 7 are, of course, possible. For example, in this study two other variations of the model were also contemplated: (*a*) to allow β and γ to be dependent on some covariates, and (*b*) to allow α and γ to be dependent on some covariates. Using the data collected in this study, both variations were found to achieve no improvements over the simpler model of Equation 8 in terms of the adjusted R^2, the adjusted coefficient of determination. Note that the adjusted R^2 was computed as follows.

$$\text{Adjusted } R^2 = 1 - \frac{\frac{1}{\text{nobs} - k - 2}\sum_t \sum_m [y_{t,m} - q_{t,m}(\hat{\theta})]^2}{\frac{1}{\text{nobs} - 1}\sum_t \sum_m [y_{t,m} - \bar{y}]^2} \quad (9)$$

where

nobs = total number of observed scrappage rates,
$\hat{\theta}$ = estimated parameter vector, and
$\bar{y}$ = average of all y's available for modeling.

For comparison, the conventional logit model that restricts the parameter α in Equation 8 to be equal to 1 was also tested.

From Equation 8, the direct elasticity of car scrappage rate $q_{t,m}(\theta)$ with respect to car age $\mathrm{AGE}_{t,m}$ can be shown to be $E_{t,m}(\mathrm{AGE}_{t,m}) = [\alpha\, q_{t,m}(\theta) - 1]\,\gamma\,(\mathrm{AGE}_{t,m})$, where $\gamma = \gamma_1 + \gamma_2 x_{t,m,2} + \gamma_3 x_{t,m,3} + \ldots + \gamma_k x_{t,m,k}$. In addition, for $\alpha \geq 1$ and $\gamma < 0$ (as required in Equation 8), it can be shown that $E_{t,m}(\mathrm{AGE}_{t,m}) = 0$ when $\mathrm{AGE}_{t,m} = 0$, and that $E_{t,m}(\mathrm{AGE}_{t,m})$ approaches 0 when $\mathrm{AGE}_{t,m}$ approaches ∞. Furthermore, the scrapping elasticity with respect to $x_{t,m,j}$, $j = 1, 2, \ldots, k$ can be shown to be $E_{t,m}(x_{t,m,j}) = [\alpha\, q_{t,m}(\theta) - 1]\gamma_j(\mathrm{AGE}_{t,m})(x_{t,m,j})$.

PARAMETER ESTIMATION

To estimate the parameters of a nonlinear regression model that has a nonconstant variance error component, such as Equation 6, the following iterative reweighted least squares (IRLS) method can be used:

1. Give initial estimates of the parameters $\hat{\theta}^o = (\hat{\alpha}^o, \hat{\beta}^o, \hat{\gamma}_1^o, \hat{\gamma}_2^o, \ldots, \hat{\gamma}_k^o)^T$.
2. Compute weights as the reciprocal of the estimated residual variances:

$$w_{t,m} = \frac{N_{t,m}}{q_{t,m}(\hat{\theta}^o)[1 - q_{t,m}(\hat{\theta}^o)]} \quad (10)$$

where $q_{t,m}(\hat{\theta}^o)$ is the scrappage rate evaluated at $\hat{\theta}^o$.

3. Reestimate the model parameters θ by minimizing the following weighted sum of squares with respect to θ:

$$\sum_t \sum_m w_{t,m}[y_{t,m} - q_{t,m}(\theta)]^2 \quad (11)$$

where the sums are performed over all appropriate t and m. Let the new estimates be $\hat{\theta} = (\hat{\alpha}, \hat{\beta}, \hat{\gamma}_1, \hat{\gamma}_2^o, \ldots, \hat{\gamma}_k)^T$.

4. If the absolute change of each parameter is less than a small positive number ϵ (e.g., 0.00001), then stop and let the final estimates be $\hat{\theta}$. That is, stop the iterative procedure when $|(\hat{\alpha} - \hat{\alpha}^o)/\hat{\alpha}^o| < \epsilon$, $|(\hat{\beta} - \hat{\beta}^o)/\hat{\beta}^o| < \epsilon$, and $|(\hat{\gamma}_j - \hat{\gamma}_j^o/\hat{\gamma}_j^o| < \epsilon$ for all j's. Otherwise, let $\hat{\theta}^o = \hat{\theta}$ and go to Step 2.

Standard error estimates of the components of $\hat{\theta}$ are computed by taking the square roots of the diagonal elements of an estimate of the asymptotic variance-covariance matrix of $\hat{\theta}$. The estimate of the matrix is given by

$$\left[\sum_t \sum_m \frac{\left[\frac{\partial \hat{q}_{t,m}}{\partial \theta}\right]\left[\frac{\partial \hat{q}_{t,m}}{\partial \theta}\right]^T}{\hat{\sigma}_{t,m}^2}\right]^{-1} \quad (12)$$

where

$$\hat{\sigma}_{t,m}^2 = \frac{q_{t,m}(\hat{\theta})[1 - q_{t,m}(\hat{\theta})]}{N_{t,m}}$$

and

$$\left[\frac{\partial \hat{q}_{t,m}}{\partial \theta}\right] = \left[\frac{\partial q_{t,m}(\theta)}{\partial \alpha}, \frac{\partial q_{t,m}(\theta)}{\partial \beta}, \frac{\partial q_{t,m}(\theta)}{\partial \gamma_1}, \ldots, \frac{\partial q_{t,m}(\theta)}{\partial \gamma_k}\right]^T_{\theta = \hat{\theta}} \quad (13)$$

See work by Beal and Sheiner (*12*) for details of the IRLS method and the asymptotic variance-covariance matrix.

In this paper, for comparison purposes the ordinary least squares (OLS) method was also used to estimate model parameters in Equation 8. The OLS method assumes that model residuals $e_{t,m}$ have zero mean and constant variance.

DATA AND DATA SOURCES

Car registration data compiled by the R.L. Polk & Company and published in *Vehicle Facts and Figures* (*1*) were used to compute car scrappage rates. Polk's registration data represent a snapshot of the number of cars in operation on July 1 of each year. Typically, the data are tabulated for the latest 16 model years, and earlier model years are grouped under one category. Registration data for the latest 16 model years from 1965 to 1992 were used in this study. The same data source has been used in earlier scrappage rate studies: Greene and Chen (*3*) used data from 1966 to 1977, Hu (*13*) used data from 1970 to 1982, and Feeney and Cardebring (*10*) used data from 1971 to 1983. Note that 1980 registration data were not used in this study because some passenger vans (1.2 percent of the passenger car fleet) were reclassified from passenger cars to trucks in that year.

To compute the "observed" average car scrappage rate for each calendar year using Polk's July 1 registration data, the following formula was used:

$$y_{t,m} = \frac{1}{2}\left(\frac{N_{t-1,m}^* - N_{t,m}^*}{N_{t-1,m}^*} + \frac{N_{t,m}^* - N_{t+1,m}^*}{N_{t,m}^*}\right) \quad (14)$$

where $N_{t,m}^*$ is the number of model year m cars in operation on July 1 of year t.

To estimate the average age of model year m cars in year t, denoted by $AGE_{t,m}$, two observations were made from Polk's registration data: (*a*) about 65 percent of model year m cars are sold by July 1 of year m (*10*), and (*b*) model year m cars are typically introduced in the fall of year $m - 1$. Similar to the linear interpolation approach used by Feeney and Cardebring (*10*), average car ages were approximated in this paper as follows:

$$AGE_{t,m} \approx t - m + 0.25 \quad (15)$$

where $t = m + 1, m + 2, \ldots$. Note that Feeney and Cardebring used 0.225 in Equation 15 instead of 0.25.

In addition to car age, $AGE_{t,m}$, other covariates considered for use in Equation 8 include one variable specific to model year and six variables specific to year:

$x_{m,2} = NCPI_m$ = new car price index for all urban consumers (1982–1984 = 100) (*1*);

$x_{t,3} = DI/HH_t$ = real disposable income per capita ($1,000, 1988) × number of persons per household (*14*) (Note that this is intended to be an estimate of real disposable household income);

$x_{t,4} = UNEMP_t$ = unemployment rate (%) (*14*);

$x_{t,5} = UCPI/MRCI_t$ = used car price index for all urban consumers (1982–1984 = 100) (*1*) divided by total maintenance and repair cost index for all urban consumers (1982–1984 = 100) (*14*);

$x_{t,6} = NCLOAN_t$ = annual rate of new car loans (%)—most common rate by commercial banks (*14*); and

$x_{t,7} = ACC/REG_t$ = number of motor vehicle accidents—from the Insurance Information Institute (*14*), divided by the total number of cars in operation (*1*).

The expected relationship between each variable and the car scrappage rate is as follows:

- $NCPI_m$: higher new car price is expected to be associated with lower scrappage rates at all ages in later years (6,9).
- DI/HH_t: The role of disposable household income on car scrappage rate is not clear from previous studies. Parks (*9*) indicated that

> Real disposable personal income per family did not appear significant in any of the equations. . . . A rise in income would . . . be associated with a shift in demand from old to new, [which] would lead to a fall in the relative price of older cars and an increase in the scrapping of older cars. This effect could be offset, however, to the extent that rising income produced a demand for multiple car ownership.

Recent data on vehicle ownership, however, appear to favor the theory of multiple car ownership as household income increases. For example, data from the decennial census indicated that the share of households owning two vehicles increased from 19 percent in 1960 to 37 percent in 1990, and during the same period the share of households owning three or more vehicles increased from 3 to 18 percent (*15*). As will be presented in the next section, the results from this study also support the multiple car ownership theory. (Note that during the same period the average size of households dropped from about 3.33 to 2.63 persons.)

- $UNEMP_t$: Unfavorable economic conditions give rise to higher unemployment rate and depress new car demand and are, therefore, expected to prolong the retention of old vehicles in the car fleet (*4*).
- $UCPI/MRCI_t$: Walker's study (*8*) indicated that higher ratio of used car price over maintenance and repair cost was associated with a lower scrappage rate.
- $NCLOAN_t$: As indicated in Greene (*4*), three-fourths of all new car purchases were financed. Higher interest rates on new car loans discourage the purchase of new cars and, therefore, slow vehicle retirement rates.
- ACC/REG_t: Vehicle accidents increase total maintenance and repair costs and may shorten a vehicle's life span. Higher values of accident-registration ratios are, therefore, expected to be associated with higher scrappage rates. The original idea was to collect the total number of cars that either were scrapped or required significant repairs (in the economic sense) as a result of being involved in severe crashes. However, because of the lack of such crash data, the total number of motor vehicle accidents (including all minor and major accidents and both car and truck accidents) was used as a surrogate variable.

MODEL RESULTS, ILLUSTRATIONS, AND DISCUSSION

Equation 8 was the main scrappage model considered in this paper. The estimated parameters from the IRLS method and the adjusted R^2 value of the estimated model are given as Model 1 in Table 1. For comparison, the results from three other models (or estimation methods) are also presented in the table:

- Model 2: The age-specific logistic scrappage model in Equation 7 that was also estimated by the IRLS method;
- Model 3: Same as Model 1, but parameters were estimated using the OLS method; and
- Model 4: A logit model estimated by the IRLS method (i.e., same as Model 1) but parameter α was set equal to 1.

Several observations can be made from the estimation results presented in Table 1:

1. All the estimated parameters in Model 1 have expected algebraic signs. Except ACC/REG_t, all other variables have very high asymptotic t-statistics (≥ 3.0). Car age, $AGE_{t,m}$, is the most dominant factor in terms of t-statistics. A high adjusted R^2 value of 0.95 suggests that the model fits the data quite well.
2. Model 2 (the age-specific logistic scrappage model) indicates that car age alone explains about 77 percent of the variance in the observed scrappage rate data.
3. The OLS results from Model 3 are consistent with the IRLS results from Model 1 in terms of the algebraic signs of the estimated parameters. The OLS method, however, renders $NCPI_m$ statistically insignificant and ACC/REG_t significant. This model is not recommended because the variance of the residuals from the model was tested to be nonconstant.
4. All the estimated parameters in Model 4 (the logit model) also have expected algebraic signs and are generally consistent with those from Model 1. The adjusted R^2 value of the estimated model is 0.74, which is even lower than Model 2, indicating that setting parameter α to 1 is overly restricted in the fitting of the observed scrappage rates.

TABLE 1 Estimated Model Parameters and Associated Statistics

Model Parameter, [Expected Sign], & Variable Name	Model 1 Eq. 8 IRLS Method	Model 2 Eq. 7 IRLS Method	Model 3 Eq. 8 OLS Method	Model 4 Eq. 8 w/ α=1, Logit Model IRLS Method
α [+] Constant	3.29163 (26.87)	4.21850 (17.06)	3.21802 (51.34)	1.0
β [+] Constant	5.56929 (75.23)	5.80231 (40.32)	5.54511 (40.47)	4.78940 (77.77)
γ [-] $AGE_{t,m}$		-0.476107 (-19.92)		
γ_1 [-] Constant Associated with $AGE_{t,m}$	-1.29996 (-11.66)		-1.49131 (-13.16)	-0.732487 (-9.76)
γ_2 [+] $NCPI_m$	0.00081693 (3.00)		0.00008022 (0.24)	0.00057406 (2.27)
γ_3 [+] DI/HH_t	0.0134764 (6.05)		0.0214045 (8.88)	0.0065747 (4.08)
γ_4 [+] $UNEMP_t$	0.0090247 (3.70)		0.0117853 (4.94)	0.0043987 (2.24)
γ_5 [+] $UCPI/MRCI_t$	0.255644 (6.91)		0.291888 (8.10)	0.166644 (5.89)
γ_6 [+] $NCLOAN_t$	0.0114301 (6.49)		0.0171277 (9.45)	0.0068181 (4.71)
γ_7 [-] ACC/REG_t	-0.258674 (-0.88)		-0.825293 (-2.84)	-0.269513 (-1.23)
Adjusted R^2	0.95	0.77	0.96	0.74

Notes: (1) Sample size: 293, and (2) values in parentheses are asymptotic t-statistics of the estimated parameters above.

The elasticities of the car scrappage rate with respect to different car ages for cars of the 1970 model year are shown in Figure 3. The greatest elasticity occurred between ages 7 and 9. (Note that all other model years considered in this paper had the same elasticity pattern as that of 1970.) The elasticities of the car scrappage rate with respect to the socioeconomic variables when averaged over the observed period and different car ages are as follows:

- $NCPI_m$: −0.21;
- DI/HH_t: −1.85;
- $UNEMP_t$: −0.24;
- $UCPI/MRCI_t$: −0.91;
- $NCLOAN_t$: −0.58; and
- ACC/REG_t: −0.27.

The average elasticity of −1.85 for DI/HH_t clearly indicates that household income has played an important role in car scrapping decisions. This result is contrary to Parks' finding in 1977 (*9*).

Table 2 presents the average annual growth rate (AAGR) of $NCPI_m$, DI/HH_t, and $UCPI/MRCI_t$ and the annual average of $UNEMP_t$, $NCLOAN_t$, and ACC/REG_t for 1965–1992. To illustrate how Model 1 can be used for estimating and predicting car scrappage and survival rates, it is assumed that these AAGRs and averages during 1965–1992 will persist up to year 2010. Under this assumption, Figure 4 shows the estimated and predicted car scrappage rates by car age for 7 calendar years between 1970 and 2000 with a 5-year time interval. Using the same assumption, Figure 5 shows the estimated and predicted survival rates by car age for five model year cars: 1970, 1975, 1980, 1985, and 1990. The median lifetime is expected to increase from 10.7 years for 1970 model year cars to 13.7 years for 1990 model year cars.

Technology is an important factor that was not considered explicitly in this paper. Over the years, new cars with better safety equipment, fuel efficiency, antipollution devices, built-in durability (due to better materials and structural design), and quality control have been introduced to the new car market. The introduction of these cars can either increase or decrease aggregate car scrappage rates. Demand for safer, more fuel efficient, and cleaner cars would increase the demand for newer cars and would lead to a rise in the scrapping of older cars if car holdings remain the same. On the other hand, higher new car prices as a result of such added safety features

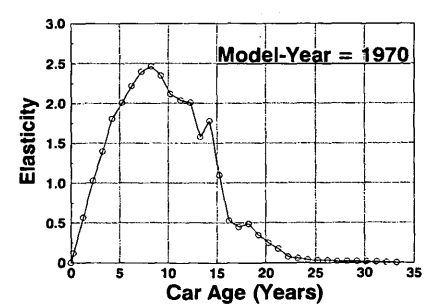

FIGURE 3 Elasticities of scrappage rate with respect to car age: 1970 model year.

TABLE 2 AAGR or Average of Socioeconomic Variables

Variable		1965-75	1975-85	1985-92	1965-92
New Car Price Index	AAGR →	2.43%	5.39%	2.77%	3.57%
Real Disposable Household Income	AAGR →	1.36%	0.26%	1.28%	0.93%
Unemployment Rate	Average →	4.96%	7.63%	6.35%	6.20%
Used Car Price Index/Maintenance & Repair Cost Index	AAGR →	-2.16%	2.70%	-2.81%	-0.48%
Interest Rate of New Car Loans	Average →	9.63%	13.15%	11.23%	11.40%
No. of Accidents/Total Car Registration	Average →	0.27	0.26	0.27	0.27

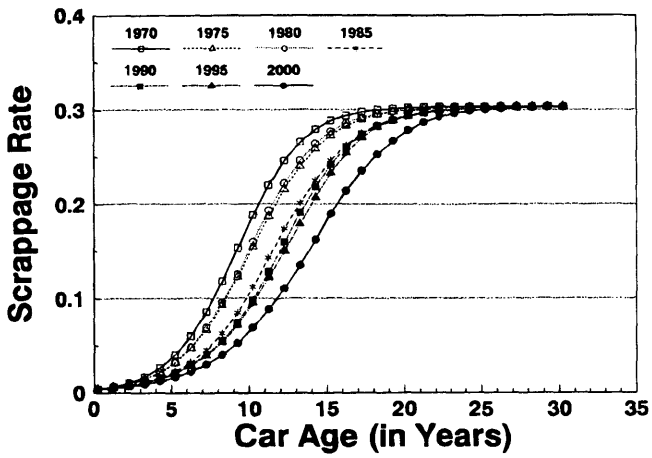

FIGURE 4 Estimated car scrappage rates by vehicle age for several calendar years.

and antipollution devices might reduce new car sales and prolong the retention of older cars. Better built-in durability and quality control reduce repair frequency and cost over the lifetime of a vehicle.

The present work could be extended in several directions:

1. It would be formally straightforward to extend the current framework to study *truck* scrappage decisions.

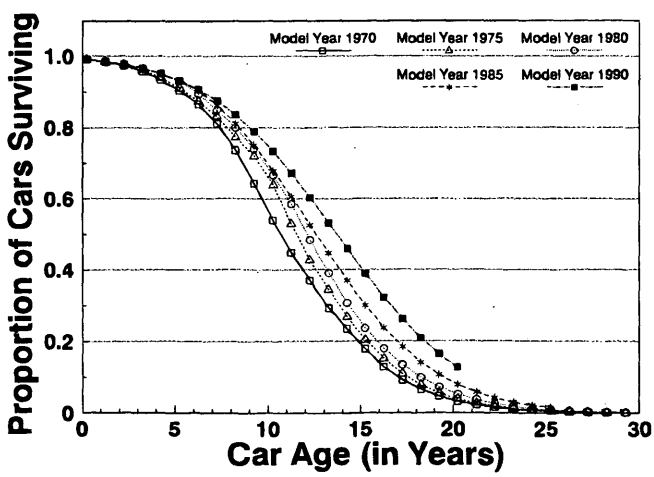

FIGURE 5 Estimated proportions of cars surviving by vehicle age for several model years.

2. Because of the lack of used car price data by model year, the variable was considered exogenous in this study. In reality, used car price may be endogenous and a simultaneous equation model may be more appropriate.

3. The available registration data grouped cars 16 years and older into one category. In this study, these data were not used in estimating model parameters. An estimation procedure should be developed to make the best use of these data that contain useful information on the scrapping rates of older cars.

4. To make long-term predictions of car scrappage rates, the potential for saturation effects in the relationships among income, size of households, and vehicle ownership should be analyzed.

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Transportation Energy Intensity Trends: 1972–1992

DAVID L. GREENE AND YUEHUI FAN

Trends in energy use and energy intensity in transportation are analyzed by growth in transportation activity, changes in energy intensity, and changes in modal structure. Trends in the fuel economy of light-duty vehicles are also analyzed. Reductions in the energy intensity of transport have held back the growth of energy use but with widely varied success across modes. Analysis of trends in the fuel economy of new passenger cars and light trucks from 1975 to 1993 shows that changes in the vehicle sales mix have had a relatively minor impact and that decreased vehicle weight has boosted fuel economy by 0.85 km/L (2 mpg). Increased performance has erased almost all of that gain, though, so the increase for new vehicles is due almost entirely to improved fuel economy technology.

The U.S. transportation sector, which remains 97 percent dependent on petroleum, used a record high 24.05 EJ of energy in 1993 (*1,2*). [One quadrillion Btus (quad) is equal to somewhat more than 1 exajoule (1 EJ = 10^{18} joules) and represents about 172 million barrels, or 0.5 million barrels per day, of crude oil.] This paper examines 20 years of energy use in the transportation sector and analyzes it into components associated with the growth of transportation activities, changes in energy use per unit of activity, and changes in the modal structure of transportation activities. Where data permit, the effects of trends in vehicle occupancy rates or load factors are also measured. The objective is to better understand when and how changes in transportation energy use came about as a guide to where energy use and energy efficiency are headed. The Divisia decomposition method, a simple yet elegant means of breaking a time trend into components, is used (*3,4*). Greene and Fan present a more detailed explanation of the Divisia analysis and documentation of the precise equations and data used (*5*).

This analysis differs from previous decompositions of transportation energy trends (*4,6*) in the period covered (1972–1992) and in that consistent activity measures are used as much as possible. Whereas passenger kilometers are used herein to measure activity for all passenger modes and ton kilometers for nearly all freight modes, Ross (*4*) used vehicle kilometers for automobiles and light trucks and measured heavy-truck activity in dollars of gross national product. One approach is not wrong and the other right, but they will give different answers. Available data suggest that important trends in highway vehicle load factors have greatly influenced energy intensity.

Data are deficient in several areas. Estimates of ton kilometers transported are poorly known for all types of trucks, especially single-unit trucks. Ton kilometers transported by pipelines are not reported on an annual basis. Estimated energy intensities for domestic waterborne transportation fluctuate widely for reasons that are not well understood, and ton kilometers and energy use in international shipping are poorly known. Consistent estimates of passenger vehicle occupancy rates are available only from infrequent surveys; intervening years must be interpolated. The reader is urged to keep these serious data limitations in mind when interpreting the results of this analysis. Broad trends are likely to be meaningful, but results involving suspect data, such as truck ton kilometers and sometimes year-to-year changes, must be interpreted with caution.

In contrast, excellent detailed data exist on the fuel economy and related characteristics of light-duty vehicles (*7*). Because of this and the fact that light-duty vehicles account for 57 percent of transportation energy use (*8*), trends in light-duty vehicle fuel economy are the subject of more detailed analysis.

ANALYSIS OF ENERGY USE TRENDS BY DIVISIA DECOMPOSITION

Divisia decomposition is a simple but elegant mathematical method for precisely analyzing any time trend that can be expressed as a product of several factors (*3*). In general, energy use (E) per unit of time (t) can be expressed as energy use per unit of activity (A) times the level of activity.

$$E_t = \left(\frac{E}{A}\right)_t \cdot A_t = e_t \cdot A_t \tag{1}$$

Here e measures energy intensiveness (energy use per dollar, passenger kilometers, ton kilometers, etc.). If the activity measured by A can be subdivided into meaningful categories such as modes of transport, Equation 1 can be written as a sum of energy uses,

$$E_t = \sum_{i=1}^{n} \left(\frac{E_{it}}{A_{it}}\right)\left(\frac{A_{it}}{A_t}\right) A_t \tag{2}$$

or

$$e_t = \frac{E_t}{A_t} = \sum_{i=1}^{n} e_{it} s_{it} \tag{3}$$

where e is energy intensity and s is the share of activity by mode. The Divisia method decomposes $e = E/A$ into changes in efficiency within subcategories and changes in the mix of activity among categories over time. By the product rule of differential calculus,

$$\frac{de_t}{dt} = \sum_{i=1}^{n} \left(\frac{de_{it}}{dt} s_i + \frac{ds_{it}}{dt} e_{it}\right) \tag{4}$$

Oak Ridge National Laboratory, P.O. Box 2008, MS-6207, Oak Ridge, Tenn. 37831.

According to the definition of the derivative

$$\lim_{\Delta t \to o} \frac{\Delta e_t}{\Delta t} = \frac{de_t}{dt} \tag{5}$$

it follows that

$$\Delta e_t = \sum_{i=1}^{n} \left[(e_t - e_{t-1})_i \frac{(s_t + s_{t-1})_i}{2} + (s_t - s_{t-1})_i \frac{(e_t + e_{t-1})_i}{2} \right] \tag{6}$$

In Equation 6, the change in energy use from year $t - 1$ to t is decomposed into two parts: change in energy intensiveness, and change in activity shares. For example, an improvement in passenger kilometer per joule (Btu) for air and highway travel would show up in the first component as a decrease in energy intensiveness. A shift in travel from less energy intensive highway travel to air travel would show up as an increase in the second component.

The year-to-year components of energy intensity changes can be added over time to produce estimates of the cumulative effects, which can be multiplied by the current activity level to obtain cumulative components in terms of energy use. Adding these to actual energy use in the current year produces an estimate of what energy use would have been for that year's activity level, at the base year energy efficiency and base year modal structure. That is called the trended energy use. The trended energy use equals the level of activity in a given year multiplied by the energy intensity of the base year. The difference between the trended energy use and the actual energy use is the net effect of changes in the efficiency and structural components.

Transportation activity is divided into (*a*) passenger, (*b*) freight, and (*c*) other. Six passenger modes are defined: three highway vehicle types (light-duty vehicles, larger single-unit trucks, combination trucks), commercial and general aviation, and passenger rail. Freight includes highway freight (divided between larger single-unit and combination trucks), domestic waterborne freight, rail, and pipeline. Air freight has not been included. Military transportation and international waterborne freight energy use make up a separate category.

Six Divisia analyses were carried out: (*a*) all transportation modes, (*b*) passenger modes, (*c*) air passenger, (*d*) highway passenger, (*e*) all freight, and (*f*) rail freight.

Combined passenger and freight activity is measured in dollars. Although reasonable estimates of freight revenues are available, most passenger travel is produced by households, so comparable revenue estimates are not available. The authors have substituted estimates of dollar costs of personal vehicle travel, based on vehicle operating costs per kilometer. The values of modal activities are computed using dollars per unit of modal activity in 1987 as an index year and multiplying that value by modal activity in each year. Productivity effects (changes in physical output per dollar) are zero by construction. For the separate analyses of freight and passenger modes, ton kilometers and passenger kilometers, respectively, are used as activity measures.

TRANSPORTATION SECTOR EFFICIENCY

Transportation would have used 4 EJ (3.8 quads) more energy in 1992, had passenger and freight movements taken place at 1972 energy intensities per dollar and relative modal activity levels (Figure 1). Shifts in activity to more energy intensive modes erased 1.16 EJ (1.1 quad) of a potential 5.17-EJ (4.9-quad) savings due to reduced energy intensities. Figure 2, which illustrates these trends, should be interpreted as follows. Cumulative component changes are shown as "stacked" bars in the lower portion of the graph, with effects tending to reduce energy use shown as negative values. The difference between the energy use trend line and the actual energy use line is the net effect, or sum, of the components. Note that in a given year an energy use component could increase due to an increase in activity with no change in energy intensity in that year.

The fact that trended and actual energy use move together from 1975 to 1979 implies that transportation energy intensity was essentially constant. The decline in energy use in 1973–1974 was

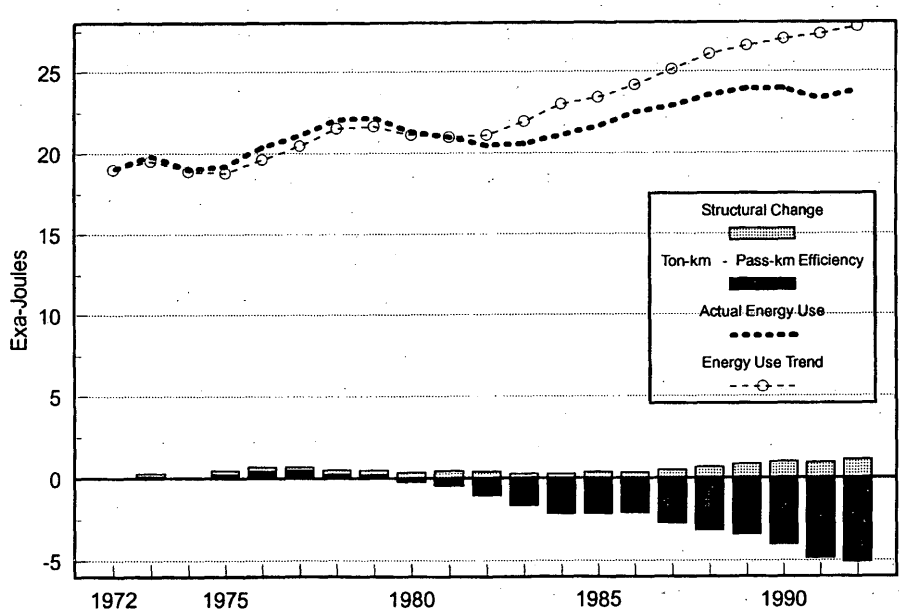

FIGURE 1 Transportation energy use.

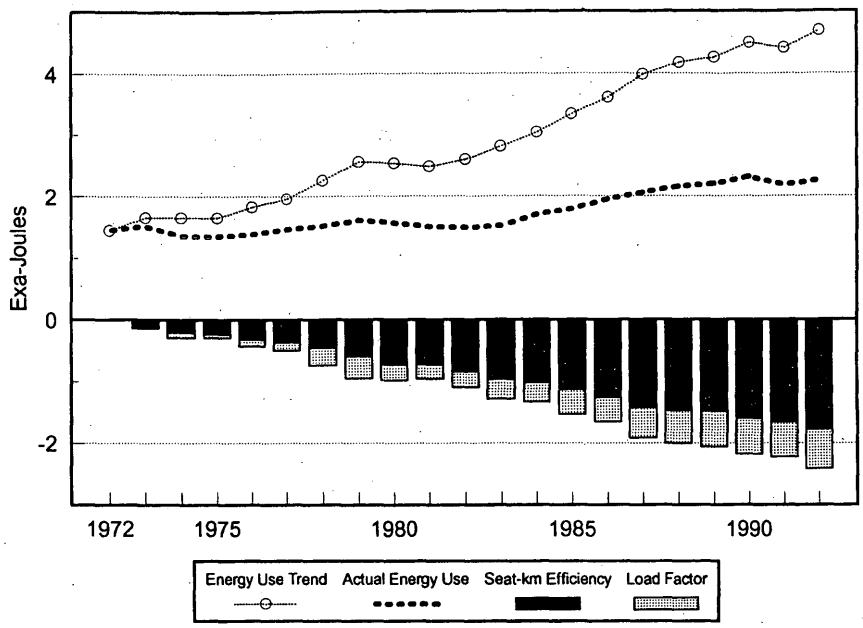

FIGURE 2 Air passenger energy use.

therefore due to decreased transportation activity. Starting in 1978, energy efficiency began improving, a trend that continued through 1992. Throughout, gradual modal shifts tended to increase energy use with a cumulative effect of 1.06 EJ through 1990.

These trends differ from those reported by the U.S. Department of Energy (DOE) (*6*) for 1972–1986 and from Ross's (*4*) calculations for 1972–1985. By 1986 the DOE study reports a savings of 4.22 EJ due to efficiency improvements, primarily due to light-duty vehicles and commercial aircraft. Ross's findings are similar, annual average growth rates in passenger and ton kilometers of traffic of 3.6 percent and 1.7 percent, but an overall growth rate of energy use of only 1 percent due to a 2.4 percent annual decrease in energy intensity for passenger travel and a 1.1 percent/annual decrease for freight. The authors' analysis finds no net energy savings until after 1980 and no net savings for the freight modes, collectively. Previous studies found earlier and larger energy savings because they measured energy intensities for highway vehicles per vehicle kilometer; the authors, however, use passenger and ton kilometers. Apparent declines in vehicle occupancy rates and in truck load factors result in smaller reductions in energy intensities.

PASSENGER TRAVEL ENERGY EFFICIENCY TRENDS

Had there been no changes in vehicle efficiencies, vehicle occupancies, and the modal shares of passenger travel, 20.47 EJ (19.4 quads) would have been required for the more than 6.44 trillion passenger kilometers (4 trillion passenger-mi) traveled in 1992, 23 percent more than was actually used. Energy intensity increased through 1977. By 1978 this trend reversed and efficiency improvements added continuously to energy savings through 1992. Structural shifts and vehicle occupancy rates gradually and continuously pushed up energy use. Because load factors on commercial aircraft improved, the increase in energy use due to structural change must be attributable to shifts to more energy intensive types of highway vehicles and the decline in highway vehicle occupancy rates (Table 1). Air travel's share of passenger kilometers increased from 5.6 percent in 1972 to 12.3 percent in 1992. The increasing popularity of light trucks boosted their share of passenger kilometers from 11.6 percent in 1972 to 20.4 percent by 1992. Declines in the shares of rail and bus had a minor impact.

Commercial air travel has achieved dramatic gains in energy efficiency. Air travel would have used more than twice as much energy in 1992 had there been no reductions in energy use per passenger kilometer (Figure 2). Three-fourths of the gain can be attributed to more seat kilometers per liter, the remainder to an increase in the average number of passenger kilometers per seat kilometer. Aircraft load factor improvements through 1989 contributed 0.53 EJ (0.5 quad) to air travel energy savings. (This analysis does not include the effects of circuity because the data necessary to evaluate it were not available.)

The 5.63 trillion passenger kilometers traveled by highway in 1992 would have required 6.96 EJ more energy had vehicle fuel economy remained at 1972 levels (Figure 3). Vehicle kilometer energy efficiency decreased until 1973 and then began continuous improvement, reflecting the gradual process of turnover of the vehicle stock. As will be seen, the fuel economy of new light-duty vehicles has not improved appreciably since 1982. Since the average life expectancy of a light-duty vehicle is about 12 years (*8*), it is not surprising that fleet efficiency improvements are slowing to a halt. The estimated average kilometers per liter (km/L) of highway vehicle travel decreased in 1992 for the first time in almost 20 years and decreased again in 1993. The increase in cumulative savings in 1992 was produced by the growth in vehicle travel, which outweighed the decline in efficiency per vehicle kilometer.

Energy savings due to fuel economy improvements since 1972 were halved by falling vehicle occupancy rates. Fewer passengers per vehicle kilometer added 3.7 EJ to total energy use, while vehicle type shifts added 1.5 EJ. The effect of the increasing light-truck

TABLE 1 Vehicle Occupancy Rates and Load Factors (*5*)

	1972	1975	1977	1980	1983	1985	1990	1991[1]
Passenger (passenger-km/vehicle-km)								
Passenger Car[1]	2.07	1.95	1.86	1.81	1.76	1.72	1.62	1.59
Light Truck[1]	2.02	1.89	1.81	1.76	1.71	1.71	1.72	1.72
Air[2]	65.2	77.3	85.2	91.6	101.0	101.4	100.0	101.6
Bus[3]	18.3	18.5	18.6	18.7	18.2	18.6	17.1	17.6
Rail[4]	26.7	25.3	26.9	28.6	25.6	24.5	23.4	23.0
Freight (ton-km/vehicle-km)[5]								
Combination Trucks[6]	10.4	8.8	9.1	7.3	7.4	7.0	6.9	7.4
Rail[7]	23.2	24.8	26.0	28.5	30.8	31.9	35.8	37.0

Data are from Greene and Fan (*3*), tables B.4 and B.5 and accompanying documentation.

[1] Represents passenger-km per vehicle-km according to the Nationwide Personal Transportation Surveys for 1969, 1977, 1983, and 1990. Intervening years are linearly interpolated.

[2] Statistics are for domestic and international operations of U.S. certificated route air carriers.

[3] Includes school bus, intercity and transit bus operations. School bus statistics are largely based on assumed load factors.

[4] Includes transit, commuter and intercity. Vehicle-km are defined as railroad car-km.

[5] Original data source uses short ton unit. Here, short ton has been converted into metric ton.

[6] Represents **intercity** truck ton-km divided by **all** combination truck-km and is therefore likely to be biased downward in all years.

[7] Intercity ton-km divided by car-km for class I freight railroads.

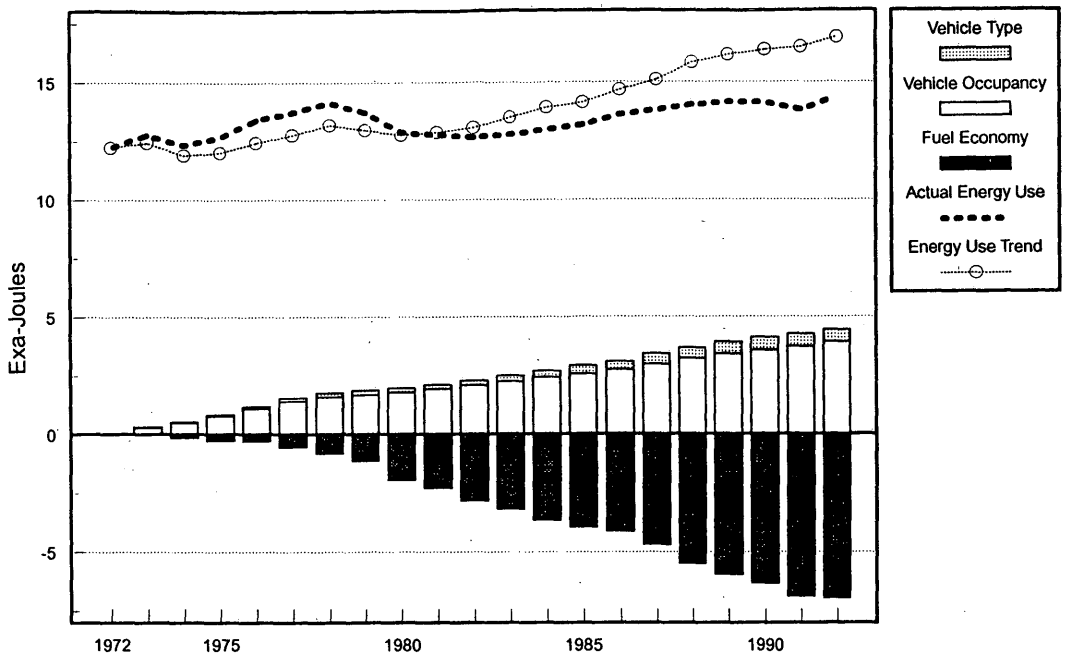

FIGURE 3 Highway passenger energy use.

market share on efficiency is small but evident at the very beginning of the period and persists despite the fuel price shocks of 1973–1974 and 1979–1980.

FREIGHT

The freight sector looks different, although the reader is cautioned that the quality of data on freight activities is poor and could be misleading. However, the available data suggest that had ton kilometer energy efficiencies and the distribution of traffic by mode remained at their 1972 levels, freight transport in the United States in 1992 would have required 0.1 EJ more energy than was actually used (Figure 4). The modal shares of ton kilometers in 1992 were very close to those in 1972. Rail carried an estimated 28 percent of ton kilometers in 1972 and 29 percent in 1991. Combination trucks increased their share from 17 to 20 percent. Changes in the energy intensity of ton kilometer movements tended to increase energy use slightly. Rail freight joules per ton kilometer, however, declined from 510,268 in 1972 to just over 288,380 in 1992. The energy intensiveness of domestic waterborne commerce shows a more erratic but still overall downward trend.

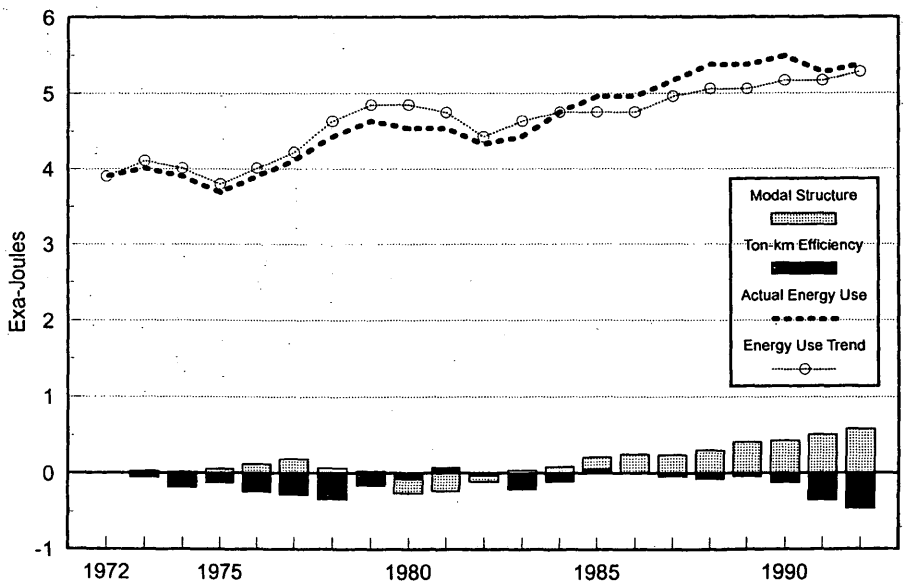

FIGURE 4 Freight energy use.

The factor most responsible for the apparent decline in freight energy efficiency is fewer tons per truck. The data are rough estimates and could be subject to substantial error, but what little other evidence there is tends to corroborate decreasing heavy-truck load factors. The Census of Transportation Truck Inventory and Use Survey (TIUS) indicates that the average load carried by combination trucks declined from 16 tons (17.7 short tons) in 1982 to 14.42 tons (15.9 short tons) in 1987 (these estimates are about twice those shown in Table 1, which are certainly biased downward). The TIUS data also suggest a decline in tons carried per heavy single-unit truck. Factors such as the changing composition and delivery requirements of freight and greater movements with part loads or empty backhauls appear to have more than offset the potential for larger trucks to increase truck load factors. Because trucks account for the majority of freight energy use, these apparent changes in truck ton kilometer efficiencies offset changes in the other modes.

In contrast, rail freight movements show enormous efficiency gains that are primarily due to increased carloads. If the 1992 rail ton kilometers had been moved at 1972 energy intensities, 75 percent more energy would have been required (Figure 5). Nearly all (85 percent) of the 0.35-EJ (0.33-quad) savings was achieved by increasing railroad carload factors from 22 tons per car in 1972 to 36 tons in 1992. More than any other mode, the rail mode has reduced energy intensity by improving the efficiency of its operations (perhaps aided by the changing composition of its freight). There must certainly have been technological efficiency improvements to vehicles, however; otherwise energy use per carload would have increased as carloadings increased.

LIGHT-DUTY-VEHICLE FUEL ECONOMY

The fuel economy of new passenger cars and light trucks improved dramatically in the decade following the oil price shock of 1973–1974. Those gains were not reversed by the price collapse in 1986 that returned motor fuel prices near to pre-1973 levels. Both passenger-car and light-truck kilometer per liter remained just above the levels required by federal automotive fuel economy standards despite falling gasoline prices and waning interest in kilometer per liter on the part of car buyers. Trends in the sizes and types of vehicles purchased had little to do with the fuel economy trends. Over the past two decades, light-truck sales boomed while demand for passenger cars became sluggish. Sales by market segment have waxed and waned in complex patterns. In the 1980s vehicle performance increased dramatically. Vehicle weight reductions made in the 1970s were reversed completely for light trucks and only partially for passenger cars. In this section, the Divisia method is used to analyze the effects of sales mix, and constant elasticity methods are used to analyze the impacts of weight and performance. All of the data used are from the Environmental Protection Agency's (EPA's) data base of light-duty vehicle fuel economy (*7*).

The key to past increases in the fuel economy of light-duty vehicles has been the improvement in km/L of all types of vehicles—large and small, car and truck. Analysis of the effects of performance and weight on fuel economy using a constant elasticity method revealed the importance of technological gains. If neither weight nor horsepower-to-weight ratios had changed since 1975, the average fuel economy of light-duty vehicles would be the same as it is today, 10.63 km/L (25 mpg). In other words, vehicle technology has been improved to the extent that a vehicle of the same size performance and weight getting 6.38 km/L (15 mpg) in 1975 would get 10.63 km/L (25 mpg) using today's technology.

Changes in Vehicle Sales Mix

From 6.50 km/L (15.3 mpg) in 1975, the fuel economy of new light-duty vehicles increased to a peak of 11 km/L (25.9 mpg) in 1987 and stands at 10.63 km/L (25.0 mpg) today (Figure 6). Essentially all (97 percent) of the 60 percent fuel economy gain had been achieved by 1982. Neither passenger-car nor light-truck fuel economy has changed significantly for more than a decade.

Since 1975 light-truck sales have nearly doubled because of the increased popularity of minivans and sport utility vehicles; passenger car sales have fluctuated near 10 million units annually. As a result, the market share of light trucks increased from 19.4 to 34.2 per-

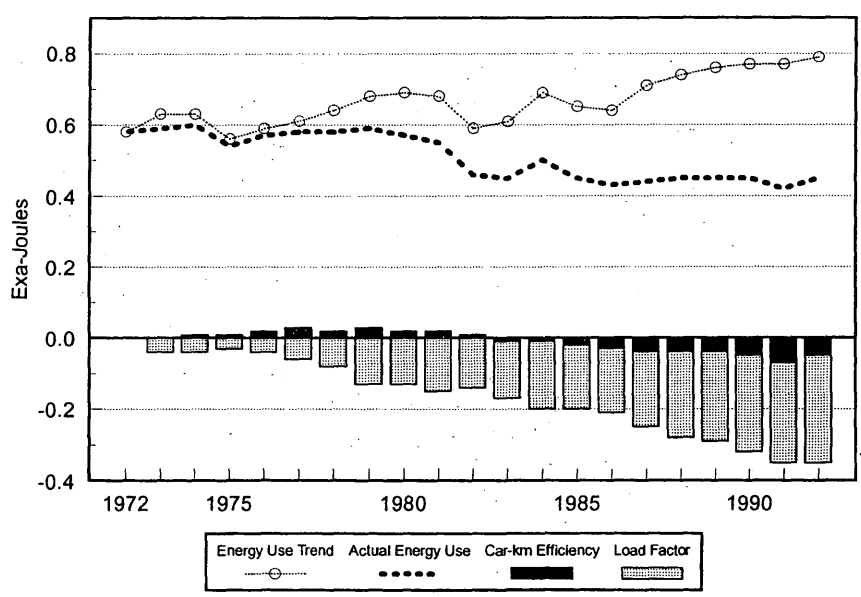

FIGURE 5 Rail freight energy use.

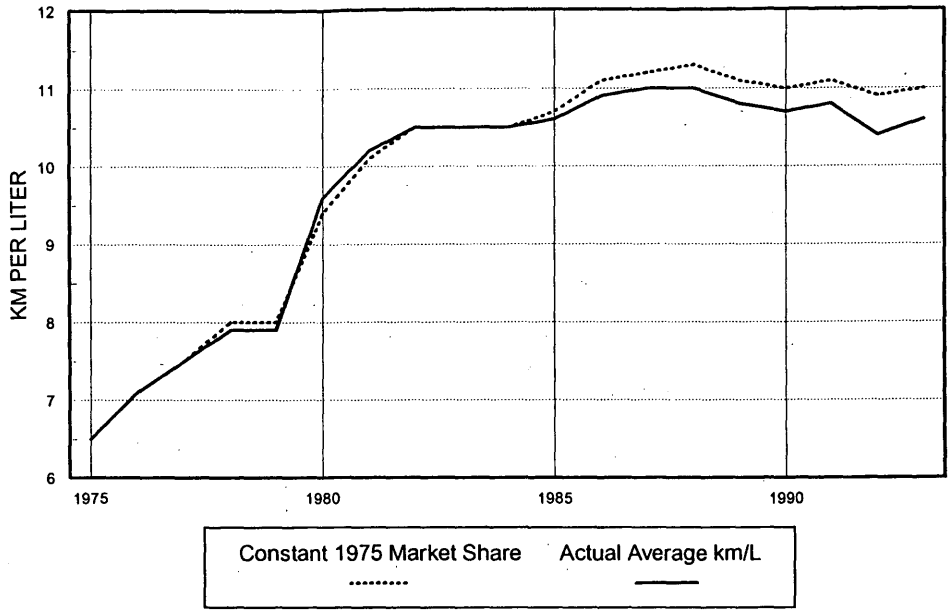

FIGURE 6 New light-duty-vehicle fuel economy.

cent. Because light-truck km/L averages only about 75 percent of passenger-car km/L, the market shift to light trucks might have been expected to seriously depress overall fuel economy. The Divisia analysis reveals that the shift to light trucks brought overall light-duty-vehicle km/L down by less than 0.425 km/L (1 mpg) (4 percent). There are two reasons for this. First, both passenger-car and light-truck km/L increased significantly over the period. Second, because average fuel economy is a weighted harmonic rather than a simple arithmetic mean, changes in market shares have less impact than intuition suggests.

Another misconception is that fuel economy increased because consumers decided to buy smaller cars. The sales mix among classes of car size based on interior volume is nearly the same today as in 1975 and, as a result, has been a minor factor in fuel economy trends. The weight and exterior dimensions of passenger cars have decreased, but the room available for driver and passengers has not.

Shifts in sales among vehicle classes have had little impact on fuel economy. The increased share of light trucks tended to reduce light-duty-vehicle fuel economy. Yet, within the car and light-truck markets, the sales shifts had the opposite effect. For passenger cars, sales shifts boosted km/L by a fraction out of a 5.1-km/L gain. For light trucks, sales shifts had a much larger beneficial impact, about 0.85 out of 12.98 km/L (2 out of 7 mpg). Thus, although the shift to light trucks tended to decrease the fuel economy of the light-duty fleet, the shift within the light-truck segment tended to increase it (Figure 7). Consumers moved away from passenger cars to light trucks, but the light trucks that they favored are basically passenger vehicles: minivans and small sport utility trucks. The net result of

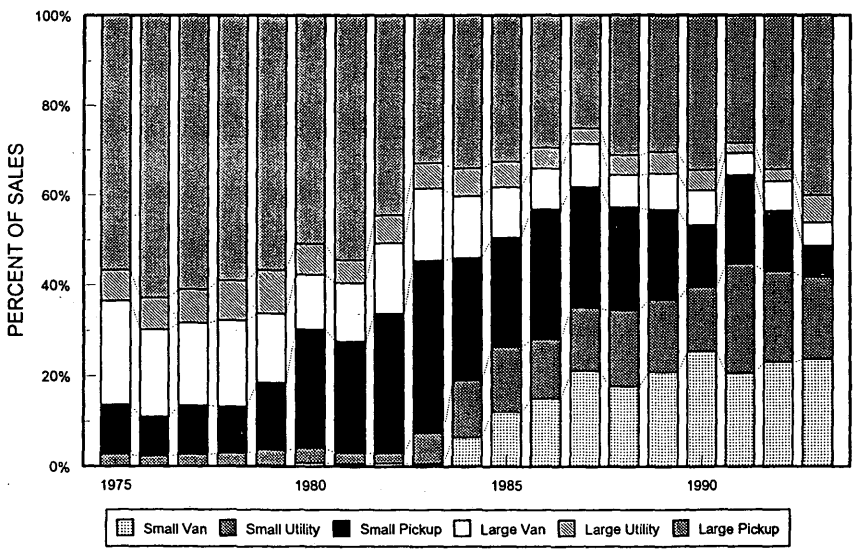

FIGURE 7 Light-truck market shares.

sales shifts among classes of cars and trucks and between cars and trucks has been to slightly increase the fuel economy of light-duty vehicles.

Changes in Performance and Weight, 1975–1993

Since 1975 passenger cars have become lighter and more powerful. The average passenger car is 363 kg (800 lb) lighter today than it was in 1975 (Figure 8). Light-truck weight fell initially but, like most dieters, light trucks have regained all of the weight that they lost during the 1980s. Measured in terms of the ratio of power to weight, performance is up 30 percent for passenger cars and 15 percent for light trucks (Figure 8). Zero–96 km/hr (0–60 mph) acceleration times are correspondingly down, 20 percent for cars and more than 10 percent for light trucks since 1975. These trends have important implications for fuel economy since, holding technology constant, weight (or mass) is the most important determinant of vehicle energy use and power is second (*9*). In the late 1970s, fuel economy gains were aided by stripping 454 kg (1,000 lb) from passenger cars and about 136 kg (300 lb) from light trucks. In the latter half of the 1980s and early 1990s, km/L gains were maintained in the face of rising weights and performance levels.

To analyze the effects of weight and power on km/L, a constant elasticity method is used. The km/L at 1975 weight and performance ($kmpl_y$) in any year, y, is computed from the actual fuel economy ($KMPL_y$) by the following formula:

$$kmpl_y = KMPL_y \left(\frac{W_y}{W_0}\right)^{\alpha} \left(\frac{P_y}{P_0}\right)^{\beta} \tag{7}$$

where W is weight and P performance in years y and 0, and α and β are the constant elasticity parameters. The elasticity values used are $\alpha = -0.66$ (*10*, p.112) and $\beta = -0.34$. [DeCicco and Ross (*11*) cite an elasticity of 0.44 with respect to 0–96 km/hr (0–60 mph) acceleration time. On the basis of work by Murrell et al. (*7*), an elasticity of acceleration time, with respect to the ratio of horsepower to weight, is estimated at -0.77. This implies an elasticity of KMPL with respect to P of -0.34.] In a previous analysis of fuel economy changes during 1979–1990, Energy and Environmental Analysis, Inc. (*12*) used weight and performance elasticities of $\alpha = -0.66$ and $\beta = -0.29$.

If the weight of light-duty vehicles had not been decreased, all else constant, passenger cars would be getting about 10.2 km/L (24 mpg) instead of 11.9 km/L (28 mpg) (Figure 9). Performance increases, on the other hand, have cost cars about 1.1 km/L (2.5 mpg). At 1975 performance levels, the 1993 new car fleet would have averaged 13 km/L (30.6 mpg) instead of 11.9 km/L (28.0 mpg). Had there been no changes in performance or weight, the 1815-kg (4,000-lb) "gas guzzlers" of 1975 vintage, using today's fuel economy technology, would still get 11.22 km/L (26.4 mpg) as compared with 6.72 km/L (15.8 mpg) in 1975. The curve labeled "Constant 1975 Weight and P" in Figure 9 represents the progress of fuel economy technology. For passenger cars, this curve trends upward at an almost constant rate of 0.255 km/L/year (0.6 mpg/year) and has continued its climb despite the leveling off of actual new car km/L.

Weight has had a negligible effect on light-truck km/L, but increased horsepower has reduced light-truck fuel economy by 0.425 km/L (1 mpg). Technological improvements do not show the same steady rate of advance as for passenger cars. The curve suggests that fuel economy technology has been applied in a very different manner in the light-truck market.

Overall, weight reduction has raised light-duty-vehicle km/L by about 0.85 km/L (2 mpg), and performance increases have reduced light-duty-vehicle km/L by about 0.85 km/L (2 mpg). Had neither changed since 1975, the combined average km/L of passenger cars and light trucks would be only 0.128 km/L (0.3 mpg) lower than the actual 1993 value.

CONCLUSIONS

At 1972 energy intensities and modal shares, the passenger and freight movements accomplished in 1992 would have required 4.2 EJ (17 percent) more energy. Trends in energy intensity vary greatly across transport modes. Commercial air travel halved energy use

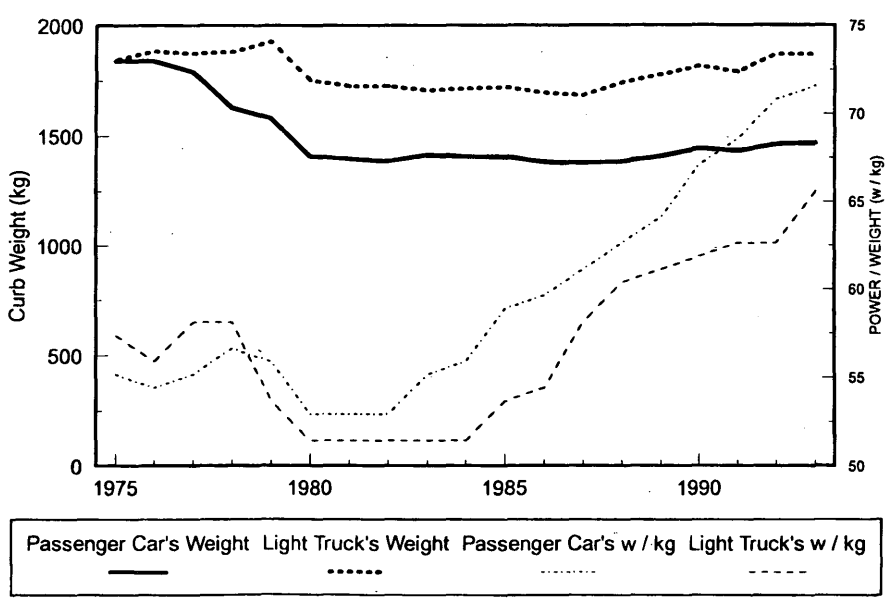

FIGURE 8 Passenger-car and light-truck weight and performance.

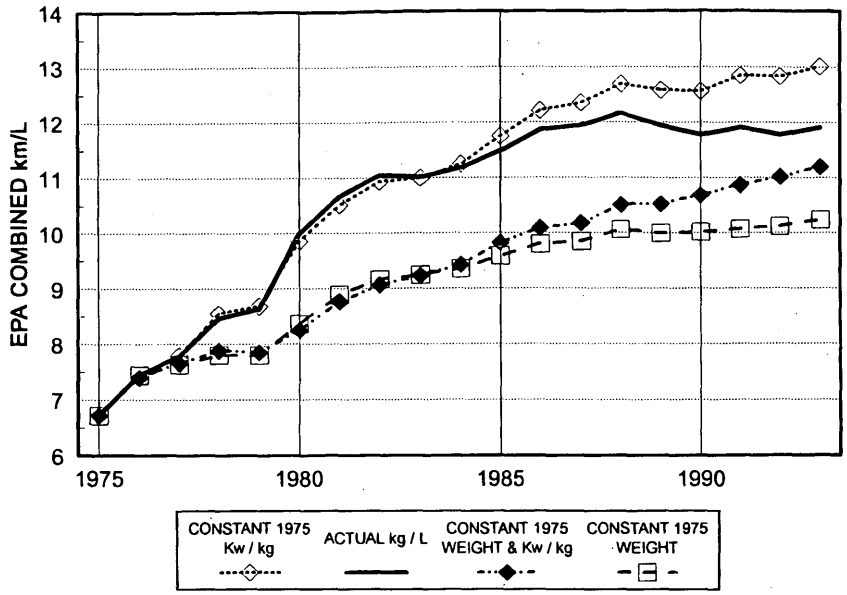

FIGURE 9 Effects of weight and horsepower on passenger-car fuel economy.

per passenger kilometer. The on-road fuel economy of light-duty vehicles improved 50 percent, from about 5.48 km/L (12.9 mpg) in 1972 to 8.245 km/L (19.4 mpg) in 1992, but the average number of passengers per vehicle dropped 25 percent, from 2.1 to 1.6, erasing half of the potential energy savings. In contrast, average energy use per ton kilometer of freight has remained essentially constant. Rail energy use per ton kilometer decreased by more than 40 percent, largely because of increased load factors. Heavy-truck load factors, in contrast, appear to have declined significantly. The increased energy intensity of truck freight and trucking's greater share of intercity ton kilometers appear to have offset rail's energy intensity reductions, resulting in nearly a constant energy intensity for freight movements over the past 20 years. For the transport sector as a whole, modal structure has been relatively unimportant compared with efficiency improvements within modes.

There is no single explanation for the varied energy intensity trends of different modes. The oil price shocks of 1973–1974 and 1979–1980 played an important role in focusing attention on energy efficiency and providing an economic incentive to reduce energy intensity by all modes, but this does not explain why modal responses have been so different. Furthermore, from a high of \$283/M^3 (\$45/barrel) (1987 dollars) in 1981, crude oil prices fell to \$176/M^3 (\$28/barrel) in 1985 and then crashed to \$94.36/M^3 (\$15/barrel) in 1986. For nearly a decade, energy prices have not signaled to the market that efficiency improvements are needed. There have also been no new regulatory initiatives to boost energy efficiency, and the fuel economy standards in place have been held nearly constant since 1985.

The analysis of light-duty-vehicle fuel economy trends from 1975 to 1993 has shown clearly that technology, rather than trends in vehicle sales, has been the force behind past fuel economy increases. The growing market share of lower-km/L light trucks has been accompanied by a transformation of the average light truck, making it more like a passenger car. The net result has been no impact on overall light-duty-vehicle km/L. Increases in vehicle performance have largely offset decreases in passenger-car weight, once again with little or no net impact on km/L. It appears that improved technology, driven in large part by federal fuel economy standards (*13*), is responsible for nearly all of the rise in km/L.

According to FHWA, the in-use fuel economy of passenger cars and light trucks declined in 1992 for the first time in 20 years and decreased again in 1993. Though contrary to nearly all past predictions, in hindsight this is no surprise since the fuel economy of new light-duty vehicles is no higher today than it was 12 years ago. Fuel economy gains from the replacement of older vehicles with low fuel economy with newer, more efficient ones have been largely played out. The countereffects of increasing urbanization and traffic congestion now appear to be causing in-use fuel economy to decline.

Today, energy use in transportation is on the rise at a rate just slightly lower than the growth of the economy. Energy efficiency, though up slightly in some areas, is down in others, and the overall rate of improvement appears to be slowing. If energy prices remain at current levels and no other significant actions are taken, there is little reason to expect anything else.

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Impact on Street Pavements of Buses Fueled by Compressed Natural Gas

ROBERT HARRISON, W. RONALD HUDSON, AND DINGYI YANG

The federal Clean Air Act Amendments of 1990 and the Energy Policy Act of 1992, along with other state regulations, have stimulated or mandated the use of alternative fuels to power transit system bus fleets. Among such fuels, compressed natural gas (CNG) is attractive, even though it must be stored in robust, pressurized cylinders capable of withstanding pressures up to 34 450 kPa (5,000 psi). Such systems are typically heavier than conventional diesel storage tanks. As a result, gross vehicle weight is raised, sometimes significantly, which then increases the consumption of the pavement over which CNG buses operate. Capital Metro, the Austin, Texas, transit authority, is evaluating a number of CNG-fueled buses. As part of the U.S. Department of Transportation's University Transportation Centers Program, the scale of incremental pavement consumption associated with the operation of these buses was studied. The study suggests that replacing current vehicles with CNG-powered models using aluminum storage tanks would raise average network equivalent single-axle impacts by about 6 percent, which means an increase in total overlay rehabilitation costs across the network of more than 4 percent a year. Finally, it recommends that a full cost study be undertaken to evaluate the adoption of alternative bus fuels, including its pavement and environmental impacts.

The study evaluated the impact of both conventional diesel and compressed natural gas (CNG) transit buses on route pavement networks in Austin, Texas. Because new conventional diesel buses had already increased pavement consumption on city routes, there was a concern that even heavier CNG buses would worsen the situation. The study, sponsored by the U.S. Department of Transportation's University Transportation Centers Program (UTCP), focused on measuring this impact for setting design, performance standard, and cost recovery mechanisms for bus routes (*1*). [It should be noted that throughout this paper, the term "*consumption*" is used instead of "*deterioration.*" Since the study addressed axle load impacts (excluding broader deterioration issues such as climate) in the context of design standards, budget, and cost recovery, the term "*consumption*" was considered more accurate.]

It is well known that U.S. transportation is highly dependent on oil derivatives, more than half of which are imported (*2*). Despite improvements in vehicle fuel efficiency since the mid-1970s, aggregate petroleum consumption has continued to grow, driven principally by vehicle ownership and total miles of travel. Strategic concerns over such dependency and concern about air quality issues have combined to sustain momentum for policies that encourage the adoption of alternative fuels.

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New policies and enacting legislation include federal and state regulations, such as the Alternative Motor Fuel Act of 1988, the Clean Air Act Amendments of 1990, the Intermodal Surface Transportation Efficiency Act of 1991, and the Energy Policy Act of 1992. Although each law addresses particular issues related to transportation, all encourage the development and use of alternative fuels. In 1989 Texas became the first state to mandate the development and use of alternative fuels in certain state- and municipally owned fleets. Under this mandate, 90 percent of these fleet vehicles must be capable of operating on alternative fuels by 1998 (*3*).

Five alternative fuels have been recognized by policy makers, namely, natural gas, methanol, ethanol, propane gas, and electricity. Among these fuels, natural gas is plentiful and, accordingly, low in price. For transportation purposes, it can be stored in either liquefied or compressed forms. Liquefaction occurs when temperatures are reached below the boiling point of −161°C (−270°F), thus requiring a highly insulated and expensive storage process. Although some city transit systems (such as Houston's METRO) are experimenting with liquefied gas, natural gas in a compressed state is likely to remain the preferred alternative transit bus fuel in this decade.

However, standards require that CNG be stored in cylinders that withstand pressures of at least 34 450 kPa (5,000 psi). Cylinders can be made from steel, steel composite, or aluminum composite; because aluminum composite cylinders are about 50 percent lighter than steel cylinders, they are attractive to mechanical engineers concerned with limiting unladen vehicular weight (*4*). Usually, cylinder capacity is expressed in liters of water, with 1 cylinder liter containing 0.16 kg (0.36 lb) of natural gas at a standard working pressure of 20 670 kPa (3,000 psi) and temperature of 21°C (70°F). The ratio of the weight (diesel fuel plus tanks) to the volume of gallons of conventional diesel fuel tanks is 4.75 kg/3.785 L (10.46 lb/gal) (*5*). Using a compound factor of approximately 1.3 to include the additional weight to hold cylinders and the reduction of fuel economy due to the extra weight (*6*), the CNG bus would carry an additional 7.7 kg (17 lb) for each equivalent 3.785 L (1 gal) of conventional fuel. If a diesel bus with a typical curb weight of 12 712 kg (28,000 lb) and a 454-L (120-gal) diesel fuel capacity used CNG to achieve an equivalent mileage range, the bus would have to carry an additional 921.6 kg (2,030 lb), representing a 7.3 percent increase in unladen weight.

The CNG fuel cylinders are typically mounted under the bus floor, such as with the Transportation Manufacturing Corporation (TMC) CNG bus, the Flexible CNG bus, and the Blue Bird CNG bus. In 1993 TMC delivered 30 CNG-fueled buses, 12.2 m (40 ft) long with 43 seats, to the Capital Metro Transit System of Austin. Currently, Capital Metro operates these TMC CNG buses on several Austin routes, and these are the vehicle types used to model pavement impacts in this paper.

PASSENGER LOADING AND AXLE LOAD OF BUSES

Relationships between axle loading and pavement deterioration were developed originally at the AASHO Road Test (1958–1961), where the concept of equivalent single-axle loads (ESALs) was developed. It permits various axle loads to be expressed as units equivalent to a standard 18,000-lb axle load, which is used in pavement design work. The relationship between load and pavement damage was developed empirically and based on observations taken at the AASHO Road Test. The relative effect, to a standard 8172-kg (18,000-lb) single axle with dual tires, was related to the ratio of any specified axle load to 8172 kg (18,000 lb) raised to the fourth power (*7,8*). ESAL calculations therefore allow different bus loads—both from unladen weight and passengers—to be related to pavement consumption.

In the study of bus pavement impacts, passenger occupancy is an important factor in determining bus-ESALs. Bus payloads differ from those of trucks because loading frequencies change with boarding and alighting at a rate greater than that of typical freight hauls. The study method included a survey of occupancy rates along each route to determine passenger occupancy patterns (and loads) for calculating pavement consumption impacts.

Although it was found that passenger demand reached 1.5 times the seating capacity (about 75) at peak times, average passenger occupancy is generally between one-third to one-half seating capacity. From the survey results, route sections and average loads were categorized as follows:

1. Highest-occupancy sections (25 passengers),
2. Dense-occupancy sections (20 passengers),
3. Medium-occupancy sections (15 passengers),
4. Low-occupancy sections (10 passengers), and
5. Lowest-occupancy sections (5 passengers).

Additionally, using passenger seating patterns observed in this survey, the center of gravity of passenger loading was determined to lie at the geometric center of the seating area. From this determination the passenger loading between axles was estimated to be 0.4 on the front axle and 0.6 on the rear axle (*1*). The marginal effect of this is to further increase weight distribution on the rear axle, therefore raising ESAL values.

The ESALs of the major bus models on flexible pavements are given in Table 1. Table 2 presents the impact of passenger occupancy on the front and rear axles of the CNG and GILLIG 1100 buses in Austin. Passenger loads have a pronounced effect on ESAL impacts. An increase of occupancy from 0 to 150 percent (peak load) of seating capacity raises the total ESALs from 100 to 358 percent. At this point, the ESAL of the rear axle is 4.31 and accounts for 93 percent of total bus ESALs. The relationship between passenger occupancy and ESALs using a GILLIG 1100 bus is shown in Figure 1.

Standard ESAL analysis indicates that one loaded GILLIG 1100 bus is equivalent to 35,400 small cars [gross vehicle weight (GVW) 908 kg (2,000 lb), single-axle load equal to 454 kg (1,000 lb)], or 4,800 medium cars [GVW 1816 kg (4,000 lb), single-axle load equal to 908 kg (2,000 lb)], or 1,710 pickups [GVW 2497 kg

TABLE 1 ESAL Factor for Different Buses

	TMC CNG diesel bus		GILLIG 1100 diesel bus		GILLIG 1700 diesel bus		GILLIG 1600 diesel bus	
Seat Capacity	43		47		39		29	
Curb Weight (kg/lb.)	13,311 / 29,320		12,830 / 28,260		11,985 / 26,400		11,377 / 25,060	
	Pt=2.0	2.5	2.0	2.5	2.0	2.5	2.0	2.5
Number of passengers	SN=2.5	3.0	2.5	3.0	2.5	3.0	2.5	3.0
0	1.349	1.347	1.292	1.287	1.040	1.057	0.970	0.987
5	1.494	1.476	1.433	1.411	1.158	1.163	1.081	1.087
10	1.653	1.615	1.586	1.544	1.287	1.277	1.203	1.195
15	1.824	1.764	1.751	1.688	1.427	1.401	1.335	1.311
20	2.009	1.923	1.930	1.842	1.579	1.533	1.479	1.436
25	2.210	2.095	2.124	2.008	1.744	1.676	1.635	1.571
30	2.425	2.278	2.333	2.185	1.922	1.829	1.804	1.717
35	2.658	2.474	2.558	2.375	2.115	1.994	1.987	1.873
40	2.908	2.684	2.800	2.578	2.323	2.170	2.184	2.040
45	3.176	2.908	3.060	2.795	2.547	2.359	2.397	2.219
50	3.464	3.147	3.339	3.027	2.788	2.561	—	—
55	3.773	3.402	3.639	3.274	3.047	2.777	—	—
60	4.103	3.673	3.959	3.538	3.325	3.008	—	—
65	4.456	3.962	4.302	3.819	—	—	—	—
70	—	—	4.668	4.117	—	—	—	—

Notes:
Pt = Pavement Terminal Serviceability (Present Serviceability Index-PSI-Units)
SN = Structural number of pavement
"—" = not applicable; seat capacity exceeds design capacity

TABLE 2 Passenger and Axle Load Distributions for CNG and GILLIG 1100 Diesel Bus

Types of Buses:		TMC (CNG)		GILLIG 1100	
Curb Weight (kg):		13,311		12,830	
Seating Capacity:		43		47	
Type of Axle		Front	Rear	Front	Rear
Passenger Load Distribution:		0.4	0.6	0.4	0.6
		Axle Load (kN)		Axle Load (kN)	
Number of Passengers	Passenger Loads (kN)	Front	Rear	Front	Rear
0	0.00	46.17	84.24	41.81	83.89
5	3.33	47.50	86.25	43.14	85.89
10	6.67	48.84	88.25	44.48	87.89
15	10.08	50.17	90.25	45.81	89.89
20	13.34	51.51	92.25	47.14	91.89
25	16.68	52.84	94.25	48.48	93.90
30	20.01	54.18	96.25	49.81	95.90
35	23.35	55.51	98.26	51.15	97.90
40	26.68	56.84	100.26	52.48	99.90
45	30.02	58.18	102.26	53.82	101.90
50	33.36	59.51	104.26	55.15	103.90
55	36.69	60.85	106.26	56.48	105.91
60	40.03	62.18	108.26	57.82	107.91
65	43.36	63.52	110.27	59.15	109.91
70	46.70	—	—	60.49	111.91

1 kg=0.453 lb
1 kN=4.448 kip
"—" = not applicable; seat capacity exceeds design capacity

(5,500 lb), single-axle load equal to 1248 kg (2,750 lb)]. Using this method, one loaded TMC CNG bus corresponds to 36,800 small cars, or 5,000 medium cars, or 1,750 pickups. Although passenger cars and pickups account for up to 90 and 9 percent of average daily traffic (ADT) on Texas city streets, respectively, the ESAL analysis showed that they have such a small influence on pavement design that consumption was linked only to bus and truck operations.

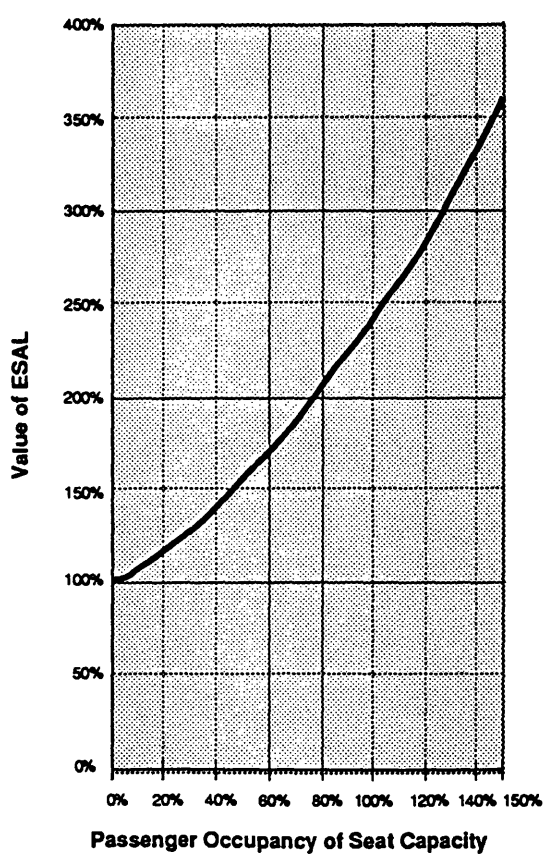

FIGURE 1 Occupancy rates versus ESAL impacts.

CNG BUS OPERATIONS

ESAL per-lane-mile calculations were chosen to evaluate an entire bus route with differing section lengths. This is defined as the ESAL impacts on any homogeneous route section multiplied by route length, which, when aggregated over the route and divided by route length, gives mean ESAL values.

However, when evaluating pavement wear, it is important to evaluate associated truck traffic volume, since buses share city streets with trucks that also contribute to pavement consumption. There are relatively few large trucks (defined as three or more axles) on Austin city streets. Using vehicle classification and registration data (*9*), the percentage of trucks in Austin ADT is estimated as 1 percent for arterial streets, 0.8 percent for collector streets, and 0.6 percent for residential streets. The reason for Austin's low percentage of trucks is that the city is essentially a university community and has no heavy industries or significant commercial sectors that require heavy truck operations.

One characteristic of the Austin bus transit system is that routes often share major streets in the downtown area. For instance, as many as 14 bus routes share a section of 11th Street in central Austin. Additionally, bus numbers may differ depending on their direction of travel on the same street, which complicates bus ESAL computations.

Three major bus routes, reflecting a range of pavement types, were chosen for the study analysis. All routes are operated with GILLIG 1100 diesel buses, and are as follows:

- *IF route (university shuttle bus),* with a length of about 4.8 km (3.0 mi). The bus runs every 4 or 6 min throughout the day, with 158 total repetitions in a weekday.

- *FW bus route (university shuttle bus),* with a length of about 7.36 km (4.6 mi) excluding the freeway segment. The bus runs every 6 to 8 min most of the day, with about 105 repetitions in a weekday.
- *No. 1 bus route (Metro bus),* with a length of about 15 km (9.5 mi). The bus runs every 10 min, with 84 repetitions during a weekday.

The key routes were then broken down into homogeneous sections with respect to pavement type and design. Under the CNG bus application, and in normal traffic, the ESAL increase among sections of the IF bus route ranges from 3.5 to 8.0 percent; over the entire IF bus route it averages 6.1 percent. The ESAL increase among sections of the FW bus route ranges between 2.7 and 9.3 percent, and for the entire FW bus route averages 7.3 percent. The ESAL increase among sections of the No. 1 bus route lies between 1.6 and 34.5 percent, and for the entire No. 1 bus route the average is 10.9 percent.

The entire route system is estimated at about 1536 lane-km (960 lane-mi) of the total 8000 lane-km (5,000 lane-mi) streets, and the percentage increase of ESAL estimated under CNG bus application is 6.7 percent. This number is based on buses alone. If trucks on bus routes were 15 percent of total ESALs, the predicted ESAL increase would fall to 5.7 percent rather than 6.7 percent. If the pavement has a 20-year design life, the service life reduction under an increase of 6 percent ESAL application is estimated as slightly over 1 year.

STREET REHABILITATION

The three routes were also used to estimate the rehabilitation cost (R-cost). A pavement rehabilitation model, Municipal Pavement Rehabilitation Design System Version 1.0, was used to determine these effects. First developed by ARE Engineering Consultants, Austin, Texas, and applied in the city of Austin, the model considers pavement condition and remaining life, structure and material properties, traffic parameters, and construction unit costs within a life-cycle cost analysis framework (*10*). Impacts are evaluated by reporting the percentage increase of overlay rehabilitation cost, and results based on a 20-year design period are given in Tables 3 and 4, which examine the IF and FW routes. The remaining life percentage (RL), a model input, is estimated on three indexes: surface distress index (SDI), riding comfort index (RCI), and pavement quality index (PQI)—each taken from the data base of the Street and Bridge Division of the city of Austin and information from a study in Alberta (*11*). The maximum and minimum values for the three indexes are SDI (10, 3.5), RCI (10, 5.5), and PQI (10, 4.7), and any index can be used to determine the remaining life of a pavement. Using PQI, for example:

$$RL_{estimate}\ \% = (PQI_{to\ date} - PQI_{min})/(PQI_{max} - PQI_{min}) \times 100 \qquad (1)$$

In this paper, a combination of the three indexes is used. First, RL is calculated from each index in the manner described, and the three RL calculations are combined to form a single value using weights of 0.6 for SDI and 0.2 for RCI and PQI. The date when the pavement was last improved is used as a base, and the RL is calculated as a percentage and rounded to 5 percent increments. The structure types and financial data are based on street category and cost information obtained from the Street and Bridge Division of the city of Austin (*12*). In addition, the traffic growth rate is estimated as 1 percent, on the basis of the projection of population growth and truck registration data (*13*).

These tables show that the average R-cost increment weighted for the IF bus route is 6.2 percent, which equates to \$1.39/yd^2 weighted by section length. The range of R-cost increment for sections of the IF route is 2.1 to 13.4 percent.

The No. 1 bus route has a weighted average cost increment of 5 percent, which is equivalent to \$1.33/yd^2. For sections of the FW route, the range of cost increment of sections in this route is from 0 to 18.6 percent.

TABLE 3 Rehabilitation (Overlay) Cost Comparison for IF Bus Route

Section Number	Structure Type Index	Remaining Life (RL) (%)	Cumulated ESAL W/Diesel bus application	Cumulated ESAL W/CNG bus application	ESAL Increase (%)	Cost (\$/SY) under Diesel bus application	Cost (\$/SY) under CNG bus application	Cost Increase (%)
1	2	20	1997000	2075000	3.9	28.31	28.9	2.1
2	2	70	2125000	2210000	4.0	8.52	9.06	6.3
3	1	30	2032000	2116000	4.1	18.57	18.99	2.3
4	1	20	2044000	2129000	4.2	21.22	21.84	2.9
5	2	35	2493000	2692000	8.0	30.42	32.37	6.4
6	2	35	2723000	2931000	7.6	33.41	35.33	5.7
7	2	60	2950000	3166000	7.3	16.64	18.45	10.9
8	2	60	3249000	3482000	7.2	18.67	20.07	7.5
9	2	60	3255000	3489000	7.2	19.21	20.1	4.6
10	2	20	3255000	3489000	7.2	44.13	47.19	6.9
11	2	70	3255000	3489000	7.2	19.89	22.56	13.4
13	2	15	3102000	3211000	3.5	34.3	35.19	2.6

Section 12 on 26th street is excluded from these calculations because it was just reconstructed in 1993.

TABLE 4 Rehabilitation (Overlay) Cost Comparison for FW Bus Route

Section Number	Structure Type Index	Remain Life (RL) (%)	Cumulated ESAL W/Diesel bus application	Cumulated ESAL W/CNG bus application	ESAL Increase (%)	Cost ($/SY) under Diesel bus application	Cost ($/SY) under CNG bus application	Cost Increase (%)
1	2	65	1399000	1455000	4.0	3.82	4.36	14.1
2a	2	25	1394000	1451000	4.1	15.44	15.99	3.6
2b	2	60	1394000	1451000	4.1	5.54	6.07	9.6
3	2	40	1633000	1779000	8.9	13.36	14.67	9.8
4	2	65	1657000	1804000	8.9	6.97	8.16	17.1
5	3	70	2415000	2480000	2.7	13.43	13.77	2.5
6a	3	55	3327000	3610000	8.5	22.94	24.42	6.5
6b	3	80	3327000	3610000	8.5	20.58	21.92	6.5
7	3	50	2793000	2991000	7.1	16.93	17.78	5.0
8	3	30	4087000	4345000	6.3	30.11	31.04	3.1
9	3	30	4333000	4672000	7.8	37.17	39.22	5.5
10	3	40	4350000	4692000	7.9	37.32	38.55	3.3
11	3	40	4694000	5037000	7.3	38.6	40.27	4.3
13	2	40	1532000	1594000	4.0	12.1	12.68	4.8
14	2	20	1532000	1594000	4.0	27.71	28.22	1.8

Section 12 on 26th street is excluded from these calculations because it was just reconstructed in 1993.

Since each section is an independent overlay design case, 45 design sections of the three pilot routes were considered to represent the whole route system. An estimate for a bus route was determined from the following:

$$\begin{aligned}&\text{Rehabilitation (overlay) cost increase (\%)}\\&= 3.2598 + 0.4595 \times [\text{ESAL increase (\%)}]\\&\quad + 0.0444 \times [\text{RL (\%)}] - 1.5177\\&\quad \times (\text{index number of structure type}) \qquad (2)\end{aligned}$$

where there are three structural types: Type 1, with an asphalt concrete surface layer of 7.6 cm (3 in.) and a base layer of 15.24 cm (6 in.); Type 2, with an asphalt concrete surface layer of 7.6 cm (3 in.) and a 25.4-cm (10-in.) base layer; and Type 3, with a 7.6-cm (3-in.) surface layer and a 30.48-cm (12-in.) base layer.

The data for remaining life and percentage ESAL increases were determined from the Austin city data base and study analysis, respectively, and are reported elsewhere, along with evaluations of other routes (*1*).

Additionally, the mean of the sample statistic RL is 45.2 percent, with a standard deviation of 19.8 percent. The mean of the ESAL percentage increase of the sample statistic is 9.6 percent, with a standard deviation of 8.9 percent, and the mean of the R-cost percentage increase of the sample statistic is 5.8 percent, with a standard deviation of 4.3 percent (*1*).

CONCLUSIONS

New technologies are increasingly being evaluated using systems processes for which all costs are identified and subjected to economic review. In this light, alternative fuels such as CNG should be subject to a full cost-benefit analysis, including pavement and the environmental impacts generally treated as externalities. Therefore, the traditional analysis of agency and vehicle cost trade-offs would be enhanced by the inclusion of safety, air quality, noise, and other impacts.

Addressing pavement issues, which are often ignored in alternative fuel analyses, current CNG systems raise the weight of transit buses and may impose additional stresses on route pavements. Accordingly, the impact of this marginal cost should be determined and included in any evaluation should it prove to be significant. Extrapolating the results of the sampled routes to the bus transit network in Austin, it is predicted that totally replacing diesel fuel with CNG stored in aluminum storage cylinders across the entire bus fleet would raise ESAL impacts by about 6 percent. If Austin had a more industrialized sector, the resulting truck traffic would cause the CNG bus impact to fall to around 4 percent.

Translating these impacts into rehabilitation costs, the Austin system under CNG bus transit operations would generate an additional overlay rehabilitation cost estimated at between 4 and 5 percent, slightly less than the rate of ESAL increase. Last year, the city of

Austin spent more than $75 million on rehabilitating bus routes, a figure that suggests the scale of potential CNG bus operations on the city's maintenance budget. Since these are nontrivial, it suggests that pavement impacts are a legitimate element to be evaluated in a full cost-benefit analysis of alternative fuel use for transit bus operations.

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Market for Electric Vehicles: Learning from Experience

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Following the zero-emission vehicle mandate of the California Air Resources Board (CARB), other states and countries are beginning to view electric vehicles as a means of reducing urban air pollution. However, duplication of the CARB mandate would face strong opposition from automobile makers and might not be effective in the marketplace. Successful introduction of electric vehicles in the short term will depend on car buyers' choosing cleanliness and quietness of electricity over the combined speed, power, range, and convenience of vehicles with internal combustion engines. This change in consumer choice could be forced by legislation or encouraged by taxes. Experience with attempts to introduce alternative fuels and to promote the use of transit can give insight into the effectiveness of different measures; such experience indicates that restrictions on the use of conventional vehicles are likely to be more effective than incentives for using electric vehicles. In the long run, electric vehicles will succeed in the market only if there is a radical shift in either technology or consumer preferences.

Around the world, electric vehicles are being developed, marketed, sold, and used, mainly as a result of the California Air Resources Board (CARB) mandate for the introduction of zero-emission vehicles (ZEVs). Automobile makers in North America, Europe, and Japan, aiming to maintain their Californian market share and to prepare for possible future developments in other markets, have at least tried to minimize risk by converting existing car models to operate on batteries and by undertaking new electric car designs. In some parts of the world, including France, Canada, and Switzerland, surplus baseload electricity generating capacity provides a supply-side push for the development of electric vehicles, and these countries have seen some of the first significant electric vehicle trials and marketing efforts.

Analysis of the market prospects for electric vehicles emerges from a variety of viewpoints. Analysts have their own justifications, based on differing perceptions of the mechanisms influencing the car market, for expectations ranging from the complete failure of electric vehicle technology to its emergence as the main successor to the internal combustion engine. This paper will outline the rationale behind the viewpoints and provide a synthesis.

Perhaps the most important point at the outset is that markets, especially those that depend strongly on culturally influenced tastes and on technology, are unpredictable. Attempts to predict the course of market penetration of a technology generally hinge on addressing limited sets of factors in this unpredictability. Thus, social scientists tend to focus on improving their understanding of what drives people's demand for the technology, whereas engineers may concentrate on the potential for designing and developing the technology to meet the needs of users.

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VIEWS OF MARKET FOR ELECTRIC VEHICLES

The views commonly found among the various disciplines involved in the electric vehicle market can be characterized as follows:

- *Engineers* usually design technology and infrastructure to meet a need or solve a problem. They may also have aesthetic preferences for particular solutions, such as electric drivetrains. These analysts can help to identify the range of consumers for whom electric vehicles are technically the best solution as well as the extent to which technology can provide a better match with consumer needs (*1,2*).
- *Microeconomic analysts* extend the engineering approach to take cost into account, often seeking the least-cost means of meeting a need. The market for electric vehicles then depends on their overall discounted lifetime cost relative to conventional vehicles. This approach is taken by DeLuchi (*3*) in his comparative analysis of gasoline, fuel cell, and electric vehicles; by the International Energy Agency (*4*) in a comparative analysis of gasoline, diesel, and compressed natural gas (CNG) vehicles; and by Energy Technology Support Unit (*5*) in a systems analysis study of energy technology options. The market identified for electric vehicles depends very much on the assumptions about costs. The expectation of high capital costs but low running costs leads to the conclusion that the best market is to be found where annual mileage is high. According to this approach, battery, electric motor, and motor controller costs must be reduced substantially and performance must improve if a significant market is to be found (*5*).
- *Econometric analysts* assume that consumer attitudes and preferences are the main determinant of market share and base analysis of future market developments on historical revealed or stated preference. Such analysis is perhaps best exemplified by Bunch et al. (*6*), who develop a model for the market share of a variety of alternative fuel and electric vehicles based on their characteristics (cost, range, performance, fuel availability, emissions, etc.) and on a stated preference survey in Southern California. The conclusion of this approach is that given the high cost and low performance of electric vehicles, they are unlikely to have a market without the pressure of regulations such as the CARB ZEV mandate.
- *Decision analysts* develop models of decision making and priority ranking. One description of decision making is given by Dietz and Stern (*7*), who develop a model of choice based on a limited number of variables or influences. Dietz and Stern emphasize the importance of peer group pressure and opinions in choice. Another model of the decision making process is discussed by Komor and Wiggins (*8*) for energy conservation measures; this analysis aims to go beyond linear correlations between the probability of consumers' taking action and the various factors that influence them (expected resulting change in comfort, peer group agreement, and

familiarity: "friends have done it," ease of taking the measure, and low cost of the measure). Instead, a decision tree is constructed, with each of these factors influencing the probability of action.

- *Psychological/attitudinal analysts* relate choice to consumer attitudes, needs, and personality attributes or to personal needs. Concerns about environmental issues are linked to action on these issues only by those who perceive the benefit of their action for themselves. Van Raaij and Verhallen (*9*), discussing energy conservation, explore the association between behavior and personality types. This approach is often used to estimate the potential market share of a new product using information about the number of people of each personality type in the population. Diekstra and Kroon (*10*) identify a range of needs or motivations associated with car use, ranging from freedom and power to love and protection.

Some analyses incorporate more than one of these views, and more views can be identified, but these are the main approaches that have been used in published literature. All are important in shedding light on factors that will influence the development of a market for electric vehicles, but none of them offers a complete or rigorous analysis of the issues. As such it is not surprising that their conclusions differ.

In combination they provide useful information. The engineer and microeconomist together tell us that pure electric vehicles are likely to be attractive only to users with high annual mileage and low variance in daily mileage with no need to be able to make trips of more than 100 mi. This characteristic restricts them to commercial and public-sector service applications and typically indicates a maximum market on the order of 5 to 10 percent of all light-duty vehicles.

Hybrid vehicles, which are attractive from the engineering point of view for their flexibility, are unattractive from the microeconomic point of view because they combine high capital with high running costs. They may have a larger market niche than pure electric vehicles: they would be of interest to those with a high annual urban mileage, low variance in daily urban mileage, and the need to use the same vehicle for long trips. These long trips would have to be frequent to justify the cost of the hybrid.

When information from the economist is combined with that from the engineer and the microeconomist, it can be seen that even if electric vehicles appear to meet the needs and cost constraints of consumers, they would not be the preferred technology given current preferences. This does not mean that there is no hope for electric vehicles, but it does mean that if a market is to be established for electric vehicles, preferences must change. The anthropologist, sociologist, and psychologist provide some insight into how this might happen.

CHANGING MARKETS

Before considering the ways that markets can be changed, it is important to consider whether we want them to change, or who wants them to change and who would prefer that they did not change, and why. As for electric vehicles, there are various reasons that some might wish to introduce them and others might prefer that they were not introduced to the market.

In favor of electric vehicles,

- There is an energy-related interest in electric vehicles because the electricity used to recharge their batteries can be derived from a wide variety of sources, reducing dependence on petroleum and fossil fuels in general and providing an opportunity to switch to renewable energy sources.
- There is a potential environmental interest in electric vehicles for their ability to reduce urban air pollution and noise as well as greenhouse gases in some cases (depending on the electricity source).
- Electric utilities may be interested in electric vehicles because not only do they provide a new market, but they can be recharged at night, providing a market for off-peak power.
- Some technologists may be interested in electric vehicles because they use a more aesthetically pleasing route of energy conversion than vehicles with internal combustion engines.
- Vehicle users may be interested in electric vehicles because they perceive them as clean, environment-friendly, quiet, durable, simple to drive, and technologically advanced. They may also be interested in attributes such as the capability to recharge the battery at home (*11*).

To the detriment of electric vehicles,

- Car manufacturers might prefer not to have electric vehicles introduced because they think it would increase their manufacturing costs, increase their exposure to risk, and require them to change their base of component suppliers (*12*).
- Oil companies might prefer not to have electric vehicles introduced because they could reduce the market for their main product.
- Some transportation and environmental interest groups might see electric vehicles as a distraction from the real need in the transport sector: a reduction in traffic volumes to address the combined problems of social equity, congestion, accidents, pollution, noise, and land use for roads.
- Vehicle users might be dissuaded from buying the vehicles by their high cost, lower acceleration, top speed, range, and carrying capacity and by long recharging times and inadequate recharging infrastructure.

Government and Electricity Industry Interest in Electric Vehicles

The implications of electric vehicles for energy and the environment depend heavily on the location in which they are used and the fuel and technology used for power generation. Where fossil fuels are used for power generation, primary energy use and hence greenhouse gas emissions for electric vehicles are likely to be of the same order of magnitude as those for gasoline or diesel vehicles (*1,13*). Table 1 compares emissions of local pollutants from electric vehicles with those from conventional and alternative fuel internal combustion engine vehicles. As the table indicates, emissions of carbon monoxide and volatile organic compounds (VOCs) fall when electric vehicles replace gasoline vehicles. However, NO_x and, in some instances, SO_x (not shown in the table) increase, especially where coal or fuel oil play a large part in power generation.

Electric vehicles will result in low levels of air pollution where the marginal source of electricity is nuclear power, hydroelectric, or renewables other than biomass. This applies in several Organization for Economic Cooperation and Development (OECD) countries, including Austria, Finland, France, Iceland, New Zealand, Norway, Sweden, and Switzerland, as well as parts of the United States and Canada. There may also be an environmental interest in electric vehicles where electricity is generated in remote regions or outside the area of concern.

TABLE 1 Operational Emissions from Alternative Fuel Cars

	CO	Non-methane VOC	NO_x	PM	Life-cycle Greenhouse Gases (CO_2 equivalent) note (e)	Notes
Internal Combustion Engine Vehicles: Estimated Exhaust Emissions, g/km						
Reformulated Gasoline/ 3 Way Catalyst/Closed Loop	0.7-1.5	0.06-0.14	0.08-0.3	0	222-268	(a)
Diesel/Oxidation Catalyst	0.2-0.5	0.1	0.6-0.8	0.2-0.3	183-266	(b)
CNG/3 Way Catalyst/Closed Loop	0.5-1	0.03-0.1	0.1-0.4	0	174-253	(c)
Hydrogen	0.01-0.02	0.005-0.01	0-0.5	0	29-48	(c)
Electric Vehicles: Estimated Power Station Emissions, g/km						
US Average Generating Mix	0.02	0.002	0.31	0	244-248	(d)
EU Average Generating Mix	0.04	0.007	0.64	0	214-218	(d)
Coal	0.03	0.003-0.02	0.51-1.33	0	344-358	(d)
Oil	0.03	0.005	0.34	0	297-301	(d)
Gas (Combined Cycle Gas Turbine)	0.08-0.12	0.004-0.01	0.14-0.26	0	174-188	(d)
Nuclear	0	0	0	0	59-63	(d)
Hydro	0	0	0	0	44-48	(d)

a. Based on (15,16)

b. Based on (16).

c. Based on (16,17,18)

d. Based on electric vehicle energy consumption and emissions from (1,13); US electricity generation emission factors from (19)and US generating mix and transmission/distribution losses from (20). Fossil fuel fired electricity generation also results in SO_2 emissions estimated at 0.9g/km for coal, 0.5g/km for oil-fired electricity (1,19). Technology changes driven by emission regulations are resulting in a rapid reduction in emissions of NO_x and SO_2 from power generation.

e. Ranges taken from (1,13,19). Emissions associated with vehicle manufacturing are based on the current fuel mix in the industry. Life-cycle greenhouse gas emissions from electric vehicles using electricity from nuclear power or hydro are mostly associated with vehicle manufacture.

The electricity supply industry is likely to be most supportive of electric vehicles as an off-peak power market where power plants with high fixed costs and low variable costs (e.g., coal and nuclear) are used to meet marginal demand. This suggests a different set of countries (*14*): Australia, Belgium, Denmark, France, Germany, Greece, Spain, the United Kingdom and, again, parts of the United States and Canada.

Consumer Interest in Electric Vehicles

One way to explore the potential electric vehicle market is to look at the historical market for technologies and fuels, especially those that have been promoted by governments or industries. There are many possible case studies—the best known are those of ethanol in Brazil and CNG in Canada and New Zealand. However, there are few real success stories among attempts to change the fuel used by car drivers. Three can be readily identified: LPG, still a minor fuel but one with an OECD-wide market share 18 times that of CNG in 1992 (*14*) and more than 20 percent of the light-duty vehicle fuel market in The Netherlands; diesel, which has become a major alternative to gasoline in many European and other countries; and unleaded gasoline, which has almost completely replaced leaded gasoline in North America and Japan and is rapidly doing so in Europe. Looking at experience with these three fuels can give some indication of the conditions required for a new fuel to enter the market. It is helpful to start by characterizing the three fuels and the vehicles that use them (Table 2).

Several points are illustrated in Table 2: consumers are more likely to use an alternative fuel that, does not require them to change their vehicle, is cheaper than the conventional fuel, is widely available, and is marketed intensively with a well-known brand name. Where a fuel or the vehicles that use it have disadvantages relative to conventional vehicles, a greater price incentive is needed to encourage its uptake. Thus, both diesel and LPG have achieved a significant market share only in countries where they are available at very low prices relative to gasoline—$0.30 to $0.60 less per liter or one- to two-thirds of the gasoline price. Unleaded gasoline requires discounts of only about $0.05/L to achieve larger market shares.

Table 3 gives details of discounted cash flow calculations for gasoline, diesel, LPG, and electric vehicles in France. Purchase and running costs for the gasoline and diesel vehicles are typical for France in 1992 (*2*). The price and tax rate for LPG and electricity are based on the average prices and taxes for light fuel oil and electricity, respectively, for domestic users in France for 1992 (*20*). The electric vehicle price range is based on that used by Deluchi (*3*). The lower ends of the alternative vehicle price ranges are intended to correspond to mass-produced original equipment manufacturers

TABLE 2 Alternative Fuel Vehicle Attributes and Market Share

Attribute	Unleaded Gasoline vs. Leaded Gasoline	Diesel vs. Gasoline	LPG vs. Gasoline.	Electric Vehicle vs. Gasoline
Need for change of car	Works in existing models, in some cases modifications required. Required in cars with catalytic converters.	Require OEM diesel car	Most existing models can be converted to dual-fuel LPG/gasoline.	Require OEM electric car
Car Retail Price (incl. tax)	Same	$0 to $2 800 higher	$250 to $1 100 higher	$5 000 to $10 000 higher
Fuel Retail Price (incl. tax)	11 ¢ lower to 3 ¢ higher per litre gasoline equivalent	1 to 65¢ lower per litre gasoline equivalent France about mid-range	10 to 60¢ lower per litre gasoline equivalent: Netherlands amongst lowest	50¢ to 85¢ lower per litre gasoline equivalent
Performance	Slightly lower acceleration and top speed reported in some cases	Lower top speed Early models were noisy and had starting problems in cold weather	Slightly lower acceleration and top speed in converted cars	*Either* lower acceleration and top speed with somewhat reduced carrying capacity and range *or* similar acceleration and top speed with greatly reduced carrying capacity and range
Range on Full Tank	Same	Longer	Shorter for same size tank	About one fifth to one third
Fuel Availability	Rapid uptake to near universal availability in most of OECD	Near universal availability	Limited availability	Limited availability initially but home recharge possible
Maintenance	Same	More frequent oil changes	Same	Less with mature technology
Reliability	Same	Better	Same	Better with mature technology
Vehicle life	Same	Up to twice as long for high annual mileage drivers	Same	Potentially much longer
Environmental Attributes Perceived by Public and Media	Perceived as "green" fuel	Perceived by some in Europe as environmentally better. Meets emission standards without catalyst. Emerging concern about particulates.	Perceived as environmentally better.	Perceived as environmentally "best"
Marketing	Enthusiastic and competitive oil company marketing making use of "green" image.	Limited car company marketing as "sensible" alternative to gasoline. French manufacturers most committed	Limited local marketing.	Depends on support from governments, major car manufacturers and utilities.
Outcome	Rapid uptake to near 100% of market	Slow uptake to 10% to 50% of market, highest in France	Moderately rapid uptake to < 30% of market in Netherlands, < 10% elsewhere	?

(OEM) vehicles and, with the exception of some diesel vehicles, are not likely to be achieved for several years.

Even when the higher vehicle cost is taken into account, and assuming that drivers choose between vehicles using a 30 percent discount rate, the levelized cost of driving an LPG or diesel vehicle can be much lower than that of driving a gasoline vehicle. The table indicates further that if electric vehicles and the electricity that they use were completely exempt from tax, they might be cheaper to operate than gasoline vehicles including tax in some circumstances. Without such exemptions they will probably remain considerably more expensive to operate than gasoline vehicles.

A simple engineering/microeconomic interpretation of the evidence presented so far in this paper would be that electric vehicles have little hope of being taken up in the market place, short of technological breakthroughs (probably in several areas of electric vehicle engineering but principally in battery technology) to reduce their cost and improve their performance. Bunch et al. (*6*) go a little farther than this and analyze the stated preference for vehicle attributes of potential vehicle buyers in Southern California. Their results indicate that given current preferences (which include a high value placed on vehicle cleanliness), not only are purchasers likely to be unwilling to buy low-performance, low-range electric vehicles that are more expensive than gasoline vehicles, but they are unlikely to buy them unless they are much cheaper than gasoline vehicles.

Other analytical approaches give different results. Turrentine and Sperling (*11*) have investigated the effects of offering test drives

TABLE 3 Cost of Running Alternative Fuel/Electric Cars

	Gasoline	Diesel		LPG		Electric	
		High	Low	High	Low	High	Low
Pre-tax vehicle cost ($)	15 168	17 443	15 168	16 083	15 384	24 768	20 928
Post-tax Car Cost ($)	**18 626**	**21 402**	**18 626**	**19 742**	**18 889**	**30 338**	**25 653**
Max. Distance Travelled (km)	160 000	200 000	320 000	160 000	160 000	320 000	320 000
Life (Body-Limited) (Years)	10.00	10.00	10.00	10.00	10.00	10.00	10.00
Pre-tax Price of Fuel ($/litre)	0.26	0.26	0.26	0.23	0.23	1.50	1.50
Fuel Excise Tax, $/litre gasoline equiv.	0.70	0.33	0.33	0.13	0.13	0.27	0.27
Fuel Retail Price, $/litre gasoline equiv.	**0.96**	**0.59**	**0.59**	**0.36**	**0.36**	**1.77**	**1.77**
Fuel Consumption (litres gasoline equiv./100km)	7.60	6.08	6.08	7.27	7.27	3.00	2.00
Cost per Service ($)	96	96	96	96	96	64	64
Distance Between Tyre Changes, km @$235	40000	38000	38000	40000	40000	30000	30000
Distance Between Servicing (km)	10000	6667	6667	15000	15000	10000	10000
Repair cost ($) per 1000 km	373	428	373	395	378	607	513
Cost of Catalyst ($) (Replaced Every 100 000 km)	768	768	0	768	768	0	0
Annual Licence Fee ($)	86	86	86	86	86	86	86
Insurance: ($)	658	727	658	686	664	950	833
Levelised Costs per km (US 1992$) (discounted costs divided by total discounted km driven in vehicle lifetime)							
Fuel (inc. taxes)	**0.073**	**0.036**	**0.036**	**0.026**	**0.026**	**$0.053**	**$0.035**
Levelised vehicle costs (vehicle purchase minus resale)	**0.303**	**0.348**	**0.303**	**0.321**	**0.307**	**$0.493**	**$0.417**
Levelised fixed costs (insurance, licence)	**0.049**	**0.053**	**0.049**	**0.050**	**0.049**	**$0.068**	**$0.060**
Levelised variable costs (maintenance, tyres, catalyst, oil, tolls, fuel)	**0.050**	**0.060**	**0.053**	**0.049**	**0.047**	**$0.063**	**$0.054**
TOTAL COST	**0.474**	**0.497**	**0.440**	**0.446**	**0.429**	**$0.676**	**$0.566**
Cost ex-tax	**0.349**	**0.395**	**0.348**	**0.361**	**0.347**	**$0.557**	**$0.465**

Notes: Derived from (21), based on Renault Clio, 1.4 litre RT, 4 cylinder, 5 door; French Fuel and Electricity Prices and Taxes Discount rate 30% Annual km 15 000

and a variety of other approaches to improve consumers' understanding of electric vehicle attributes and their own requirements. About three-quarters of participants said that their view of electric vehicles had improved as a result of the study, and a significant proportion said that they would be prepared to buy electric vehicles if they were no more expensive than gasoline vehicles.

Approaches based on the analysis of personality types and attitudes indicate that electric vehicles will be taken up initially by "innovators" (people who are prepared to invest in the latest technology, regardless of cost). Their further uptake in the market will depend on the extent to which consumers see them as offering personal benefits in comfort, convenience, cost, and their local environment.

Given that the introduction of electric vehicles appears to depend on drivers' changing their behavior, if not their preferences, it might be helpful to look at experience elsewhere with attempts to bring about behavioral change.

Experience with Public Transport—Lessons for Policy

Experience with public transport may be relevant to the market for electric vehicles. Various views of the comparison between electric vehicles, public transport, and conventional cars are summarized in the following.

From the engineering viewpoint, electric vehicles are less convenient than conventional cars but more convenient than public transport. Owners of electric vehicles must plan their trips around battery recharging and within limited vehicle range, whereas public transport users are constrained by service schedules and routes. Electric vehicles are likely to have less cargo and passenger capacity than conventional cars, and they probably are slower than conventional vehicles although faster on a door-to-door basis than public transport.

From the microeconomic viewpoint, electric vehicles are unattractive compared with conventional cars because their costs are much higher, whereas public transport costs are usually lower per passenger kilometer on average (*5*). However, variable costs at the time of use for the user are usually lower for cars than for public transport (where the user may have to pay the full costs as a variable cost) and lower for electric vehicles than for gasoline vehicles.

Diekstra and Kroon (*10*) describe some of the more compelling motivational aspects of cars as consumer products:

- Freedom of movement,
- Power,
- Individualism/status/communication,
- Love object,
- Narcotic,
- Womb,

- Archetypal identification,
- Winning territory,
- Identification/anthropomorphization,
- Common interest, and
- Time-filler.

Of these features, the ones that may be lacking in electric vehicles are in their roles in providing freedom of movement, power, and narcotic effects (which Diekstra and Kroon link to high-speed driving). Public transport, conversely, provides very few of these features.

Analysis of behavior with regard to public transport may give some indication of the way consumers respond to a less convenient and more expensive transport option. Experience indicates that people's willingness to use public transport depends partly on the quality of the service provided and that ridership can be increased by improving services and information. However, improvements in public transport have rarely proved to be an effective means of stemming the rise in private transport use unless they are combined with measures to limit the attraction of car travel such as access and parking constraints (*22–24*).

Simply making electric vehicles available, even at a lower cost than gasoline vehicles, may not lead many drivers to switch to using them, unless technology progresses to the point that they offer greater convenience than gasoline vehicles. However, if they are cheaper than gasoline vehicles, they may be used by people who could not afford a gasoline vehicle or as additional cars in multiple-car households: that is, they are likely to lead to additional car use rather than to a switch from gasoline to electric car use.

But if electric vehicle use is encouraged by making it more expensive or more difficult to use gasoline vehicles—whether through higher gasoline taxes, taxes on gasoline cars, or parking and access restrictions that do not apply to electric vehicles—drivers are more likely to switch to electric cars.

CONCLUSIONS

There may be energy and environmental reasons for using electric vehicles in several OECD countries, in particular France and parts of the United States.

Electric vehicles using current technology are less convenient than gasoline vehicles. Experience with alternative fuels indicates that drivers require substantial financial incentives to persuade them to switch to any form of transportation that is less convenient than the gasoline car. However, if there is no inconvenience the financial incentive required is minimal.

Mass-produced electric vehicles will probably be more expensive to make but cheaper to operate than gasoline vehicles. Their overall levelized costs will most likely be higher than those for gasoline vehicles. Without a change in consumer attitudes and preferences, they are therefore unlikely to find a significant market without government intervention and short of a significant leap forward in electric vehicle technology.

If governments wish to encourage the use of electric vehicles, they will have more success with policies that discourage the use of gasoline cars than with subsidies for, or information about, electric vehicles. The most effective policies for encouraging electric vehicle use in urban areas will be similar to the policies that discourage gasoline car use, principally restrictions and charging for parking and access.

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Monetary Values of Air Pollutant Emissions in Various U.S. Regions

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Monetary values of emissions of criteria pollutants are needed for evaluating the costs and benefits associated with technologies that have the potential to reduce emissions. Emission values can be estimated by using either a damage value method or a control cost method. With the damage value method, emission values are estimated on the basis of estimated emissions, air quality simulation, damage identification, and valuation of damages. With the control cost method, the marginal control cost—the cost of controlling the last unit of emissions for meeting a given air quality standard—is estimated; the estimated marginal cost is treated as the value of emission reductions achieved by a given control technology. Although studies have been conducted to estimate emission values in some U.S. areas, emission values are still lacking in many others. Estimating emission values for various U.S. areas by using either method can be time-consuming and resource-intensive. Regression relationships are developed between emission values and air pollutant concentrations and population exposed with emission values already estimated for some U.S. areas. On the basis of the developed relationships, emission values have been estimated for various U.S. areas that lack them. These estimates can serve as interim values for these areas until detailed, original estimates become available.

Various measures and strategies to control air pollution are proposed for helping solve air pollution problems in U.S. cities. In determining which control measures are to be implemented, their benefits and costs must be estimated and compared. Usually, those measures with the greatest net benefits should be implemented first. Thus, the monetary value of air pollution reductions achieved by various control measures needs to be quantified.

In particular, various clean transportation technologies are being proposed for solving urban air pollution problems. These clean technologies usually bear high private costs—the costs are paid directly by private users. However, if the monetary value of emission reductions achieved by these clean technologies is taken into account, they may be cost-competitive compared with conventional transportation technologies. To evaluate various transportation technologies from the perspective of social cost accounting, society must consider both private costs and external costs attributable to environmental pollution. Estimating monetary values associated with air pollution is essential when determining the social costs of various technologies.

Studies have been conducted to estimate the monetary value of air pollutant emissions in some U.S. areas, but such values are lacking for many areas. Because air quality status and population exposed to pollution differ among areas, emission values should differ considerably. Applying emission values estimated for one area to another without any adjustment is inaccurate. Thus, area-specific emission values must be estimated.

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Two general methods have been used to estimate emission values: the damage value method and the control cost method. In this paper, using emission values for some U.S. regions already estimated with both methods, the authors estimate emission values as functions of air pollutant concentrations and total population. With the established emission-value functions, emission values are estimated for various U.S. regions.

METHODS FOR ESTIMATING EMISSION VALUES

Air pollution, created in association with the activities of industries or individuals, damages human health, agricultural crops, ecosystems, structural materials, and natural scenery. To reduce damage, emissions of air pollutants must be controlled. Monetary values of emission reductions are needed in order to evaluate the cost and benefit of a control measure. The two general methods for estimating air pollutant emission values are presented in the following.

Damage Value Method

The damage value method directly estimates monetary values of damages caused by air pollutants. The method can involve seven steps: identify emission sources, estimate emissions, simulate air pollutant concentrations in the atmosphere, estimate exposure of humans and other objects to air pollutant concentrations, identify physical effects of air pollutant concentrations on humans and other objects, valuate physical effects, and calculate emission values in dollars per ton (*1*).

Sources of emissions usually are identified by the air quality control authority in the region, mainly for preparing state implementation plans (SIPs) for meeting air quality standards. Emissions from identified sources usually are estimated through the preparation of SIPs. When the concentrations of pollutants in the atmosphere are estimated, dispersion, reaction, residence of air pollutants, meteorology, and topography are taken into account. These three steps—identifying emission sources, estimating emission inventory, and simulating air quality—can be avoided if air quality data are available. In this case, damage estimates can be based directly on measured rather than on simulated concentrations of air pollutants.

Models for simulating human exposure to air pollution are usually based on the assumption that an individual's time-integrated exposure is the product of (*a*) the air pollutant concentrations in a specific set of microenvironments, and (*b*) the time spent by the individual in those microenvironments. Most researchers use clinical studies or epidemiological studies to generate dose-response relationships. The monetary values of adverse air pollution effects can be determined through various economic valuation methods. For example, values of adverse health effects of air pollution can be

related to medical expenses, loss of work, discomfort, and inconvenience that result from such effects.

The damage value method has been used in several studies (*2–10*). Among the damage-based studies, Small and Kazimi (*10*) estimated damage values for emissions from motor vehicles; others cited here estimated damage values for emissions from stationary sources. A detailed review of past studies is presented elsewhere (*11*).

The damage value method appears logical and theoretically sound. In practice, however, the necessary assumptions and simplifications as well as the tremendous uncertainties involved in each of the estimating steps diminish the method's effectiveness. The compounding effect of the uncertainty involved in each estimating step results in values that are very uncertain. Some air pollution effects are often excluded, leading to underestimated values. The principles and theories of modeling air quality and determining air pollution effects as well as their value are in dispute. Outside the discipline of economics, attempting to place dollar values on such items as human life leads to philosophical uneasiness, thus diminishing the method's credibility. Finally the complexity of the damage estimate steps makes the method time-consuming and resource-intensive.

Control Cost Method

Value estimates generated by the control cost method are based on the assumption that ideal emission or air quality standards have been established in that the marginal damage of pollution is equal to the marginal cost of controlling pollution. Supposedly, the control cost required to meet predetermined air quality standards imposed by legislators "reveals" the value that society places on the emissions being controlled [thus, the method is sometimes known as the revealed preference method (*12*)]. Therefore, the marginal control cost, as estimated to meet an emission standard, represents the marginal damage value of air pollution when the standard is met.

This method involves two major steps: determining marginal control measures and estimating dollars-per-ton control costs for identified control measures. Determining marginal control measures for a region can be difficult and subjective. Moreover, selecting one control measure over another can significantly affect the estimate of marginal control costs. Calculating control costs for a control measure requires data on costs and emission reductions associated with the control measure over its lifetime. Initial capital cost, operation cost, maintenance cost, and other cost components must be included to estimate the cost. When estimating reductions in emissions, the emission control deterioration over the lifetime of an equipment must be taken into account. To estimate the dollars-per-ton cost for a particular pollutant, the cost of a measure needs to be allocated among the pollutants reduced, if the control measure reduces emissions for more than one pollutant. Many past studies on estimating emission values used the control cost method (*6–8,13–16*). A detailed review of these studies is presented elsewhere (*11*).

Relative to the damage value method, the control cost method is easy to carry out and does not involve as many estimating steps and assumptions. However, the unrealistic assumption that legislators and regulators establish emission and air quality standards on the basis of costs alone is a weakness. In reality, emission and air quality standards are established through a highly political and scientific (but not economic) process, with scientifically identified health effects as the most dominant of the many factors considered. Although some argue that the method assumes a composite control cost to represent economic, political, and social implications, such a concept suggests that political and social implications can be interpreted in the economic sphere, which may trouble others deeply. In practice, marginal control cost is rarely equal to marginal damage. Thus, it is improper to treat the estimated marginal control cost as the value for emission damage. Nevertheless, the estimated marginal control cost represents the opportunity cost that can be avoided by implementing some control measures other than the marginal control measure in meeting standards—that is, if some other control measures are implemented, the most costly control measure can be avoided. It is this avoided opportunity cost concept that the authors prefer to adopt for interpreting the values estimated with the control cost method.

DEVELOPMENT OF EMISSION VALUES FOR VARIOUS U.S. AREAS

Approach

Estimates of emission values must be generated for societal cost-benefit analysis of the projects that cause air pollutant emissions. A proper, or societal cost-benefit analysis must place dollar values on externalities—among these are air pollutant emissions. Ideally, to generate region-specific emission values, damage models should be run for a particular region so that damage values can be estimated for the region, or emission control costs should be estimated from the control measures and their costs applied to the region. However, limited resources often prevent such detailed, accurate estimates for individual regions. In practice, emission values estimated for one region are often used for another region, without any adjustment.

Because emission values are determined by air quality status and population exposed, these values vary considerably among regions. The authors propose a simplified method to develop region-specific emission values. With the method, emission values are estimated as functions of air pollutant concentrations and total population. A regression analysis is conducted to establish emission value functions. For damage-based emission values, total population determines how many people will be exposed to air pollution, thereby determining the magnitude of health damage values attributable to air pollution—the most significant air pollution damage in most cases. For cost-based emission values, total population in a region partly determines the number of emission sources in the region. For a larger population, more human services are required and more human activities occur; both of these conditions mean more emission sources, causing a higher level of emissions. To meet given air quality standards in such regions, emissions of each source must be reduced. It is more expensive to reduce emissions to a lower percentage of the uncontrolled level. In fact, the costs to accomplish lower and lower percentages of uncontrolled emissions go up nonlinearly. It is certainly more expensive to control average emissions per source to a low value in order to reduce total emissions in a geographic area to a given target level, when the number of sources and uncontrolled emissions are high because of a need to serve a large population. Thus, meeting air quality standards is more expensive in a high-population region than in a low-population region, all else being equal.

To allow the freedom of choosing between damage-based and control-cost-based emission values, the authors establish two sets

of regression relationships: one for estimating damage-based values, and the other for estimating control-cost-based values.

Data Sources

In this paper, emission values estimated in previous studies are used to establish regression relationships.

In 1987 ECO Northwest conducted a study for the Bonneville Power Authority to estimate damage-based emission values for a generic 1,300-MW coal-fired power plant presumably located in the Pacific Northwest (*2*). The study included air pollution damages to human health (mortality and morbidity), agricultural crops, materials, visibility, ecosystems (forest and lakes), livestock, and timber. On the basis of the ECO Northwest study, the Bonneville Power Authority adopted dollars-per-ton emission values for nitrogen oxides (NO_x), sulfur oxides (SO_x), and particulate matter (PM) for the areas east and west of the Cascade mountain range (*17*).

Since 1989 the California Energy Commission (CEC) has been estimating emission values by using both the damage value and control cost method (*6–8*). CEC has estimated damage- and control-cost-based emission values for 11 of California's air basins. With respect to control-cost-based values, CEC was concerned that taking the highest marginal control costs from any sector may not represent the public's true willingness to pay for additional emission reductions in the electricity sector. In addition, CEC maintained that the marginal control cost for a source classification may often be overestimated. For these reasons, when selecting marginal control measures, CEC decided to exclude arbitrarily the control measures with costs over $100,000/ton. With respect to damage-based values, Regional Economic Research, Inc., CEC's contractor, developed an air quality valuation model to estimate emission damage values (*1,18–20*). The model included emission estimation, air quality simulation, estimation of physical effects of air pollution, and monetary valuation of air pollution effects. Estimation of emission damage values included human health effects (mortality and morbidity), visual aesthetic effects, material effects, forest-related aesthetic effects, and agricultural effects.

In 1989 the New York State Energy Office estimated emission values for the state of New York using the control cost method (*13*). In determining costs of marginal control measures, the agency used average costs of low- and high-cost measures that were applied to a 200-MW coal-fired power plant. The agency maintained that low-cost measures reflected control in attainment areas and high-cost measures reflected control in nonattainment areas.

In 1990 the Tellus Institute of Boston conducted a study to estimate emission values by means of the control cost method (*12*). The Tellus researchers suggested that control cost estimates could be surrogates for damage values of emissions. They estimated emission values for Southern California and the northeastern United States. In determining marginal control measures, they took the measures with the highest control costs necessary for complying with emission and air quality standards.

In 1993 National Economic Research Associates completed a study to estimate emission damage values in southern Nevada (*9*). In the study, changes in air pollutant concentrations were estimated in terms of emissions from given hypothetical power plants located in and out of the Las Vegas valley. The study included effects of air pollution on human mortality and morbidity, visibility, building materials, agriculture, and ecosystems.

In 1990 the Center for Environmental Legal Studies of Pace University conducted a study to review and analyze existing studies on air pollution externalities (*4*). The Pace University study included emission values estimated on the basis of the damage value method. The study did not make its own damage value estimates; instead, it assessed values estimated in a variety of studies and proposed a "starting point" for each effect of air pollution identified.

On the basis of these studies, emission values estimated for 15 U.S. regions are used in the regression analysis (Table 1). Data on air pollutant concentrations and total population for each of the 15 regions are obtained from the Environmental Protection Agency (EPA) (*21–23*).

Resultant Regression Relationships

Various functional forms were tried in establishing the regression relationship for a particular pollutant. The most statistically significant functional form of the variables generally was chosen as the final regression relationship for the pollutant. However, in some cases, theoretical expectations for signs of coefficients made it necessary to adopt models with less goodness of fit (i.e., smaller R^2). For some pollutants, the constant term was found not to be significant. In those cases, the constant term was forced to be 0. Although some coefficients for air pollutant concentrations or population were found not to be statistically significant, these relatively insignificant coefficients occasionally were kept in the regression relationships because simple theory implies that both air pollutant concentrations and population affect the dollar emission values being estimated. The established regression relationships for damage-based and control-cost-based emission values are presented in the following (note that emission values are expressed in 1989 constant dollars):

$$NO_{x,damage} = 1{,}640 \ln(pop) + 4{,}220 \ln(O_3) \quad (1)$$

$$ROG_{damage} = 871 \ln(pop) + 2{,}310 \ln(O_3) \quad (2)$$

$$\ln(PM_{10,damage}) = 0.764 \ln(pop) + 0.685 \ln(PM_{10}) \quad (3)$$

$$\ln(SO_{x,damage}) = 5.41 + 0.325 \ln(pop) + 0.0138 \ln(SO_2) \quad (4)$$

$$NO_{x,cost} = 40{,}000 + 5.71 \ln(pop) + 15{,}100 \ln(O_3) \quad (5)$$

$$ROG_{cost} = 30{,}200 + 385 \ln(pop) + 12{,}000 \ln(O_3) \quad (6)$$

$$PM_{10,cost} = -16{,}800 + 793 \ln(pop) + 3{,}790 \ln(PM_{10}) \quad (7)$$

$$SOx,cost = -51{,}100 + 956 \ln(pop) + 13{,}500 \ln(PM_{10}) \quad (8)$$

$$CO_{cost} = -6{,}390 + 579 \ln(pop) + 2{,}110 \ln(CO) \quad (9)$$

where

$NO_{x,damage}$ = NO_x damage value ($/ton),
ROG_{damage} = reactive organic gases (ROG) damage value ($/ton),
$PM_{10,damage}$ = particulate matter less than 10 microns (PM_{10}) damage value ($/ton),
$SO_{x,damage}$ = SO_x damage value ($/ton),
$NO_{x,cost}$ = NO_x control cost ($/ton),
ROG_{cost} = ROG control cost ($/ton),
$PM_{10,cost}$ = PM_{10} control cost ($/ton),
$SO_{x,cost}$ = SO_x control cost ($/ton),
CO_{cost} = carbon monoxide (CO) control cost ($/ton),
pop = total population (in 10^3),

TABLE 1 Data for Regression Analysis Between Emission Values and Air Pollutant Concentrations and Population

Region	Emission Values Estimated with the Damage Value Method (1989 dollars, $/ton)					Emission Values Estimated with the Control Cost Method (1989 dollars, $/ton)					Air Pollutant Concentration [j]				Total Pop (10^3)
	NO_X	ROG	CO	PM_{10}	SO_X	NO_X	ROG	CO	PM_{10}	SO_X	O_3, 2nd 1-hr max. ppm	PM_{10}, highest $\mu g/m^3$	SO_2, highest ppm	CO, highest 2nd 8-hr ppm	
CA South Coast Basin[a]	14483	6911	3	47620	7425	26400	18900	9300	5700	18900	0.28	63	0.004	14	13183
CA San Joaquin Valley[a]	6473	3711	0	3762	1500	9100	9100	3200	5200	17800	0.14	63	0.004	9	2404
CA S.F. area[a,b]	7435	90	1	24398	3482	10400	10200	2200	2600	8900	0.11	35	0.003	8	5828
CA Sacramento Valley[a]	6089	4129	0	2178	1500	9100	9100	5000	2800	9600	0.14	39	0.006	11	1816
CA Ventura Co. [a]	1647	286	0	4108	1500	16500	21100	0	1800	6200	0.16	38	0.001	4	642
CA Santa Barbara[a,c]	1647	286	0	4108	1500	9100	9100	0	900	3000	0.13	36	0.002	6	351
CA North Central Coast[a]	1959	803	0	2876	1500	9100	9100	0	900	3000	0.09	24	0.001	2	572
CA San Diego[a]	5559	98	1	14228	2676	18300	17500	1100	1000	3600	0.18	41	0.005	9	2357
CA North Coast[a,d]	791	467	0	551	1500	6000	3500	0	900	3000	0.10	44	0.003	3	222
CA Southeast Desert[a,d]	439	157	0	680	1500	6000	3500	2900	5700	19700	0.17	76	0.003	10	225
CA O_3 att. and PM_{10} Vio.[a,e]	439	90	0	551	1500	6000	3500	0	900	3000	0.11	50	0.003	7	152
OR West of Cascade Range[f]	839	NA	NA	1950	NA	3350	NA	NA	3800	1400	0.11	31	0.006	8	1877
Eastern Massachusetts[g]	1640	NA	NA	3170	4060	6500	5300	870	5330	1500	0.12	33	0.012	6	4403
Greater New York Area[h]	1640	NA	NA	3170	4060	2460	5300	820	5330	603	0.16	45	0.017	10	11417
Las Vegas Valley[i]	210	0	NA	1350	280	6450	1120	820	5280	1480	0.10	65	NA	13	647

[a] Damage-based and control-cost-based emission values estimated for California air basins are from the CEC (*8*).
[b] The San Francisco area includes San Francisco metropolitan statistical area (MSA) and Oakland MSA.
[c] Emission values estimated by the CEC for the South Central Coast Air Basin are adopted for Santa Barbara.
[d] Two sets of air pollutant concentration measurements were available. One set was EPA's measurements presented in its air quality and emission trends report (*21-23*). EPA presents its measurements for each MSA nationwide. The other set was California Air Resources Board's (CARB's) measurements. CARB presents its measurements for each county in the state (*19*). In establishing regression relationships, we used EPA's air pollutant concentration measurements. There are no EPA measurements in the North Coast Air Basin or in the Southeast Desert Air Basin. We used EPA and CARB measurements available for other California air basins to establish regression relationships between EPA measurements and CARB measurements. We then used the established relationships to estimate EPA measurements from CARB measurements for the North Coast and Southeast Desert Air Basins.
[e] The ozone attainment and PM_{10} violation areas in California include four counties — Mendocino, Siskiyou, Modoc, and Lassen. Portions of Placer and El Dorado counties belonging to these areas were not considered here. The CEC-estimated emission values for this area with the control cost method, but not with the damage value method. We selected the lowest damage-based values among the California air basins as the damage-based values for the ozone attainment and PM_{10} violation area. EPA measurements of air pollutant concentrations for this area were estimated on the basis of the relationships between EPA measurements and CARB measurements (see footnote d).
[f] The damage-based values are from ECO Northwest's study for the Bonneville Power Authority (*2,17*). The cost-based values are from Oregon Public Utility Commission's estimates (*16*). The area includes Portland, Salem, Eugene-Springfield, and Medford. Air pollutant concentrations are population-weighted concentrations from the four MSAs.
[g] The damage-based values are from Pace University's estimates (*4*). The cost-based values are from Massachusetts Department of Public Utilities' estimates (*24*). The area includes Boston, Brockton, Fall River, Fitchburg-Leominster, Lowell, New Bedford, Salem-Gloucester, and Worcester. Air pollutant concentrations in the area are population-weighted averages among the eight MSAs.
[h] The damage-based values are from Pace University's estimates (*4*). The cost-based values are from New York State Energy Office (*12*). The area includes New York, Nassau-Suffolk, and Poughkeepsie. Air pollutant concentrations in the area are population-weighted averages among the three MSAs.
[i] The damage-based values are National Economic Research Associates' estimates (*9*). The cost-based values are based on the Public Service Commission of Nevada's estimates for the entire state (*25*).
[j] Data on air pollutant concentrations and total population for each MSA are from EPA's air quality and emission trends report (*21-23*). The values presented here are 3-year average values for the period 1989-91.

O_3 = highest second daily maximum 1-hr ozone concentration (ppm),
PM_{10} = highest arithmetic mean PM_{10} concentration ($\mu g/m^3$),
SO_2 = highest arithmetic mean SO_2 concentrations (ppm), and
CO = highest second max nonoverlapping 8-hr CO concentration (ppm).

Table 2 presents statistics for these regression relationships. For damage-based regressions, the *t*-values for the coefficient of the population variable always exceed those for the pollutant concentration. This result appears consistent with the damage value method, which focuses on the number of individuals exposed, using population directly in the damage function, whereas the control cost method is, in principle, affected by the size of the population exposed, but population per se does not enter into the computations of estimating control costs. For control-cost-based regressions, the *t*-values for the coefficient of the pollutant concentration variable always exceed those for the population variable, and the coefficient of the population variable is generally insignificant (though correct in sign). This result appears consistent with the focus of control cost on achieving reduced concentrations, regardless of the size of population exposed.

By the nature of regression analysis, these relationships are applicable only to areas in which air pollutant concentrations and population lie within the ranges of air pollutant concentrations and population used for the regression analysis (see Table 1 for the ranges). Application of air pollutant concentrations and population below the ranges to the regression relationships can result in unrealistic negative emission values.

Among the cited original studies, only the CEC study estimated CO damage values for California's air basins. CEC estimated a value of $3/ton for the South Coast Air Basin, $1/ton for both the San Francisco Bay Area and San Diego, and $0/ton (i.e., zero value) for other California air basins. The CEC estimates imply virtually zero CO damage value. The CEC study estimated CO damage values on the basis of power-plant CO emissions. Generally, CO nearly is a nonreactive pollutant that disperses rapidly from its point of origin and is not a problem at great distance from the source. Although power plants and people are not close together, motor vehicles and people usually are. For example, the greatest CO concentrations are usually found near busy intersections. In addition, total CO emissions from motor vehicles are far greater than from stationary fuel combustion, leading to higher CO concentrations along roads than near stationary combustion sources. For example, nationwide, the transportation sector accounts for more than 60 percent of total CO

TABLE 2 Statistics of Emission Value Regression Relationships

Variable	Statistical parameter	NO_X	ROG	PM_{10}	SO_X	CO
Damage-Based Regressions						
Regression	Adjusted R^2	0.43	0.36	0.30	0.67	N/E
	Standard error	2775	1686	0.9785	0.3250	N/E
	F value	7.39[a]	4.93[b]	4.55[b]	12.0[a]	N/E
Constant	Standard error	N/E	N/E	N/E	1.33	N/E
	t value	N/E	N/E	N/E	4.05[b]	N/E
Population	Standard error	371	248	0.179	0.0868	N/E
	t value	4.43[b]	3.51[b]	4.27[b]	3.75[b]	N/E
Pollutant concentration	Standard error	137	881	0.353	0.148	N/E
	t value	3.09[b]	2.62[b]	1.94[b]	0.0934	N/E
Control-Cost-Based Regressions						
Regression	Adjusted R^2	0.42	0.29	0.56	0.32	0.35
	Standard error	4817	5224	1362	5658	2116
	F value	5.99[b]	3.64[c]	9.73[a]	4.33[b]	4.47[c]
Constant	Standard error	14900	16600	4800	19900	3000
	t value	2.69[b]	1.82[b]	-3.49[b]	-2.56[b]	-2.13[c]
Population	Standard error	1010	1120	254	1050	441
	t value	0.00564	0.345	3.12[b]	0.907	1.31[d]
Pollutant concentration	Standard error	4950	5540	1140	4740	1170
	t value	3.06[b]	2.61[b]	3.32[b]	2.86[b]	1.81[c]

[a] At the significance level of 99%.
[b] At the significance level of 95%.
[c] At the significance level of 90%.
[d] At the significance level of 85%.
N/E = Not estimated (see text).

emissions, whereas stationary fuel combustion accounts for only about 12 percent (*22*). In summary, CO emissions from motor vehicles are far more damaging than those from power plants. Accordingly, the authors conclude that using the available damage estimates for CO would be inappropriate and consequently do not estimate a CO damage equation.

Comparison of Emission Values Between Original Estimates and Regression Estimates

Figures 1 and 2 present comparisons between original and regression estimates for a selection of 8 of the 15 U.S. regions in which estimated emission values have been obtained for this study: Boston, Las Vegas, Los Angeles, New York, Sacramento, San Diego, San Francisco, and California's San Joaquin Valley. With respect to the damage-based emission values, regression-estimated values for SO_x and ROG are close to the original estimates in the eight areas. For NO_x, regression-estimated values in four California areas (Los Angeles, San Francisco, Sacramento, and the San Joaquin Valley) are considerably lower than the original estimates, and regression-estimated NO_x values in Boston and New York are significantly higher. The largest difference exists in PM_{10} values. Regression-estimated PM_{10} values in Los Angeles, San Francisco, and San Diego are underestimated significantly, and the value in New York is overestimated significantly. Overall, damage-based values in Los Angeles are always underestimated by the regression relationships. The variation in these estimates probably is closely tied to methods and scientific judgments used in the original studies from which the regression input data were obtained.

With respect to the control-cost-based values, the NO_x estimate is lower than the original value in Los Angeles, San Francisco, San Diego, and Las Vegas but higher in the other four areas. For ROG, the estimated value is lower than the original value in San Francisco and San Diego, but it is higher in New York, Las Vegas, and Boston. In Los Angeles, the San Joaquin Valley, and Sacramento, the regression-estimated ROG value is close to the original estimate. For PM_{10}, the regression-estimated values in New York, Los Angeles, the San Joaquin Valley, and Sacramento are close to the original estimates. The PM_{10} regression relationship underestimates the PM_{10} value in Boston and Las Vegas but overestimates it in San Diego. The SO_x regression relationship underestimates the SO_x value in Los Angeles, San Francisco, the San Joaquin Valley, and Sacramento but overestimates it in San Diego, Las Vegas, Boston, and New York. The CO regression relationship underestimates the value in Los Angeles and Sacramento but overestimates it in New York, San Diego, and Las Vegas. In San Francisco, the San Joaquin Valley, and Boston, the estimated values are close to the original values. Overall, for these eight locations, differences between regression estimates and original estimates of control-cost-based values are smaller for PM_{10} and CO than for any of the other three pollutants.

Regression-Estimated Emission Values for Various U.S. Regions

With the regression relationships established previously, the authors estimate both damage- and control-cost-based emission values for nine U.S. metropolitan areas where estimates of emission values are not available: Atlanta, Baltimore, Chicago, Denver, Houston, Milwaukee, New Orleans, Philadelphia, and Washington, D.C. Among them, Baltimore, Chicago, Houston, Milwaukee, and Philadelphia are among the nine ozone nonattainment areas specified in the 1990 Clean Air Act Amendments for introducing reformulated gasoline. Atlanta, Denver, New Orleans, and the Washington, D.C., metropolitan area are included as geographically representative of large metropolitan areas with violations of one or

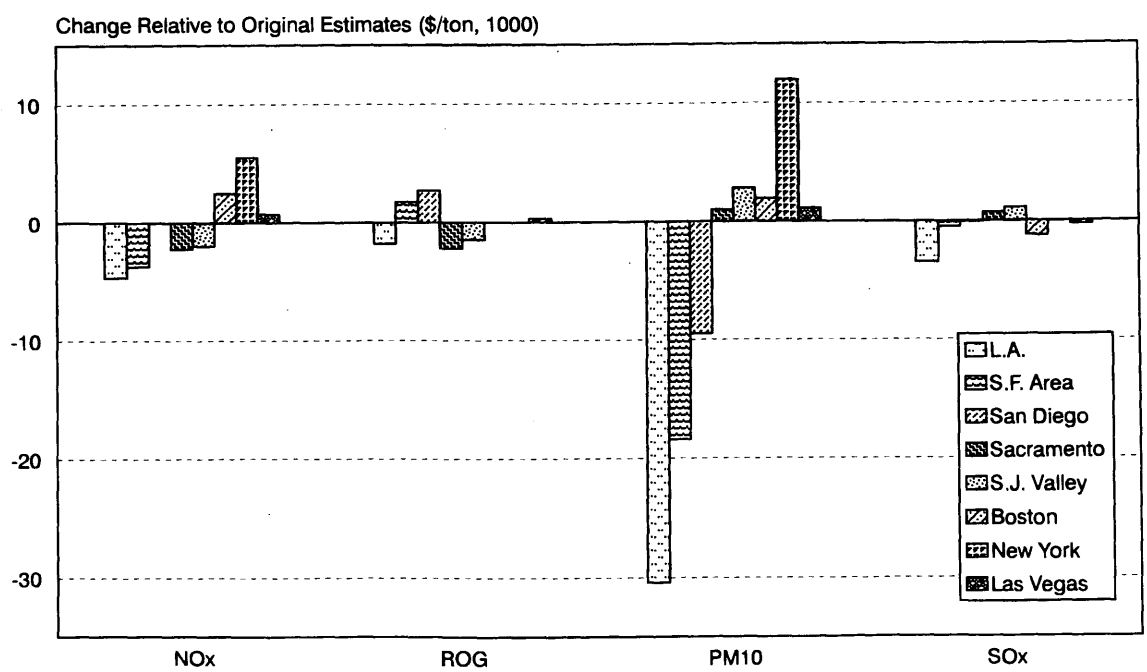

FIGURE 1 Comparison between regression estimates and original estimates, damage-based values.

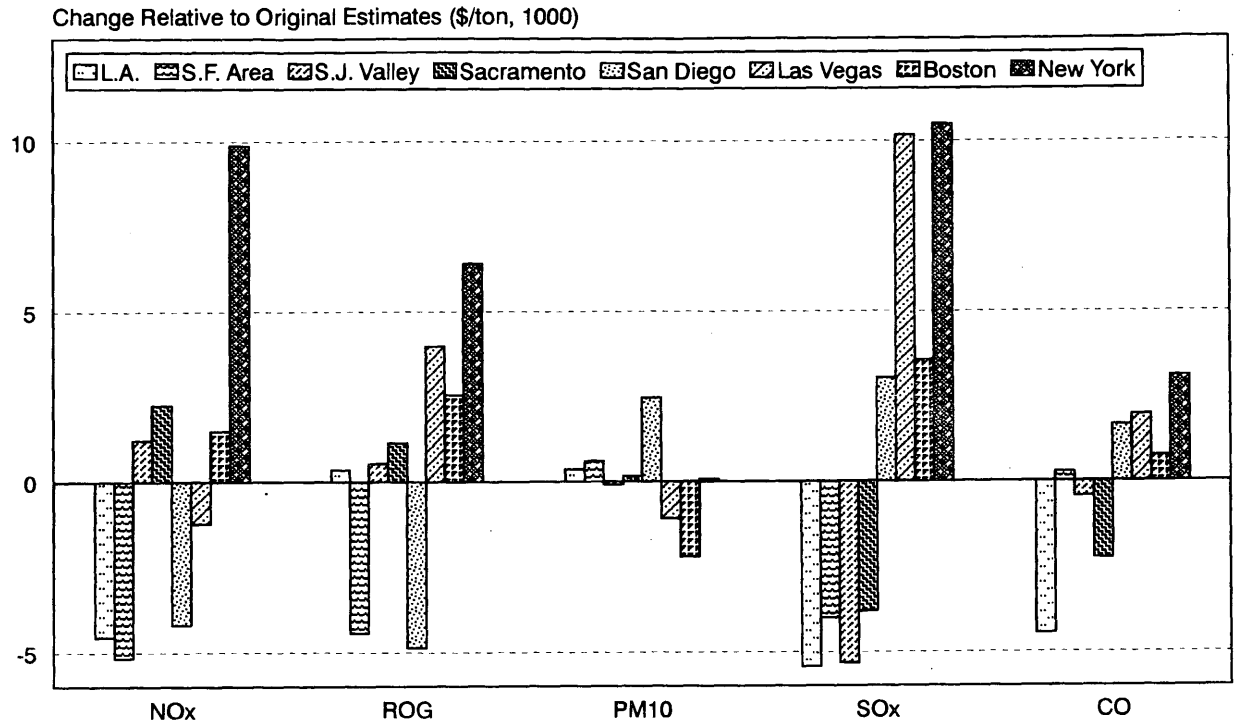

FIGURE 2 Comparison between regression estimates and original estimates, control-cost-based values.

more air quality standards. Many other areas also have air quality violations. In practice, one can select his or her own target metropolitan areas and use the preceding regression relationships to estimate emission values for the target areas.

Table 3 presents emission values estimated by using the established relationships for the nine nonattainment areas. Not surprisingly, there are significant variations in emission values across the nine areas. Damage-based emission values vary from $2,840 to $6,890 for NO_x, $1,350 to $3,540 for ROG, $2,960 to $10,840 for PM_{10}, and $2,210 to $3,600 for SO_x. Control-cost-based emission values vary from $7,990 to $17,150 for NO_x, $6,590 to $15,160 for ROG, $2,400 to $4,600 for PM_{10}, $3,130 to $9,120 for SO_x, and $1,410 to $3,160 for CO. Estimated damage-based emission values are usually lower than estimated control-cost-based values for each pollutant except PM_{10}. The underestimated damage values for PM_{10} in previous studies probably account for this outcome, because those studies did not consider all air pollution effects. For those who believe that the damage value method normally does underestimate damages, this is certainly convincing evidence that PM_{10} emissions have been undercontrolled.

QUALIFICATIONS

The regression-estimated emission values presented in this paper are based on previously estimated emission values. Compared with original estimates for a given region, regression estimates are rather rough and can only indicate the magnitude that emission values might have for the region. The regression relationships given earlier rely on original estimates, so it is recommended that original emission values, when available, be used. The authors' purpose is not to supplant a more careful study, but to provide working values that will be useful until studies are completed for the locations that lack estimates.

One can select either damage-based or control-cost-based emission values. As indicated earlier, both the damage method and the control cost method have advantages and disadvantages. One should be aware that selecting either could have significant consequences.

Past estimates of emission values were based primarily on emissions of stationary sources. Therefore, the established regression relationships, based on these past studies, rely on the estimates conducted for emissions of stationary sources. With respect to damage-based emission values, since many major stationary sources are located away from the core of a metropolitan area (while emissions from motor vehicles may occur primarily in or near the core of the metropolitan area), damage-based values for mobile-source emissions are likely to exceed those for stationary-source emissions. This phenomenon is especially true for CO emissions from motor vehicles, because CO emissions in street canyons pose a significant exposure threat to an extensive population. With respect to cost-based emission values, very few control measures for mobile-source emissions have been included in the original studies. Again, the established regression relationships are based primarily on emission control costs estimated for stationary sources. Emission values based on stationary-source control costs may be higher or lower than those based on both stationary- and mobile-source control costs.

CONCLUSIONS

Two general methods for estimating monetary values of air pollutants are presented in this paper. The damage value method directly

TABLE 3 Estimated Emission Values for Nine U.S. Regions

Area	NO_x	ROG	PM_{10}	SO_x	CO
		Damage-Based Emission Values			
Atlanta	4,330	2,150	5,170	2,720	N/A
Baltimore	4,430	2,210	4,520	2,620	N/A
Chicago	5,380	2,700	10,840	3,600	N/A
Denver	2,840	1,350	3,390	2,330	N/A
Houston	6,890	3,540	5,190	2,910	N/A
Milwaukee	3,890	1,930	2,960	2,210	N/A
New Orleans	3,880	1,910	3,600	2,470	N/A
Philadelphia	5,940	3,010	8,360	3,340	N/A
Wash., D.C.	4,900	2,450	6,260	3,070	N/A
		Control Cost-Based Emission Values			
Atlanta	9,190	8,780	3,460	6,420	2,280
Baltimore	10,310	9,620	3,170	5,600	2,490
Chicago	7,990	8,150	4,660	9,120	2,440
Denver	6,660	6,590	2,790	4,900	2,960
Houston	17,150	15,160	2,780	3,590	2,680
Milwaukee	11,350	10,250	2,560	4,380	1,590
New Orleans	9,190	8,670	2,400	3,130	1,410
Philadelphia	11,360	10,730	4,040	7,330	3,160
Wash., D.C.	9,190	8,910	3,340	5,320	3,010

estimates air pollutant damage values by simulating air quality, identifying health and other welfare impacts of air pollution, and valuating the identified impacts. Although the method is theoretically sound, its estimation steps involve many assumptions, and uncertainty exists in each step. The control cost method estimates the marginal emission control cost, which represents the opportunity cost offset by avoiding the need for spending on emission reductions from the most costly available emission control measures previously considered for implementation to meet regulatory requirements.

Studies conducted to estimate emission values in U.S. regions have used both methods. By taking emission values estimated for some U.S. air basins, the authors have established regression relationships between emission values and total population and air pollutant concentrations. On the basis of the established relationships, both damage-based and control-cost-based emission values have been estimated for nine major U.S. urban areas.

Although the emission values estimated by using the regression relationships may not be as accurate as the estimates obtained by applying the damage or control cost method to a region, they are superior to values adopted for the region on the basis of ad hoc selection of estimates in other regions. Ideally, emission values should be estimated for each specific region. Therefore, the authors suggest that original estimates be used for a region if they are available.

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PART 2

Environmental Analysis

Geophysical and Immunoassay Techniques To Accelerate Hazardous Waste Site Remediation

SUSAN L. FERREL, ILEANA IVANCIU, AND JAMES SWEET

Remediation of soil can be a long, difficult, and costly process. The combination of innovative technology, strong project management, close regulatory liaison, and the integration of a variety of remedial options turned an unexpected drum burial site into the successful completion of a highway access ramp. Buried drums containing hazardous polychlorinated biphenyl (PCB) waste were encountered directly in the path of a proposed highway access ramp during construction activities. Geophysical techniques such as ground-penetrating radar and magnetometry were used to define the horizontal and vertical extents of buried drums and waste. Field-testing kits that exploit immunoassay techniques were used to screen and segregate the excavated PCB-contaminated soils quickly and inexpensively and minimize the number of required postexcavation samples. Analysis of duplicate soil samples confirmed the accuracy of the field-testing kits before and during the remedial activities. Buried waste and soils containing hazardous concentrations of PCBs were excavated, loaded into trucks, and transported to an approved Toxic Substance Control Act facility. Approximately 7256 Mg (8,000 tons) of the remaining nonhazardous soil was used on-site as fill during the ramp construction. Careful planning of the work and the establishment of an informal but highly effective partnering relationship among all participants resulted in a remedial project that proceeded expeditiously with significant cost savings for the client. Ultimately, the ramp was constructed and the highway was opened to the public on schedule.

The New Jersey Department of Transportation (NJDOT) was completing the construction of a long-anticipated, high-profile section of highway in northern New Jersey. During excavation activities related to building an access ramp, an undetermined number of buried drums were encountered directly in the path of the proposed ramp alignment. The buried drums effectively blocked the construction area, which consisted of a narrow wedge of land confined between a river and a protected wetland (Figure 1). Construction activities stopped so that a site investigation and subsequent remedial activities could be implemented. With construction already under way, design changes and change orders would have resulted in astronomical cost increases and months of delay. On-time construction of the ramp was important to NJDOT in order to open the highway to the public as planned.

Although virtually any form of remediation can be very costly, developing a well-planned, cost-effective strategy at the beginning of a cleanup project can minimize expenses that accumulate during the project. As much as possible was learned about the nature and extent of the contamination so that the remediation approach and equipment needs could be planned carefully to accommodate the limited site space and other requirements before the actual start of excavation, thus helping to avoid unexpected delays. The development of innovative solutions helped to achieve the client's ultimate goal of the project, which was to complete the cleanup as quickly as possible so that the ramp construction could be finished, thereby allowing the highway to be opened as scheduled.

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REMEDIAL APPROACH

On the basis of information obtained during the initial site remediation activities, the buried waste consisted of drums in various stages of decomposition, drummed waste, and soils. The contents of the drums were homogeneous and compatible and consisted of a highly viscous, tar-like material with concentrations of polychlorinated biphenyl (PCB) above the federal Toxic Substance Control Act (TSCA) standard of 50 m/kg [parts per million (ppm)], which regulates PCB wastes as hazardous.

With the size of the work area limited by construction equipment, the adjacent river, and the protected wetland, site remediation had to be planned carefully. Geophysical surveys were used to define the extent of the buried drums. Information obtained on the hydrogeology and an initial ground-penetrating radar (GPR) survey indicated that the drums were buried in trenches within a 0.61-m (2-ft) layer located 1.83 m (6 ft) above the water table. A large amount of soil covered the buried drums and was probably unaffected by contamination. Samples were collected from these soils and were analyzed for PCB concentrations. The results indicated that soil mounded over the buried waste contained PCB concentrations below 2 ppm. From these results, a two-phase approach was developed for the remedial activities.

During Phase 1, approximately 9904 Mg (10,920 tons) of overburden material that was mounded over the buried drums was removed and used as fill during mainline highway construction. In Phase 2, the actual hazardous waste remediation, the decomposed drums and drummed waste were removed from the excavation, loaded directly in dump trucks, and taken to a specially constructed, TSCA-regulated landfill.

Field-testing kits employing immunoassay technology were used to segregate soil and minimize the number of postexcavation samples submitted for laboratory analysis. Postexcavation soil samples were collected at an approved frequency that was lower than typical regulatory agency requirements and submitted for laboratory analysis to validate the effectiveness of the PCB cleanup. A magnetometer (MAG) survey was conducted to ensure that no additional drums were present in the area of the excavation.

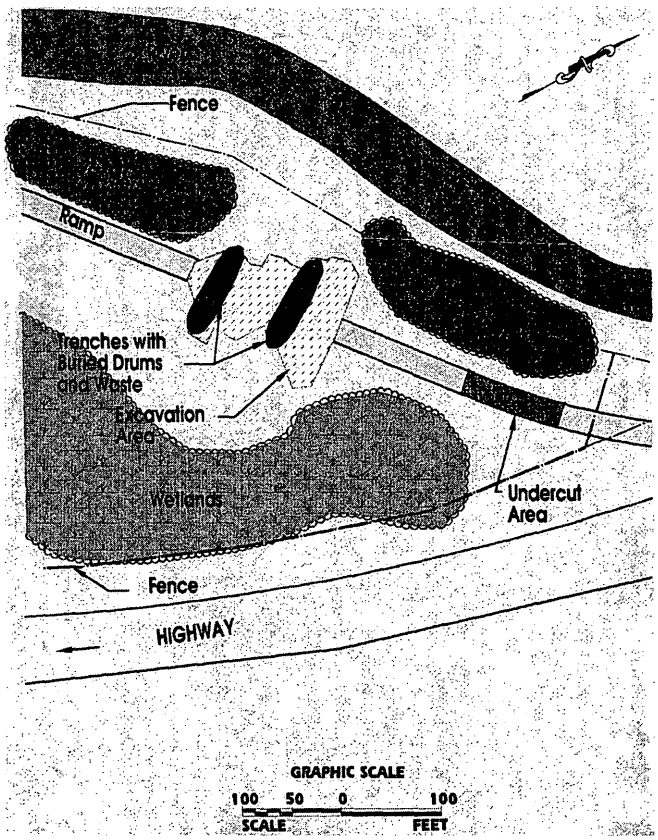

FIGURE 1 Site map.

The total excavation area was approximately 1148 m^2 (12,352 ft^2), with the average depth of excavation approximately 1.83 m (6 ft.) Soil sampling along the perimeter of the excavation confirmed that the contamination was localized and did not affect the wetlands or river sediments. A total of 3066 Mg (3,381 tons) of waste was excavated and transported off-site for disposal, and approximately 7256 Mg (8,000 tons) of nonhazardous soil was reused during construction.

The New Jersey Department of Environmental Protection did not require the remediation of surface soil (0 to 0.61 m) with PCB concentrations below 0.49 ppm on residential sites or up to 2 ppm on sites designated as industrial. For subsurface soils (below 0.61 m), soil with PCB concentrations up to 100 ppm could remain in place. However, if the soil is excavated and brought to the surface, it is judged a hazardous waste under TSCA if it contains PCB concentrations greater than 50 ppm; solids must be disposed of in a specially designed lined landfill, and liquids, in a specially licensed incinerator.

GEOPHYSICAL SURVEY

Background

Three geophysical techniques—MAG, electromagnetics (EM), and GPR—were used during the preliminary site investigation to assess the amount of buried waste and drums and to delineate their physical extent.

In MAG studies, magnetic anomalies are detected by measuring the magnetic field strength at evenly spaced points (a grid) throughout the area of interest. By plotting the location and magnetic field strength of each sampling point, a contour map can be generated to determine the location of anomalous areas.

EM methods use an alternating magnetic field generated by a coil at the ground surface, which penetrates the ground. A second coil, also at the surface, measures the earth's response. The response is proportionate to the electrical resistance of the soil's conductivity. The depth of the investigation is a function of the intercoil spacing. EM can detect differences in subsurface electromagnetic conductivity between two different layers.

GPR can provide high-quality data of near-surface conditions. GPR detects both metallic and nonmetallic targets. GPR instruments obtain subsurface information by inducing pulses of very high frequency electromagnetic energy into the ground. A portion of the induced pulse is reflected upward to the antenna from a reflection boundary and its return time is measured. The reflection boundary is the interface between materials having a measurable contrast in electrical properties. A cross section of the area of interest is generated by converting velocity and time-delay information.

Utilization

The performance of geophysical surveys at the site during various stages of the investigation enabled information about the subsurface to be collected without invasive techniques such as drilling or excavation. The geophysical surveys provided a mechanism to estimate accurately the soil volume and constituted a powerful tool in planning the excavation and remediation processes.

EM and MAG techniques were used to obtain an initial understanding of the subsurface conditions. An initial GPR survey established that a mound of soil, averaging 3.5 m (11.5 ft) high and about 0.1 ha (0.25 acre) in size, contained no debris. A subsequent GPR survey revealed that the waste and drums were buried within trenches oriented parallel to one another. The GPR survey indicated the presence of a single layer of drums within each trench buried under the mounded soil to a depth of about 1.83 m (6 ft) below the original ground surface.

A magnetometer survey conducted after the excavation of the buried drums and waste established that all the drums were removed and that no additional drums were present below the excavated area.

PCB ANALYSIS

At the onset of the remedial activities, PCB action levels had been negotiated with the regulatory agency having jurisdiction over the site. This was important since the latest guidance on soil remediation of PCB spills advocates a statistical sampling program with many samples, which would increase significantly the cost of analysis.

Standard turnaround time for PCB laboratory analysis (typically 3 to 4 weeks) would have delayed the remedial efforts and subsequently the construction schedule. Expedited turnaround time for laboratory analytical results was not a financially viable option. These problems were resolved by using what was then a little-known, innovative on-site analytical technology: enzyme-linked immunosorbent assay. Field tests using immunoassay techniques were approved by NJDEP for use at this site to aid in the segregation of the contaminated subsurface soil and to provide a means for reducing the number of postexcavation samples required to assess the effectiveness of the remediation.

Although the results of field-screening procedures typically are not accepted by regulatory agencies, including the Environmental

Protection Agency (EPA), as proper measurement of contamination for predisposal analysis or ultimate definition of contamination boundaries, the field analyses performed as part of this PCB remediation were approved and used as preliminary tests designed to help the technical personnel direct the assessment and cleanup activities.

Besides facilitating the segregation of the excavated soils, the use of field test kits also helped reduce the amount of postexcavation samples submitted for laboratory analysis. The 0.1-ha (0.25-acre) site may have required as many as 33 postexcavation samples, but the field test kits helped establish ahead of time the areas of the site where, based on the PCB concentration in the soil, the cleanup had proceeded to an acceptable level. Only 12 postexcavation samples were required for laboratory analysis to verify that contaminant concentrations above regulatory concern were not left behind. Duplicate samples were sent to the analytical laboratory to verify the results obtained by the field test kits.

Immunoassay testing techniques were selected because they possess a significant advantage over other field-screening tests in that the chemistry is PCB-specific. This feature precludes interference from other compounds and from native chlorine, such as that typically found in certain soils and other waste mixtures.

The manufacturer of the PCB field test kit was contacted concerning its application to this particular site. It was critical to know whether the field and soil conditions would allow for accurate and reproducible results. After the initial soil tests were conducted in the field and the duplicate samples that were sent to the laboratory revealed accurate results, the manufacturer provided a field test kit with PCB concentrations specific to the negotiated cleanup levels. The test kit provided results to determine if the concentration of PCBs in the sample was less than 2 ppm, greater than 2 ppm but less than 50 ppm, or greater than 50 ppm.

Immunoassay Overview

The PCB analysis approach used for this project employs a semiquantitative colorimetric method incorporating immunoassay technology, using tubes coated with antibodies that specifically detect PCBs (*1*). The test is "competitive," since the immobilized antibodies will bind to the PCB contaminant in a sample, the enzyme conjugate supplied with the test kit, or both in proportion to their relative concentrations. (The enzyme conjugate is prepared by covalent attachment of a PCB analog to the enzyme horseradish peroxidase.) After the used test tubes are washed to remove the sample solution, leaving behind the enzyme conjugate and PCB molecule immobilized by the antibodies, a chromogenic substrate that produces a vivid blue color in the presence of horseradish peroxidase is added to the test tubes. Color production is inversely proportional to the concentration of PCB contaminant in the sample: the more enzyme conjugate present, the faster the solution turns color and the darker it becomes. On the other hand, the more sample PCB molecules present, the fewer sites available for the enzyme conjugate and the lighter the solution. Therefore, the depth of the color determines the concentration range of the sample PCB solution.

Correlation of PCB Data by Field and Laboratory Analysis

To compare the results of PCB analysis by field and laboratory methods, six soil samples were analyzed for PCBs by both the field PCB test and by the gas chromatograph/electron capture detector method according to the EPA Contract Laboratory Program (Statement of Work for Organic Analysis, March 1990). Results of these analyses by both methods are given in Table 1. As shown in Table 1, the results obtained by the field-screening method for two samples are greater than those obtained by the laboratory method.

The scatter diagram of the relationship between PCB data by laboratory analysis and field screening is shown in Figure 2. When PCBs are undetected by the field-screening method, they are also not detected by the laboratory method. Higher values of PCBs by field screening are also associated with higher PCB values by laboratory method. A linear regression analysis was conducted by the StatView II program to see if there is a correlation between PCB laboratory data and field data presented in Table 1. As indicated in Table 2, the coefficient of correlation (r) was calculated to be 0.894 (a value of +1 or −1 stands for a perfect relationship and a value of 0 for no relationship), which is quite large. The coefficient of determination (r^2) is the square of the correlation coefficient. It is a number between 0 and 1 that shows how much of a relationship in correlation is due to the factors being compared. The closer the value of r^2 is to 1, the higher the degree of linearity of the points in the scatter diagram. For this correlation analysis, r^2 is determined to be 0.799. The adjusted r^2 is the square of the correlation coefficient adjusted for the small sample size and is calculated to be 0.749. It is the unbiased estimate of the population squared correlation coefficient. The root mean square residual is the square root of the mean square for residual of the analysis of variance (ANOVA) table (Table 2). It represents the standard deviation of the residuals, which are the errors of prediction, and is 2.415.

If

y = PCB lab data

and

x = PCB field data

Then the line of regression, expressed in the form of $y = bx + a$, is estimated to be

$$y = 0.22x - 0.912$$

where the slope (b) equals 0.22 and the intercept (a) equals −0.912.

The ANOVA procedure in linear regression analysis can be employed to test the significance of the slope b via an F-ratio. The ANOVA table (Table 2) represents a partition of the total sum of squares of the deviations into two parts: the sum of squares due to regression, and the sum of squares for residuals. The regression mean square is the variance of the fitted values, whereas the residual mean square is the variance of the residual values. The F-ratio, listed under F-test, is obtained as follows:

$$F\text{-ratio} = \frac{\text{regression mean square}}{\text{residual mean square}}$$

If the null hypothesis $b = 0$ is true, then there is no correlation between y (lab data) and x (field data).

However, the F-ratio is calculated to be 15.89 (Table 2) and is significant at $p = 0.016$. Therefore, the null hypothesis must be rejected. The slope b is significant by the ANOVA procedure.

The t-test was also used to test the significance of the slope b. The t-value is calculated to be 3.986. The level of significance (p) is 0.016, which is highly significant.

Although a small population was used for the correlation, there is a statistically significant correlation between PCB data by laboratory analysis and field screening.

TABLE 1 Data Correlation Between Laboratory and Field Analysis for PCBs

Sample ID	PCB Concentration By Lab Analysis (mg/kg) *a*	By Field Analysis (mg/kg)
1	12.00	greater than 50
2	0.54	between 2 - 50 *b*
3	0.37	less than 2
4	<0.07	less than 2
5	5.20	between 2 - 50 *b*
6	<0.07	less than 2

a mg/kg = milligrams per kilogram = parts per million
b The mid-point concentration fo 26 mg/kg was used in linear regression analysis.

MANAGEMENT OF EXCAVATED SOIL

Before any excavation activities, NJDEP approved on-site segregation and reuse of the nonhazardous soil. According to the approved plan, soil with PCB concentrations between 2 and 50 ppm were encapsulated under the ramp itself, with the roadway serving as a cap, and any soils with concentrations above 50 ppm were landfilled according to TSCA requirements. The cleanest soils, with PCB concentrations no greater than 2 ppm, were placed in the roadway embankment under 0.61 m (2 ft) of clean soil. This approach was considered to involve no danger to public health and no further degradation of the environment while providing suitable fill for geotechnical applications. It enabled NJDOT to save substantially on the cost of fill while also saving the expense for the transport and disposal of moderately contaminated soils. For example, a portion of the excavation for the ramp was undercut (Figure 1) to accommodate some of the contaminated soil.

The soil generated during the excavation was segregated before reuse into potentially clean and potentially contaminated categories. The soil was staged in preselected and specifically designed storage areas. Extensive use of PCB field test kits aided in the segregation of these soils. The segregation was confirmed through sampling and laboratory analysis before a decision was made on the final management of the excavated soils.

PROJECT MANAGEMENT AND REGULATORY AGENCY COORDINATION

Before the implementation of the excavation activities, a well-defined cleanup approach was developed and presented to NJDEP for approval. Although the approach used state-of-the-art testing technology, the project management approach emphasized close cooperation and coordination among the many project team mem-

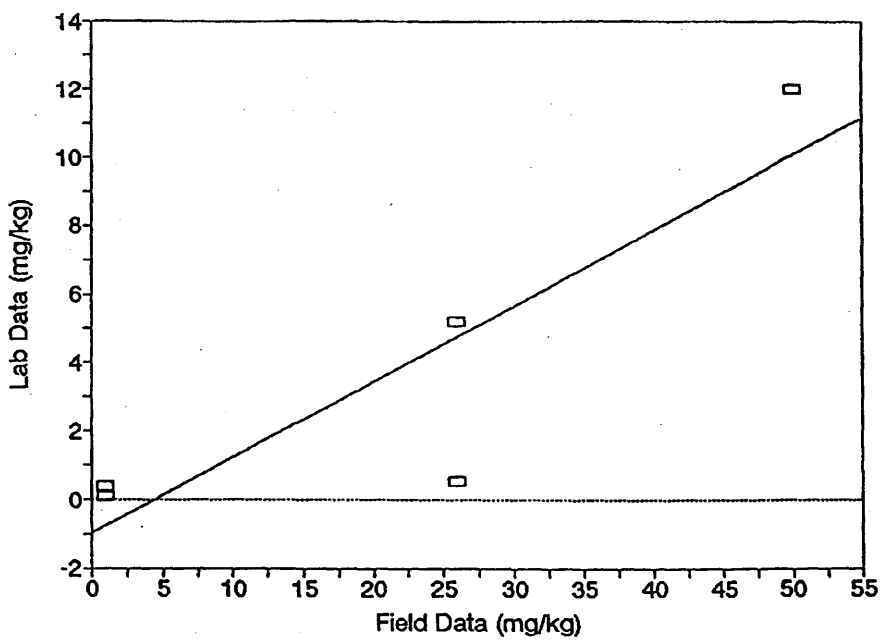

FIGURE 2 Scatter diagram: relationship between PCB data from laboratory analysis and field screening.

TABLE 2 Results of Linear Regression Analysis

Simple Regression	X	1:Field Data (mg/kg) *a*	Y	1:lab Data (mg/kg)
Count:	**R:**	**R-squared:**	**Adjusted R-squared:**	**RMS Residual:**
6	0.894	0.799	0.749	2.415

Analysis of Variance Table

Source	DF:	Sum Squares:	Mean Square:	F-test:
Regression	1	92.647	92.647	15.89
Residual	4	23.321	5.83	P=.0163
Total	5	115.968		

No Residual Statistics Computed

Beta Coefficient Table

Simple Regression	X	1:Field Data (mg/kg)	Y	1:lab Data (mg/kg)	
Variable:	**Coefficient:**	**Std. Err.:**	**Std. Coeff.:**	**t-Value:**	**Probability:**
Intercept	-0.912				
Slope	0.22	0.055	0.894	3.986	0.0163

Confidence Intervals Table

Variable:	95% lower:	95% Upper:	90% Lower:	90% Upper:
Mean (X,Y)	0.304	5.779	0.94	5.14
Slope	0.067	0.373	0.102	0.34

a mg/kg = milligrams per kilogram = parts per million

bers, including NJDOT's engineering, environmental, and project support departments; NJDEP; the consultant's own technical staff; and the contractor.

Once the operation started, daily communication with NJDEP was maintained to address the many unknowns that developed during the subsurface cleanup. Although all parties were working with cleanup goals that were well-defined and negotiated before the start of the actual remedial activities, close contact was maintained with the NJDEP case manager during the entire excavation operation to provide a daily status report and solicit feedback and agreement on the future course of action. In addition, close coordination between the consultant, NJDOT's resident engineer, and the contractor resulted in the identification of the most appropriate locations along the right of way where excavated material could be used as fill.

Careful planning of the work and the establishment of an informal but highly effective partnering relationship among all parties resulted in a remedial project that proceeded expeditiously with significant time and cost savings for the client.

CONCLUSIONS

The geophysical surveys provided a noninvasive technique for defining the limits of the buried drums and approximating the amount of waste and potentially impacted soil before the start of excavation. After the excavation was complete, geophysical surveys helped establish that all of the buried drums had been removed.

Field screening by immunoassay testing for PCBs allowed for a rapid and inexpensive way to segregate the soils and minimize the number of postexcavation samples submitted for laboratory analysis. Close liaison with regulatory agencies allowed the project to proceed as planned and maintained the accelerated schedule imposed by construction needs. The site was remediated below the NJDEP proposed cleanup levels. No residual contamination was left on-site, as indicated by the results of the postexcavation sample analyses.

The environmental solution resolved the contamination issue without modifying the construction ramp and highway design. Hence, remediation activities were completed ahead of schedule, which helped to expedite the ramp construction, and the highway was opened to the public as planned.

The actual site remediation cost $3.8 million. The use of immunoassay testing kits, upfront negotiation of cleanup levels, soil segregation, and soil reuse resulted in a $1 million savings from the estimated cleanup cost.

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Integrating Major Metropolitan Transportation Investment Study Process with National Environmental Policy Act Process

KENNETH J. HESS AND LAWRENCE E. PESESKY

FHWA and FTA recently adopted statewide and metropolitan planning regulations in response to the Intermodal Surface Transportation Efficiency Act of 1991. These regulations, in part, created a process known as the major metropolitan transportation investment study that was designed to evaluate the effectiveness and cost-effectiveness of alternative transportation investments. One of the intents of this process is to integrate it with the environmental review process required under the National Environmental Policy Act of 1969 (NEPA). The implications of integrating the two processes and the differences between each approach are explored. Specifically, review agencies and the general public must be given adequate opportunity to evaluate the consequences of alternative actions at several levels, an activity that is often implemented most successfully through the NEPA process. The two processes must also be integrated in recognition of differences in level of detail available at various stages of analysis, since major investment study appropriately would be performed at a broad, conceptual level for a variety of modal and intermodal alternatives, whereas NEPA requires enough design detail for fully assessing the environmental impacts of a specific project. Finally, the integration approach must account for timing differences between actions at the metropolitan planning organization level and the project design level. It is suggested that the tiered or programmatic environmental impact statement (EIS) be applied as an approach to integrating major investment studies with NEPA under certain circumstances. The tiered EIS approach has the potential of providing a structure that enhances the cooperative process specified in the planning regulations, avoids redundant analyses, and accounts for differences in timing between planning and design efforts.

The Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA) and its various implementing regulations have established systems and processes intended to strengthen transportation planning and project selection in the United States. The process-oriented requirements were established as the statewide and metropolitan planning regulations of FHWA and FTA on October 28, 1993 (*1*). The changes in transportation planning practice engendered by these regulations evolve over time while transportation planners test and adapt approaches intended to fulfill the requirements and intent of the regulations. As is typical of process-oriented regulations, the actual implementation will most likely be subject to interpretation, and interpretations are likely to vary by situation.

One of the specific requirements of FHWA's and FTA's metropolitan planning regulations that has stimulated much discussion among transportation planners is that of the major metropolitan transportation investment study. The complexity and uncertainty associated with this type of study is demonstrated by the variety of terms used by transportation agencies across the country to describe it, including major investment analysis, major investment study, major transportation investment analysis, and major transportation investment study/alternatives analysis. For purposes of this discussion, the general terms "major investment analysis" and "major investment study" will be used interchangeably throughout.

The intent of the major investment study is to identify early in the planning process the major investment alternatives and strategies that will most likely be the most effective and cost-effective when evaluated in relation to a variety of factors. However, the implication of the requirement for preparing a major investment study is that the total time involved from project or plan inception to final project approval under the National Environmental Policy Act of 1969 (NEPA) process may increase dramatically beyond the already time-consuming environmental process. The issue at hand is how to integrate the major investment study and NEPA processes in an effort to streamline the overall time required from beginning of project planning to final NEPA approval, and to do it in a manner that is consistent with the intent of both processes.

Before the published release of the federal metropolitan planning regulations, FTA required a combined alternatives analysis/draft environmental impact statement process for certain projects proposed with discretionary Section 3 "New Start" funding. This FTA combined process has been superseded by the major investment study, which does not explicitly integrate it with NEPA, although both FTA and FHWA are preparing new environmental regulations to modify their procedures in response to the new requirement. These regulations were anticipated to be published sometime in early 1995.

One potential method of integrating the major investment study and NEPA processes is that of adapting tiered or programmatic environmental impact statements (EISs) to respond to the early development and analysis of major transportation investment alternatives. Under certain conditions, this method appears to be a workable solution to streamlining and integrating the two processes, regardless of the actual revised environmental regulations that ultimately will be published by FHWA and FTA. The tiered EIS approach and its potential applicability to the major investment study requirement under certain circumstances is explored in further detail in this paper. The interpretation of the existing rules and regulations on major investment studies and tiered EISs and the resulting conclusions are entirely those of the authors and are presented in an effort to promote further understanding of the complex relationship between major investment analysis and NEPA, as well as

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an attempt to identify an approach that may be most suitable for integrating the two processes under certain situations.

MAJOR INVESTMENT STUDIES

Fundamentals of Process

A major metropolitan transportation investment is defined in the FHWA and FTA metropolitan planning regulations as "a high-type highway or transit improvement of substantial cost that is expected to have a significant effect on capacity, traffic flow, level of service, or mode share at the transportation corridor or subarea scale" (*1*). Major transportation investments may include, but are not necessarily limited to (a) construction of new partially controlled principal arterials, (b) extension of partially controlled principal arterials for a distance of 1 mi or more (c) capacity expansion equivalent to one or more lanes on partially controlled principal arterials, (d) construction or extension of high-occupancy vehicle facilities or fixed-guideway transit facilities for a distance of 1 mi or more, (e) addition of lanes or tracks to fixed guideways for a distance of 1 mi or more, and (f) substantial increases in transit service on a fixed guideway.

The regulations further state that "where the need for a major metropolitan transportation investment is identified, and Federal funds are potentially involved, major investment (corridor or subarea) studies shall be undertaken to develop or refine the plan and lead to decisions by the MPO" (metropolitan planning organization) (*1*). In other words, any major federally funded investment that is proposed to result in a significant transportation improvement within an MPO's jurisdictional region must first undergo a major investment analysis to identify and evaluate all reasonable alternatives. Although the major investment studies may be performed by the MPO, the state, or the proposing transit operator, the study must be completed before the inclusion, or at least the finalization, of the particular investment in the transportation plan and transportation improvement program (TIP) prepared by the MPO and ultimately incorporated into the overall state plan and TIP. In this regard, the major investment analysis is intended to be an early planning tool used in decision making.

Major investment studies are intended to evaluate the effectiveness and cost-effectiveness of alternative investments or strategies, considering direct and indirect costs of reasonable alternatives and such factors as mobility improvements, safety, operating efficiencies, land use and economic development, financing, energy consumption, and social, economic, and environmental effects. These factors are essentially the same as the factors previously required to be considered as part of FTA's alternatives analysis process, although they have been expanded to include highway and transit options as well as multimodal options. The intent of the major investment analysis is to provide a very broad and well-balanced consideration of multimodal and intermodal choices to improve the performance of the transportation system within a given corridor (i.e., linear transportation service area) or subarea (i.e., nonlinear part of a metropolitan area). The intended result of the analysis is to identify the preferred alternative or set of alternatives appropriate for that corridor or subarea, after taking into account the full array of potential effectiveness and cost-effectiveness factors.

Relationship of Major Investment Study to NEPA

Since it is not the intent of this paper to provide a full interpretation or practical application of the regulations and requirements of major investment analysis as a planning tool, no further discussion on this specific topic is warranted. However, it is appropriate to identify ways in which regulations relate this effort to the environmental studies required pursuant to NEPA. The preamble to the regulations specifically states that "these studies should be undertaken with the intent that they will substantially improve the linkage between the planning process and environmental review process" (*1*). The intent in this regard is to minimize or reduce redundancies in analysis as well as to incorporate early consideration of environmental impacts in all major transportation investment decisions.

The regulations allow the major investment studies to relate to the environmental studies in either of two ways. First, the major investment study can be used as input to an environmental assessment (EA) or EIS prepared subsequent to the completion of the study. Alternatively, a draft EA or EIS can be prepared as part of the major investment study, in order to address one or more of the effectiveness and cost-effectiveness evaluation factors identified earlier.

The first option establishes that an EA or EIS prepared for a specific project would incorporate by reference the findings of a previously prepared major investment study and the alternatives planning process leading to the selection of a preferred alternative or set of alternatives. Although this approach would allow the environmental documentation to focus on the preferred alternatives from the outset, thereby potentially streamlining the EA/EIS process, it does present an inherent risk that could result in an even longer approval process than if the full range of alternatives were considered initially as part of that process. This is because environmental and resource agencies such as the Environmental Protection Agency and the U.S. Army Corps of Engineers are less likely to become involved in a major investment study that is performed before and outside of the NEPA process than if all reasonable alternatives are identified and assessed equally as part of that process. Given the competing project commitments and time constraints on the staffs of such agencies, it is probable that unless and until the NEPA process is officially initiated and under way, these agencies will not be active participants in the early project planning efforts, even though provisions are made in the regulations to allow agency coordination. As a result, when the preferred alternative is presented to the agencies during initial project scoping under NEPA, the agencies conceivably could request reinvestigation of alternatives that have already been rejected or even conclude outright rejection of the preferred alternative.

The issue related to the first integration approach actually leads directly into a more fundamental issue. The fact that the major investment analysis is supposed to result in a selection of a preferred alternative or set of alternatives that would occur outside of the NEPA process could result in a basic violation of NEPA. The Council on Environmental Quality's (CEQ's) NEPA regulations specifically require that all reasonable alternatives be considered and presented in comparative form (*2*). Although only the preferred alternative identified through major investment analysis would be carried forth for NEPA documentation and review, other alternatives that were originally considered may also have been reasonable and should have been subjected to public review under NEPA. As a result, a literal interpretation of the intent of the major investment analysis to identify the preferred alternative would always eliminate any other alternatives from any real consideration within the EA/EIS process. This outcome could generate a high level of controversy from environmental and other review agencies, as well as members of the public, who believe that the sponsor and lead federal agency (or agencies) had reached a decision before even starting the NEPA process.

The second option of integrating the major investment studies and the environmental process would eliminate the potential problem associated with the first scenario because the sponsor agency and the lead federal agency would actually develop a draft or even a final federal environmental document as part of the corridor or subarea study. However, there are two basic problems with this second approach to integrating the major investment analysis and NEPA. The first is that the level of analysis of alternatives required for the two separate procedures is different. For major investment, a broad array of modal and intermodal alternatives would be developed and considered in a broad fashion since the intent is to identify a single strategy or combination of strategies that best satisfies the particular need within the subject corridor or subarea. Therefore, the level of environmental information that is required at this stage is much less detailed than that required for a full EA or EIS analysis. It would be inappropriate, in fact, even to attempt to study the broad range of alternatives at this point in the same level of detail as in a conventional EA or EIS, since it is inevitable that many of these alternatives will be eliminated from further consideration on the basis of factors other than environmental, and therefore such study would result in a great deal of wasted effort. Similarly, it is unlikely that the broad array of alternatives developed at the major investment analysis stage would be at a sufficient level of detail to allow a complete environmental investigation to occur at the level required for a conventional EA or EIS.

The other problem associated with the second approach is one of timing. The regulations require that the major investment study be prepared before the inclusion or finalization of a given project or group of projects on the MPO's transportation plan and TIP. Once the major investment study has been completed and the project has been included in the MPO planning, it could be several years before it is intended to achieve the level of design necessary to evaluate the environmental impacts of the project under NEPA. Therefore, if major investment analysis is integrated with NEPA using a conventional EA or EIS approach, the process of environmental documentation and review under NEPA could not be completed until a sufficient level of design has been achieved. The result would be a seemingly endless NEPA process that would delay any single element or project proposed within a given corridor or subarea from proceeding until the process has been completed entirely for all of the components of the preferred alternative.

Hypothetical Case Study

Using a hypothetical example to illustrate each of these issues, suppose that a major investment analysis of a 20-mi corridor in a rapidly suburbanizing area is proposed. The corridor already contains an arterial highway running from end to end, ranging from two lanes in some areas to four lanes in others. In general, this highway and some of the approach roadways at major intersections suffer from extreme congestion problems during peak commuting hours. Two separate bus lines provide service along portions of the corridor, and a third line crosses the corridor from end to end. Other modes and transportation services are virtually nonexistent. Fifteen basic alternatives or combinations of alternatives are identified initially as being reasonable, including construction of a new limited-access highway on any of three general alignments, widening of the existing highway, specific spot and intersection improvements, the use of a variety of transportation control measures (TCMs), the provision of pedestrian and bicycle facilities, transit service upgrades, and the construction of one or more park-and-ride facilities.

The broad range of alternative strategies for reducing the congestion within the corridor necessitates a broad level of analysis for assessing the relative ability of each to respond to the overall corridor need. Initially, each alternative would be developed to a sketch level of detail in order to assess each one's effectiveness, cost-effectiveness, general environmental issues, operational efficiencies, potential financing mechanisms, relative degree of safety, and so on. Unless it becomes the intent of the sponsor and lead federal agencies to perform a complete and detailed analysis of all 15 alternatives without knowing which will actually satisfy the need, the outcome of the sketch level of analysis could be to select the preferred alternatives or to narrow the range of viable choices to a more manageable number that will be studied in some greater level of detail under NEPA. Either way, at the conclusion of the major investment study, the preferred alternatives will be identified and included on the MPO's transportation plan and TIP.

Assume that in the hypothetical example, the major investment study resulted in a preferred alternative that included a new limited-access highway in addition to construction of one park-and-ride lot. Under the first scenario of integrating major investment analysis and NEPA, once the various review agencies and general public become involved in the project via the NEPA review process, it would not be surprising if they were to disagree with the preferred alternative combination that was previously chosen and argue that a different alternative—such as a park-and-ride lot in conjunction with transit service upgrades, spot improvements on the existing highway, and several TCMs instead of the new limited-access highway—would be more appropriate. In this case, the fact that a preferred alternative was already selected without their participation becomes in itself a major issue, even though input may have been solicited unsuccessfully from them during the course of major investment study preparation due to their existing commitments on NEPA-related projects. A fundamental disagreement between resource agencies and the project sponsor agency on the composition of the preferred alternative could force the sponsor agency to reconsider its earlier decision, thereby requiring a new alternative combination to be selected with concomitant additional environmental investigations. The result could be a lengthier review and approval process because of the lack of specific review authority provided to the resource agencies outside the NEPA process and, therefore, the inability of those agencies to become involved until after the major investment analysis is completed.

Similarly, the general public would be less likely to become involved in the major investment decision-making process if it precedes NEPA because of the more conceptual nature of this process, especially given that the results of major investment analysis become further diluted in the metropolitan long-range transportation plan. In this regard, the most meaningful public involvement usually occurs when people are aware that they may be affected directly by a design or location decision, which would normally happen at the time that more detailed information becomes available, such as when an EA or EIS is being undertaken.

Consider the hypothetical example again using the second option for integrating major investment analysis and NEPA. Given the diversity of the alternatives being considered, the first step should be a determination of how well each alternative satisfies the overall corridor problem and need, with an analysis of environmental impacts at a level sufficient to compare generally each against the others. The level of detail required to perform such an analysis could be purely conceptual, with plan drawings at a scale of 1 in. = 400 ft or smaller. This level of detail, used in conjunction with traffic demand studies, is certainly adequate to determine whether a par-

ticular alternative would satisfy demand and to provide a general indication of how each would most likely affect the environment so that a comparative evaluation could be made.

On the basis of this information, a preferred alternative could certainly be selected as part of the major investment analysis, but an insufficient basis exists for evaluating and making decisions about alternatives for conventional EA or EIS purposes. For instance, it should be possible at this stage to determine if only construction of a new limited-access roadway, with or without other improvements as well, would satisfy the need for the corridor, as well as the number of lanes and interchanges that are appropriate. Conversely, it could be determined if a variety of TCMs, improved transit facilities and services, and the construction of a park-and-ride lot would meet the demand and minimize environmental impacts. Since details of the number of acres of wetlands and farmlands to be affected and the full range of other potential impacts cannot be determined precisely until more detailed plans are developed, either a decision on the preferred alternative must be postponed until later in the NEPA process, when greater detail on the alternatives has been developed, or more detailed plans must be prepared from the outset. Either way, the preferred alternative should be identified early enough in the process so that it can be placed in the MPO's or state's transportation plan in a timely fashion.

The timing issue associated with the second integration approach can also be illustrated with this hypothetical example. Once the new limited-access highway and park-and-ride lot have been identified as the projects in the preferred alternative and have been included in the MPO's transportation plan and TIP, it is possible that one of the projects—say, the highway—is scheduled to be implemented several years after the other—in this case, the park-and-ride lot. Accordingly, the design of the highway would probably lag behind that of the park-and-ride lot by several years as well. By linking the major investment study with a conventional EA or EIS process, delays could be experienced since the EA/EIS could not be completed to an adequate level of detail until the greater level of design of both projects is completed. Therefore, in this case, the overall approval process could actually take much longer than expected, despite the intent to streamline the overall process by integrating major transportation investment analysis and NEPA.

Obviously, the particular issues just presented are not guaranteed to develop on all projects, but the potential does exist. Given this possibility, if would be preferable to use an approach that would satisfy the intent of integrating major investment analysis and NEPA while reducing the potential for these issues to occur. One approach that appears to have some merit in this regard and deserves further consideration before the federal environmental regulations are revised by FHWA and FTA is the use of tiered EISs, including a programmatic or Tier 1 EIS to address the full range of broad alternatives considered as part of the major investment study, followed by one or more project-specific EAs or EISs. Details on programmatic or Tier 1 EISs and their potential use for this purpose follow.

TIERED EIS PROCESS

Fundamentals of Process

The concept of tiered EISs is based on the fact that the CEQ, in its NEPA regulations, allows for a process known as tiering (*2*). This process refers to the coverage of general matters in broader environmental impact statements (such as for a program, plan, or policy), followed by more focused, narrower statements or analyses (such as for a site-specific project) that incorporate by reference the general discussions of the broader-based document. Tiering has been determined by CEQ as being appropriate under either of two basic conditions:

1. When a program, plan, or policy is evaluated within an EIS, followed by a separate EIS or analysis of a program, plan, or policy of lesser scope or a site-specific project; and
2. When a specific action at an early stage (such as need and site selection) is evaluated within an EIS, followed by a supplement or subsequent EIS or analysis of a more specific element (such as environmental mitigation).

Programmatic or Tier 1 EISs, which would be the first-tiered environmental documentation required under either of the preceding conditions, represent an opportunity to focus on environmental impacts of federal programs before the commitment of major funding, as well as an opportunity to consider environmental issues early in the planning process. Programmatic EISs make up only a small percentage of the total EISs prepared throughout the country during a given year, although use of such documents is increasing as more agencies recognize the value and legal validity of programmatic assessment. Although guidance on preparing environmental documents at a programmatic level is limited, traditionally the level of detail available for analyzing the environmental effects at this stage is somewhat broad and general, while projects are developed to greater specificity for subsequent environmental documentation. Even so, the programmatic EIS must contain enough information to conduct a meaningful evaluation.

In the transportation arena, FHWA has included the concept of preparing tiered environmental documents in its own regulations prepared for implementing NEPA and CEQ's regulations (*3*). These regulations state the following:

> For major transportation actions, the tiering of EISs as discussed in the CEQ regulation . . . may be appropriate. The first tier EIS would focus on broad issues such as general location, mode choice, and areawide air quality and land use implications of the major alternatives. The second tier would address site-specific details on project impacts, costs, and mitigation measures.

Despite the provision for tiered EISs in FHWA's regulations, the concept has been used only rarely for highway development projects in this country. Programmatic studies are known to have been utilized as a method of preserving transportation rights of way in rapidly developing areas. For instance, a programmatic EIS, referred to by the Nevada Department of Transportation and FHWA as a Tier 1 EIS, is being prepared for that purpose for a proposed beltway around the western and northern perimeters of Las Vegas. A Tier 2 EIS addressing the actual transportation improvement will be prepared after the proposed corridor(s) have been preserved and the project has been designed to a greater level of detail.

Although tiered studies give an agency the opportunity to begin the NEPA process for a project that is not yet well developed, some opponents of the tiered assessment process have argued that such studies result in an additional and unnecessary stage of NEPA review, which ultimately increases the total time involved and results in duplication of analysis between stages. Although there may be some truth to these claims at times, tiered EIS studies do have a place in the NEPA process and can yield overall time benefits under appropriate circumstances.

Integration of Tiered EIS Process with Major Investment Analysis

As discussed previously, metropolitan planning regulations state that the major investment analysis should be undertaken and preferably completed relatively early in the planning process, since the scope and design concept to be included in the MPO's or state's transportation plan cannot be made final until such analysis is completed and a preferred alternative or combination of alternatives is identified. The wide variety of potential transportation alternatives to be considered for major investment, each developed to a conceptual or general level of detail, appears to make an environmental impacts evaluation particularly suited to the tiered EIS approach. In this manner, the alternatives assessment and selection of preferred alternatives can be performed early in the planning process, using limited design detail, but still be covered by NEPA review. Therefore, when the MPO decides to include a project in its transportation plan and subsequently in its TIP, the selection of that project will already have complied with NEPA as well. In turn, the project sponsor agency would be satisfied before initiating a more detailed design and environmental evaluation that the project is acceptable to the MPO and has a "real" commitment to funding allocation. This would also ensure that all relevant review and resource agencies are involved in the alternatives study from the outset because it will be incorporated into a formal NEPA review process, complete with project scoping and public outreach.

Figure 1 identifies a reasonable sequence of events that illustrates the potential to integrate major investment analysis into the NEPA process using a tiered assessment approach. The sequence begins with an initiation of conceptual alternatives development, encompassing the full range of potential transportation improvements for a given corridor or subarea, and the initiation of a Tier 1 EIS. During the course of Tier 1 EIS preparation, the major investment analysis would be undertaken, including an analysis of purpose and need and a variety of broad transportation concepts, culminating in the selection of a preferred alternative or set of alternatives. The Tier 1 Draft EIS would then present the results of the evaluation of all reasonable alternative concepts and identify the preferred alternative, assuming that the major investment analysis is completed by that time. Otherwise, the preferred alternative would not be presented until the Tier 1 Final EIS. Either way, this entire Tier 1 EIS process would precede the MPO's inclusion or finalization of the project on its transportation plan and TIP.

While the process of including the project on the plan and TIP is under way (or already completed), the preferred alternative can be refined and developed to a greater level of detail. At this point, a more specific and focused environmental document, which could be either an EA or Tier 2 EIS depending on the scale of the project, would also be initiated. During this analysis details pertaining to project design and location, possibly resulting in several alternatives in this regard, would be developed and studied in terms of environmental impact. Preferably, the project already would have been evaluated for its air quality conformity and included in the MPO's plan and TIP prior to Draft EA (if applicable) or Tier 2 Draft EIS publication. However, these actions for which the MPO is responsible would have to be completed at least before Tier 2 Final EA/EIS completion and subsequent federal project approval.

Use of Tiered EIS Process in Hypothetical Case Study

Applying the previous sequence of events to the hypothetical example presented earlier provides a clear picture of the entire process. During project initiation, a long list of potential alternative transportation strategies would be developed and subjected to a qualitative analysis in order to reduce the field to 15 alternatives that appear to be reasonable given the specific nature of the problem and the corridor or subarea. At this point, the 15 broad alternatives would be developed to a conceptual level and presented to resource agencies and the general public, as appropriate, through Tier 1 EIS project scoping. As major investment analysis proceeds, these 15 alternatives would be evaluated in terms of ability to satisfy need and the complete range of other evaluation factors required for consideration, including an environmental analysis to a level appropriate given the conceptual nature of the alternatives. The result is the selection of a new four-lane, limited-access highway several miles to the north of the existing arterial highway running through the length of the corridor, in addition to the construction of one park-and-ride lot at a proposed interchange near the middle of the project, with the park-and-ride intended to be constructed several years before the new highway. This result of the major investment study and the information on all 15 alternatives investigated are then presented in the Tier 1 Draft EIS, before being modified in the Tier 1 Final EIS in response to public comments received. At this point, the regulatory and other resource agencies should have reached a general acceptance of the purpose and need and the general alternative concepts.

The MPO would then initiate air quality conformity studies to ensure that if the construction of a new four-lane, limited-access highway and park-and-ride lot were to be included on its transportation plan and TIP, they would still conform to the state implementation plan (SIP). At that point, both elements of the preferred alternative would be approved by the MPO.

Once it is known that the project will conform with the SIP and is being included in the MPO's plan and TIP, the proposed new highway alignment and park-and-ride lot can be engineered to a greater level of detail, such as a scale of 1 in. = 100 ft or larger. In the interest of time, however, the project sponsor may begin its Tier 2 studies while the MPO is preparing its SIP conformity work and transportation plan and TIP. At this point, minor location and design alternatives can be developed in an attempt to minimize environmental impacts, provided that they do not change significantly the results of the major investment study that was already completed. These alternatives would be presented in the Tier 2 environmental documents, as appropriate, before final approval. Because the general concepts were considered and approved in a Tier 1 EIS, it is possible that at this stage of project development and evaluation, an EA, or even separate EAs for each part of the project, will suffice rather than a full Tier 2 EIS. Since the park-and-ride lot and the new highway are proposed to be designed and constructed under separate schedules, it may be preferable and appropriate to prepare separate environmental documents, assuming that they have independent utility and the cumulative effects of both projects were addressed in the Tier 1 EIS.

Circumstances of Applicability of Tiered EIS Approach

The most appropriate application of the tiered EIS approach to major investment study is in situations for which a wide variety of modal and intermodal options are available and reasonable to satisfy an apparent need within a corridor or subarea, such as the case presented in the hypothetical case study. The actual number of options that would have to exist before a sponsor agency could anticipate the benefits of using a tiered environmental approach is purely subjective and would undoubtedly be applied on a case-by-case

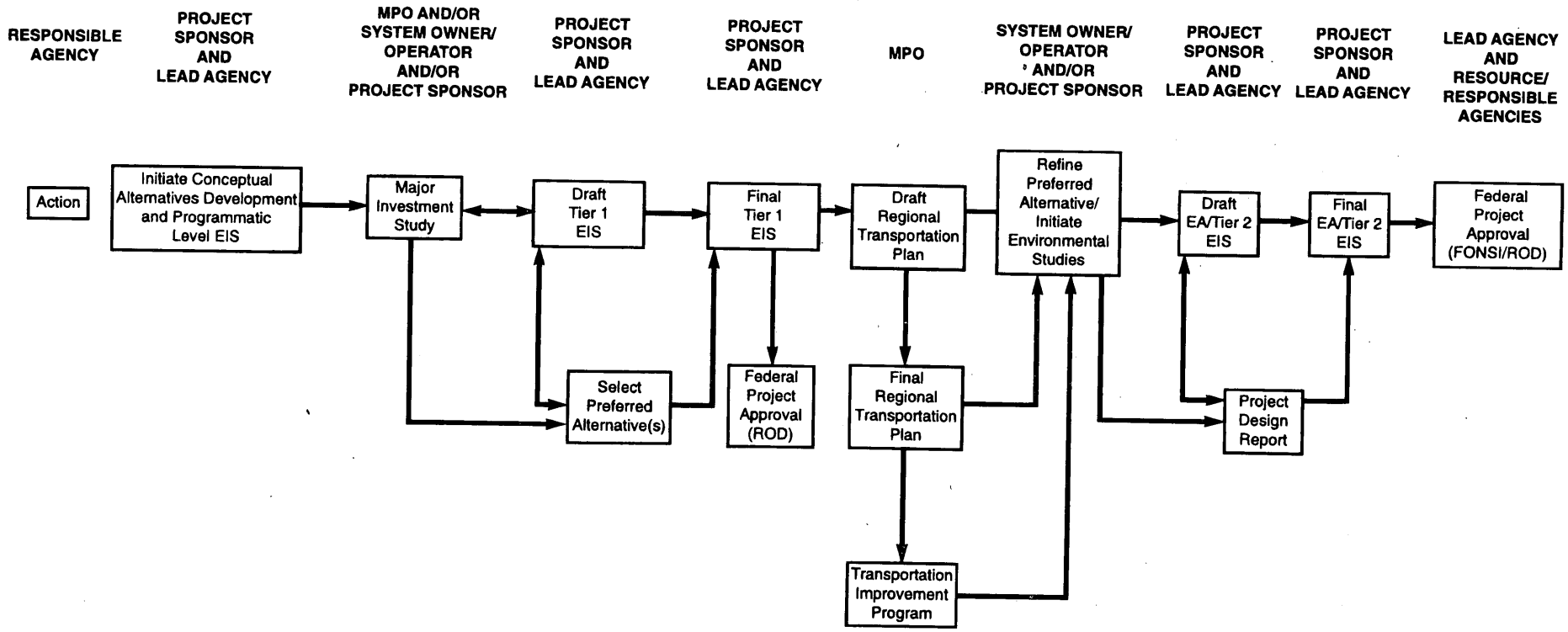

FIGURE 1 Proposed process for integrating major investment analysis with NEPA using tiered assessment approach.

basis. This approach is also particularly applicable when there is anticipated to be significant opposition to a particular project, or at least to a particular alternative. By using a tiered EIS approach, input from the agencies and the public can be received even before the full range of modal and intermodal options is developed. The conclusion of the major investment study and Tier 1 EIS, at least in theory, would be a general approval and acceptance of the preferred alternatives before any further development or consideration of the specifics of that alternative or combination of alternatives is performed.

It is recognized that without a sufficient number of transportation system alternatives available within a corridor or subarea, application of the tiered EIS approach would not necessarily offer the best opportunity for streamlining the overall approval process and allowing a project to get under construction as quickly and efficiently as the project need demands. If the types of options are limited, then a sponsor agency can more quickly move to the specifics of a given type of alternative. However, even in such cases, adequate demonstration and documentation within the NEPA process that other options are virtually non-existent within the corridor or subarea may be the key to a project's success.

For situations in which a wide variety of modal and intermodal options initially are proposed to be considered in the major investment study, and when there is a high potential that the preferred alternative could include more than one project within the corridor or subarea, the potential is also high that the individual projects will be designed on separate schedule tracks. It would be entirely plausible if one or more of the projects were proposed to occur a number of years after the first. This difference in schedule may be due to funding limitations or higher priorities at the state and MPO levels. The tiered approach allows the individual projects to proceed on separate schedules, thereby relating the NEPA requirements with the actions proposed in the transportation plan and TIP more effectively and efficiently.

CONCLUSIONS

This paper has presented a potential approach for dealing with a complex set of new regulations requiring that a major investment study be performed whenever a major transportation investment is being contemplated. The ability to develop a workable approach for integrating major investment analysis into the NEPA process is an important element in evaluating the long-term success of this new requirement for alternatives assessment. The tiered EIS approach that is presented for integrating the two separate processes is an attempt to demonstrate to transportation planners and transportation agencies that workable options do exist, even if they require the consideration of techniques that traditionally have been avoided whenever possible. Under certain circumstances, the tiered EIS approach appears to have the potential to successfully link major investment analysis and NEPA, provide a structure for regulatory agency and public involvement, avoid redundant analyses, and allow for differences in timing between the MPO's actions and the project sponsor's design development efforts.

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PART 3

Transportation Noise

Radiated Aerodynamic Noise Generated by High-Speed Tracked Vehicles

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The origins and manifestations of aerodynamic noise generated by high-speed tracked vehicles are discussed, and examples of measurements on magnetically levitated and wheeled trains are used to illustrate the significance of this noise. Sound-source location measurements with microphone arrays and the difficulties encountered in predicting aeronoise are also discussed.

Some press reports have described the sound produced by a magnetically levitated (maglev) vehicle traveling at high-speeds as "wind noise." Without further qualification, however, this description lends itself to gross misinterpretation. "Wind noises" can be as gentle as the whisper of a spring breeze or as awesome as the roar of a tornado, but neither extreme bears any resemblance to the sound emitted by a passing vehicle. As shall be demonstrated, the level of wind noise, or aerodynamic noise, generated by the passage of a high-speed vehicle lies within the accustomed range of wayside levels produced by conventional trains. Indeed, a well-designed high-speed tracked vehicle will generate lower sound levels than does its conventional counterpart traveling at much lower speeds.

In Germany the phrase "high-speed tracked vehicles" refers to the electrically powered InterCity Express (ICE), the new generation of Deutsche Bahn (DB) trains, and the TRANSRAPID maglev TR 07, which has been certified for commercial operations but is not yet in regular service. The ICE carries passengers at speeds up to 250 km/hr which the DB plans to increase to 280 km/hr in 1995 and to 300 km/hr in the near future. The maglev TR 07 is designed for sustained operation at speeds up to 500 km/hr.

When the research and development of high-speed ground transport systems began in the 1970s, it appeared axiomatic to many people that higher speeds equal higher noise levels. To belie the logic of this equation, the DB, in cooperation with the German Ministry for Science and Technology, has invested heavily in seeking ways to reduce wayside noise levels. Since it was recognized early on that some of the important noise sources at speeds in excess of 250 km/hr would have flow-generated origins (*1,2*), the new high-speed vehicles were designed to minimize aerodynamic noise levels. As a result of these efforts, wayside noise levels generated by the ICE at 300 km/hr are comparable to those produced by average conventional InterCity trains traveling at speeds between 160 and 200 km/hr. And the maglev TR 07, which is significantly quieter than wheeled trains at corresponding speeds, generates noise levels at 400 km/hr that lie within the range of sound levels produced by conventional trains at much lower speeds.

Sound sources on railway trains can be grouped into three categories:

1. On-board machinery (traction motor, air-conditioning units, etc.),
2. Wheel/rail (W/R) interactions, and
3. Aerodynamic interactions.

The first category is important generally only up to speeds of between 50 and 80 km/hr, whereas the second category is the principal source of wayside noise up to speeds of at least 220 km/hr. At higher speeds, aerodynamically generated forces begin vying with W/R interactions for dominance. One cannot specify any particular speed at which the former sound sources become more important than the latter because this speed depends on a number of factors, including the design of the vehicle, condition of the rails and wheels, use of wheel-noise absorbers or sound barriers, and the definition of wayside noise.

The three corresponding categories for maglev vehicles are

1. On-board machinery and magnetostrictive forces,
2. Vehicle/guideway interactions, and
3. Aerodynamic interactions.

In the following sections, the aerodynamically generated sound component will be discussed and examples to illustrate its significance will be given.

GENESIS AND MANIFESTATIONS OF AERODYNAMIC NOISE

The immediate cause of aerodynamic noise is flow interactions between the moving vehicle and the air. In this paper only the radiation field of aerodynamic noise will be discussed but there is also a near-field component that could cause cabin noise problems for maglev vehicles in particular. The fluid mechanical phenomena to be discussed have aeroacoustical consequences.

Aerodynamic Drag

Solid bodies traveling through the atmosphere encounter resistance to their motion. This resistance, called aerodynamic drag, can be considerable for tracked vehicles. Gawthrope (*3*) found that a conventional train uses up to 70 percent of the traction power available at the wheels to overcome aerodynamic drag. For a high-speed train operating at 300 km/hr, this figure could reach 90 percent (*4*).

The aerodynamic drag of a body comprises three components: (*a*) skin-friction drag caused by viscous shear in the layer of air adjacent to the body, (*b*) form or pressure drag due to the modified pressure distribution around the body, and (*c*) induced drag when the

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body has nonzero lift. Since tracked vehicles generally have a zero or very low, positive or negative, lift coefficient, induced drag plays a very minor role at best in establishing their total aerodynamic drag, and this component shall be ignored. Of the first two components, skin-friction drag is usually slightly larger than pressure drag for tracked vehicles (*3*). Taken together, these first two components are called profile drag.

The viscous nature of air is the underlying cause of profile drag, and it is absent if the fluid is inviscid. Thus, bodies having zero lift traveling through inviscid fluid experience no resistance to their motion, and no mechanism exists for generating flow-induced noise. When the fluid is air, however, drag forces do act on the moving body, and it radiates noise. Although the facts that the body experiences drag and sound is generated are simply observations, it shall be assumed that a causal relationship exists between them (i.e., aerodynamic drag produces aerodynamic noise). If only 10^{-6} of the mechanical power dissipated by aerodynamic drag were to be converted into acoustic power, a 60-m-long vehicle traveling at a speed of 300 km/hr would generate a sound level greater than 80 dB at a point 25 m from the vehicle.

This probable causal relationship was studied by Revell et al. in their investigations of airframe noise (*5,6*). They found that the root-mean square (rms) sound pressure $\tilde{p}$ is related to the aerodynamic drag coefficient C_x of a structural element of the aircraft by

$$\tilde{p}^2 \sim C_x^n \tag{1}$$

where n has a value of 3 for most components, including the fuselage. Therefore, if a tracked vehicle is relatively "clean" in an aerodynamic sense, Equation 1 tells us that a decrease in the drag coefficient produces a corresponding decrease in the rms sound pressure of aerodynamically generated noise.

A vehicle's aerodynamic drag is strongly affected by crosswinds. Gawthrope (*3*) writes that even the "wind on a typical breezy day could easily increase drag by 20 percent."

Turbulent Boundary Layer

The viscosity of air must be taken into account when considering the behavior of an airflow close to the surface of a solid body. One of the boundary conditions of fluid mechanics is the "no-slip" condition. If there is relative motion between a viscous fluid and a solid body, the no-slip condition requires that the fluid particles in direct contact with the body have zero velocity relative to the body. To simplify the discussion, consider a fluid moving with free-stream velocity U_0 interacting with a stationary body. At the body's surface, the fluid velocity is zero, whereas at some distance from the surface the fluid has to attain its free-stream velocity. Therefore, within a layer of fluid adjacent to the surface, there must be a velocity gradient with its accompanying shear stresses. This layer of fluid is called the boundary layer.

The boundary layer on the vehicle begins at the stagnation point on the tip of the nose, at which the flow velocity is zero, and moves around the convex surface in a generally downstream direction. Initially the airflow is laminar, but within a short distance of the stagnation point the flow undergoes transition to turbulence. The chaotic motion of fluid within a turbulent-boundary layer (TBL) produces pressure fluctuations on the vehicle's surface. These pressure fluctuations will be discussed later.

Flow Separation

To satisfy the continuity equation, the air adjacent to the surface of the nose, but not in direct contact with it, accelerates along the convex surface. Depending on the geometry of the head shape, the accelerating air can rapidly attain speeds that are up to 60 percent higher than U_0. The accelerating air flow on the head produces a favorable pressure gradient (i.e., $dp/d\xi < 0$, where p is pressure and ξ is distance along the head). A pressure gradient is favorable when it inhibits the separation of the boundary layer. When the air reaches the region of constant head width, the flow decelerates, thereby creating an adverse pressure gradient (i.e., $dp/d\xi > 0$). In this region, the thickness of the boundary layer increases more rapidly with ξ than it did in the region of favorable pressure gradient. Both the wall shear stress and the adverse pressure gradient suck off momentum from the flow, thereby causing it to decelerate further. The boundary layer can then often no longer maintain itself on the surface and separation occurs. If the air flow in the region of separation can be considered two-dimensional, the line of flow separation coincides with the disappearance of the wall shear stress and the beginning of a region in which the flow reverses itself. On the front of a full-size moving vehicle, however, the air flow is often three-dimensional, and boundary-layer separation can occur without the shear stresses going to zero or the flow reversing itself (*7*).

The momentum in the vehicle's boundary layer is usually high enough for the separated flow to reattach itself at a short distance downstream, thereby forming a separation bubble. As mentioned earlier, crosswinds can modify the boundary layer on a vehicle, particularly on its head shape. For example, wind gusts could trigger an incipient flow separation. The shape of a vehicle's head is a very important parameter for reducing the probability that a boundary-layer flow separation will occur (*4*), but because of difficulties in the manufacturing process or operational reasons, head shapes are often less than optimal. In a numerical study of flow over a head designed for a maglev vehicle, Siclari et al. (*8*) found that the flow separated on the nose and produced vortices that were swept downstream along the sides of the vehicle.

A different kind of separation occurs when vortices are shed on structural elements of the vehicle (i.e., on salient or trailing edges, axles, cut-outs, pantographs, etc.). Vortex shedding is a very important source of aerodynamic noise on high-speed vehicles.

Noise Sources on High-Speed Vehicles

According to Gutin's principle (*9*), fluctuating forces acting on a surface generate sound regardless of the origin of such forces. Strong sound sources are generated within regions of TBL flow separation. Although rms fluctuating pressures (i.e., forces) within such a region can be 20 or more times higher than those beneath an attached TBL (*10*), the principal source of noise may be the time rate of change of pressure rather than the fluctuations per se. Other strong sources of pressure fluctuations and sound are generated by vortex shedding from edges and protuberances. The pressure fluctuations within an attached TBL are also fluctuating forces acting on a surface and, as such, also generate sound. The specific sound power generated by these fluctuating forces is, however, relatively weak, and the author is not aware of any unambiguous laboratory measurements of TBL sound. Because TBL noise is a strong function of flow speed, however, it is conceivable that a very large surface such as that on a 200-m-long maglev vehicle traveling at very high speed could generate a TBL sound power that would substan-

tially contribute to wayside noise levels. Model calculations (*11*) indicate that TBL noise could be important at speeds over 400 km/hr, but this prognosis has not yet been verified directly.

Fluctuating forces generate sound having a dipole pattern. A couplet of such forces lying side by side with their fluctuations 180 degrees out of phase produces a lateral quadrupole, whereas when the two fluctuating out-of-phase forces lie end to end, they form a longitudinal quadrupole. On a flat, smooth, infinite, rigid surface, sound generated by the pressure fluctuations in a TBL would combine with sound reflected from the surface to produce such longitudinal quadrupoles. Relative to an acoustic wavelength of TBL noise, however, the width of a vehicle is not large, and dipole noise is more likely to be important.

Sound generated by aerodynamic sources is proportional to flow speed raised to a power, namely,

$$\tilde{p}^2 \sim U^{\alpha} \tag{2}$$

where α depends on the source, flow speed U, and whether or not the sound is A-weighted. The Mach number of a flow is $M = U/c$, where c is the local sound speed. For $M << 1$, α equals 6 for dipoles and 8 for quadrupoles. Sound generated by W/R and vehicle/guideway interactions can also be represented by Equation 2 if we let $\alpha \approx 3$ for A-weight sound. For machinery noise, α can be taken as ≈ 1 *(11,12)*.

Since α equals at least 6 for aerodynamic sound (trailing edge noise where $\alpha \approx 5$ is an exception) and 3 for noise generated by W/R and vehicle/guideway interactions, there must be some speed at which the sound power level produced aerodynamically equals that due to W/R or vehicle/guideway interactions. This speed is called the upper acoustical transition speed U_{t_2}. The problem is to determine whether βU_{t_2}, when $\beta \approx 0.8$, lies within the range of operating speeds for each type of vehicle.

The peak frequencies of vortex-shedding sound are proportional to the local flow speed. Although the peak frequencies of sound generated by a TBL flow separation or surface-pressure fluctuations also increase with flow speed, their dependence on it is more complicated. For cavity noise, peak frequencies do not generally exhibit this dependence on flow speed. When the surfaces of the rails are smooth and free of corrugations, the results of many array measurements have shown that the peak frequencies of W/R noise are independent of train speed. The levels of the higher-frequency peaks tend to increase at a slightly higher rate with increasing speed than do the levels of the lower-frequency peaks, but the frequencies themselves remain essentially constant.

Most important aerodynamic sound sources on high-speed vehicles have peak frequencies lying below 1,000 Hz. Consequently, when this sound is A-weighted, the sound pressures are attenuated in such a way that the lower the frequency, the greater the attenuation. The effect on the speed exponent α when vortex-shedding sound is A-weighted is illustrated in Figure 1. Sound produced by vortex shedding has a dipole radiation pattern, and, hence, $\alpha = 6$ when the sound is unweighted. The three peaks in the figure represent vortex-shedding sound generated speeds of 100, 200, and 400 km/hr (200, 400, and 800 Hz peaks, repectively). The increase of sound level with increasing speed is represented by a speed exponent of 6 for unweighted sound; when it is A-weighted, however, α can range from 6 to about 8, depending on frequency and, hence, speed.

Two other effects that influence sound emitted by moving sources are (*a*) the well-known Doppler frequency shift and (*b*) convective augmentation of the sound pressure. This augmentation is slightly different for point sources than it is for line or surface distributions of sources. Since the important sound sources on a tracked vehicle are all dipole-like, the increase of level due to convective augmentation shall be approximated with an expression similar to what one would obtain for a point dipole:

$$\Delta = -20 \log(1 - M^2) \tag{3}$$

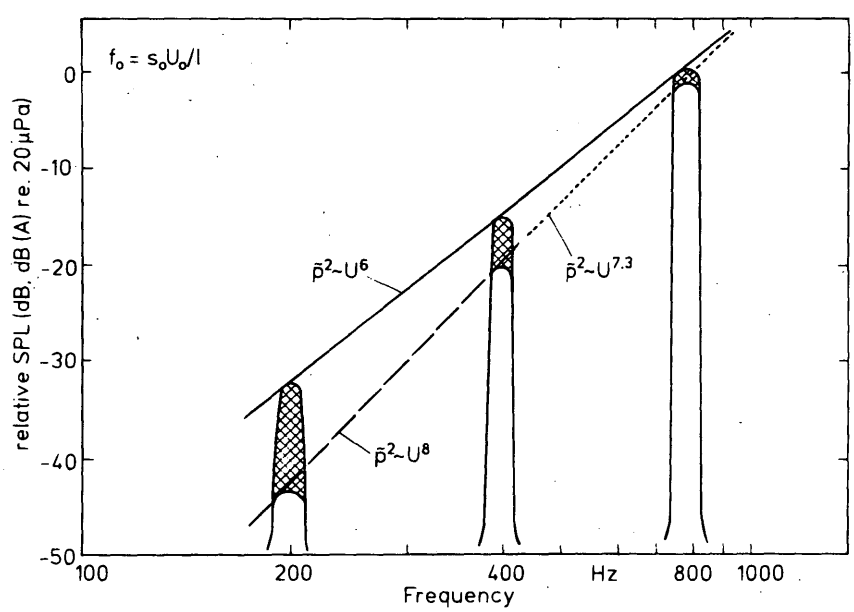

FIGURE 1 Simplified example showing effect of A-weighting on vortex-shedding sound.

Wind Tunnel Measurements

An important parameter for many flow-generated sound sources is the Reynolds number, defined as $Re_d = Ud/\nu$ where d is some dimension of the body and ν is the kinematic viscosity of the fluid. For example, skin-friction drag, vortex shedding from certain bodies including rods having circular cross sections, and the properties of a boundary layer and where it undergoes transition to turbulence are dependent on Reynolds number. Aeroacoustical measurements on scale models in an open-jet wind tunnel can help identify locations of probable aeronoise sources, but if these sources depend on the Reynolds number, erroneous conclusions could be drawn. Although Reynolds-number scaling of even a single railway car is impossible in most wind tunnel facilities, subcomponents of a train, such as the pantograph or structural elements in the bogie region, can often be scaled by using oversize scale models. The measured frequencies and sound levels can then be adjusted to represent the values that they would have on the full-scale component.

EVIDENCE FOR IMPORTANCE OF AERODYNAMIC SOUND

All single-microphone results in this section are given in pass-by sound pressure levels $L_{eq,p}$ which are simply equivalent sound pressure levels averaged over the time of passage.

Figure 2 shows two sets of wayside noise levels (*13*) for the four coaches on a dedicated TGV-Atlantique (TGV-A) operated by the French National Railway. The data were measured with a microphone positioned 25 m lateral to the centerline of the track and at the height of the rails (6 m above the local ground). One set of measurements was made under free-field conditions, whereas the boundary conditions for the second set involved a 2-m-high conventional sound barrier. From the measuring station, only about 20 percent of the coach bodies were visible above the barrier.

If an average frequency of about 2,000 Hz for W/R noise is assumed, the effect of the sound barrier can be estimated with expressions given elsewhere (*14*). For a line of incoherent sound sources located just below the wheel axles, Kurze and Beranek [Fig. 7.9 (*14*)] indicate that the barrier should provide an excess attenuation of W/R noise of about 14 dB. For a speed of 160 km/hr, a speed at which aerodynamic noise is relatively insignificant, Figure 2 shows that the barrier does indeed afford an excess attenuation of approximately 14 dB. The attenuation of sound by a barrier is frequency dependent: the higher the noise frequency, the greater the excess attenuation up to a maximum of about 24 dB for a practical barrier (*14*).

As train speed increases, the levels of the peak frequencies of W/R noise also increase, the higher-frequency peaks at a slightly higher rate than the lower-frequency peaks, but the frequencies themselves remain essentially constant. Because the peak frequencies are invariant, the excess attenuation attributable to the barrier should also remain constant as vehicle speed increases. But, as can be seen in Figure 2, the excess attenuation decreases as train speed increases. This behavior implies the existence of additional sound sources whose importance increases progressively with increasing train speed. These additional sources are generated by flow interactions with structural elements of the coaches in the bogie regions. Because the peak frequencies of this flow-generated sound are substantially lower than those of W/R noise, the excess attenuation of sound provided by the barrier at higher speeds is less than it was at lower ones where the level of aeronoise is negligible. In addition, the higher speed exponent of aerodynamic sound sources means that the rate of increase of intensity with speed for aeronoise is significantly greater than it is for W/R noise. Therefore, the net effect on the curve of wayside noise level is that its slope increases with increasing train speed.

Other results that demonstrate the presence of aerodynamic noise are given in Figure 3. All measurements were made 25 m from the centerline of the track or guideway. Results are shown for a two-

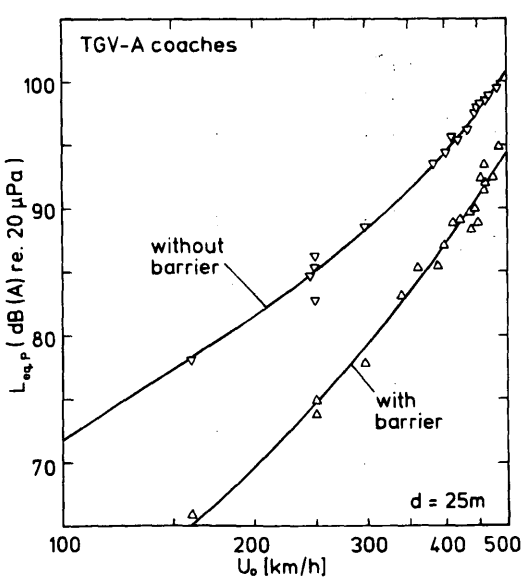

FIGURE 2 Wayside noise levels for TGV-A with and without sound barrier (*13*).

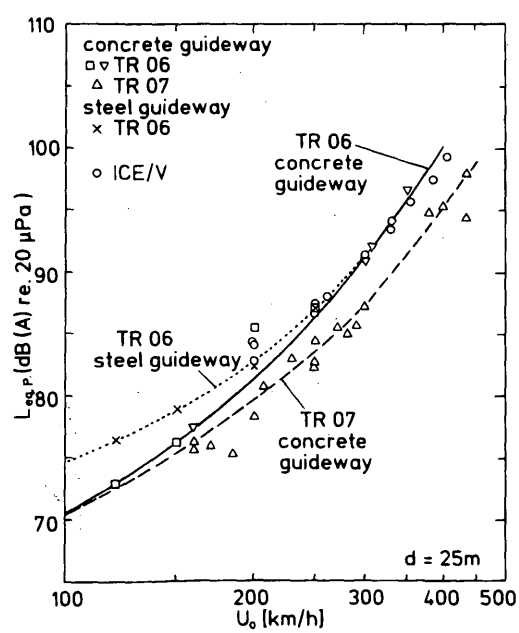

FIGURE 3 Wayside noise levels for TR 06 and TR 07 (*15*) and ICE/V.

section TR 07 operating on a concrete guideway (*15*), a two-section older TR 06 maglev vehicle traveling on a steel and concrete guideway, and a two-coach ICE/V (test version of the ICE) operating on dedicated track. Results for the TR 06 on a steel guideway and some of those on the concrete guideway were measured by Korb and Largof of the firm IABG and are not generally available. The other results, for the TR 06 and those for the ICE/V, were measured by the DLR.

For the ICE/V, U_{t_2} is about 270 km/hr. Thus, according to Figure 3, if the only sound sources on the train were those generated aerodynamically, it would produce a sound level of approximately 85 dBA at 270 km/hr. Average conventional InterCity trains traveling at 160 km/hr have wayside noise levels that fall within the range of 84 to 93 dBA. The level of the aeronoise component generated by the ICE/V at 270 km/hr therefore lies within the lower eighth of this range of noise levels produced by conventional trains traveling at 160 km/hr.

For speeds below 265 km/hr, Figure 3 shows that the TR 06 operating on a steel guideway generates higher sound levels than it does on a concrete guideway at corresponding speeds. At speeds above 265 km/hr, however, the sound-level curves for the TR 06 on either type of guideway merge into one. The reasons for this behavior of the curves are that within the lower speed range, vehicle/guideway interactions are the principal sources of radiated noise, whereas at higher speeds, aerodynamic interactions become the dominant source of wayside noise. These latter sources depend only on the vehicle itself, and the guideway construction becomes irrelevant.

Figure 3 also shows that within the higher speed range, sound levels generated by the ICE/V are essentially identical to those produced by the TR 06 at corresponding speeds. It is interesting to note that the drag coefficients for the two-coach ICE/V and two-section TR 06 are approximately the same. The TR 07, with its improved aerodynamic shape and roughly 25 percent lower drag coefficient, generates correspondingly lower noise levels at speeds above 290 km/hr, where aerodynamic noise is dominant.

In comparing sound levels generated by the TR 06 and TR 07 when both vehicles are traveling on the same concrete guideway, it is seen that as speed decreases, vehicle/guideway interaction noise becomes progressively more important. At 100 km/hr, both vehicles generate essentially the same wayside noise levels. If the guideway were acoustically damped, both vehicles would produce significantly lower sound levels at lower speeds.

EXAMPLES OF SOUND SOURCES ON ICE/V

The results presented in this section were measured with linear line arrays of microphones. Since line arrays can resolve sound sources in only one spatial dimension, they were mounted in two mutually perpendicular positions on a ground plate along the wayside: in the wayside vertical (WV) position with the line of microphones perpendicular to the ground plate, and in the wayside horizontal (WH) position with the line of microphones parallel to the near rail. In the WH position the array can resolve sound sources lying along the longitudinal axis of the vehicle. The array beam can be swept in the direction of motion to track any point on the train, thereby increasing the bandwidth-time product and eliminating the effects of the Doppler frequency shift (*16*). In its WV position, the array can resolve sound sources lying at different heights on the vehicle. Figure 4 shows a large WV array, "large" being identified by the number 2, positioned to measure sound generated by flow interactions with the pantographs and associated equipment on the roof of the ICE/V. An array is said to be shaded (S) when the side lobes in its beam pattern are suppressed below the usual −13 dB relative to the main beam. The side lobes in our shaded array were 25 dB down. More details about the use of directional arrays for locating sound sources on moving vehicles can be found elsewhere (*16–18*).

The ICE/V comprised two power cars separated by two middle coaches. All wheels were equipped with disc brakes and noise absorbers that lower W/R noise levels by from 5 to 6 dB. For all measurements, the line of microphones was positioned at a distance of 5 m lateral to the near rail.

Figure 5 shows three superimposed time histories measured with the SWH2 array in the frequency range 300 to 1,200 Hz for pass-bys at 200, 250, and 300 km/hr. The hatched bars in the figure indicate the increase in sound levels for an increase in speed from 200 to 300 km/hr when α equals 3 and 6 (i.e., for W/R and aerodynamic dipole noise, respectively). As can be seen in the figure, the highest peak sound levels originate between 4 and 5 m downstream of the tip of the nose on the forward power car. The increase in these peak levels between 200 and 300 km/hr is obviously greater than the increase represented by the hatched bar for $\alpha = 6$. The actual speed exponent here is about 8, much greater than α for W/R noise. Measurements made with the SWV2 array show that what appears as a single peak level near the front of the train at each speed in Figure 5 actually comprises two sound sources, one of which is located 3 m above the rails and the other at about 0.5 m. The upper peak could be due to a local region of boundary-layer flow separation or near separation, whereas the lower peak level is most likely caused by vortex shedding from protuberances in the bogie region.

Figure 6 shows two superimposed scans measured in the frequency range 200 to 1,400 Hz with the SWV2H (H = high) array shown in Figure 4. These measurements, made at a train speed of 300 km/hr, were designed to study pantograph noise. As can be seen in Figure 6, a higher sound level is produced when the pantograph on the front power car is retracted than when the pantograph on the rear power car is raised. Although seemingly paradoxical, there is a simple explanation for these results. The boundary layer on the roof of the front power car is much thinner than it is on the rear power car. Consequently, the retracted pantograph and equipment on the leading power car are subjected to what is essentially the free-stream speed of the airflow. On the roof of the rear power car, on the other hand, only the upper part of the raised pantograph can interact with the free-stream velocity; the rest of the equipment lies within the thick boundary layer, where flow speeds are lower than they are in the free stream.

Figure 6 also shows a peak in the sound-level distribution on the side of the rear power car at a height of about 2.8 m above the rails. The inlet louvers for the automatic cooling fans are located at this height. The high noise level is probably due to vortex shedding on the louver vanes when air is drawn in by the fans.

CONCLUDING REMARKS

If wayside noise is defined by the peak sound level measured during a pass-by, the principal sound sources at high speeds usually are generated either by a separation or near separation of the boundary layer or by vortex shedding from the pantograph and its associated equipment. On the other hand, if the pass-by level is the pertinent

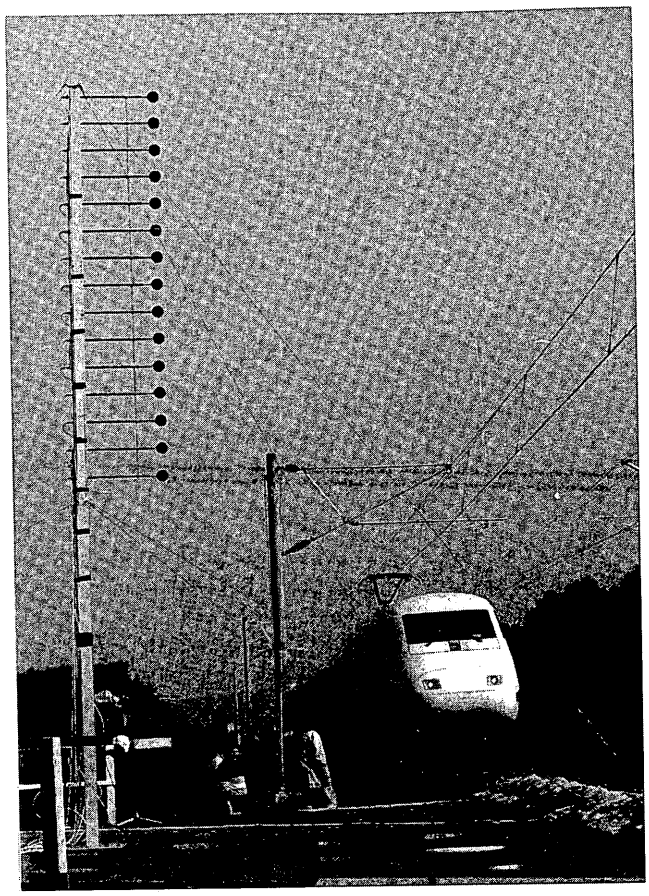

FIGURE 4 WV2H 15-microphone array designed to measure sound generated by flow interactions with equipment on roof of ICE/V.

measure of wayside noise, the important sources at high speeds are produced chiefly by vortex shedding from protuberances and edges distributed along the train, primarily in the bogie regions.

The discussion of these sound sources has been phenomenological rather than analytical because the author elected to demonstrate the significance of this noise via measured results instead of mathematical analysis. If the problem of aerodynamic noise is tackled theoretically, the functional dependence of sound pressure on the various parameters can be established, but, since several of these are functions of both Reynolds number and the local geometry, the appropriate experimental values of these parameters must be incorporated into the analysis in order to calculate the radiated noise. When such values are available, this procedure can give satisfactory results for sound generated by flow interactions with individual structural elements having relatively simple geometries. However, it is difficult to apply this theoretical approach to ensembles of structural components, particularly if they have complicated geometries (e.g., the components in the bogie regions). A simpler method of obtaining an expression for predicting radiated noise is to combine information pertaining to the character of the sound sources with an empirical fit to measured sound levels.

The most accurate method of predicting whole-train time histories, pass-by sound levels, and so forth is with a computer model such as those described by Barsikow and Müller (*11,12*). In these models, the strength, location, and speed exponent of each sound source are taken from the results of measurements made with microphone arrays.

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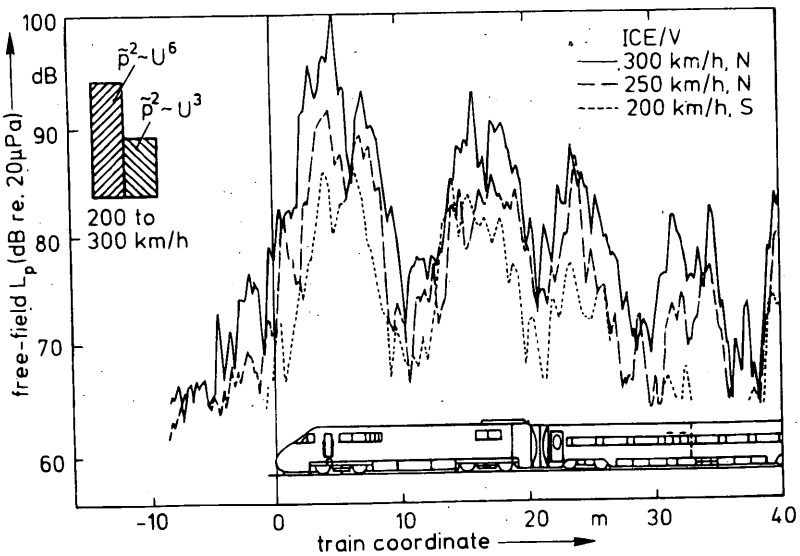

FIGURE 5 Radiated noise generated by ICE/V in frequency range 300 to 1,200 Hz, measured with SWH2 15-microphone array positioned 5 m from near rail; shaded bars indicate expected increases of sound level for aero- and W/R noise; L_p = SPL.

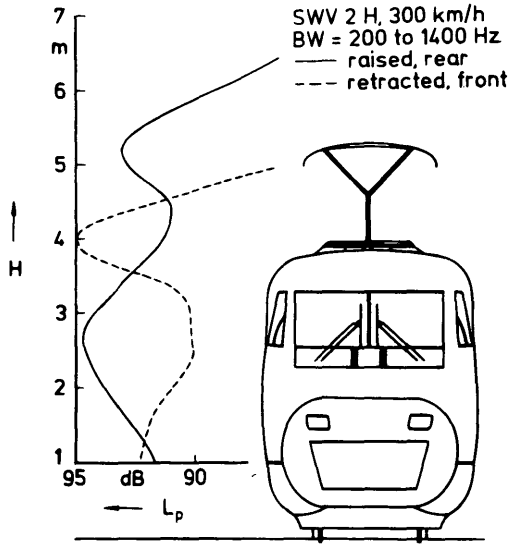

FIGURE 6 Scans on ICE/V power cars measured in frequency range 200 to 1,400 Hz with SWV2H 15-microphone array; H = height (m), L_p = SPL.

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Interpreting Airport Noise Contours

ALLEMANDER J. PEREIRA FILHO, JOHN P. BRAAKSMA, AND JOSEPH J. PHELAN

Aircraft noise is a major environmental issue in areas surrounding airports. The noise exposure forecasting (NEF) method has been adopted in Canada and other countries for land use planning around airports. Specific noise contours have been implemented as rigid guidelines for development near airports, leading to questions about the interpretation and validity of these conceptual noise contours for particular locations. A comprehensive survey was conducted to investigate people's attitudes toward noise in an area close to the Macdonald-Cartier International Airport in Ottawa, Canada, which has particular geographical conditions. The results revealed that responses related to the degree of annoyance, disturbance, and complaint were lower than results from similar surveys carried out elsewhere. The survey findings showed that noise contours should be considered carefully in areas where geographical characteristics are not the same as those employed in the NEF method. Comments on some field-specific geographical factors are provided to improve land use planning based on NEF contours.

The primary responsibility for integrating noise aspects into the urban planning process rests with local governments. At this level of government, land use compatibility planning has been adopted to guide noise-sensitive land uses away from the noisier areas and encourage nonsensitive land uses.

The analysis and development of compatible land use near airports in Canada is based on the noise exposure forecasting (NEF) method (*1*); in the United States it is based on the day-night average sound level (DNL) method. Both methods are supported by the integrated noise model (INM) (*2*), which has been adopted by Transport Canada and the FAA. NEF and DNL noise levels correlate well with each other (DNL = NEF + 35). Forecasting of aviation noise depends on the number of aircraft movements, fleet composition, runway utilization, flight paths in and out of runways, air speed, and engine power during approach and landing procedures as well as atmospheric pressure and temperature distributions and wind directions and velocities.

Important elements that may attenuate the exposure of individuals to aircraft noise around airports, such as topography of the area; existence of buildings, vegetation, and other types of sound barriers; and shielding near the airport are not considered in the INM. The variation in the level of individual exposure and human reaction to noise may also involve several factors such as type of dwelling, construction material, and socioeconomic standards.

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PROBLEM STATEMENT

Despite all efforts to improve the NEF method to calculate aircraft noise impacts around airports, it is still difficult to relate forecasted noise with the prediction of people's reaction to noise (*3*). As emphasized by Ashford (*4*), "it is not surprising, therefore, that forecasting the impact of aircraft noise on nearby neighborhoods is an inexact process that must be applied with considerable attention to its subjective aspects."

The concern with noise forecasting is that it is expressed by noise contours representing specific NEF or DNL values. These contours have become rigid boundaries in terms of zoning decisions for land use near airports limiting areas deemed to be noncompatible with some human activities (*5*). Mistakes in zoning decisions caused by mislocation of the noise contours may have appeared in areas with atypical geographical characteristics that are not similar to the standard field conditions adopted in the NEF/DNL method.

The purpose of this paper is to summarize research (*6*) to gauge people's perceptions toward aircraft noise under atypical field geographical conditions in noisy areas defined by NEF contours and to compare its outcome with previous noise attitude surveys.

NOISE CONTOUR LINES

The NEF method produces noise contours that are an estimation of the total noise exposure for a particular airport resulting from aircraft movements over a specific period of time, usually a planning peak day. The noise contours are defined in printouts usually plotted on a 8.5 × 11 in. paper and then transferred mechanically to a map of the region. In general, the scale of printouts varies from 1:100,000 to 1:200,000; regional maps are drawn on charts at scales of 1:25,000 to 1:50,000.

NEF contour maps yield a helpful delineation for visualization of noise fields. However, these NEF lines may not be precise. Errors may happen in the noise contours proportionally to the precision of the assumptions used for the input data. Furthermore, because of scale reductions, the exactness of transferring contour lines from the computer printouts to regional maps and then to the terrain cannot be maintained. For example, 1 mm of a noise contour line on a computer printout may represent up to 200 m in the field.

Land use planning based on noise exposure contours has caused many complaints. These complaints have happened because as soon as noise contours are sanctioned as a rigid boundary for land use, regardless of factual local evidence, the resulting noise contours are taken as "unquestionable." At present, there is no methodology for modifying noise contours to reflect local conditions.

COMMUNITY REACTIONS TO AIRCRAFT NOISE

People's reaction to noise depends on the way in which individuals experience the undesirable effects of noise. Many advances have

been made in noise measurement and forecasting, but there still is a lack of knowledge in the area of people's reaction to noise, especially under atypical field conditions. Some attitude surveys have been done to measure reaction and annoyance to aircraft noise. Three major studies developed in the United States and Canada, by Schultz (*7*), Kryter (*8*), and Hall et al. (*9*), are of importance.

OTTAWA SURVEY

Background

The purpose of the field investigation at Macdonald-Cartier International Airport (MCIA) in Ottawa was to better understand the influence on the community response to aircraft noise of important local geographical characteristics, such as topographic, vegetation, and climatic conditions, which differ from the standard adopted in the NEF method. This field work allowed a comparison of the residents' annoyance response to aircraft noise, with the results of previous noise attitude surveys carried out elsewhere.

Description of Survey Area

The survey area was selected to present as many different field characteristics as possible from the standard in the NEF method. Another factor for selection was that of low noise complaints. Transport Canada (*6*) records showed that in 1983 and 1984, of 115 formal complaints, there was just 1 from the chosen area.

The survey area is situated in the Rideau River Valley, some 30 m below the altitude of Runway 07. The area contains 194 single-family homes, most which have man-made noise barriers such as multiple glazing and insulated walls. The area is covered by natural noise barriers composed of big trees and dense vegetation.

Data Requirements

The noise exposure levels in the survey area were set using noise contours derived from the NEF method. They were based on a typical peak day at MCIA with 870 movements (landings plus takeoffs), which included local and itinerant aircraft. The survey area was divided by four NEF contours: 40, 35, 30, and 25 NEF to produce three NEF areas: 25–30 NEF, 30–35 NEF, and 35–40 NEF. People's reactions to noise were collected through face-to-face interviews using questionnaires.

Survey Method

In the survey, no more than one person was interviewed at the door of each dwelling. The survey took place at different times during weekdays and weekends in order to reach a random sample of residents. The sample size was 140 interviews.

Analysis of Results

In the first set of questions, respondents reported that the general living conditions were good and that most of them like living there. Most thought that the noise situation had remained the same. A few residents (5 percent) said that they had experienced worsening living conditions because of air and road traffic.

The second set of questions showed that most residents did not perceive their neighborhood as noisy even though the areas are crossed by roads and are situated under the flight approach path. However, they did identify aircraft and road traffic as a noise heard more regularly.

The third set of questions addressed the extent of annoyance and activity disturbance caused by noise. Degrees of annoyance aggregated into NEF areas indicated that just a small percentage (fewer than 10 percent) of the residents had been extremely annoyed by aircraft noise (Figure 1). The results also showed that conversation (for an average of 40 percent of the respondents) was disturbed more than were listening to and watching television (about 20 percent of the respondents) (Figures 2 and 3). The activity that was least interfered with was sleeping (fewer than 10 percent of the respondents).

Comparisons with Previous Attitude Noise Surveys

The first comparison, shown in Figure 1, indicates the percentage of people highly annoyed in Ottawa versus that of other researchers' findings. This figure suggests that residents interviewed in Ottawa are not as annoyed as those in earlier surveys elsewhere. The Ottawa curve takes an almost identical shape, exponential, as the curves from earlier surveys, but it occurs approximately 10 NEFs below Schultz's curve.

The second comparison, shown in Figures 2 and 3, indicates the percentage of people in Ottawa who reported being disturbed often in conversation, sleep, and listening to radio or television versus results from previous noise attitude surveys. In this case, Ottawa residents appeared to be less disturbed by aircraft noise than people interviewed in surveys elsewhere.

Important Findings

The magnitude of people's annoyance toward aircraft noise in all three NEF areas nearby MCIA is lower than the degree of annoyance and activity disturbances noticed for the same noise levels from earlier noise survey results. The most plausible explanation for the low degree of annoyance found in Ottawa is that the NEF method takes into account only acoustical emissions produced by aircraft under standard field conditions. (Even though the latest

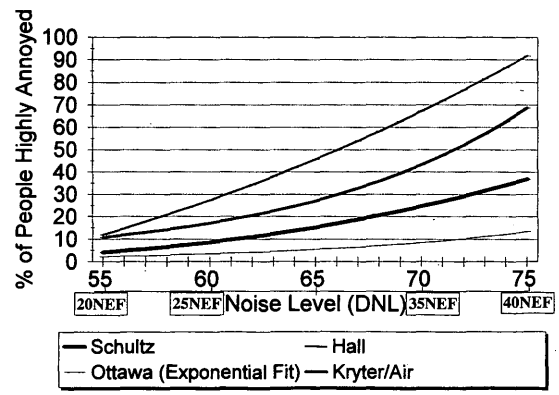

FIGURE 1 Noise annoyance curves.

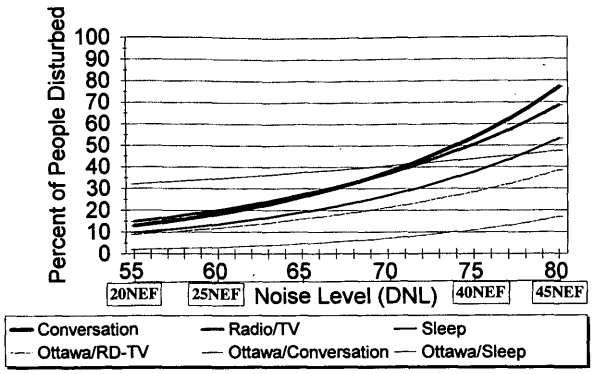

FIGURE 2 Activity disturbance.

INM Version 4.11 considers local topography, it is limited to calculating slant range distances.) That means NEF contours are relative to the runway configuration on flat terrain, with no barriers or shielding surface. However, the survey area at Ottawa is nonstandard.

Cold climatic conditions did affect the type of windows and insulation materials used in the buildings, which can reduce noise from outdoors. This climatic condition also influences time spent in outdoor activities, reducing exposure to noise since cold weather clearly forces residents to keep windows closed for most of the year and modifies their lifestyles. Therefore, the effects of a cold climate should be considered when adopting the NEF method as a basis to support land use planning around airports. Kryter has suggested that 5 dBA in the DNL method should be added to the noise exposure level expressed by a noise contour in order to have a similar effect between "warm" and "cold" cities (*10*).

Another local field characteristic that may explain the low degree of annoyance is related to the topography of the area. A study carried out by the Airport Land Use Commission of the county of Santa Clara, California (*11*), demonstrated that after it installed an accurate noise monitoring system on terrain that dropped off laterally from the airport runway in a ratio of 1 percent into a shallow flood plain, previous computer-based noise contours overestimated the noise by about 10 dBA using the DNL method. The survey area in Ottawa is located at the extension of Runway 07, which is in a depression, 30 m (100 ft) below Runway 07, with almost the same ratio (approximately 1 percent). The noise attenuation in this area is probably reinforced by the presence of many mature trees.

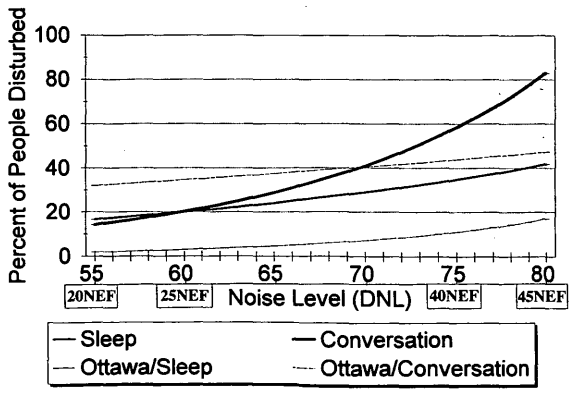

FIGURE 3 Activity disturbance.

CONCLUSIONS AND RECOMMENDATIONS

Land use planning guidelines are used to plan urban development in harmony with airport operations. Since noise is a big factor in land use planning near airports, noise exposure forecasts are used. As a general planning approach, the NEF method is a useful tool for identifying areas close to the airport under heavy impact of noise.

The adoption of specific noise contours as a strict limit for development in land use has been criticized by developers because of restrictions placed on large portions of land and by airport neighbors because of the loudness in the areas where they live. These criticisms often arise because of the misallocation of the noise contours, which leads to inaccurate levels of noise exposure. Such inaccuracy usually originates from the weakness of the NEF method in failing to account for important variations in community noise impact due to local field geographical conditions that are atypical. As a result the regulation and planning of land use around airports, based solely on noise contours, have been challenged.

Recently, Transport Canada and the Ministry of Municipal Affairs (*12*) agreed that a site's specific natural topography, ground condition, or presence of reflective or shielding surfaces may provide enough attenuation of ground-based aircraft noise to reduce NEF values. However, it does not bring any change or revised methodology to improve the applicability of the NEF method at a specific location.

Land use planning around airports can be improved by paying particular attention to specific geographical characteristics. However, the NEF method should be modified by field adjustment factors. Therefore, it is recommended that research be carried out to determine these field factors. The study of people's perception to aircraft noise should also be carried out over a long period to identify and quantify any important change over time.

ACKNOWLEDGMENTS

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

Analysis of Rural Community Perceptions of Helicopter Noise

P. D. PREVEDOUROS AND C. S. PAPACOSTAS

Helicopter noise intrusion in rural areas of Hawaii is described, and the impacts on exposed and nonexposed communities are compared using a mail-back survey. Analysis of variance, factor analysis, and logistic regression revealed factors underlying the attitudes and perceptions of residents, their preferred choice of filing complaints, and their level of tolerance to helicopter flyovers. Among the most important attributes were residential location, level of exposure, general attitudes toward growth, and propensity to complain. Specific recommendations are made. Whereas most results are specific to one geographic area, the methodology, general behavioral findings, and recommended actions could be useful elsewhere.

This paper describes the major findings of a study sponsored by the Airports Division of the Hawaii Department of Transportation (HDOT), which, in its role as operator of the statewide system of airports, is facing a growing problem with helicopter noise. The study (*1*) developed a set of recommendations based on (*a*) a literature review of human response to helicopter noise (*2*), (*b*) identification of the problem's extent in rural areas of the state and a comparison of the impact on exposed and nonexposed communities via the analysis of a mailback survey (this paper), and (*c*) measurement of ambient, traffic, and helicopter noise in exposed communities (paper in preparation).

Aviation-related complaints to HDOT's statewide, toll-free telephone hotline were analyzed. Helicopter complaint records were aggregated by Zip code; they revealed a decrease in the number of helicopter noise complaints on all islands except Oahu between 1990 and 1991. This occurred before the establishment of the local Fly Neighborly Program (FNP) by the Hawaii Helicopter Operators Association (HHOA). About half of all complaints during the period analyzed were filed on the island of Hawaii. The dot-density pattern in Figure 1 displays the areas with many, few, or no complaints per thousand residents and illustrates that, on Hawaii, the problem of helicopter noise may be acute in some areas, including a corridor between Hilo and Volcano. (In Figure 1, no complaints were filed in ZIP codes without a tag.)

SURVEY

The survey collected information on the perceptions of residents to answer (via estimated models) questions such as

- Is there public demand for increased helicopter regulation?
- Have people noticed a change since the FNP was enacted?
- Which complaint hotline would people prefer to call?
- Is helicopter noise annoying at home?
- What factors affect annoyance at home or outdoors?
- Do flyovers invade people's privacy?
- How many flights are people willing to tolerate?

Zip code areas with high and low frequencies of complaints on the islands of Hawaii and Maui were identified and selected so that, at the aggregate level, the key factors of income and land value were comparable, thereby reducing potential biases due to large socioeconomic differences between groups of high and low exposure to helicopter noise. This was accomplished by using a geographic information system and ZIP code Census files.

The questionnaire package consisted of three parts: (a) the cover page, a sheet with instructions, and an incentive-prize drawing card for four $50 prizes; (b) a questionnaire on general issues, including some helicopter noise questions, and household information; and (c) a questionnaire on the respondents' experiences, perceptions, and attitudes toward helicopter operations.

After pilot testing, 5,118 surveys were mailed out in November 1992; 1,560 responses were received. The 30 percent response rate was excellent given the length and complexity of the survey.

RESULTS

Annoyance

One part of the analysis distinguished between those who stated that they had heard no helicopters on the previous day (nonexposed respondents) and those who stated that they had heard one or more helicopters (exposed respondents). It was assumed that the reference day represented normal conditions. Sufficient and roughly equal samples were available for both groups. On average, the exposed respondents reported 8.65 helicopter flyovers, of which 3.94 were perceived as low-altitude (i.e., near tree-top) flights.

Both groups rated vehicular traffic, people, and natural noise sources as equally annoying (Figure 2); 20 to 40 percent of the respondents found most noises "somewhat" and "very" annoying. Thus, it is surmised that the exposed group did not include a higher proportion of people who are "hypersensitive" to noise. Such a finding would have threatened the validity of the inferences. Furthermore, both groups gave identical ratings to the noise-specific and overall quality of life in their neighborhoods.

As expected, exposed respondents had a less favorable disposition toward helicopter operations. For the nonexposed group, helicopters are not a major source of noise (Figure 2, *top*). The responses of the exposed group were much different. Helicopter noise was rated at the same level of annoyance ("somewhat" and "very" annoyed) as motorcycles and barking dogs. Those who indicated that they were "very" annoyed rated helicopters as the worst source of noise (Figure 2, *bottom*).

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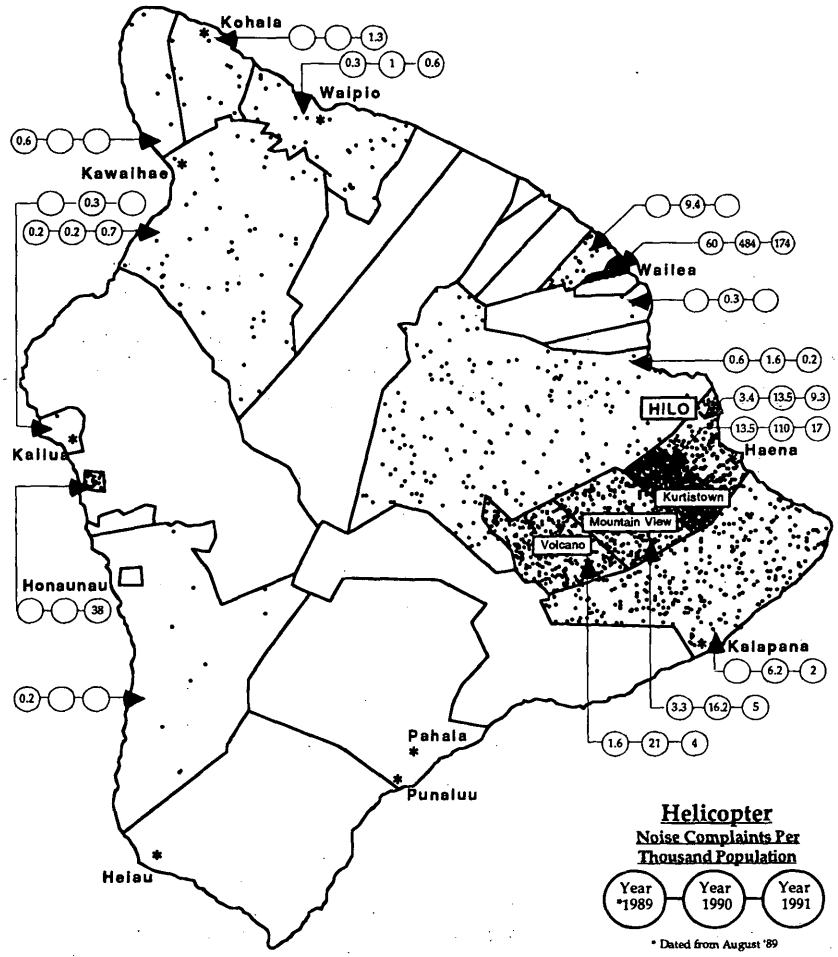


FIGURE 1 Rate of helicopter noise complaints on island of Hawaii.

Hotlines

Respondents in the exposed group were considerably more aware of the FNP and the HDOT and HHOA hotlines. Very few in the nonexposed group had called either hotline. Of the exposed group, 21.3 percent called the HDOT hotline and only 9.4 percent called the HHOA. The latter rate suggests that people may not prefer self-regulation by the helicopter industry. Moreover, about 32 percent of the exposed group declared that they would not call any hotline if annoyed, partly because of perceived ineffectiveness of hotlines.

Most of the nonexposed group (64 percent) reported no change in helicopter noise since 1991 (when the FNP was introduced), 12 percent reported more noise, and 24 percent reported less noise. The exposed group had a much different distribution, with 48 percent reporting no change, 33 percent more noise, and 19 percent less noise.

MODELING AND INTERPRETATIONS

Methodology

The analysis consisted of three steps:

1. Analysis of variance revealed that residential location, attitudes toward supplemental uses of tour helicopters, attitudes toward growth, exposure to helicopter flights, and propensity to file a complaint ("*call soon?*") were the most important explanatory variables. The last variable has a complex role because it may mean either that a person is not bothered by helicopter noise or that he or she is willing to tolerate it.

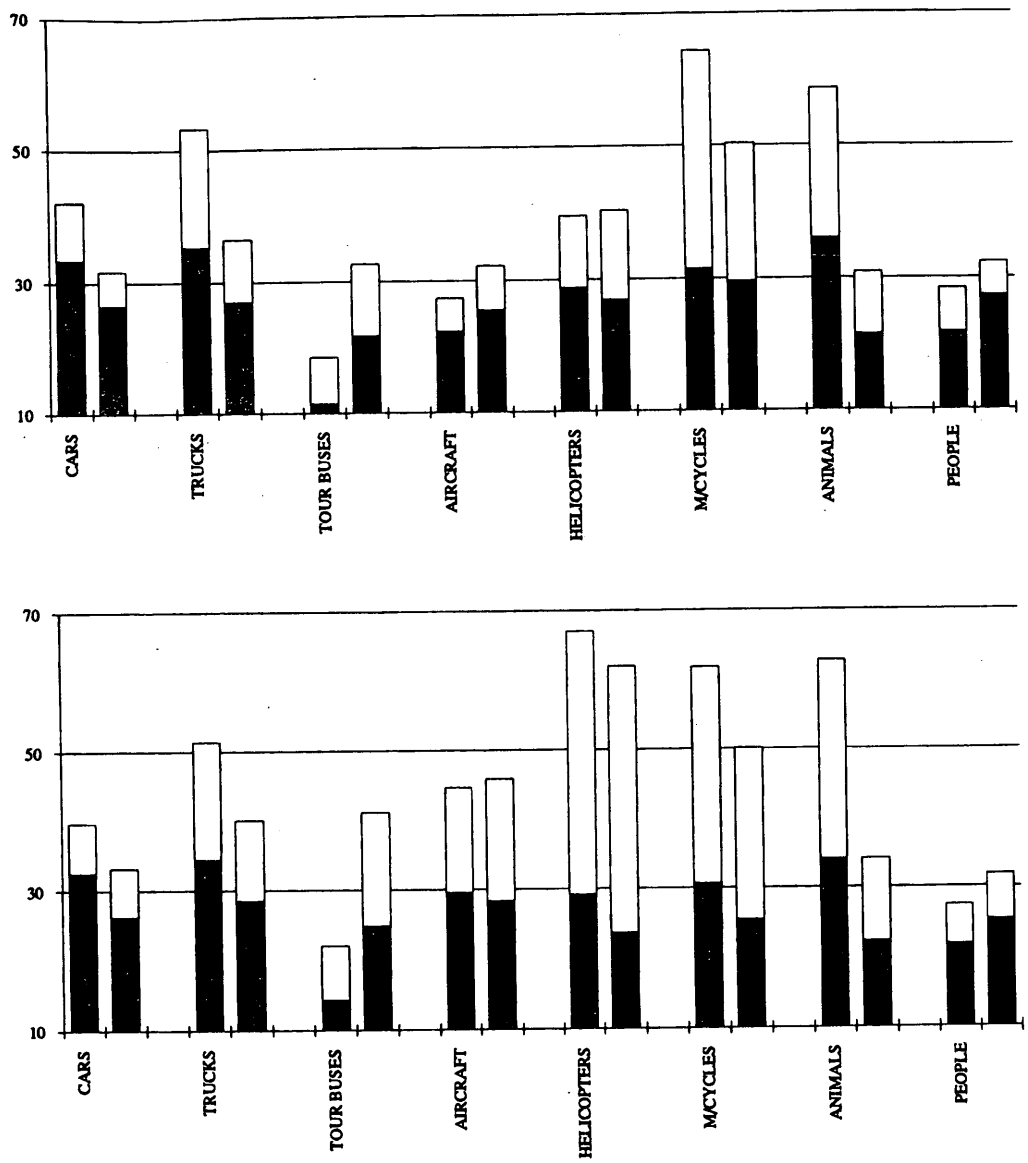
2. Factor analysis was used to combine related variables into composite variables. For example, the following three variables were combined into the composite factor "*attitude*":

–*Important*: Tour helicopters are important to island's tourism and economy.

–*Drug*: Hired tour helicopters help eradicate drug traffic.

–*Crisis*: Tour helicopters can be helpful in an emergency.

3. Model estimation: Most of the questions were dichotomous (i.e., agree or disagree, yes or no), thus binomial logistic regression models were estimated. Tables 1 and 2 present two of the models. The heading of each model describes the dependent variable. The left three columns present the explanatory variables, the coefficient estimates, and the statistical significance of each coefficient. The remaining six columns of each model enable the derivation of answers. The mean values for each explanatory variable are furnished separately for each island and for four specific subareas: two on the island of Hawaii (rural Hilo—exposed—and Kona) and two on Maui (Haiku-to-Hana—exposed—and Pukalani/Kalawao). Goodness-of-fit statistics are also shown.



Legend: 1) For each pair of columns, the first represents daytime at home and the second outdoors.
2) Within each column, black represents "% somewhat annoyed" and white "% very annoyed".

FIGURE 2 Perception of annoyance from helicopter noise by nonexposed (*top*) and exposed (*bottom*) residents.

Interpretations

Model 2 showed that all but respondents from Kona (who are seldom exposed to helicopter noise) found helicopter noise annoying compared with the noise from other sources (probability 36.6 percent) (Table 1). Respondents from areas with frequent flyovers display a high probability of being annoyed: 76 percent for rural Hilo and 60 percent for Haiku-to-Hana.

Model 10 was designed to answer whether respondents were willing to tolerate four or more helicopter flyovers a day as compared with three or less (Table 2). The answer was affirmative, but the probability decreased from about 65 percent (tolerate one or more) to about 57 percent (tolerate four or more). Another model (i.e., willing to tolerate five or more flights) showed a reversal of the majority. Thus, four flights a day appears to be the threshold of tolerance (using the simple majority as criterion).

Models 2 and 10 show that employment status, presence of children in the household, attitude toward helicopters, and perception of helicopter noise relative to noise from heavy trucks are important explanatory variables. Helicopter noise annoyance (Model 2) also is affected by the propensity to complain and the level of exposure.

Only about 25 percent of the respondents had an overall negative reaction to the consequences of helicopter noise in terms of annoyance, fear of crashes, invasion of privacy, and disruption of sleep. The very exposed rural Hilo area, where more than 60 percent of the respondents harbored negative perceptions, was the exception.

TABLE 1 Sample of Model Estimations, Model 2

Explanatory Variables	Parameter Estimates	Stat. Sign.	Mean values for each explanatory variable					
			MAUI	HAWAII	RURAL HILO	KONA	HAIKU TO HANA	PUKA-LANI
Constant	-1.563	0.0000						
Full time	0.293	0.0687	0.67	0.55	0.45	0.51	0.58	0.69
Child	0.280	0.0867	0.38	0.32	0.31	0.30	0.39	0.39
Attitude	-0.449	0.0000	0.39	0.60	0.00	0.56	0.10	0.49
Other noise	-1.515	0.0000	-0.70	-0.73	-1.02	-0.55	-0.61	-0.74
Kona	-0.386	0.0549	0.00	0.00	0.00	1.00	0.00	0.00
Call soon?	0.110	0.0000	6.72	6.27	7.24	6.51	6.94	6.64
Exposure	0.683	0.0000	0.47	0.42	0.67	0.33	0.52	0.45
Heavy truck	0.045	0.0640	0.34	0.50	1.00	0.34	0.74	0.21
Police	-0.201	0.0547	1.89	2.02	1.75	1.86	1.74	1.93
Prob[negative perception] =			0.580	0.529	0.759	0.366	0.598	0.577

% Correctly Predicted:			
	P=0	67.17	Number of cases = 1003
	P=1	77.98	Model chi- square = 336
	overall	73.08	Model significance = 0.0000

TABLE 2 Sample of Model Estimations, Model 10

Explanatory Variables	Parameter Estimates	Stat. Sign.	Mean values for each explanatory variable					
			MAUI	HAWAII	RURAL HILO	KONA	HAIKU TO HANA	PUKA-LANI
Constant	0.041	0.6749						
Full time	0.234	0.0419	0.67	0.55	0.45	0.51	0.58	0.69
Child	0.237	0.0475	0.38	0.32	0.31	0.30	0.39	0.39
Attitude	0.092	0.0513	0.39	0.60	0.00	0.56	0.10	0.49
Heavy truck	-0.058	0.0009	0.34	0.50	1.00	0.34	0.74	0.21
Change	-0.081	0.0000	-0.15	0.05	0.61	-0.23	0.10	-0.24
Prob[willing to tolerate 4+] =			0.578	0.567	0.528	0.570	0.557	0.586

% Correctly Predicted:			
	P=0	43.63	Number of cases = 1409
	P=1	73.40	Model chi- square = 56
	overall	59.36	Model significance = 0.0000

Another model revealed that clear majorities in rural Hilo and Haiku-to-Hana felt that their homes' privacy was invaded by helicopter flyovers. This compares with only 21 percent in the overall sample.

The answer to the question on more active government involvement was unequivocally affirmative regardless of place of residence. Respondents from districts that experience frequent flyovers showed a higher degree of agreement (75 and 63 percent) than those from other districts (53 and 55 percent).

RECOMMENDATIONS

Reduction of exposure to helicopter noise and some government regulation are part of the solution. Exposure to helicopter noise can be decreased by using separate corridors for the outgoing and return trips and sufficiently separated over-the-land routes (e.g., 1 mi apart). Each of the designated routes should be assigned about four flights a day.

Government actions (by FAA and HDOT) that may ameliorate the problem include the creation of a task force to determine alternative routes. Involvement of helicopter operators and affected communities could result in a mutually acceptable plan of routes. A governmental unit could become more active in the reception and investigation of noise complaints, too. The HHOA hotline could fold, because people clearly prefer the HDOT hotline, by a 3 to 1 margin. HDOT could subcontract this service to a private firm. The complaint hotline operation is crucial in assessing the effectiveness of any actions that may be taken. A campaign to increase public awareness is necessary. The hotline should be an easily memorized number (e.g., 800-TOO-LOUD).

Much could be gained if the local FAA office were to become the arbitrator of unacceptable patterns of helicopter operations, instead of the HHOA. This would be a preferred way to satisfy the respondents' need for government regulation.

ACKNOWLEDGMENT

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Vibration-Attenuating Egg-Shaped Rail Fasteners Used by Washington Metropolitan Area Transit Authority

HOMER M. CHEN

The principal method for mitigating underground noise and vibrations in the Washington Metropolitan Area Transit Authority's (WMATA's) Metrorail system has been floating slabs. One type of polyurethane isolator pads supporting the floating slabs has been defective, however, and about 18,800 track-ft of floating slabs has settled unevenly, causing operation and maintenance problems. In seeking an alternative method for mitigating underground noise and vibrations, WMATA conducted an in-service testing program of vibration-attenuating rail fasteners in 1983 under FTA sponsorship. The fastener tested, which is manufactured by Clouth of Cologne, Germany, is known as Cologne egg. The testing results indicate that the Cologne egg fasteners can yield vibration attenuation up to 8 dB, a moderate reduction yet one that is adequate for certain locations. A set of specifications was then developed for vibration-attenuating rail fasteners by De Leuw, Cather & Co., WMATA's general engineering consultant. The testing program under the contract specifications was successful. Accordingly, about 11,000 units will be procured for new construction. With the egg-shaped rail fastener, WMATA not only has found an alternative method for mitigating underground vibrations, but also has saved $3.5 million in the new construction by replacing the floating slabs with the egg-shaped fasteners in the areas where moderate vibration mitigation is required.

Noise and vibration control has been a primary consideration in the design of the Washington (D.C.) Metropolitan Area Transit Authority's (WMATA's) Metrorail system since 1966. The goal has been to assure Metro patrons and neighbors of a quiet and comfortable environment.

Floating slabs have been the principal method for mitigating underground noise and vibrations. Figure 1 shows the typical configurations of WMATA's floating slabs. Because one type of polyurethane isolator pads supporting the floating slabs has proved to be defective, though, about 18,800 track-ft of floating slabs has settled, causing operation and maintenance problems. In seeking an alternative method for the mitigation of underground noise and vibrations, WMATA conducted an in-service testing program of vibration-attenuating rail fasteners in 1983 under the sponsorship of the Urban Mass Transportation Administration, now FTA. The type of tested was manufactured by Clouth of Cologne, Germany. It was an egg-shaped fastener used by Cologne Transit, thus named the Cologne egg. This testing program was assisted by WMATA's general engineering consultant, De Leuw, Cather & Company (DCCO), and the acoustical consultant, Wilson Ihrig & Associates, Inc. (WIA) of Oakland, California. The testing results indicate that the Cologne egg fasteners can yield vibration attenuation up to 8 dB, a moderate reduction yet one that is adequate for certain locations. On the basis of these results, DCCO developed a set of specifications for vibration-attenuating rail fasteners. The fasteners subsequently were procured from Advanced Track Products, Inc. (ATP) of Stanton, New Jersey (now Mattituck, New York). The following describes the essentials of the specifications.

Washington Metropolitan Area Transit Authority, 600 5th ST. N.W., Washington, D.C. 20001.

GENERAL DESCRIPTION OF FASTENERS

The metal components, consisting of a body ring or frame and a floating top or rib plate, were ductile iron. The elastomer component was natural rubber, although a neoprene or a blend of the two was also acceptable. The vibration-attenuating fastener must meet all operation requirements in the WMATA Metrorail system, so the new egg-shaped fastener went through several modifications in order to pass the qualification tests before production. The shape was the only portion of the design that was adopted from the original tested Cologne egg fasteners.

QUALIFICATION TESTS

The fastener qualification tests required four prototype fasteners complete with the modified rail section as shown in Figure 2. The test sequence was as follows:

1. Dynamic stiffness test,
2. Electrical resistance test,
3. Longitudinal restraint test,
4. Spring rate and deflection test (Cases 1 and 2),
5. Repeated-load test (1.5 million cycles),
6. Heat-aging procedure,
7. Push-pull test (1 million cycles),
8. Repeated-load test (1.5 million cycles),
9. Spring rate and deflection test (Cases 1 and 2),
10. Longitudinal restraint test,
11. Electrical resistance test, and
12. Dynamic stiffness test.

The elastomer tests and the fastener fabrication were performed by the Goodyear Tire & Rubber Company of St. Marys, Ohio, and the dynamic stiffness tests were performed by WIA. All other tests

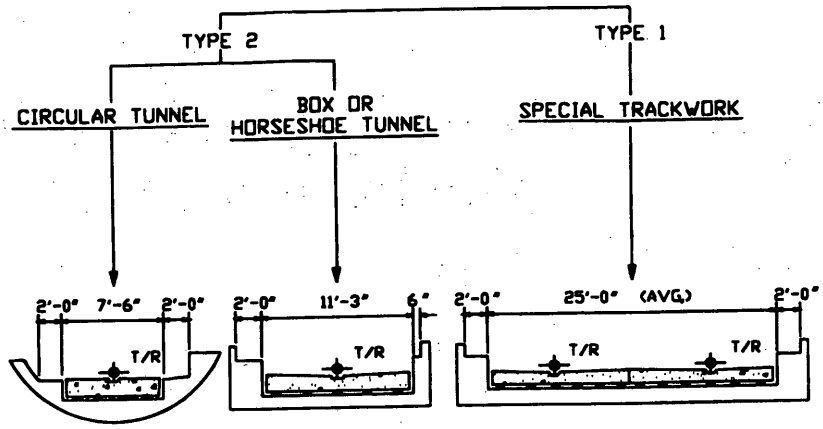

FIGURE 1 WMATA floating slab configurations.

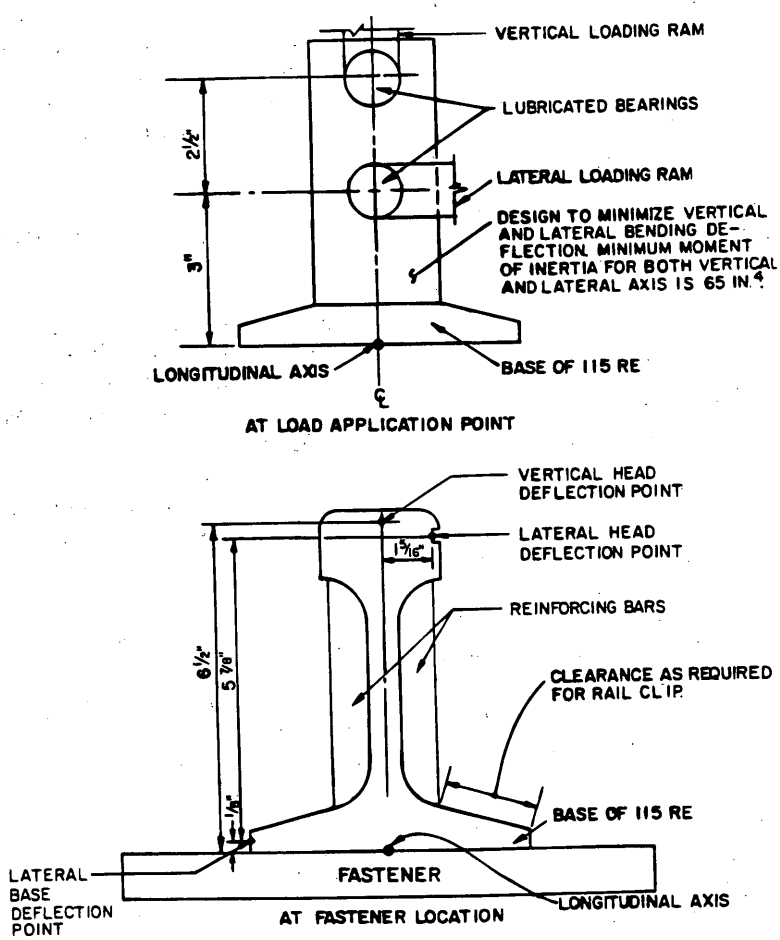

FIGURE 2 Modified rail section.

were conducted by Construction Technology Laboratories, Inc. of Skokie, Illinois. The WMATA project team consisted of George Skorupski and Art Lohrman of DCCO and Albert Maden and Homer Chen of WMATA.

After the seventh test (push-pull), the first set of prototype fasteners showed signs of cracks of the elastomer. The remaining tests were stopped. After the fasteners were modified, a new set of prototype fasteners was produced.

TEST RESULTS

Typical test results for dynamic stiffness are shown in Figure 3. The data fall within the acceptance limits.

Typical results from the electrical resistance and impedance tests are given in Tables 1 and 2. The acceptance criteria are 1.0 μamp maximum current for 100 volts DC and 10,000 ohms minimum impedance for any frequency with 50 volts RMS AC.

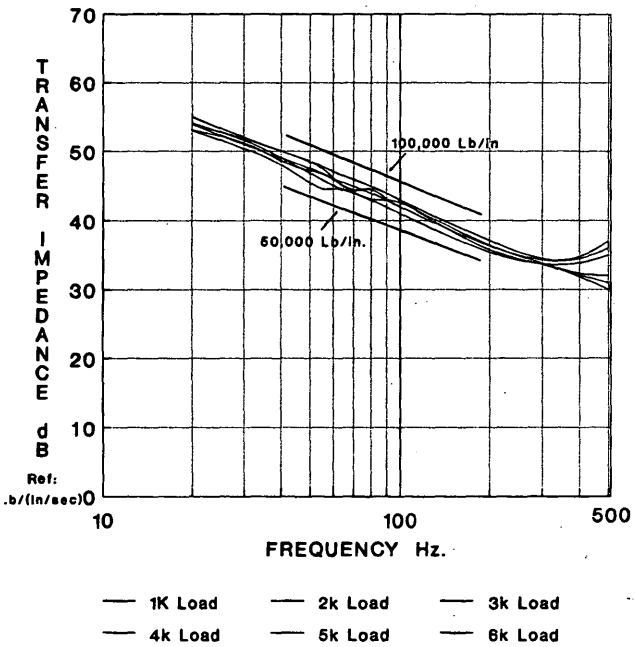

FIGURE 3 Dynamic stiffness test results, Fastener 3H10P20.

The results of the longitudinal restraint test, are shown in Figure 4, and the acceptance criteria are shown in Figure 5. For the spring rate and deflection test, the four prototype fasteners were loaded and had the deflections measured. Figures 6 and 7 show the vertical and lateral response loadings as a function of time. The vertical load points were loaded equally with a load that varies as shown by Curve V. The lateral load points were loaded equally with a load that varies as shown by Curve L.

The vertical and lateral loads were applied simultaneously in accordance with values shown in Figures 6 and 7. Typical test results for each vertical and lateral load are shown in Figures 8 and 9, respectively. The results of Case 1 and 2 tests can be seen in Tables 3 and 4.

The repeated-load test was for endurance. The four prototype fasteners went through the testing procedure for loading conditions under Cases 3, 4, and 5 as shown in Figure 7. The following are the acceptance criteria: at no time during the test shall any fastener component, including the anchorage to the test block, exhibit any sign of failure by slippage, yielding, or fracture, and more than a 10 percent increase in deflection or decrease in spring rate during the test is a sign of failure.

For the heat-aging test, each of the four fasteners with all components was aged in an air oven for 336 hr at 70°C using the aging methods specified by ASTM D573.

TABLE 1 Electrical Resistance Test Results

	Measured Current, microampere			
	Fastener L3H5P10	Fastener 3H10P20	Fastener 3H15P30	Fastener 3H20P40
Before 1KV Standoff	0.010	0.010	0.010	0.020
After 1KV Standoff V.	0.005	0.008	0.006	0.009

TABLE 2 Electrical Impedance Test Results

Frequency Hz.	Impedance, K ohms			
	Fastener L3H5P10	Fastener 3H10P20	Fastener 3H15P30	Fastener 3H20P40
20	12,499.0	12,499.0	16,665.2	16,665.7
40	7,141.9	7,141.9	7,141.4	7,141.9
60	4,544.5	4,544.5	4,998.6	4,999.0
80	3,570.4	3,570.4	3,570.0	3,845.2
100	2,776.8	2,776.8	2,939.7	2,940.2
200	1,387.9	1,427.6	1,427.1	1,469.6
400	693.4	703.2	712.8	745.3
600	462.0	470.7	474.7	494.0
800	346.2	351.1	358.3	369.4
1,000	278.5	283.2	287.6	296.6
2,000	141.6	143.2	145.2	150.9
4,000	81.2	82.3	83.3	86.6
6,000	62.7	63.6	64.2	67.0
8,000	55.0	55.9	56.4	58.7
10,000	50.3	50.9	51.4	53.6

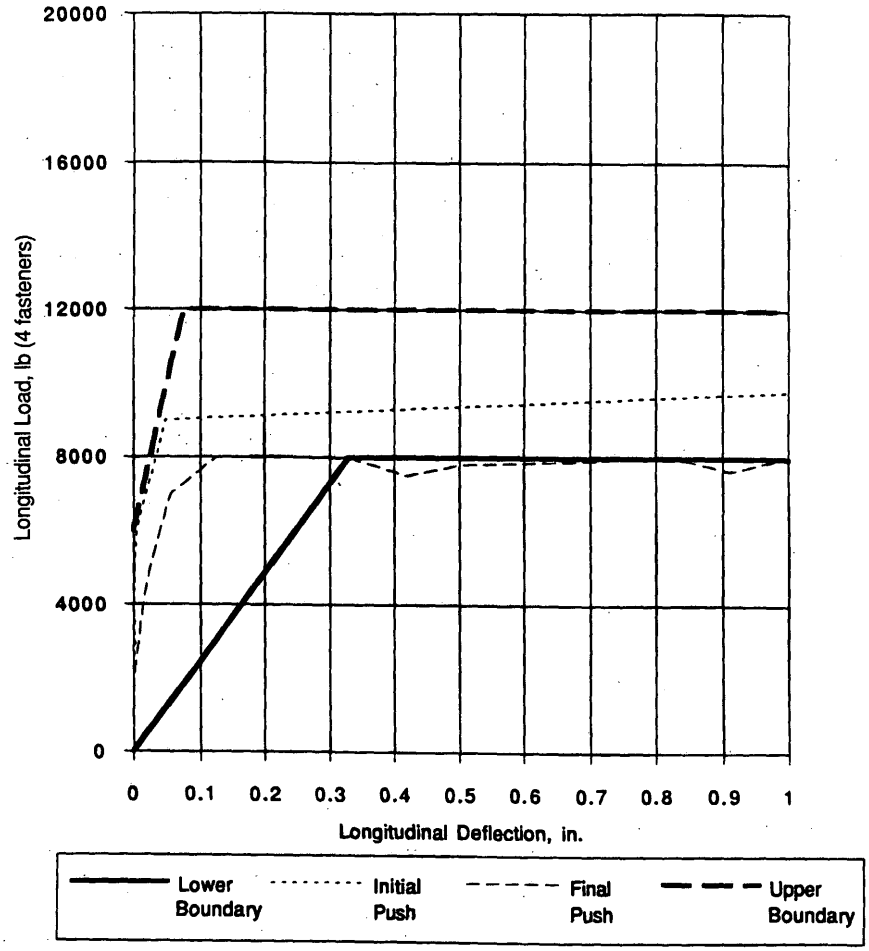

FIGURE 4 Longitudinal restraint test results, WMATA Fasteners 10, 20, 30, and 40.

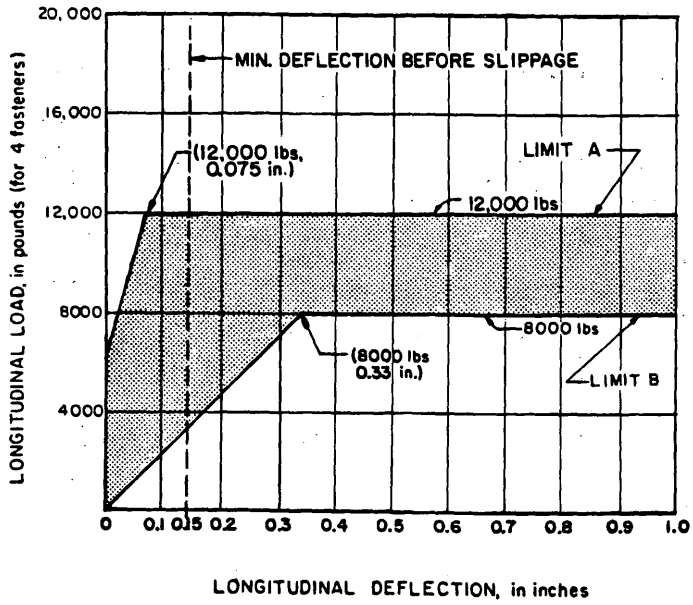

FIGURE 5 Longitudinal restraint test acceptance criteria.

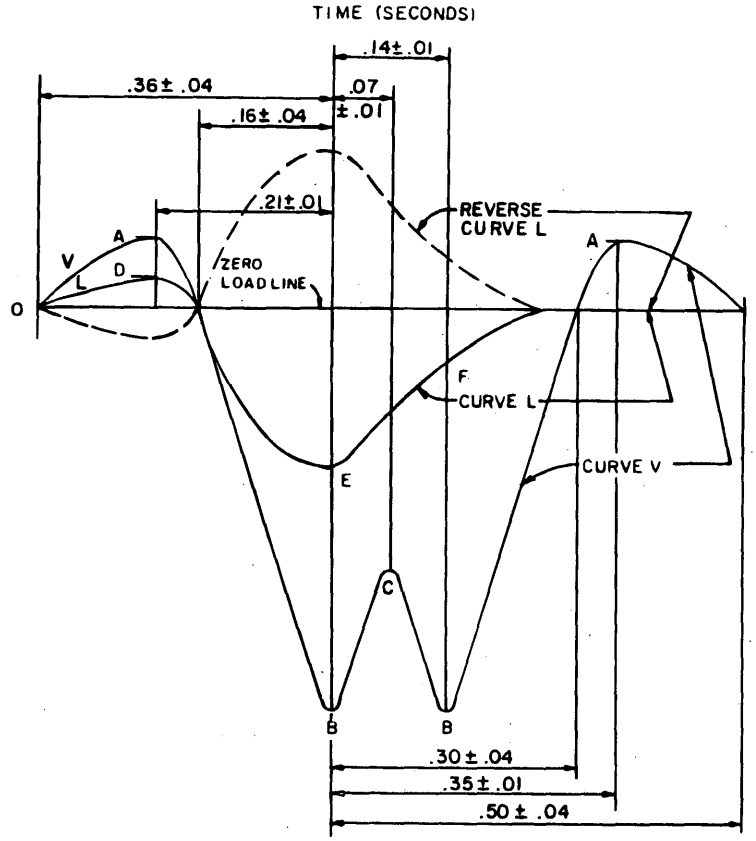

FIGURE 6 Spring rate, deflection, and repeated load tests.

		SPRING RATE AND DEFECTION TEST			REPEATED LOAD TEST				
		CASE							
		1	2		3	4	5		
VERTICAL CURVE V	A	-900	-540		-1060	-1343	-892	LBS	TOTAL RESPONSE LOAD
	B	+21	+12.6		+25.2	+31.5	+21	KIPS	
	C	+13.5	+8.1		+16.2	+20.25	+13.6	KIPS	
LATERAL CURVE L	D	-535	-800		-640	-1340	-1340	LBS	
	E	+12.6	+18.9		+15.1	+4.9	+4.9	KIPS	
	F	+4.9	+7.4		+5.8	+12.3	+12.3	KIPS	
					99	1	1		

NO. OF CYCLES OF EACH CASE PER 100 CYCLES OF REPEATED LOAD TEST.

FIGURE 7 Loading cases for spring rate, deflection, and repeated load tests.

In the push-pull test, a cyclic longitudinal load was applied at the rate of one cycle per second to the base of the rail at the rail centerline to deflect the rail ±⅛ in. about the initial position relative to the test block for 1 million cycles. The four fasteners were to withstand the 1 million cycles of loading with no evidence of failure. No component of the fastener was to exhibit any evidence of failure by yielding, slippage, or fracture.

The second repeated-load test was to determine the conditions of the four fasteners after undergoing the heat-aging and push-pull tests. After they passed these tests, the four fasteners went through, once more, the spring rate and deflection, longitudinal restraint, electrical resistance, and dynamic stiffness tests before they were considered acceptable.

During the fastener production run, four fasteners were selected randomly by the WMATA engineer from the initial 50 and from each subsequent 2,000 fasteners, or portion thereof, for quality-control tests in spring rate and deflection, longitudinal restraint, electrical resistance, and dynamic stiffness. The quality-control plan also included the assurance that the material used in the fasteners met the approved specifications.

Figure 10 shows the top, side, and end views of the egg-shaped fasteners produced by ATP.

APPLICATION

As of August 1994, 4,100 units had been delivered to WMATA. About 370 of them were installed 30 in. apart in the Green Line tunnel near the Waterfront Station so that their effectiveness in mitigating underground vibrations could be tested against the effectiveness of the floating slabs mounted with other existing direct-fixation fasteners; Table 5 presents the test results. On the basis of this information, about 8,700 units for the Mid-City Route and 2,200 units for the Outer F Route, both in the future Green Line extension, were

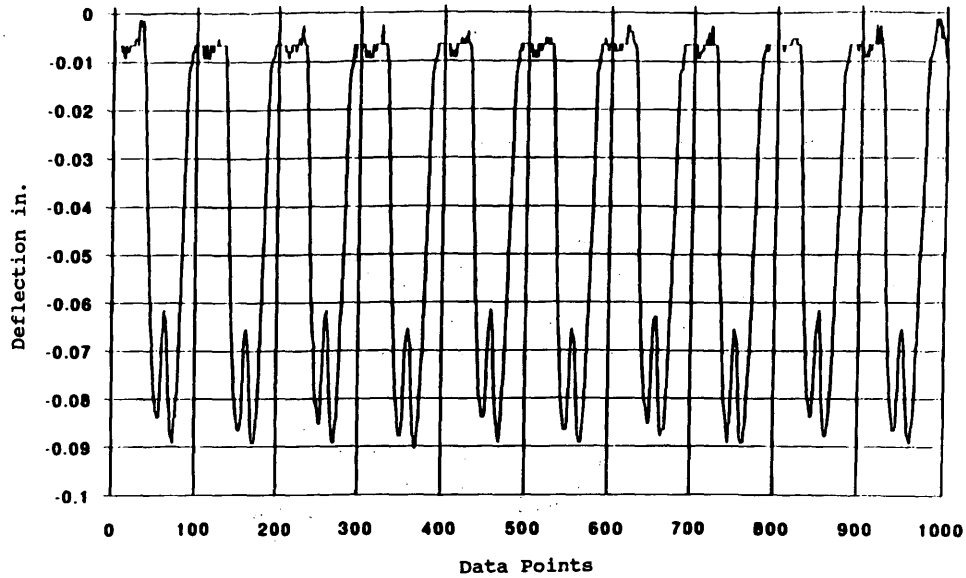

FIGURE 8 Average vertical deflections, Case 1, WMATA Pads 10, 20, 30, and 40.

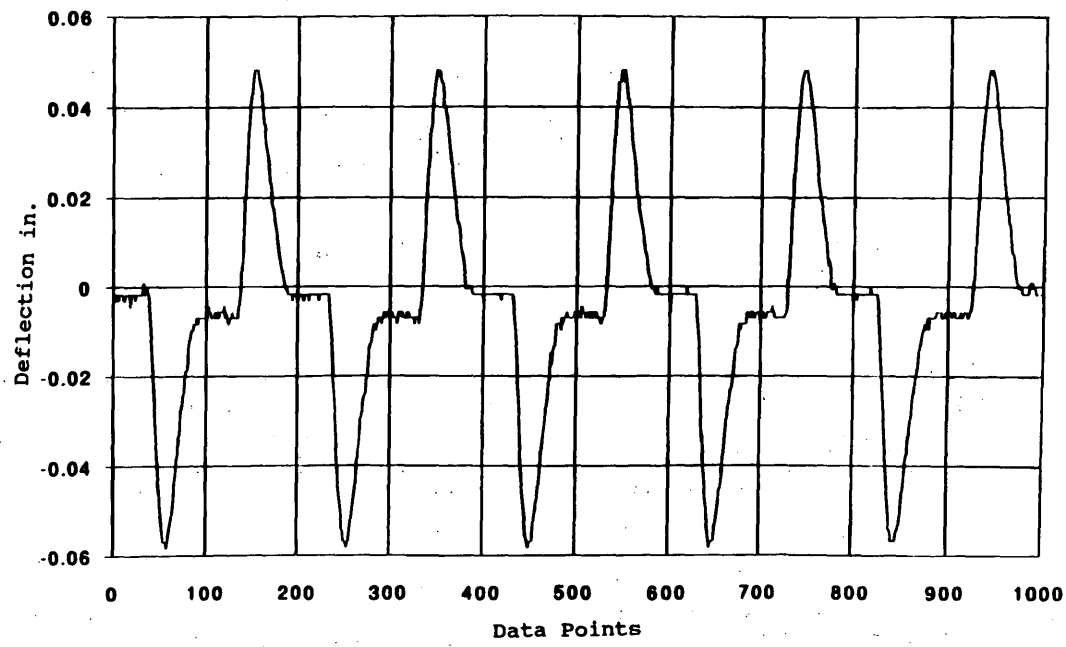

FIGURE 9 Average lateral base deflections, Case 1, WMATA Pads 10, 20, 30, and 40.

TABLE 3 Spring Rate and Deflection Test Results, Case 1

	Avg. Incremental Spring Rates		Avg. Lateral Deflection.in.	
Increment	Vert. lb/in	Lat. lb/in	Rail Base	Rail Head
0 - Max. Load	67,745	58,893	0.054	0.105
0.20 - 0.25 sec.	61,580	53,030	-	-
0.25 - 0.30 sec.	70,890	58,110	-	-
0.30 - 0.36 sec.	76,630	56,890	-	-
Average	67,700	56,010	-	-
Ratio*	0.80	0.86	-	-
			Avg. Rotation	
			0.510	

TABLE 4 Spring Rate and Deflection Test Results, Case 2

Avg. Increment Spring Rates			Avg. Lateral Deflection. in.	
Increment	Vert. lb/in	Lat. lb/in	Rail Base	Rail Head
0 - Max Load	80,214	38,523	0.122	0.223
0.20 - 0.25 sec.	62,940	39,010	-	-
0.25 - 0.30 sec.	75,890	35,860	-	-
0.30 - 0.36 sec.	94,360	42,040	-	-
Average	77,730	38,970	-	-
Ratio*	0.69	0.82	-	-
			Avg. Rotation	
			0.997	

* Ratio of smallest incremental spring rate divided by largest incremental spring rate.

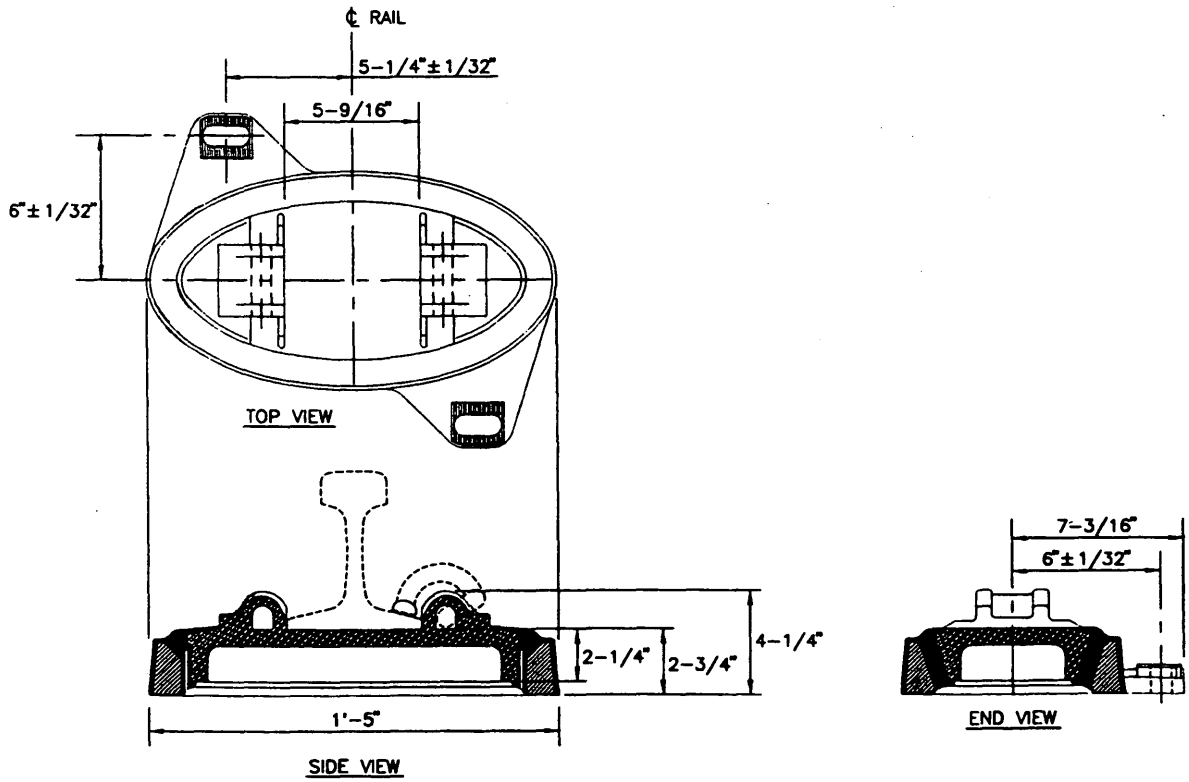

FIGURE 10 Egg-shaped direct-fixation rail fastener.

processed for contract award in late December 1994. Testing is expected for fall 1995. According to ATP, the Boston Transit Authority has also placed an order for 3,800 WMATA egg-shaped fasteners.

The WMATA egg-shaped fasteners, when the required vibration attenuation is less than 8 dB, are the alternative means for alleviating underground vibration. Substantial cost savings can be achieved when they are substituted for floating slabs ($48/ft versus $300/ft for floating slab). Floating slab construction is still necessary where vibration mitigation of 8 dB or more is required.

The general description of the WMATA egg-shaped fastener and specification can be obtained from ATP, the contractor.

TABLE 5 Performance of Ground borne Vibration Mitigation Devices

DEVICE	ATTENUATION dB	FREQUENCIES	COMMENT
FLOATING SLABS	2 TO 15 15 TO 20	31.5 TO 63 63 TO 250	FLOATING SLABS PERFORM BEST BETWEEN 31.5 TO 250 Hz RANGE AND MITIGATE UP TO 20 dB
COLOGNE EGGS	0 TO 2 2 TO 8 8 TO 10	< 20 Hz 31.5 TO 63 63 TO 250	UP TO 8 dB REDUCTION IS PROVIDED IN AUDIBLE RANGE OF GROUNDBORNE VIBRATION INDUCED NOISE

NOTE: THESE dB ATTENUATION ARE RELATIVE TO WMATA DFF HIXON AND LORD RAIL FASTENERS INSTALLED BETWEEN 1978 - 1986.

CONCLUSIONS

In conclusion, the testing program of the egg-shaped rail fasteners was considered successful. With these fasteners, WMATA not only has found an alternative method for mitigating underground vibrations, but also has saved $3.5 million in the new construction by replacing the floating slabs with the egg-shaped fasteners in the areas where moderate vibration mitigation is required.

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1. *Contract Specifications—Trackwork 12, Vibration Attenuating Underground d.f. Fastener Procurement.* Contract 2Z708R. Washington (D.C.) Metropolitan Area Transit Authority, Dec. 1988.
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PART 4

Waste Management

Arizona Department of Transportation and Environmental Protection Agency Cooperative Superfund Site Cleanup Effort for Red Mountain Freeway

THOMAS M. MONCHAK AND CHARLES K. EATON

Three kilometers (2 mi) of the 10-lane Red Mountain Freeway being constructed in Tempe, Arizona, passes through an Environmental Protection Agency (EPA) Superfund site. The Red Mountain Freeway alignment is adjacent to and crosses the Salt River within the Superfund site. Six alignments through the Superfund site were evaluated thoroughly. The two most critical constraints prevented location of the alignment on either the north or south bank of the river. These constraints were the hazardous wastes in the landfills on the south side of the river and the Indian community to the north. As a result, the freeway alignment is located on structure in the Salt River. The magnitude of the required twin bridge structures caused significant complications in obtaining a Section 404 permit from the U.S. Army Corps of Engineers. Such a river crossing within an EPA Superfund site is a unique situation. It took 4 years of negotiations with EPA to reach agreement on conditions under which the Arizona Department of Transportation (ADOT) would be allowed to remove landfills on property acquired for the freeway. In March 1992, a one-of-a-kind "agreement and covenant not to sue," which sets forth ADOT's cleanup responsibilities and relieves ADOT from any future liabilities for Superfund cleanup costs, was executed between EPA and ADOT. The cleanup is expected to be completed by January 1, 1996. Two phases of cleanup work are required. The first phase—to clear for freeway construction—was completed in 1993, and the second—to clear an additional area for river channelization—will be performed in 1995.

In October 1985 the citizens of Maricopa County, including the entire Phoenix metropolitan area, voted to increase the sales tax a half cent for the purpose of building a 370-km (231-mi) system of freeways and expressways. The system includes the Red Mountain Freeway, which is located in Phoenix and Tempe (Figure 1) and is considered to be the centerpiece of the system because of the congestion relief it will provide, carrying up to 200,000 vehicles per day. Construction is to be completed in mid-1995.

Three kilometers (2 mi) of the 10-lane Red Mountain Freeway currently being constructed in Tempe passes through an area designated by the Environmental Protection Agency (EPA) as the Indian Bend Wash Superfund site. The circumstances associated with an environmental constraint of this nature proved to be extremely difficult and challenging and ultimately resulted in the execution of a one-of-a-kind formal "agreement and covenant not to sue" between EPA and the Arizona Department of Transportation (ADOT) so that the freeway could be built. Under the terms of this covenant, ADOT would not be responsible for any existing groundwater contamination within the purchased right of way. In return, ADOT would clean up all landfill material in the freeway construction work area.

The Indian Bend Wash Superfund site is an area of 30 km^2 (12 mi^2), 3 km (2 mi) wide, bounded by Scottsdale Road on the west and Pima Road on the east. The area was designated on the National Priorities List of hazardous substance sites in September 1983 because contaminated groundwater exists under the site. Since the Superfund site is 10 km (6 mi) long from south to north, it could not be avoided by any viable freeway alignment. The portion through which the freeway was to pass is characterized by a number of construction debris landfills and isolated potential hazardous waste sites.

Another significant factor in determining the location of the Red Mountain Freeway was the proximity of the Salt River Pima-Maricopa Indian Community (SRPMIC). The Indian property boundary between McClintock Drive and the Pima Freeway falls approximately along the north bank of the Salt River. Because ADOT has no rights of condemnation for Indian property, the Indian Community had absolute control over any possible freeway alignment north of the river.

FREEWAY ALIGNMENT

Finalizing the freeway alignment through the Superfund site was extremely challenging. Six alternatives for this 3-km (2-mi) reach were eventually considered (see A, B, C, D, E/Selected, and Initial on Figure 2): three along the south bank of the Salt River, two along the north bank, and one on structure in the river.

Initial Alignment

As identified in the East Papago (now Red Mountain) Freeway location and design concept report of September 1987, the alignment initially selected for the Red Mountain Freeway crossed the Salt River in a southeasterly direction east of McClintock Drive and continued easterly along the south bank of the Salt River to the interchange with the Pima Freeway 1.6 km (1 mi) east of McClintock Drive.

This alignment would not have resulted in any significant hydraulic impact to the Salt River because of the alignment of the river crossing, nor would there have been any significant discharge of fill material into the Salt River resulting from construction activities.

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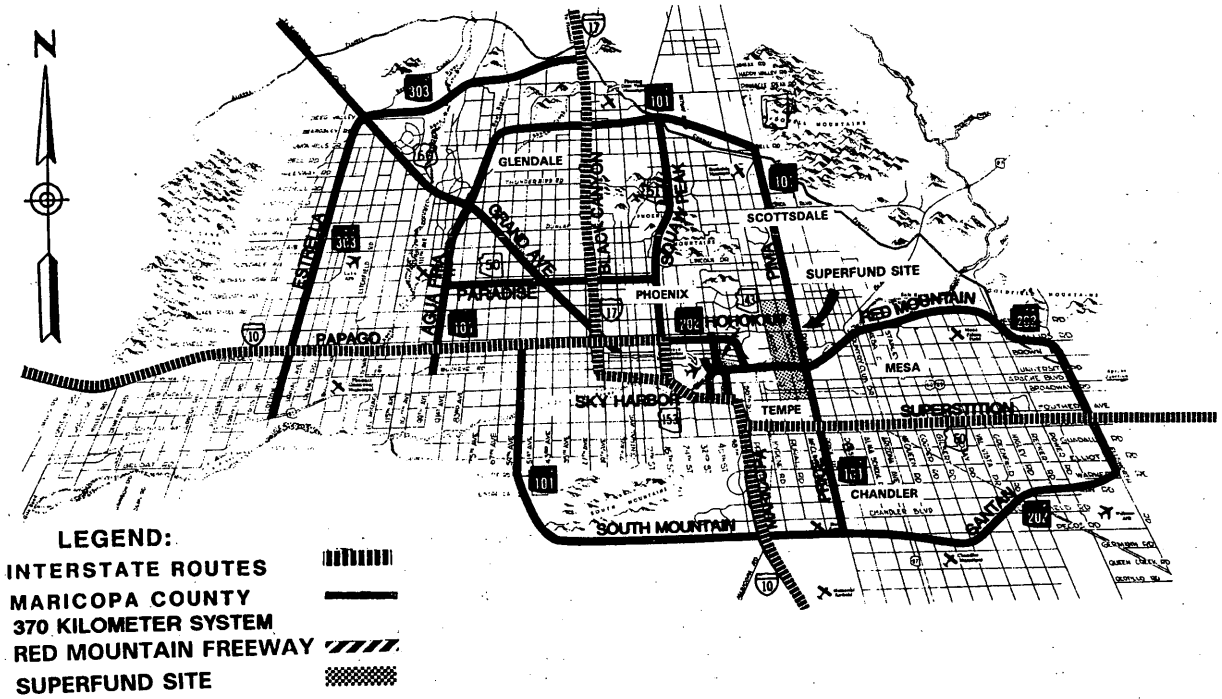

FIGURE 1 Phoenix area freeway system.

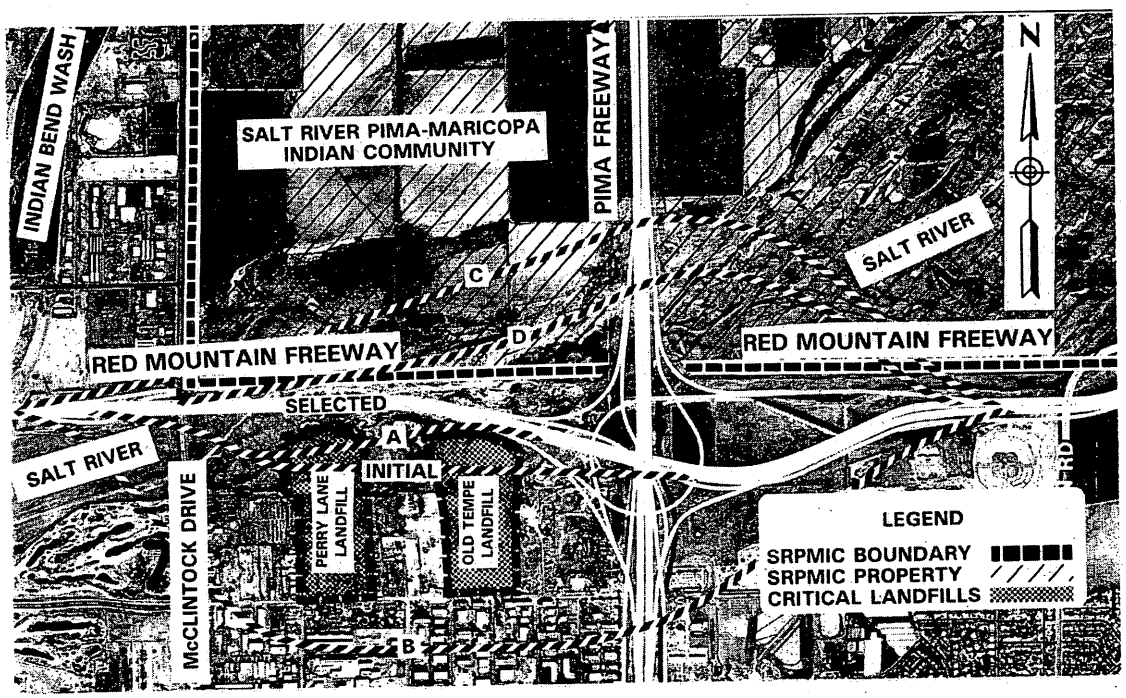

FIGURE 2 Alternative alignments.

Environmental factors were the most significant considerations related to this alignment. Crossing the Salt River at this location caused the freeway to traverse the Perry Lane landfill on the south side of the river and continue east on an alignment that crossed through the Old Tempe landfill. Results of an extensive environmental testing program indicated that these landfills potentially contained considerable amounts of hazardous materials, especially the Old Tempe landfill. The cleanup cost required to mitigate these hazardous materials was considered to be prohibitive, estimated to be as high as $100 million.

Bioremediation, soil gas extraction, removal, and incineration were considered as mitigation measures. Complete removal is the

only way to fully mitigate impacts from landfills—because of their heterogeneous nature—so this initial alignment was determined to not be prudent because of the possibly exorbitant cost of the environmental mitigation measures.

Alternative Alignments

Four other alignments were evaluated on the basis of five key factors:

1. Environmental considerations,
2. Impact on the Salt River Pima-Maricopa Indian Community,
3. Hydraulic considerations,
4. Cost, and
5. Highway geometrics.

Alternatives A and B were located on the south side of the Salt River and Alternatives C and D, on the north side, as shown in Figure 2. All four of these alignments were eventually rejected. The evaluation matrix in Table 1 indicates which factors were negative and caused each alternative to be eliminated from consideration. It also reflects the impact of the selected alignment.

Selected Alternative

The selected alignment crosses McClintock Drive at the north bank of the Salt River, continues east up the river on structure, and intersects the Pima Freeway on the south bank at the Red Mountain traffic interchange (Figure 3).

Extensive environmental investigation was performed for this alignment in cooperation with EPA's Superfund staff after all other alignments had been rejected. This alternative avoids the major areas of contamination (landfills), and no hazardous material was found on the river property required for construction of the Red Mountain Freeway. Additionally, the Salt River environment would be enhanced by the removal of a considerable amount of municipal solid waste, rubbish, and construction debris deposited in the area, as well as unidentified hazardous wastes that are sometimes found in conjunction with such material.

Only minor hydraulic impacts caused by the freeway bridges crossing the Salt River are associated with this alignment, and discharge into the Salt River is not a significant factor. Building a longer bridge crossing of the Salt River increased the freeway costs ($15 million) for this particular alignment. However, the fact that little or no hazardous waste cleanup costs are anticipated for this alignment readily offsets the higher bridge costs.

In conclusion, the selected alternative is acceptable in terms of environmental, hydraulic, cost, highway geometric, and social and economic factors. The Indian community concurred with and supported this alignment, which was a critical factor. Therefore, the Arizona State Transportation Board approved this alignment with the concurrence of EPA.

EPA AGREEMENT

The Red Mountain Freeway alignment passes through the EPA-defined South Indian Bend Wash study area as previously described. The freeway development plans had to be coordinated with the EPA cleanup activities. The design concept report that recom-

TABLE 1 Matrix for Evaluating Alternatives

FACTOR	ALTERNATIVE					
	INITIAL	A	B	C	D	SELECTED
ENVIRONMENTAL	●	◪	●	○	○	○
SRPMIC IMPACT	○	○	○	●	●	○
HYDRAULICS	○	●	○	○	○	◪
COST	●	●	●	◪	◪	◪
HIGHWAY GEOMETRY	○	◪	○	○	◪	○

Severely Negative ●

Moderately Negative ◪

Neutral ○

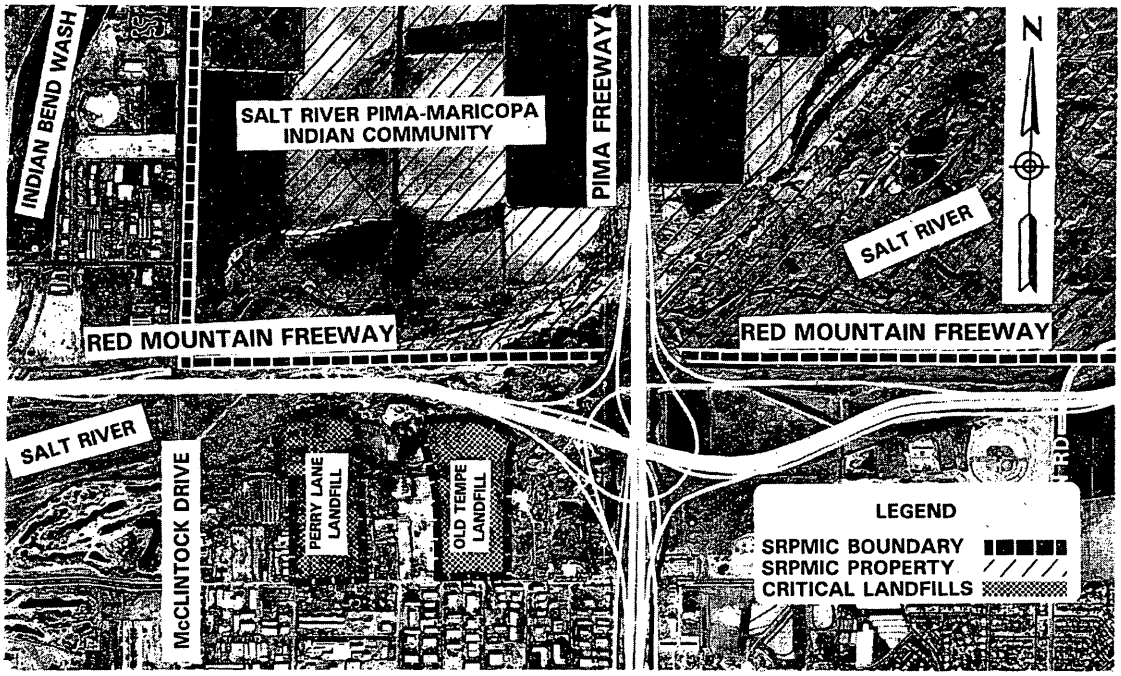

FIGURE 3 Selected alignment.

mended the initial alignment for the Red Mountain Freeway identified the landfills and Superfund involvement as major issues requiring resolution before final design development.

In 1987, when initial discussions with EPA began, EPA had done little investigative work on the location and extent of hazardous waste within the Superfund site. Since the South Indian Bend Wash study area potentially contained many isolated hazardous waste sites in addition to the landfills, and since the landfills were of such a heterogeneous nature, EPA had anticipated that it would be many years before it would complete its study, identify the responsible parties, and determine the most appropriate remedy for clean-up. This meant that ADOT would not be able to define its liability under the Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (CERCLA, or the Superfund law) for many years.

At that time the target for completing construction of the Red Mountain Freeway was the end of 1992. To expedite the freeway development process, coordination meetings were held frequently with EPA to (a) determine how ADOT could sample, test, and characterize wastes found on properties to be purchased for the freeway, and (b) find a way to limit ADOT's liability before it bought right of way.

Under Superfund law, if ADOT purchased right of way that contained hazardous wastes that were contributing to the groundwater contamination, ADOT could become a "deep pocket" and be held responsible for the costs to clean up properties outside the freeway right of way owned by parties unable to pay their own cleanup costs. This "deep pocket" provision in CERCLA law is called joint and several liability. Additionally, ADOT did not want to be responsible for the Superfund site groundwater cleanup which could cost hundreds of millions of dollars over a 10- to 50-year period.

As a result of the discussions with EPA over many months and of extensive environmental sampling and testing of right of way necessary for the initial alignment, it was determined that the potential liability for hazardous waste remediation was cost-prohibtive and could not be accomplished within the desired time frame for completion of the Red Mountain Freeway. This decision resulted in the evaluation of the alternative alignments as previously discussed.

The selected alternative minimized the involvement with properties that might contain hazardous wastes by avoiding landfills to the extent possible, which was achieved by constructing a major portion of the freeway within the South Indian Bend Wash area on structure within the floodway of the Salt River. Doing so increased the roadway costs but substantially reduced the potentially high cost of remediating or removing hazardous and nonhazardous wastes.

After extensive discussion, EPA staff determined that there might be a way to assist ADOT with its potential joint and several liability. In 1989 negotiations were initiated and ultimately resulted in the "agreement and covenant not to sue," which was made final in August 1991. The negotiations generated many iterations of the agreement and required considerable legal review on both sides. This was the first time that EPA had executed a prepurchase agreement with another government agency.

The agreement called for ADOT to sample, test and perform a study called an engineering evaluation/cost analysis (EE/CA) to determine an appropriate removal method or remedial action for hazardous wastes that might be encountered.

ADOT would be responsible for transporting any hazardous wastes to depositories approved by EPA. This action would require the development of a detailed plan for removal that EPA had to approve before landfill removal activity could begin. In return, EPA agreed to relieve ADOT from joint and several liability and not hold ADOT responsible for costs of cleaning up groundwater.

To keep the freeway project on schedule, nearly all the sampling and testing were done before the agreement was consummated. The agreement was executed in August 1991, and the EE/CA was approved in July 1992 so that right of way could be purchased and landfill removal within the right of way could begin.

The entire process of gaining the clearance from EPA concerning Superfund involvement took nearly 4 years. It was a particularly

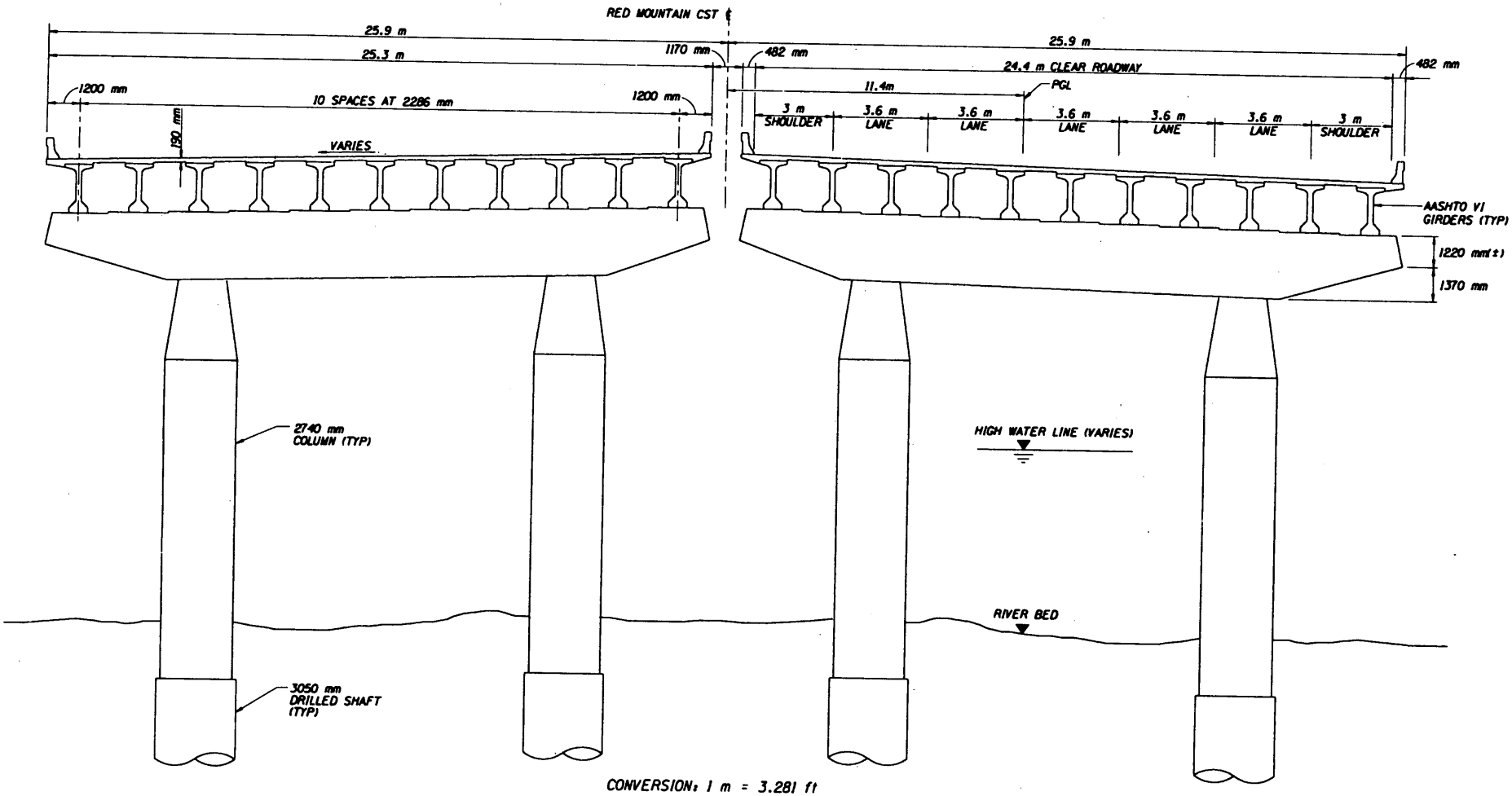

FIGURE 4 Salt River Bridge frame design.

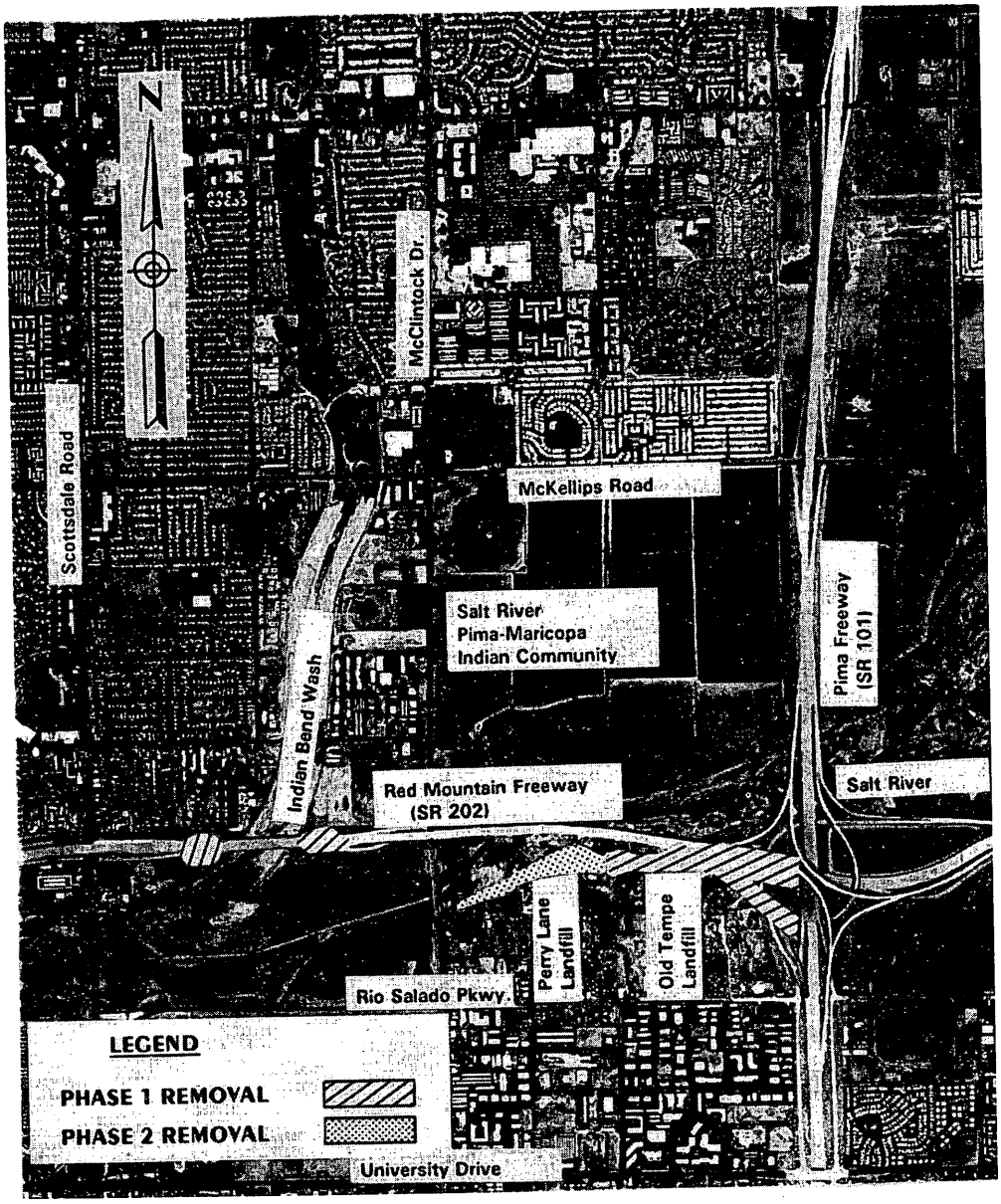

FIGURE 5 Landfill removal.

difficult and frustrating process; ADOT was breaking new ground with EPA, and there did not appear to be any defined policies or procedures to indicate what to expect in advance so that planning related to the construction schedule could have been done.

Even though funding shortfalls have caused delays in completing the Red Mountain Freeway, the requirement of clearing the right of way through the EPA Superfund site would have resulted in at least a 2-year delay. The current completion date is anticipated to be mid-1995. The EPA cleanup efforts will benefit significantly from ADOT's contribution, with approximately 760,000 m^3 (1 million yd) of material processed.

It is critical that any potential involvement with Superfund sites or other on-site cleanup activity be addressed early in the freeway planning and development process, and that those individuals involved diligently pursue resolution with EPA. The Superfund process as it exists today is laborious and tedious.

The EPA staff in San Francisco with whom ADOT dealt to obtain the agreement and covenant not to sue indicated that this would be a unique arrangement with another government agency, and that no other such agreements would be considered. However, under favorable circumstances in which a win-win situation might exist, a similar arrangement certainly should be explored.

U.S. ARMY CORPS OF ENGINEERS SECTION 404 PERMIT

The selected Red Mountain Freeway alignment necessitated construction of twin structures over the Salt River, each 25 (83 ft) wide and more than 1.6 km (1 mi) long. Because of the landfill encroachment along the south side of the river channel, the hydraulic impacts of these bridges had to be minimized in order to ensure that

a U.S. Army Corps of Engineers Section 404 permit could be issued.

The initial concern was the effect of the bridge piers on the river hydraulics. To minimize the number of support columns needed, a two-column frame supported by two drilled shafts was designed (Figure 4). Additionally, span lengths were set at 43 m (140 ft) so that standard AASHTO Type VI girders could be used. The resulting hydraulic analysis showed that the freeway caused no significant increase in water surface elevation [less than 300 mm (1 ft)] or velocity [less than 0.3m/sec (1 ft/sec)].

However, erosion of the landfills adjacent to the bridges on the south bank of the Salt River was an issue identified to the U.S. Army Corps of Engineers during the comment period for the Section 404 permit application. Concern about this matter was expressed by several agencies, including EPA, the U.S. Fish and Wildlife Service, the Arizona Department of Environmental Quality, the Arizona Game and Fish Department, the Maricopa County Flood Control District, and the city of Tempe. All agencies wanted to ensure that the Red Mountain Freeway would not increase the erosion of the potentially hazardous material in the landfills.

To satisfy agency concerns, ADOT agreed to provide bank protection in the form of a soil cement levee along the south bank of the Salt River from McClintock Drive to the Pima Freeway. This commitment made it necessary that ADOT also agree to provide similar bank protection along the north side of the river so that the Indian community property would not be eroded by water forced to the north side of the Salt River by the south side bank protection.

The net result is that the portion of the river between McClintock Drive and the Pima Freeway will be channelized, thereby providing a secondary benefit of flood control for 1.6 km (1 mi) of the Salt River.

CONSTRUCTION

The landfill removal effort was split into two phases, the first to allow for the construction of the Red Mountain Freeway and the second to accomplish the Salt River channelization. The first phase was completed in 1993, and the second phase is scheduled to be completed during 1995.

The first phase (Figure 5) addressed (a) the area north of the Old Tempe landfill composed of approximately 380 000 m^3 (500,000 yd^3) of rock/soil fill, construction debris, and municipal solid waste and (b) two landfills adjacent to Indian Bend Wash, one on either side, containing approximately 115 000 m^3 (150,000 yd^3) of debris.

Initiating construction was a challenge because the varying interests of the agencies involved complicated the resolution of the 404 Permit issues. The agencies finally reached agreement in July 1992, and the Corps of Engineers issued the permit to ADOT on July 16, 1992. This enabled the Arizona State Transportation Board to award a $4.9 million construction contract on July 17, 1992, to Sundt Corporation for the first phase of the landfill removal.

Before excavation could begin, Sundt was required to develop a detailed work plan for the excavation, monitoring, segregation, loading, and hauling activities. This document set forth Sundt's responsibilities, which covered landfill removal activities up to the point of discovery of any suspicious materials. At this point, ADOT's on-call emergency response team would be called in to evaluate and treat suspicious materials as appropriate.

The removal effort was quite successful, with the only discovery of contaminated material being about 3800 m^3 (5,000 yd^3) of rock/soil fill containing petroleum hydrocarbons. The final removal cost was $5.5 million, including the handling of the special materials and quantity overruns. Despite being hampered by high river flows during 1993, the landfill removal efforts did not delay the freeway construction.

Construction of the Red Mountain Freeway bridges began in January 1993. Of the 13 contractors Sundt Corporation submitted the low bid of $40.0 million at the November 20, 1992, bid opening; it was awarded the project on December 18, 1992. Thirty months were allowed for completion of the two bridges, and the work remains on schedule.

The second phase of the landfill removal (Figure 5) consists primarily of removing the northern portion of the landfills west of the Old Tempe landfill, including the Perry Lane landfill. This removal will allow for channelization of the Salt River from McClintock Drive to the Pima Freeway to provide flood control for the 100-year event.

The estimated cost for the removal is $5 million. ADOT will use the work plan developed by Sundt for the first-phase removal because of its successful implementation and utilization. Construction is expected to be completed by the end of 1995.

Once the landfill removal work has been completed, ADOT will produce a final version of the EE/CA that will document the actual findings of the removal (including disposition of any hazardous wastes found) and the costs for the work performed.

CONCLUSION

ADOT's extraordinary coordination efforts with EPA were extremely successful from the perspective of costs. The agreement and covenant not to sue has relieved ADOT of any future Superfund liability, and the Red Mountain Freeway will be constructed in a cost-effective manner.

Publication of this paper sponsored by Task Force on Waste Management in Transportation.

Plume Capture During Construction

GORDON DEAN AND JON G. BERRY

Groundwater contamination can affect significantly construction activities in areas of the country where the depth to groundwater is relatively shallow. An innovative method of controlling groundwater contamination plumes during construction to prevent worker exposure to the contaminants and exacerbation of the contaminant plume is presented. Application of this method can reduce delay claims, injuries, and potential litigation related to the contamination. The plume capture principles were applied successfully at two sites with petroleum hydrocarbon groundwater contamination adjacent to a dewatering project in Orlando, Florida. Contamination plumes were decreased greatly after plume capture, with no exacerbation of either plume.

Construction activities in areas with high groundwater often involve dewatering for installation of utilities, piping, and storm water control structures. The discovery of groundwater contamination in the area can affect the construction schedule since most roadway contractors are not equipped or certified to deal with exposure to contaminants. Initial impacts may include work stoppage, delay claims, and worker compensation claims. In addition, the parties responsible for the contamination may decide to sue if they can demonstrate that the plume was exacerbated. Exacerbation, in such cases, may be defined as enlarging or moving the plume from its preconstruction location. Any movement of this sort may prolong the time to remediate the site or require an increase in the number or size of equipment needed for remediation. Either possibility could increase substantially the cost of remediation.

In current practice, groundwater contamination usually is addressed if it happens to be discovered during the construction of a transportation project. However, many states have begun procedures to identify contamination in and adjacent to the construction right of way. The Florida Department of Transportation (FDOT) has formalized its contamination assessment procedures in Chapter 22, Part 2 of its *Project Design and Environment Manual.* This manual has served as the basis for preconstruction assessment activities for a number of states and countries. The institution of procedures similar to these greatly reduces the difficulty in addressing contaminated sites by allowing more time for avoidance or design and implementation of remedial measures.

A firm understanding of the principles of groundwater movement and control will allow a rapid response to the contamination. Two general situations may be encountered: the first, and most common, is construction through an area of groundwater contamination; the second is construction adjacent to but outside of an area of contamination. Both situations require that a preconstruction assessment be performed. The movement of the contaminated groundwater must be controlled so that the plume is not exacerbated during the project's progression.

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Groundwater control measures commonly used in both the construction dewatering and groundwater remediation industries include groundwater pumping from dewatering points and recovery wells; reinjection of water through well points, trenches, or galleries; and treatment of contaminated water by air stripping and granular activated carbon polishing. Applying these measures to groundwater contamination encountered during roadway construction can minimize the potential problems.

THEORY OF PLUME CAPTURE

Many equations can be used to predict groundwater movement and drawdown from recovery wells. Two of the oldest and most commonly used are the Theis equation and the related Cooper-Jacob nonequilibrium equation. The first applies to all pumping durations but, until the recent proliferation of computers, required the extensive use of tables to evaluate. The Cooper-Jacob solution requires a steady-state, long-term pumping scenario. Since most construction dewatering operations are short term, the Theis equation is recommended. It should be noted that most computer models assume steady-state conditions. It is recommended that the placement of recovery wells be determined using the Theis equation and then input into a model for verification.

Plume capture theory is based on established principles of hydraulics and groundwater movement. Dewatering creates a depression in the groundwater along the line of the well points. In a cross-sectional view, this depression is curved, with the deepest part at the well points and reaching a point of zero drawdown some distance away. A recovery well will produce a similar drawdown profile in a radial pattern around the well. If a recovery well is placed close enough to the required dewatering activities, the drawdown curves from the dewatering and the recovery well will intersect. The intersection point will be at a higher elevation than any other point along the drawdown curves. This intersection point is called the groundwater divide and theoretically represents the point across which groundwater will not move. Groundwater on the dewatering side of the divide will flow to the dewatering operation, whereas groundwater on the other side of the divide will flow to the recovery well. The theory of plume capture is to place one or more recovery wells in a position to create a groundwater divide at a desired location between the dewatering activities and the recovery wells to prevent movement of contaminated groundwater toward the dewatering.

APPLICATION OF PLUME CAPTURE METHODOLOGY

The first step in applying plume capture theory is to evaluate the possibility of not using plume capture at all. Simpler and less expensive alternatives include changing the design, working in the

wet, and using sheet pile. Changing the design may be possible if the contamination is detected early enough in the construction process. Design changes to avoid contaminated conditions include raising the invert of drainage structures and pipes and moving the piping or structure locations. Working in the wet (i.e., not dewatering) is possible if the construction does not extend more than 0.7 to 1 m (2 to 3 ft) below the water table. Sheet piling is commonly used to provide sidewall stability in excavations and to limit the amount of pumping required to dewater. It can also be used to limit the movement of a plume.

If design changes are not possible or will not address fully the groundwater contamination, a plume capture system must be designed and implemented. The process of designing a plume capture system starts with a complete assessment of the proposed work, site, extent of contamination, and aquifer properties in the area.

Construction Project and Site Assessment

A complete understanding of the scope of the construction and dewatering work obviously is essential. The design plans must be reviewed to determine the depth and location of the proposed piping and structures, as well as the location of all existing utilities and other obstructions. If the construction will be taking place through a groundwater contamination plume, it may also be necessary to modify the design to prevent the contaminants from migrating through the backfill after construction has been completed. The dewatering contractor must be consulted to determine the expected well point locations, pumping rate, radius of influence, and duration of the dewatering activities. A site visit should be conducted to verify the locations of any utilities or obstructions, ascertain other potential sources of contamination, and identify possible treatment compound locations and effluent discharge options. The availability of electric power and water at the potential compound locations and the presence of any existing monitor wells or groundwater treatment systems should also be noted.

Plume Assessment

Regulatory agency files should be reviewed to obtain information on the previously known location and concentration of the groundwater contamination. These files may also contain information about the aquifer characteristics, and the design of the treatment system.

In addressing plume exacerbation, it is essential to define the horizontal and vertical extent of the contamination. Existing monitor wells may be used or temporary wells installed. It is preferable to delineate fully the areal extent of the plume; however, access to properties adjoining the right of way may be denied. In this case, the contamination underneath the roadway and right of way should be defined. The purpose of the plume assessment is to provide a baseline plume configuration and a basis for estimating influent concentrations into the treatment system.

Aquifer Assessment

An understanding of the aquifer characteristics at the site is necessary for designing the plume capture system. The properties of interest are the transmissivity (or hydraulic conductivity and saturated aquifer thickness), hydraulic gradient, and porosity or specific yield. In order of preference, these may be obtained by evaluation of data from an existing recovery well, a short-term pump test on a recovery well, slug tests on monitor wells, and typical values from geologic literature.

Plume Capture Design

The first step in designing a plume capture system is to estimate the radius of influence form the dewatering system, expected radius of influence from a recovery well, and pumping rate necessary for plume capture and creation of a groundwater divide. Dewatering shorter sections of trench will reduce the required pumping rate and reduce the radius of influence from the dewatering, both of which are beneficial from a plume capture standpoint. The design objective for the recovery well(s) is to create a groundwater divide at a selected location. In situations where the construction will take place outside of the contaminant plume, the divide should be located between the plume boundary and the construction site. Otherwise, the divide should be located so that the minimum plume area is disturbed. Use of sheet piling will help in creating the divide, although it is not totally effective in preventing groundwater movement and cannot be used in areas with rock or underground utilities. Reinfiltration of a portion of the treated water through appropriately placed well points, ditches, trenches, or galleries to create a mounding effect in the groundwater will also help to establish and maintain the groundwater divide in the desired location. Once the general drawdown contours and the location of the groundwater divide have been calculated using these principles, the results should be entered into a groundwater flow model to verify the results and present them graphically.

Treatment System Design

A complete description of the design process for a groundwater treatment system is beyond the scope of this paper. The two most commonly used treatment methodologies are air stripping and granular activated carbon adsorption. They may be used alone or in combination to treat the flows from the dewatering operation and the recovery well.

The design effluent concentration is generally equal to or less than the drinking water standard for the contaminants, although this may vary depending on the selected disposal method. Disposal options for the effluent include reinfiltration between the recovery and dewatering systems to help create a groundwater divide, reinfiltration away from the plume, injection wells, sanitary sewer, storm sewer, and discharge to surface water. Each option has differing permit conditions that must be met. The final treatment system design must contain the flexibility to be adjusted to field conditions once the plume capture operation has begun.

Plume Capture System Startup

The plume capture system should be installed and tested before the dewatering begins. This will allow evaluation of the actual influent concentrations and the radius of influence of the system and will en-

sure that the equipment has been installed and is operating properly. The system can then be adjusted as necessary to provide adequate capture and treatment of the groundwater.

Plume Capture System Operation

The plume capture system must start up before the dewatering activities begin at the site. Establishing the cone of influence of a recovery well is not an instantaneous process. The more time available before dewatering, the better the results will be. Plume capture should also continue until after the dewatering is completed for similar reasons.

While the system is operating, water levels must be monitored regularly to ensure that the groundwater movement is being controlled. Influent and effluent samples must be collected to verify the treatment efficiency and to provide enough time to adjust the treatment system if the influent concentrations begin to increase. Samples should also be taken from selected monitor wells at regular intervals to monitor any changes in the plume configuration. The most rapid and convenient method for providing the analytical data is through a mobile laboratory. If mobile facilities are not available, a fixed-base laboratory should provide rapid-turnaround analyses.

Project Completion

A plume capture project is completed by resampling all monitor wells to determine the postconstruction plume configuration. This configuration is then compared with the baseline plume configuration to demonstrate that the plume was not exacerbated as a result of the construction activities. A final report typically is prepared to document these results for future reference.

CASE STUDY

The Goldenrod Road project in Orlando, Florida, is presented as a case study. FDOT planned to conduct dewatering operations to place storm sewer piping in conjunction with road construction along Goldenrod Road in June 1994. Two retail gasoline facilities with known groundwater contamination were identified at the intersection of Lake Underhill Road and Goldenrod Road. The two facilities were located on the southeast and southwest corners of the intersection, Sites 1 and 2 respectively, as shown in Figure 1.

Construction Project and Site Assessment

The proposed dewatering activities were to take place along the eastern side of Goldenrod Road, adjacent to Site 1. The design dewatering rate, as provided by FDOT's dewatering contractor, was to be no more than 5.2 L/sec (83 gal/min). The intent of the dewatering was to depress the water table approximately 3 m (10 ft) in order to facilitate installation of the storm sewer piping. Sheet piling was to be installed adjacent to Site 1 for sidewall stability during excavation. Sheet piling was not planned for the west side of the road because of the presence of underground utilities.

All structures at Site 1 had been demolished and the underground storage tanks removed. Five monitor wells were located on-site. No other facilities were available.

Site 2 was an active retail gasoline facility. Seventeen permanent monitor wells were located on-site, and a groundwater treatment system had been installed. The system consisted of three recovery wells, an air stripper, and an infiltration gallery. Because of problems with the infiltration gallery flooding, the system was operating at only 0.2 L/sec (3 gal/min) from one recovery well. A drainage ditch discharging to a storm sewer surrounded the east, north, and west sides of the site.

Plume Assessment

Contamination assessment reports for both facilities were obtained from a review of regulatory agency files. A small groundwater contamination plume was reported to extend north from the former tank pit area at Site 1. Groundwater contamination at Site 2 reportedly underlaid most of the northern portion of the site. Additional assessment work was performed in May 1993 to confirm these reports.

The existing plume conditions at Site 1 were determined through installation and sampling of five additional monitor wells in the right of way along the north and west property boundaries. The highest concentrations—384 parts per billion (ppb) benzene, 1,032 ppb total volatile aromatics—were found in one well on the western edge of the site. Trace amounts of hydrocarbons were found in two wells along the north property boundary. Further investigation was not possible because of the construction schedule.

The baseline plume configuration at Site 2 was determined by sampling all monitor and recovery wells. The results confirmed that the plume was centered on the north pump islands, in the north-central portion of the site. The highest concentrations detected—1688 ppb benzene, 2,064 ppb total volatile aromatics, 786 ppb methyl tertiary-butyl ether (MTBE)—were found in a well adjacent to one of the pump islands.

Aquifer Assessment

The groundwater flow direction was to the east-northeast, as determined from measuring water levels in monitor wells. The rest of the aquifer characteristics were obtained from a review of the previously prepared contamination assessment reports and an evaluation of the operating recovery system at Site 2.

Plume Capture Design

The impact of the dewatering on the contamination at Site 1 was impossible to predict because the contamination plume was not well-defined. The highest concentration found on-site was immediately next to the dewatering operation. The sheet pile would restrict plume movement, but complete prevention of any movement was deemed impossible. The plume capture design for Site 1 therefore addressed only treatment of the dewatering discharge to prevent spreading the contamination and the trace contamination along the northern portion of the property. One recovery well was installed in this area to capture the known extent of this plume.

The design of the plume capture system at Site 2 concentrated on keeping the plume boundaries on the site. The existing recovery and treatment system was inadequate to create a groundwater divide

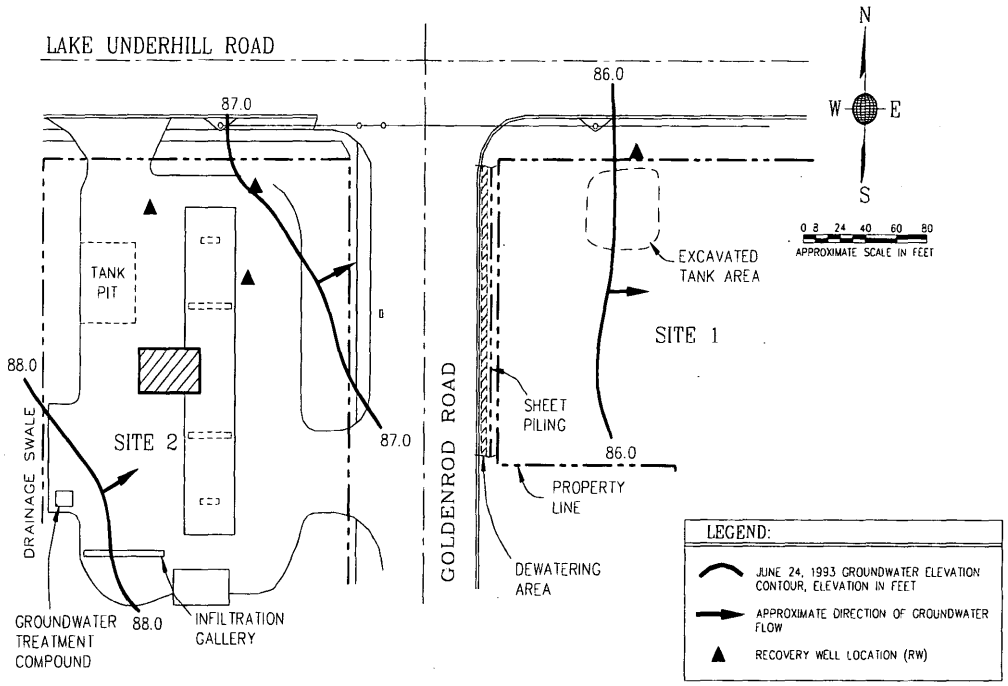

FIGURE 1 Site plan and June 24, 1993, groundwater elevation map.

along the property line. The final design used two of the three existing recovery wells, fitted with larger pumps, to create a groundwater divide along the eastern property boundary. The groundwater treatment system was located adjacent to the existing system, and the existing piping used to transport the recovered groundwater. The outlets from the drainage ditch surrounding the site to the storm sewer were raised temporarily with sandbags to maintain approximately 1 m (3 ft) of water in the ditch. The treated effluent was discharged to the ditch, where a portion of the water infiltrated and helped create the groundwater divide.

Treatment System Design

Two separate treatment systems were required because of the construction taking place in the roadway between the sites. Carbon adsorption was selected as the treatment methodology for both systems because of the relatively low flow rates and expected concentrations. The expected flow rates were 7.25 L/sec (115 gal/min) for the combined flow from the Site 1 recovery well and the dewatering discharge and 2.5 L/sec (40 gal/min) total from the two recovery wells at Site 2. Two 4540-kg (10,000-lb) carbon cells were used at Site 1, and one 900-kg (2,000-lb) cell was used at Site 2. The cells were designed to produce an effluent with no detectable contaminant concentration. The design was approved orally by the Florida Department of environmental Protection (FDEP). FDEP personnel has been contacted at project inception and had been kept informed of progress during the assessment and design activities. This close coordination greatly facilitated the design approval and implementation.

At system startup, it was determined that the recovery wells at Site 2 could produce only about 0.6 L/sec (10 gal/min) each and that the dewatering flow rate had increased to approximately 12.6 L/sec (200 gal/min). The treatment system was capable of handling these flow rates without change. The Mobil recovery wells appeared to produce an adequate drawdown to create the groundwater divide, so no design changes were needed. The plume capture system was started on June 24, 1993, 4 days before the dewatering activities in the area began.

Results

Figures 1 through 7 illustrate the results of the plume capture effort. Figure 1 shows the groundwater flow immediately before starting the plume capture system. Flow is uniform to the east-northeast. Figure 2 shows the groundwater flow with dewatering taking place next to the sites. The cones of influence are apparent around the two recovery wells at Site 2. Groundwater flow from Site 1 has been reversed and is now flowing to ward the dewatering area. Figure 3 shows the change on the following day. The cones of influence around the Site 2 recovery wells have increased, and a distinct cone has formed around the Site 1 recovery well. The groundwater gradient at Site 1 is essentially flat, with a slight trend in the easterly direction. Figure 4 illustrates the groundwater flow after the dewatering has moved north of the area. The gradient is returning to the normal east-northeast direction but is still clearly influenced by the dewatering to the north. Figures 5, 6, and 7 show the pre- and post-construction benzene, total volatile aromatic, and MTBE concentrations at the two sites.

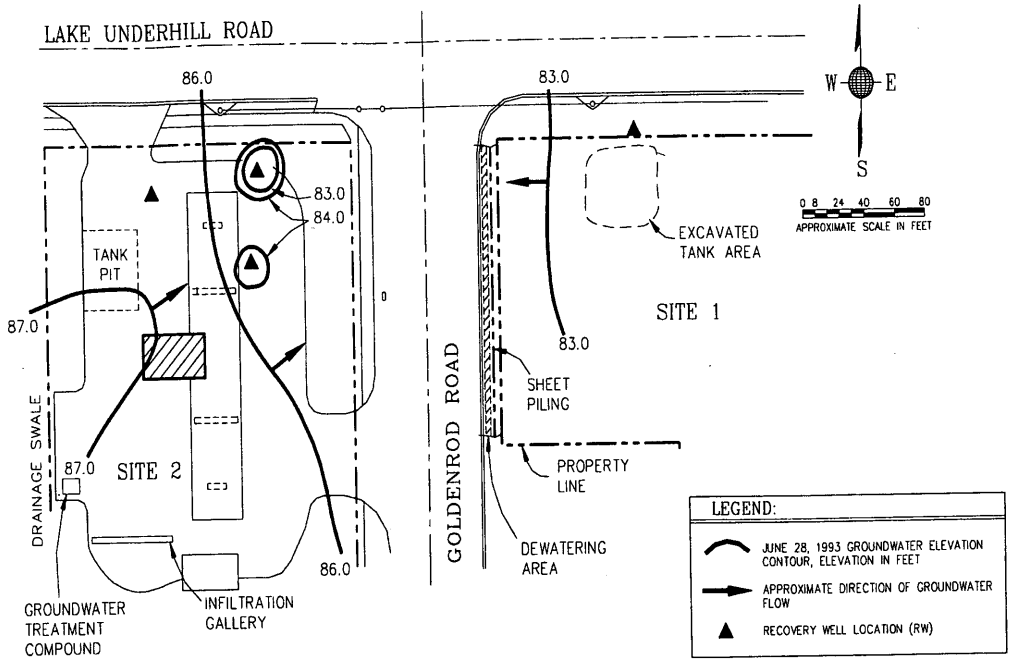

FIGURE 2 June 28, 1993, groundwater elevation map.

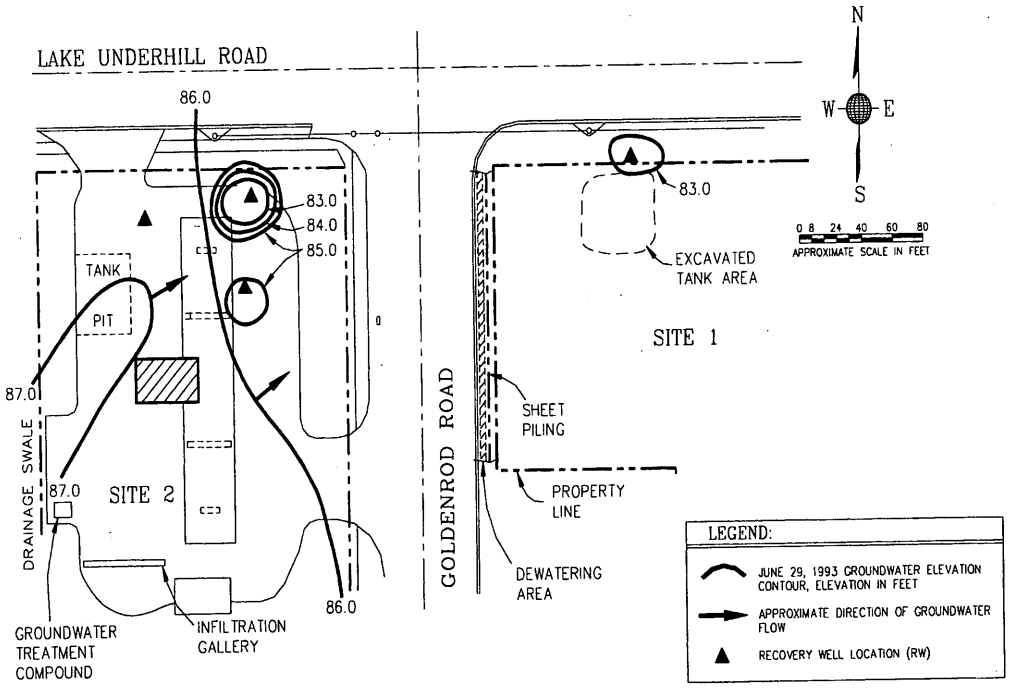

FIGURE 3 June 29, 1993, groundwater elevation map.

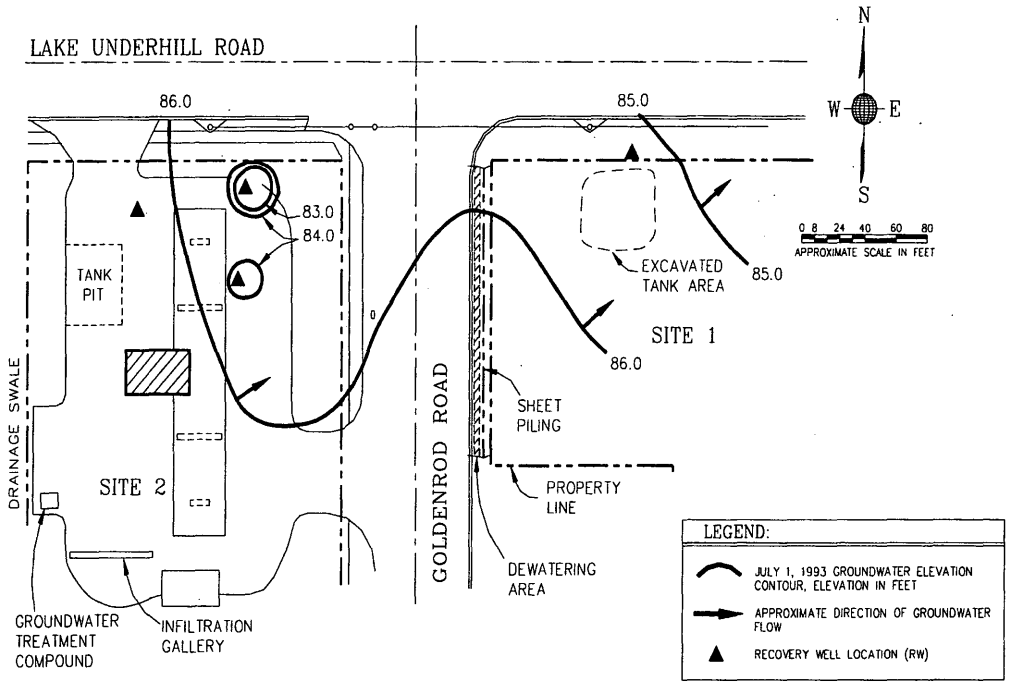

FIGURE 4 July 1, 1993, groundwater elevation map.

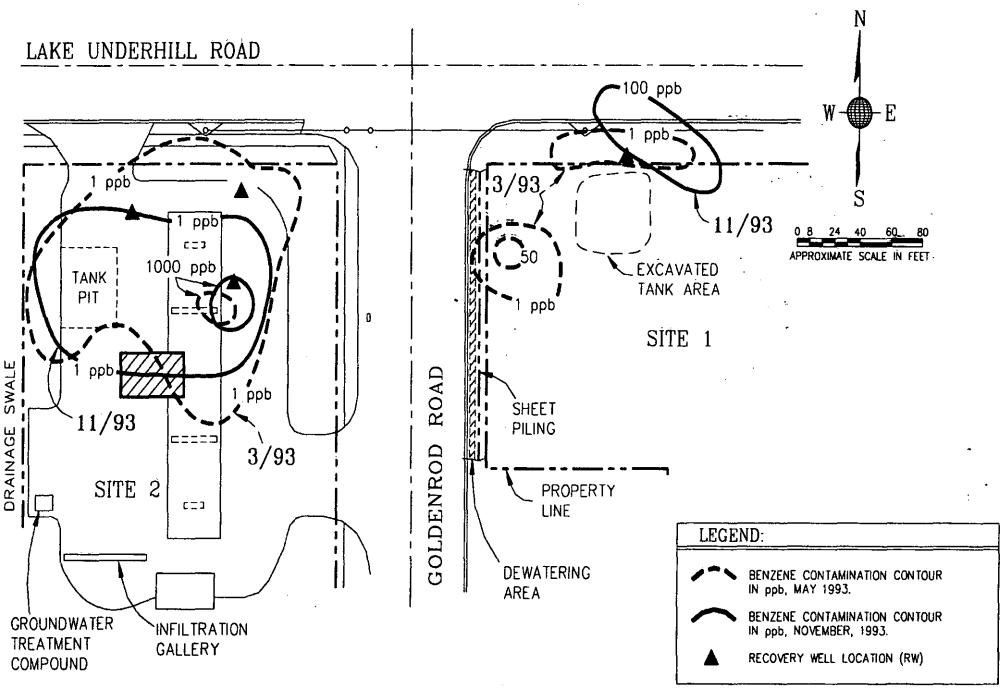

FIGURE 5 Pre- and postconstruction benzene concentration map.

The contamination plume at Site 2 was significantly smaller after the construction than before. The contamination found on the west side of Site 1 was removed completely by the plume capture and dewatering operation. The contamination on the north property boundary remained and it increased in concentration. The previously reported contamination north of the site had clearly migrated underneath Lake Underhill Road. The plume capture activities pulled the plume back to Site 1, which was not regarded as exacerbation of the contamination.

In summary, the plume capture system worked as designed. Neither plume was exacerbated—in fact, the contamination plumes at both sites were reduced significantly as a result. These same plume capture principles have been applied to other FDOT projects with similar successful results. Plume capture therefore is recom-

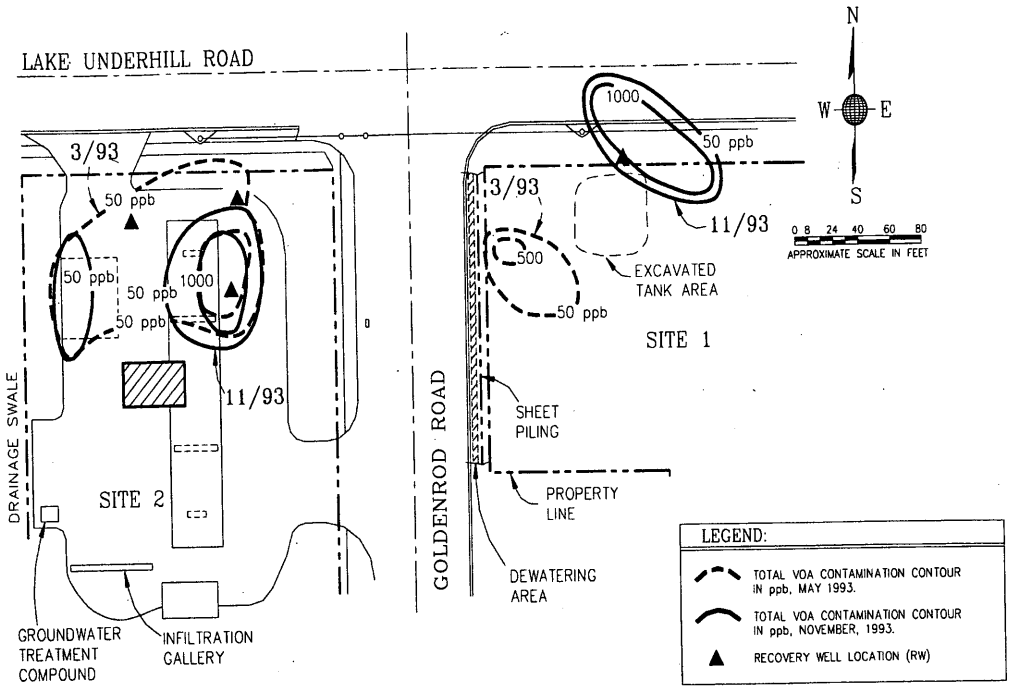

FIGURE 6 Pre- and postconstruction total volatile aromatics concentration map.

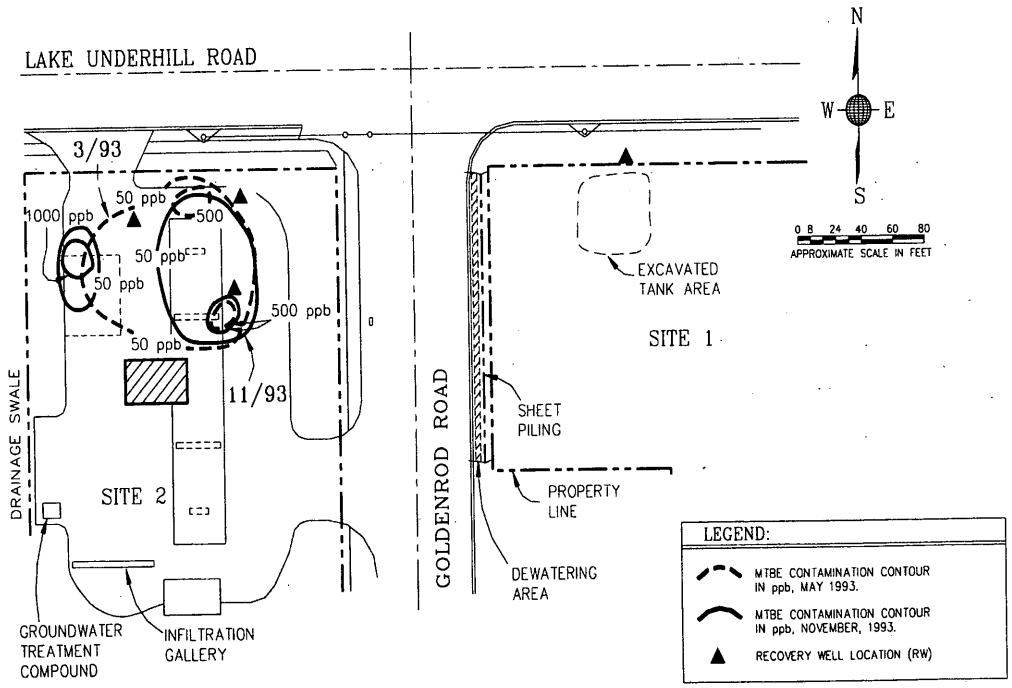

FIGURE 7 Pre- and postconstruction MTBE concentration map.

mended highly as a means of addressing groundwater contamination and reducing potential impacts to the construction schedule while protecting FDOT from the liabilities of exacerbation.

The total cost of the case study project was $200,000. FDEP petroleum reimbursement personnel indicate that the average total cost to remediate a petroleum contamination site, from assessment through postremediation monitoring, is approximately $250,000 and may range from $50,000 to more than $1 million. Contractor delay claims from work stoppages due to contamination usually range from $5,000 to $50,000/day. Attorney fees range from $100 to $300/hr and may approach $500,000 to litigate a complex case. Considering the potential exposure of the department to one or more of these costs, plume capture proves to be economically attractive as well.

Publication of this paper sponsored by Task Force on Waste Management in Transportation.

Expedited Remedial Action by Florida Department of Transportation at I-595 and Davie Boulevard Corridor Expansion Project: Case History

JON G. BERRY AND LUKE FRANTZ

The Florida Department of Transportation planned to begin construction of a portion of the I-595 corridor in Fort Lauderdale, a 2½-year project valued at $83.5 million. The designed storm water retention pond for the project spanned two parcels of land, which were discovered to contain petroleum-based contaminants. The pond was scheduled to be constructed early in the project to receive storm water runoff during construction and remain as a permanent storm water pond after completion of construction. The contaminated conditions prevented construction and use of the pond. It was therefore imperative that the site contamination be cleaned up quickly and effectively; otherwise, the construction schedule and budget would be hurt substantially. Site assessment and remedial planning were expedited, requiring close coordination between the involved regulatory agencies, other public agencies, general contractor, and remediation contractor. The design for the contaminated groundwater recovery system included high-recovery-rate horizontal drains, the first such application in Florida, as well as deep vertical wells. The groundwater treatment system employed filtration, clarification, and carbon adsorption treatment. Treated water was discharged into recharge ponds and infiltrated in designated site areas to flush the soils in the vadose zone. This action minimized the rebound effect typical of pump and treat operations that is caused by the interaction of the recovered water table and vadose zone soil contamination. This unique, large-scale groundwater remediation was effective, removing more than 99 percent of the benzene and 95 percent of total volatile organic aromatics in 3 months.

In September 1991 the Florida Department of Transportation (FDOT) acted on the discovery that construction of the I-595 corridor expansion project would be affected by the presence of petroleum-related contamination in the right of way. The project was due to be let in October 1991. Expeditious remediation of the contaminated property was imperative to prevent project delays.

From October 1991 to February 1992, the contaminated area was assessed and remediated. Working in close cooperation with the Florida Department of Environmental Protection (FDEP, formerly the Department of Environmental Regulation), a major groundwater remedial action was completed. A key factor contributing to the success of this remedial activity was the close coordination and cooperation among FDOT, FDEP, other public agencies, the general contractor, and the remedial contractor.

This paper presents a case history of the expedited groundwater remedial action. The remediation is believed to be the first and largest application of high-recovery-rate horizontal recovery drains (horizontal drains) in Florida. Initial estimates indicated that remediating this site using conventional pump and treat methods would have required 3 to 10 years to complete.

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PROJECT BACKGROUND

I-595 Expansion Project

The Interstate highway I-595 expansion project involved widening I-595 throughout Broward County, Florida. In October 1991 FDOT let the construction contract to begin the 2½-year construction of the $83.5 million "last link" of the I-595 expansion project in Fort Lauderdale. The last link involved widening a 3.22-km (2-mi) stretch of Interstate 95 from north FL-84 to south of Sunrise Boulevard. The project scope also included construction of park-and-ride facilities, erection of noise barrier walls, and widening or relocating portions of Davie Boulevard, a local main east-west feeder route to I-95.

Remediation Site

The remediation site was part of the right-of-way acquisition required to complete the construction project. As is usually the case in roadway construction projects, the storm water retention/detention ponds were planned to be built first, so that they could be used to collect storm water runoff associated with construction. The storm water pond was designed to be located on two parcels of land, identified in this paper as Parcels 268 (P268) and 269 (P269). One parcel was occupied by an active gasoline station; the other was occupied by an insurance company, which was previously the site of a gasoline station. The two parcels were determined to affect construction because of preexisting petroleum contamination of soils and groundwater, which resulted from releases during present and past operations at the sites.

P268 and P269 are adjacent parcels separated by a dead end street (S.W. 19th Avenue). Petroleum contamination plumes from each parcel intersected, forming a mixed plume; therefore, from an environmental perspective, the area was treated as one site. Figure 1 presents a plan view indicating the principal physical features of the site area. Figures 2 and 3 show the delineation of the horizontal and vertical limits of the petroleum contamination plume. The site is bordered to the west by I-95 and to the north, south, and east by residential com-

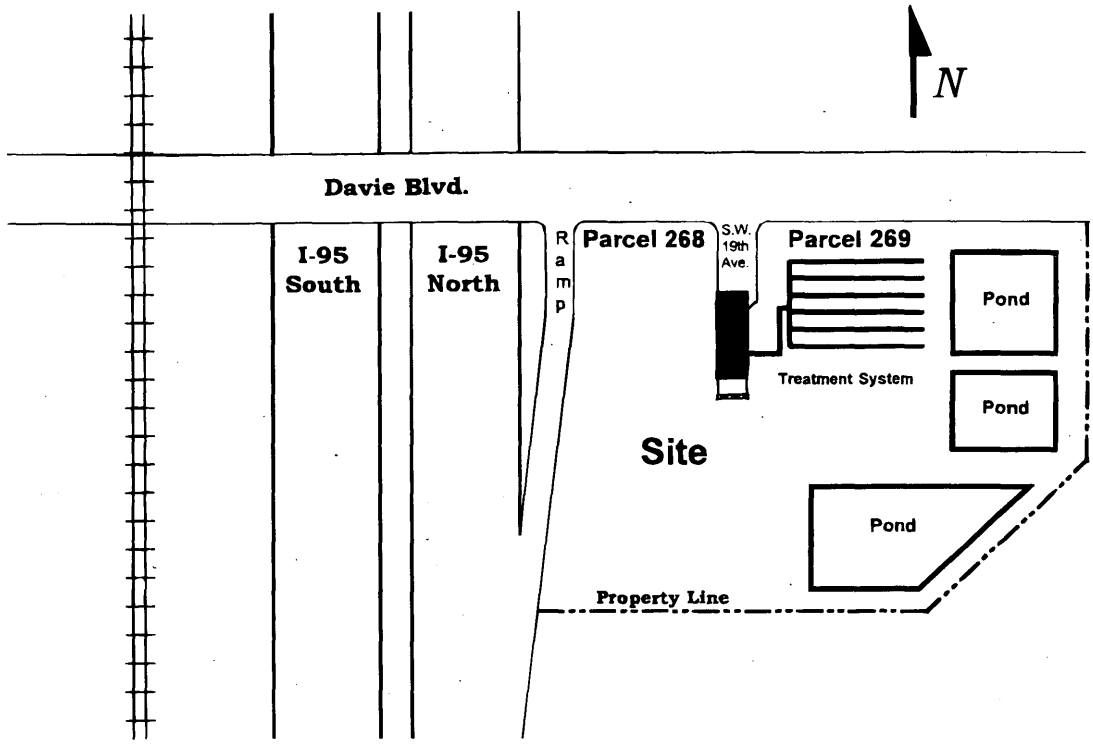

FIGURE 1 Site plan.

munities and small businesses. The tide-controlled South Fork of the New River is located to the east and south of the site.

Regulatory and Administrative Considerations

Petroleum-contaminated sites in Florida are administered by FDEP under the criteria of Chapter 17-770 Florida Administrative Code (FAC), *Petroleum Contamination Site Cleanup Criteria.* The criteria of Chapter 17-770, FAC require that petroleum-contaminated sites undergo a sequence of studies and submittals to FDEP designed to identify the extent of the contamination and the plans for remedial action. The principal documentation required to be submitted is

- Contamination assessment report (CAR): Identifies the findings of investigations and analyses performed to characterize the vertical and horizontal extent of soils and groundwater affected by releases of petroleum hydrocarbons from the underground storage tanks (USTs).
- Remedial action plan (RAP): Identifies the technology selected and engineered to remediate the site.
- Site rehabilitation completion report (SRCR): Identifies the work performed, level of cleanup attained, and actual performance of the system.

Early Detection Incentive

In recognition of the need to protect Florida's surface water and groundwater, the Florida legislature created the Inland Protection Trust Fund to provide funding for cleaning up petroleum-related contamination at eligible sites. These funds are administered by FDEP through the early detection incentive (EDI) program. Enacted in 1986 the EDI program provides state-funded cleanups or reimbursement of the cost of remediating UST-related petroleum contamination. Eligibility for reimbursement of remediation costs under the EDI program requires that the tanks be registered with the state and that all remediation-related activity is conducted in accordance with the provisions of Chapter 17-770, FAC, and records are submitted that document that the owner has paid "reasonable rates for allowable costs" in accordance with the rules.

South Florida Water Management District

The South Florida Water Management District (SFWMD) maintains jurisdiction throughout southeast Florida, where the site is located, for issues concerning water use and quality. Its oversight involvement with petroleum contamination is related to water use and quality and the potential for dewatering activities to exacerbate a contaminant plume. The usual requirements of SFWMD specify that the owner or remedial contractor establish the following:

- The engineering design must provide satisfaction that the entire plume will be captured and that the discharge will not cause previously uncontaminated areas to become contaminated through hydraulic plume movement,
- The owner/remedial contractor must obtain (at a minimum) a general use permit, and
- The owner/remedial contractor must provide monitoring data for the treatment system.

Memorandum of Understanding

FDOT regularly acquires property throughout the state for transportation improvements and often discovers unknown contaminated sites. Since the discovery of these sites furthers the mission of

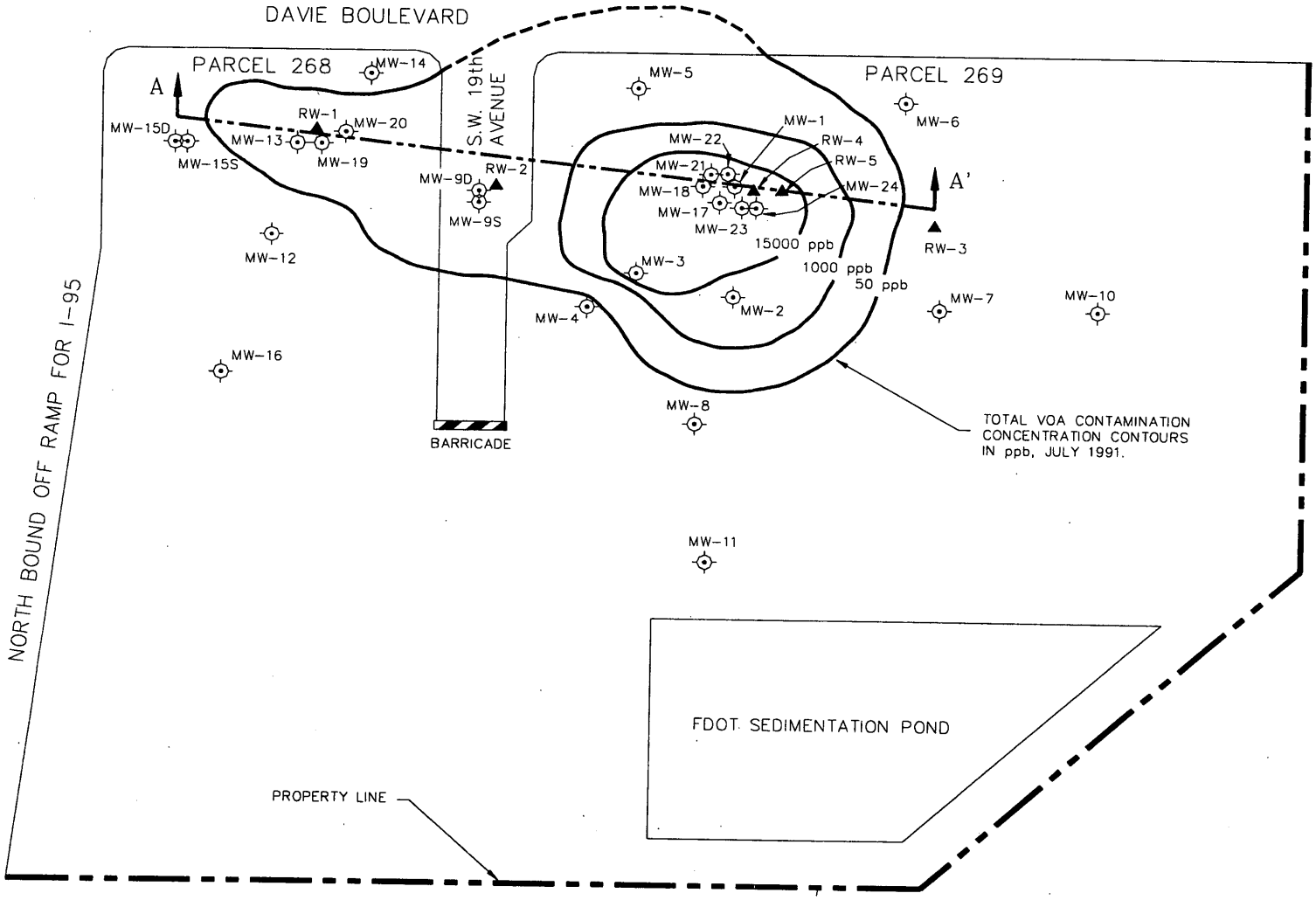

FIGURE 2 Site plan view of horizontal limits of contamination plume.

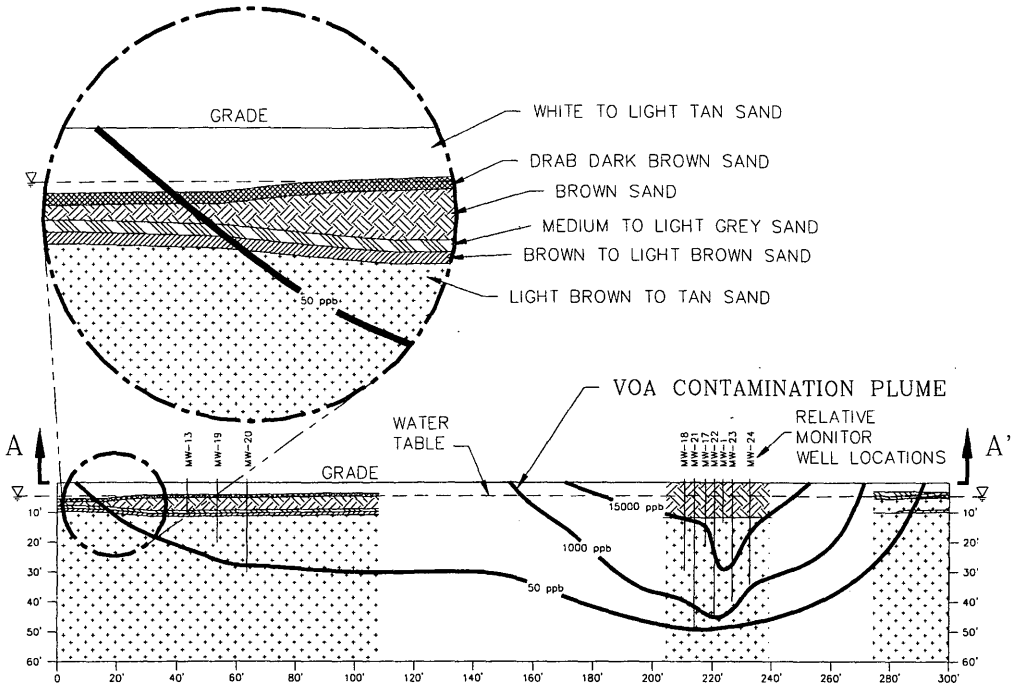

FIGURE 3 Site cross section showing vertical limits of contamination plume.

FDEP to protect the ground and surface waters, the two agencies entered an agreement in July 1989 that allows them to address and resolve contamination issues in a timely manner. That agreement, known as the memorandum of understanding (MOU), defines the role of FDOT in cleaning up contamination sites that accrue to FDOT through right-of-way acquisition. It also describes procedures for FDOT to seek reimbursement of the allowable cleanup costs from the Florida Inland Protection Trust Fund.

SITE ASSESSMENT AND REMEDIAL PLANNING

Previous Site Characterization

P269, occupied by a recently active service station of a major oil company, was an EDI site. P268, currently occupied by an insurance company, was previously the site of a gasoline station that had unregistered USTs that were leaking and, therefore, not eligible for EDI reimbursement. A CAR for P268 and P269, prepared by the FDOT general right of way consultant for this project, had been submitted to FDEP. That CAR concluded that the plume of contamination originally emanating from two separate sources had interacted and combined to create one plume. The CAR also indicated that tanks associated with the site had been removed and the associated petroleum-contaminated soils around the tank areas had been removed and incinerated, as part of initial remedial action activities.

Site Assessment

Upon reviewing the data provided in the CAR, it was determined that additional investigation was necessary to delineate the horizontal and vertical extents of the affected groundwater and soils. To fully delineate the plume, the following tasks were completed at the site:

- Additional monitoring wells were installed to determine the plume's horizontal and vertical extents.
- Groundwater samples were collected from newly installed wells and existing wells.
- The parcels were surveyed, depth to water was measured, and water table contour maps were constructed.
- Aquifers were tested in situ to determine the hydraulic conductivity.

Addendum documents to the original CAR, required by the regulatory agencies, were prepared and submitted to document that the extent of the contaminant plume was delineated horizontally and vertically.

Remedial Planning

Remedial planning and design took place almost contemporaneously, as new information became available. Planning required close interaction and coordination among FDOT, FDEP, Broward County Office of Natural Resource Protection, SFWMD, city of Fort Lauderdale, general contractor, and FDOT statewide environmental consultant performing all assessment and remediation activities. The following issues were considered:

- Timing of the construction operations,
- Coordination of highway construction efforts,
- Coordination with FDOT,
- Regulatory issues,
- Space constraints and site construction features,
- Traffic control,

- Ability to treat the plume effectively, and
- Discharge of the treated water on site.

A groundwater treatment system using conventional technologies to treat the contaminant levels found at the site would have taken 3 to 10 years to achieve "clean" conditions. Cooperation among FDOT, FDEP, and SFWMD was essential to accomplish a cleanup that satisfied each agency's rules and regulations. Because of the limited time frame available for remedial action to be implemented before construction, no time was available for normal regulatory review and approval, which routinely takes 12 to 18 months. Meetings were held frequently so that all agencies were informed about the selected remedial system. Key among the meetings were the brainstorming sessions held with all parties. These meetings were focused to address time constraints, parameters for technology implementation, consideration of specific technologies, and technology selection.

Technology selection considered the complex regulatory framework and FDOT's needs, addressing the following regulatory and technical issues:

- Regulatory:
  –Permitting,
  –Technology effectiveness,
  –EDI reimbursement eligibility, and
  –Monitoring requirements.
- Technical:
  –Performance,
  –Reliability,
  –Cost, and
  –Schedule.

The technologies considered at the brainstorming sessions included the following:

- Recovery:
  –Vertical wells, and
  –Horizontal drains.
- Treatment:
  –Carbon adsorption,
  –Air stripping,
  –Sparging,
  –Soil venting,
  –Soil washing,
  –Excavation/thermal treatment, and
  –Bioremediation.
- Discharge/disposal:
  –Sanitary sewer publicly owned treatment works,
  –Storm sewer,
  –On-site percolation, and
  –Deep well injection.

The remediation technologies selected for the different elements of work were as follows:

- Remedial element:
  –Groundwater recovery,
  –Groundwater treatment, and
  –Discharge.
- Selected technology:
  –Horizontal drains and deep vertical wells;
  –Clarification, filtration, and carbon adsorption; and
  –Surface infiltration.

A process layout is presented is presented in Figure 4.

Remedial Design

Groundwater Recovery

It was determined during remedial planning and subsequent groundwater modeling that a principal element of timely remediation would be to effect high rates of groundwater recovery. The desired groundwater recovery rate was determined to be about 3785 L/min (lpm) [1,000 gal/min (gpm)], with 2650 lpm (700 gpm) out of six horizontal drains and 1135 lpm (300 gpm) out of deep vertical recovery wells.

The six horizontal drains consisted of corrugated, perforated PVC pipes, 40 to 60 m (130 to 200 ft) long and 12.7 cm (5 in.) in diameter. The specific discharge capacity of these drains was estimated to be 3.4 lpm (0.90 gpm) per foot of pipe. The horizontal drains were installed typically at 4.88 to 5.49 m (16 to 18 ft) below land surface (BLS) using a pipe trencher. The trencher was configured to excavate the trench, place the pipe, and backfill the trench in a single operation. The corrugated pipe was fitted with continuous geotextile filter fabric cover to filter out fine sand particles.

Five vertical recovery wells were used (three operating at a time) to recover deeper elements of the plume of contaminated groundwater. These deep wells were 20.3 cm (8 in.) in diameter and screened from 1.53 to 10.68 m (5 to 35 ft) BLS and from 6.10 to 15.25 m (20 to 50 ft) BLS near the middle of the plume. The location of the screened interval was based on the depth of the plume being captured. The vertical wells were capable of producing 378.5 lpm (100 gpm) each.

Groundwater Treatment

A process flow diagram representative of the groundwater treatment system is shown in Figure 5. Because of the range of contaminant concentrations expected at the site and the presence of sands and fines accumulated through the horizontal drain recovery system, a system employing filtration and carbon adsorption treatment was selected and designed. The system features are described in the following sections.

Filtration The recovered groundwater was pumped from the drains or wells through a filtration system to remove suspended solids. The system consisted of a clarifier to remove the larger particles followed by bag filters to remove the fine particles (>50μm). The bag filters were numbered and sized to allow their replacement without interrupting system operation.

Carbon Adsorption The groundwater was then passed through a granular activated carbon (GAC) system. The system consisted of two parallel banks of dual 4540-kg (10,000-lb) carbon adsorbers 2.29 m (7.5 ft) in diameter operated in series. With this configuration, each parallel GAC train had a bed carbon adsorber and polishing filter. A third parallel carbon filtration system was installed that had a 6356-kg (14,000-lb) lead unit and a 4086-kg (9,000-lb) polishing cell. The empty bed contract times (EBCTs) for the two trains with 4540-kg (10,000-lb) units was 8.7-min at 1135.5 lpm (300 gpm) per cell, or a total of 17.4 min. The 6356-kg (14,000-lb) carbon column had an EBCT of 9.3 min with 1514.0 lpm (400 gpm). The 4086-kg (9,000-lb) column had an EBCT of 5.8 min. This train had a total EBCT of 15 min.

Infiltration A portion of the treated effluent was routed back over the site in designated areas to flush the vadose zone soils.

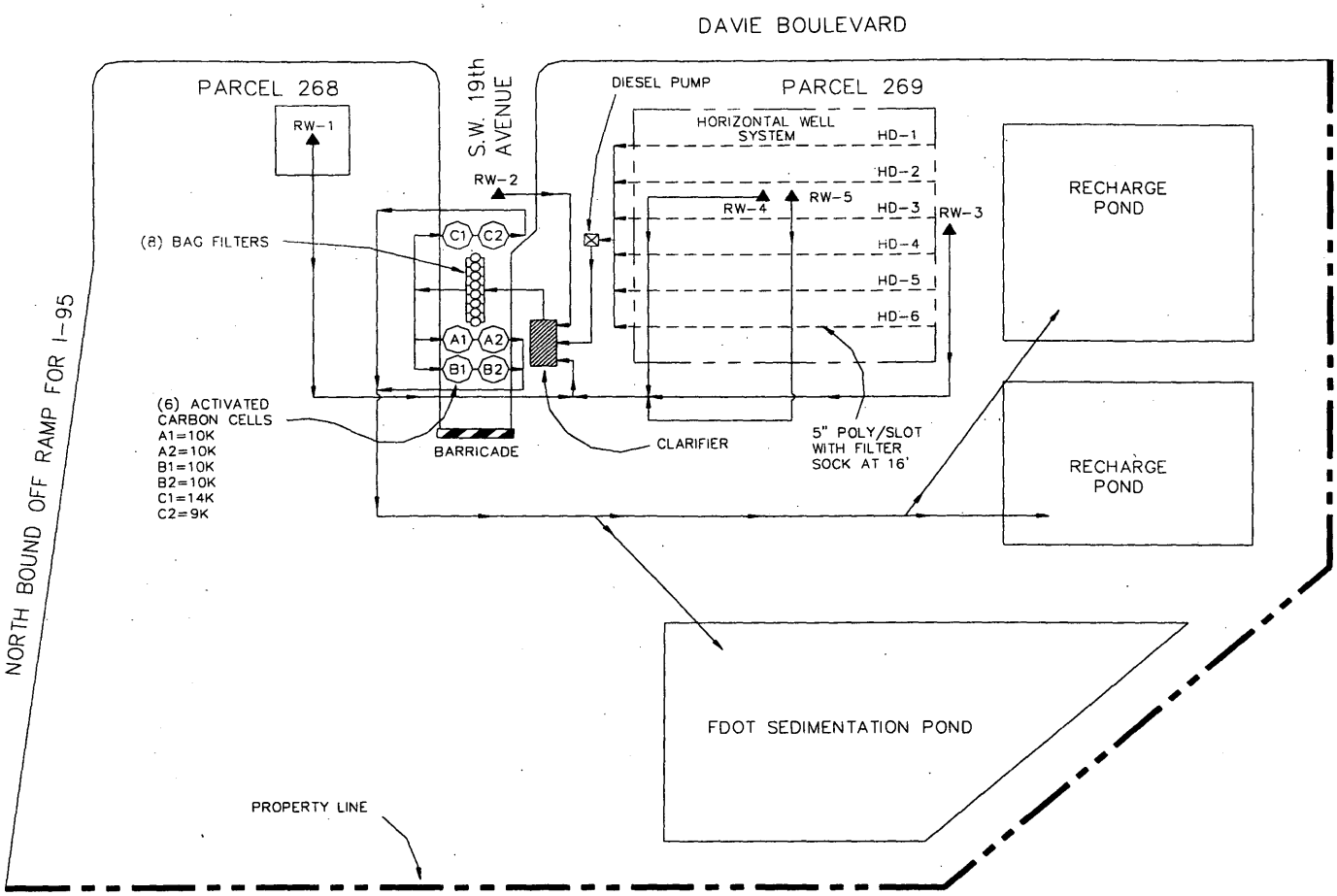

FIGURE 4 Process layout.

Treated Water Discharge

The effluent from the groundwater treatment system was discharged into three recharge ponds having a total area of 3380.55 m^2 (0.336 ha) [36,350 ft^2 (0.83 acre)]. Additionally, five horizontal perforated PVC pipes, paralleling the drain pipes, were installed above the horizontal underdrains at a depth of approximately 5 ft to discharge treated effluent.

Design provided that the ponds would be rotated in operation—that is, one pond would receive treatment system effluent while the other two rested. The discharge of treatment system effluent was theorized to aid in the remediation of overlying soils through flushing with clean water and also in groundwater capture by providing a hydraulic mounding effect to the groundwater plume. The mounding effect would exert a hydraulic pressure on the plume to move it to the horizontal drains and vertical wells to enhance capture.

REMEDIAL ACTION DESCRIPTION

Overview

Remedial action began before the RAP was approved: remediation began in December 1991, and the RAP for the site was not submitted for regulatory review until March 1992. The authority for this action was granted by FDOT, which did this at some risk to reimbursement eligibility. However, the risk was minimal because of the frequent communication and coordination with FDEP, where each step was discussed before implementation and after receiving oral agreements as the project developed.

The remediation system was operated from mid-December 1991 until mid-February 1992. With the exception of brief periods of downtime for holidays or maintenance, the system was in operation 24 hr/day, 7 days a week. Pulse or cyclic pumping was employed to enhance removal rates. Periodically, the system was shut down to reestablish the static groundwater level. This action served to flush contamination from the soil in the zone between the static and drawn-down water levels. Most maintenance activities were conducted during these shutdowns.

Site Preparation

The site required clearing, grubbing, and grading to accommodate the installation of the horizontal drains as well as other facets of the treatment system. Site preparation activities were coordinated to maintain traffic control around the site. An added benefit of this site preparation was that it could be removed from the construction contract since the site would be turned over to construction in a ready-to-build state.

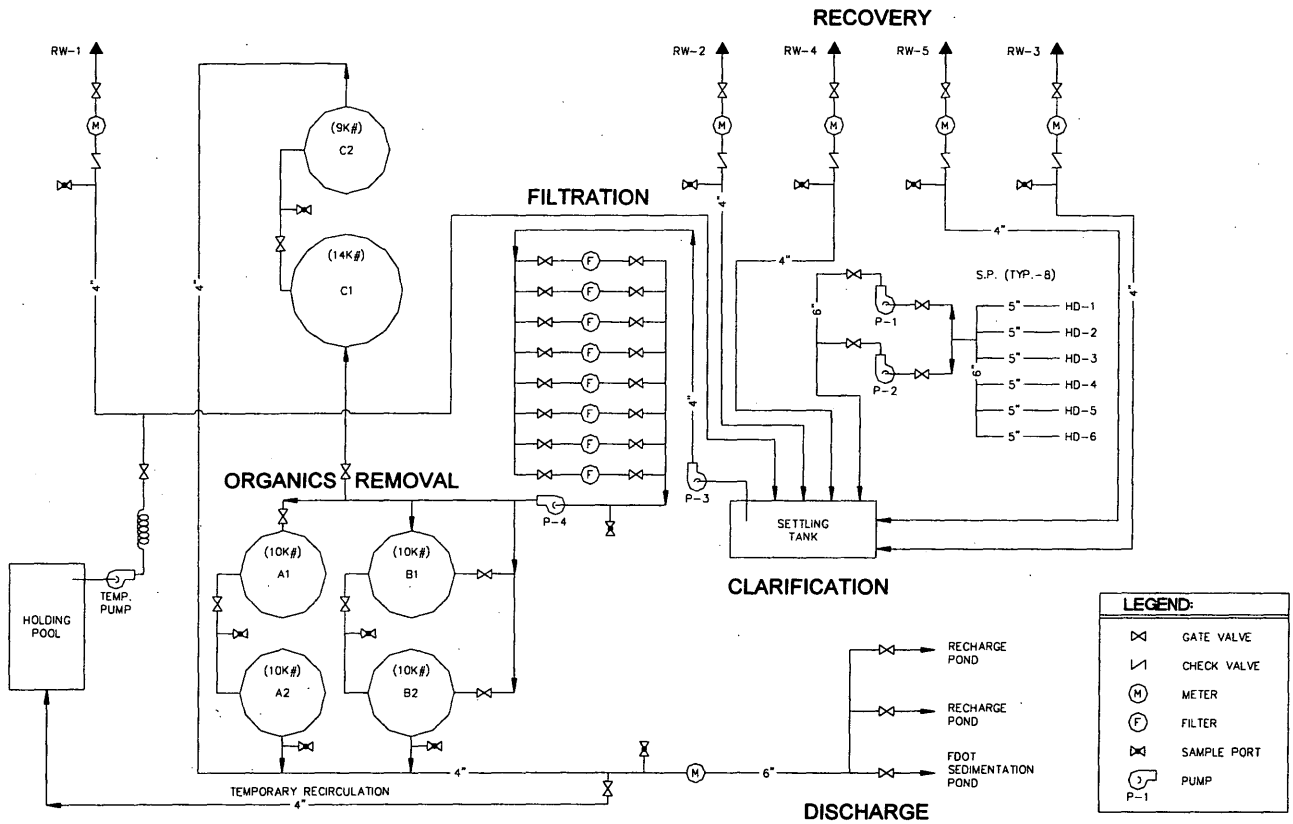

FIGURE 5 Process flow.

Groundwater Extraction

The groundwater extraction system consisted of deep vertical extraction wells and shallow horizontal drains. The application of horizontal drains in such a remedial action is unique in Florida and other locations with similar hydrogeologic parameters. Using horizontal drains as the primary technology for groundwater extraction at this scale is also unique.

The system generally performed as expected, recovering approximately 132 475 000 L (35,000,000 gal) from the site over 90 days. The average recovery rate at the site was approximately 3785 lpm (1,000 gpm), and the area of influence and rates of recovery were consistent with the remedial design.

Groundwater Treatment

In the early stages of treatment system operation, the bag filters repeatedly clogged with fine sand and silt particles. The filter fabric covering on the horizontal drains allowed passage of some fine particles. To limit this problem, a primary settling tank/clarifier was added to the system. Settling out the fine sands and silt resulted in a dramatic decrease in solids loading on the bag filters. This solution enabled the system to operate for longer periods without maintenance.

The treatment system, set up as designed and modified, operated efficiently. Throughout the treatment period, analytical monitoring (both on-and off-site) showed no treated effluent discharge above required regulatory discharge levels [1 part per billion (ppb) benzene and 50 ppb total volatile organic aromatics (VOAs)].

Monitoring Program

A field laboratory was established to expedite sample analysis. The laboratory included a bench-top gas chromatograph (GC) to meet the parameters established in Environmental Protection Agency Method 602 analysis inclusive of quality assurance/quality control. This unit was used at the site to analyze samples of influent and effluent and run spot checks on system performance. The sampling and analysis program was designed and implemented in compliance with quality assurance and system requirements and the brainstorming meetings with the regulatory agencies, as follows:

- One sample was collected from influent, intermediate (between the primary unit and polishing cell), and effluent every hour for the first 8 hr;
- One sample was collected from influent, intermediate, and effluent every 4 hr for the next 16 hr; and
- One sample was collected from influent, intermediate, and effluent every 8 hr thereafter.

Samples from monitoring wells and other points of interest were collected and analyzed daily to assess the conditions of the plume distribution. After periods of rainfall, elevated contaminant levels were noted in the influent and most of the monitoring wells around the center of the plume at the site. These anomalous readings were attributed to desorption of contaminants from the vadose zone soil matrix by infiltration of rainfall. When this phenomenon was discovered, it was decided that the treated effluent would be reapplied to the site by horizontal drains to flush the soil. Extreme care was taken to monitor the loading rate to ensure that the plume was not

pushed to uncontaminated areas. The GC was used to analyze real-time samples, providing the flexibility to make real-time adjustments to maximize the efficiency of the system in recovering and treating groundwater.

Treated Water Discharge

Multiple retention ponds were built to accommodate effluent from the treatment system. The surface area of these ponds was 3380.55 m^2 (36,350 ft^2). It was determined that one of the retention ponds planned as part of the roadway construction project (to be constructed after remediation by the general contractor) could be used in the remediation process. Therefore, the remedial contractor built the pond early for use during remediation and left it as a permanent feature, expediting the construction schedule.

The ponds were used to control the plume and facilitate mounding to expedite remediation. Mounding caused by infiltration through the retention ponds was established by design and served to intensify the gradient pushing the plume of petroleum-affected groundwater toward the recovery system.

The mounding effect, demonstrated through the rotating use of the three pond areas, was evaluated through the monitoring program to have the desired effect of pushing the contaminant plume to the recovery system, thus shortening the time to capture the plume using normal infiltration techniques.

Further, the monitoring program demonstrated that the soil flushing achieved through use of the horizontal drains for discharging treated groundwater within the plume of contamination was effective by eliminating the "rebound effect" experienced in most pump and treat sites.

The infiltration rates ranged from 50 to 75 percent of the removal rate—that is, when 1,000 gpm was removed, 500 to 750 gpm was discharged to the horizontal drains for soil flushing with the remaining 500 to 250 gpm discharged to the ponds for mounding effects. Treated water was never discharged off-site.

Site Restoration

Because the site would ultimately support highway-related structures [a reinforced earth embankment, 7.63 to 9.15 m (25 to 30 ft) high], the principal element of site restoration activities was the compaction of soils affected by the remedial action to state construction compaction standards. After the remedial activities, the remedial contractor backfilled the site in accordance with FDOT compaction requirements for structural fill. Compacted fill was placed atop the lateral drains, which were to remain in place following construction, and compacted backfill was placed above the rest of the collection and distribution piping associated with the treatment system.

When remedial activities were finished, all equipment was removed from the site, which was then graded to a generally level surface.

Community Relations

Because the site is so close to residential communities, several steps were taken to ensure minimal intrusion and safety for the residents; they included

- Procurement and use of ultra-quiet generators,
- Erection of protective fencing,
- Construction of sound barriers,
- Use of the city of Fort Lauderdale police force for security, and
- Observation of holidays to avoid disrupting the residents.

RESULTS

Site Rehabilitation Completion Levels

Groundwater remediation was effective at the site, removing more than 99 percent of the benzene and 95 percent of the total volatile organic aromatics (VOAs). The graphs in Figures 6 and 7 are examples of the reduction of contaminant levels over the 3-month course of the remediation.

The contaminant reduction is also demonstrated by the groundwater data presented in Table 1. Total VOA levels in all wells at the site decreased dramatically during the period of active remediation. Total VOA levels remained slightly elevated in MW-1, MW-2, and MW-13 (MW-13 was located in the center of highest original con-

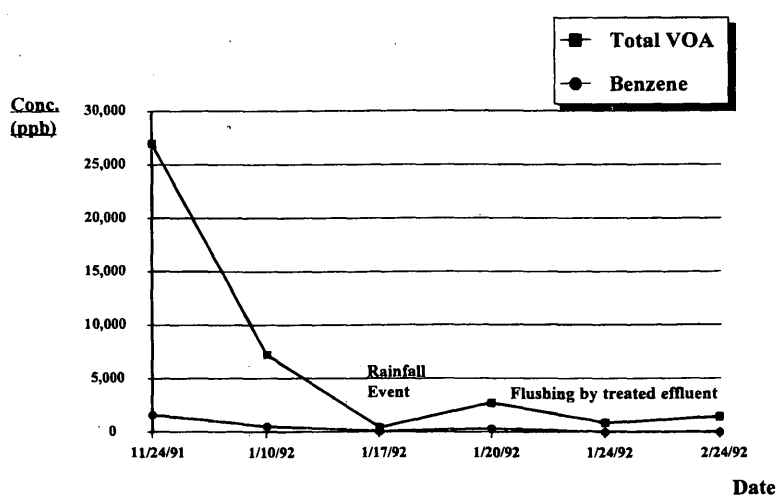

FIGURE 6 Contaminant concentrations in MW-1.

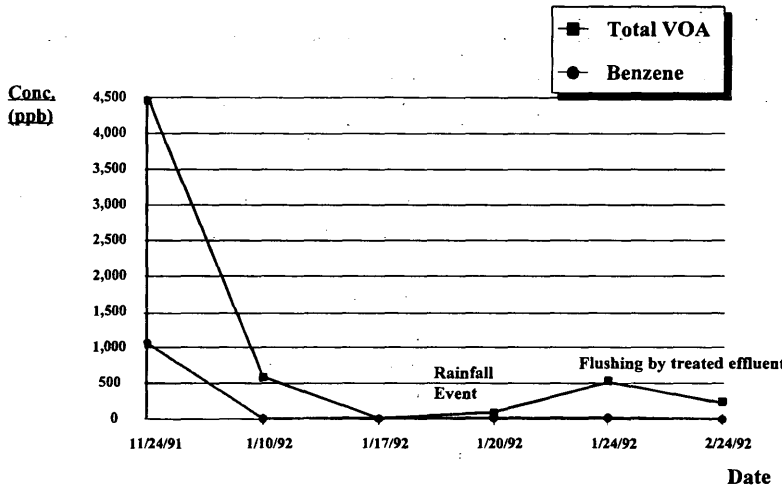

FIGURE 7 Contaminant concentrations in MW-2.

taminant concentrations). The treatment system reduced benzene concentrations from a preremediation maximum of 1,600 ppb to a postremediation maximum of 10 ppb, a reduction of 99.6 percent. Total VOAs were reduced from a preremediation maximum of 27,000 ppb to a post/remediation maximum of 1,429 ppb, a reduction of 95 percent.

In many conventional pump and treat operations, there is a rebound effect due to the interaction of the recovered water table and vadose zone soil contamination. This effect is believed to have been limited at this site by the thorough flushing of vadose zone soils during remediation with treated groundwater in areas of higher concentrations.

TABLE 1 Summary of Remedial System Performance

Well No.	Benzene (ppb)		Total VOA (ppb)	
	11/91	2/24/92	11/91	2/24/92
MW-1	1,600	<5	27,000	1,429
MW-2	1,040	<1	4,450	240
MW-3	2,700	9.3	17,500	84.2
MW-4	---*	---	---	7.1
MW-5	233	<1	484.2	7.2
MW-7	<1	<1	---	---
MW-8	---	---	---	3.2
MW-9S	72.3	10	79.1	22.5
MW-9D	5.1	<1	5.1	<50
MW-13	5	<1	510	136
MW-14	<1	<1	<50	<50
MW-17	1,800	<1	2,522	46.2
MW-18	1,700	<1	4,781	<50
MW-19	13	<1	92.8	<50
MW-20	58	<1	17.1	<50
MW-21	84	<1	35.5	<50
MW-22	330	<1	1,362	<50
MW-23	1,800	<1	6,102	<50
MW-24	430	<1	1,081	<50
Regulatory Clean-up Standards	1 ppb	1 ppb	50 ppb	50 ppb

Note: --- indicates no sample collected

TABLE 2 Cost Comparison and Alternative Evaluation

As Performed		Alternative	
Actual Cost (1)	$750,107.52	Acquire new right-of-way (2,3) 30,000 SF @ $5/SF	$150,000.00
		Administrative Costs for Acquisition (4)	$150,000.00
		Delay to Project to accomplish acquisition 4 months (120 days) @ $25,000/day (5)	$3,000,000.00 (Maximum)
		Requirement to remediate previously purchased parcels (6)	$741,702.00
Reimbursable amount through MOU	$(750,107.52) (7)	Reimbursable amount through MOU	$(741,702.00) (7)
Total actual cost to the Department	$0.00	Total actual cost to the Department	$3,300,000.00

Footnotes:

1) From FDOT's reimbursement request submitted to FDEP.
2) Area defined as needed to accommodate retention pond.
3) Real estate pricing for nearby properties acquired by the Department.
4) Administrative costs for acquisition and re-design costs.
5) Time and delay charges due to the time required to acquire the alternative location.
6) With the alternative location, the Department would still be required to remediate the project. Average cost for petroleum contaminated sites has been $250,000 according to FDEP sources. Assumed $500,000 average cost for two sites with co-mingled plumes and then converted this cost to present worth value to allow proper comparison. Assumptions made include 12% time value of money and seven year clean-up program (estimated routine clean-up would require 3 to 10 years).
7) Actual remediation costs for both the actual performance and the alternative would be reimbursable thorough the MOU between FDOT and FDEP.

Costs and Evaluation of Alternative Solutions

Alternative solutions were limited because the project had been awarded and the general contractor had begun his purchasing, planning, fabrication, and other mobilization activities. Damages due to delays to the $83 million project were established at $25,000/day, and the use of the proposed storm water retention pond was a critical path task on the project schedule.

The two best options available to the department were to relocate the retention pond to a separate, uncontaminated area of the project and to remediate the known contaminated site in a manner so as to minimize any delay to the project. The department chose the latter as the most viable.

Table 2 includes a cost analysis that provides an evaluation of the two alternatives. The actual costs to perform the project were $750,107.52, which is expected to be reimbursed to FDOT through the Inland Protection Trust Fund as allowed under the MOU between FDOT and FDEP.

The alternative solution to relocate the pond would have required the department to acquire new right of way and provide the necessary administrative services in order to accommodate the proposed retention pond and redesign drawings to accommodate the relocated pond. Because FDOT had already acquired the original site of the retention pond, it would still be required to remediate the site; however, this cost would be reimbursable through the MOU. Table 2 provides the estimated costs for the alternative, including the estimated delay that the project would have incurred.

After comparing the two alternatives, it is evident that FDOT's expedition of the remedial action saved the taxpayers approximately $3,300,000. In addition, recognizing the time value of money and comparing the cleanup costs on present-worth value, the cost alone to expedite the cleanup is virtually equal to what the de-

partment would have spent on a routine cleanup over the assumed 7-year period. These factors show that the alternative chosen was the most cost-effective option available to the department.

Related Construction Activities

The construction of the Davie Boulevard overpass over I-95 has progressed. The former remediation site is covered with an embankment 7.63 to 9.15 m (25 to 30 ft) high, and the storm water retention pond is in use. Following completion of the remedial activities, an SRCR was presented to FDEP. The SRCR included the following key points:

- No potable supply wells were present within 0.40 km (0.25 mi) of the site.
- Biological agents and dilution factors are expected to effectively mitigate the localized areas of VOA and benzene concentrations remaining above target levels of 1 ppb for benzene and 50 ppb for VOAs.
- The proposed construction of the 7.63- to 9.15-m (25- to 30-ft) embankment and the addition of impervious surface area (travel lanes) would make the site inaccessible for further remediation.
- Linear regression analyses results were within the range of acceptable correlation, indicating that the concentrations were decreasing asymptotically.

FDOT and FDEP have agreed to implement a 1-year postremediation monitoring plan at the site. Because of current construction activities within this area, the monitoring plan has not yet been implemented.

LESSONS LEARNED

To expedite a remedial action such as that described in this case history, the following elements must be addressed:

- A method of soil flushing within the vadose zone must be implemented to minimize the rebound effect typical of most pump and treat remedial operations.
- Given an expedited construction schedule and defined budget, it is imperative that there be frequent and thorough coordination among the regulatory agencies, contracting agency or client, remedial contractor or consultants, and other participating entities. This project demonstrates that up-front planning meetings are essential to developing mutually agreeable remedial objectives and strategies.
- Because of the close and intense coordination required, each participant should have one point of contact.

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Soil Gas Sampling and Analysis in Petroleum-Contaminated Transportation Department Right of Way

DAVID W. OSTENDORF, ALAN J. LUTENEGGER, AND SAMUEL J. POLLOCK

The lateral distribution, approximate composition, and aerobic biodegradation potential of vapors from a petroleum hydrocarbon spill in a Massachusetts Highway Department right of way was inferred from soil gas sampling technology and analyses. Stainless steel vapor probes were driven into the heterogeneous, nonuniform, contaminated sand of the right of way by a drill rig–mounted hammer. Stainless steel tubing clusters with sintered stainless steel filters were installed at selected locations in the right of way as well. A metered vacuum pump transferred soil gas from the probes and clusters into Tedlar bags for on-site analysis by a combustible hydrocarbon meter, an oxygen analyzer, and a portable gas chromatograph. Floating product from existing monitoring wells was brought to the laboratory for headspace analysis by gas chromatograph/mass spectrometer to identify the hydrocarbon vapor constituents and estimate the saturated vapor pressure. This headspace sample was used to calibrate the portable gas chromatograph and integrate the meter readings and chromatograms into a common hydrocarbon data base used to delineate the horizontal extent of the petroleum spill. The observed oxygen levels were input to a simple coupled transport model that confirmed the aerobic biodegradation potential of naturally occurring microbes in the site soil.

University of Massachusetts (UMASS) and Massachusetts Highway Department (MHD) researchers used soil gas sampling technology and analysis to estimate the lateral distribution, approximate composition, and aerobic biodegradation potential of petroleum hydrocarbon vapors from leaking storage tanks. The spill was in the right of way of State Route 128/Interstate 95 in Lexington, Massachusetts, about 600 m upgradient from a reservoir in the capillary fringe of the unconfined aquifer about 2.5 m below the ground surface.

SOIL GAS SAMPLING TECHNOLOGY

Soil gas sampling has proved to be a useful means of delineating the areal extent of gasoline (*1*), diesel fuel (*2*), heating oil (*3*), and other light petroleum distillate spills beneath the ground surface. These immiscible hydrocarbons are lighter than water and so spread out over the water table. Evaporation is a preferential transport mechanism because the contaminants are volatile, giving rise to elevated concentrations of hydrocarbon vapors in the soil gas above the separate phase hydrocarbons. Thus, soil gas surveys may be used to delineate the separate phase source of petroleum contamination.

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Soil gas sampling works best in dry, coarse-grained soils with low organic carbon content (*4*). Infiltrating water, perched water tables, low-permeability lenses, barometric pressure fluctuations, lower soil temperatures, and biodegradation can all significantly reduce hydrocarbon vapor concentrations with increasing distance from the separate phase source. The infiltrating water, barometric pressure, and soil temperature effects are transient and can introduce seasonal or diurnal variations in gaseous contamination (*1,5*), so that frequent sampling from a permanent soil gas monitoring point is needed for a quantitative measure of contamination. Aerobic biodegradation of hydrocarbon vapors consumes oxygen (*6*) and generates carbon dioxide (*7*), whereas anaerobic degradation creates methane gas (*8*). The correlation of these constituents with an inert tracer gas is used to assess the biodegradation potential of petroleum spills in the subsurface environment (*9,10*).

A suite of increasingly sophisticated technologies is available for sampling and analyzing soil gas. Probes as simple as a 1.3-cm-diameter stainless steel tube tipped with a loose carriage bolt (*11*) or a drive point (*1*) have been deployed successfully in the field, as have more elaborate 2.0-cm-diameter stainless steel systems with side ports (*12*) or retractable shields (*13*). The driving force may be a manual or handheld electric hammer (*11,12*), truck-mounted piston (*14*), or a drill rig–mounted hammer, depending on the type of soil and sampling depth. Shields or filter elements may be required for finer-grained soils to prevent clogging of ports. Soil gas is pulled from the probes through stainless steel or flexible tubing to the ground surface by manual (*12*) or electric vacuum sampling pumps, where it can be trapped for subsequent laboratory analysis (*15*), subsampled by syringes (*12*), or fed directly into field meters (*11*). Organic vapor analyzers with built-in vacuum pumps and catalytic combustion chambers are used to measure total hydrocarbon vapor pressures, whereas potentiometric cells and infrared absorption sensors also see widespread use for detecting oxygen and carbon dioxide content, respectively. Tedlar bag dilution may be needed for field meter readings of highly contaminated soil gas (*16*). Petroleum distillates are blends of many hydrocarbon compounds with varying saturated vapor pressures, solubilities, and biodegradation potentials (*17*), and a catalytic combustion chamber does not differentiate constituents. Soil gas consequently is analyzed by direct injection or trap desorption into portable or mobile gas chromatographs to elucidate its hydrocarbon composition.

Elements of this existing technology were incorporated into the present study, which featured new developments as well. Durable vapor probes of simple design and rugged construction were designed and fabricated by UMASS investigators for deployment with electric and rig-driven hammers into relatively dense soil. Commercially available soil gas meters were used with a field gas

chromatograph and a laboratory gas chromatograph/mass spectrometer (gc/ms) analysis to yield calibrated estimates of total hydrocarbon vapor pressures. These data were combined with oxygen measurements in a coupled mathematical analysis of natural biodegradation in the unsaturated zone as an assessment of remediation potential at the site.

SITE CHARACTERIZATION

The study site is the parking lot of a service area (Figure 1), located on SR-128/I-95 northbound in Lexington and owned by MHD. More than 160,000 vehicles a day travel SR-128/I-95 in Lexington on six lanes of traffic. The highway borders an ephemeral stream that flows about 600 m south to a reservoir that serves as a surface drinking water source. An access road runs between the northbound travel lanes and the service area, and a grass strip separates this access road from the parking lot. The grass strip forms the downgradient boundary of the study area. The site is underlain by crystalline bedrock about 8.5 m below the ground surface, with a westward sloping water table that varies seasonally from 2 to 3 m below the ground surface.

UMASS efforts focused on the unsaturated zone, which consists of heterogeneous, nonuniform sands with considerable fine and gravel fractions. An array of Omega thermocouple leads was installed on 15.2-cm intervals tied to a PVC riser pipe installed down a borehole in the grass strip to measure soil temperature, T (Figure 1). The leads were read with an Omega Model HH21 handheld thermometer; depth-averaged temperatures of 281.0 and 282.2°K were read on December 28, 1993, and May 13, 1994, respectively. Gravimetric moisture contents were measured in soil borings taken by UMASS during drilling operations in July 1993; data below the water table implied an average volumetric porosity of 0.37, and near surface observations suggested an irreducible moisture content of 0.079. Thus the depth-averaged air porosity θ_A was 0.291.

The service area began operation as a restaurant with a gasoline and diesel filling station in 1954 (*18*), coincident with completion of road improvements to its present configuration. The complex is serviced by municipal water, sewer, and electrical utilities and is heated by fuel oil. The original service area included single-walled steel underground tanks for storing gasoline (seven tanks), diesel fuel (two tanks), heating oil (one tank), and waste oil (one tank), with approximate locations shown in Figure 1 (*bottom*). MHD engineers conducted an environmental site assessment in 1987 (*19*) and found liquid petroleum in two of four monitoring wells. All 11 original tanks were pulled in 1988 and replaced with new double-walled steel underground storage tanks for gasoline and diesel fuel and an above-ground heating oil tank [Figure 1 (*bottom*)]. MHD engineers installed 21 additional monitoring wells and 3 product recovery wells as part of a remediation system that operated from 1988 to 1991 (*20*). Separate phase petroleum hydrocarbons persisted in five of the monitoring wells, with episodic occurrences in two others. Spill masses were found under the service area parking lot and under the access road. The oil recovery system removed 1.93 m^3 of separate phase petroleum until its closure in June 1991 due in part to biofouling and corrosion (*21*). UMASS gauging in June 1994 confirmed persistent separate phase contamination in the five wells: three under the access road spill and two under the parking lot spill. The latter contamination is the focus of this paper.

SAMPLING AND ANALYTICAL METHODS

UMASS researchers mapped the lateral extent of total hydrocarbon and oxygen vapor pressures in the service area parking lot with stainless steel vapor probes on field trips in December 1993 and June 1994. Two different probes were designed, fabricated, and deployed by UMASS personnel (Figure 2). A 140-lb SPT rig-mounted safety hammer drove a retractable probe of 3.82-cm diameter with a 5.09-cm-diameter friction reducer and a flush-mounted shield through dirtier, more compacted soils to a depth of nearly 3 m. Cleaner, compacted soils were sampled successfully to a similar depth by a rig-driven probe equipped with a high-density polyethylene filter in place of the retractable sleeve. Both probes admitted soil gas through four 3.18-mm-diameter ports to a plenum connected to flexible Nalgene tubing routed to the surface through the rod annulus. A generator powered, Cole Parmer Model 7530-40 single-head diaphragm vacuum pump equipped with a water trap and Cole Parmer 0-5 L/min adjustable flow meter pulled soil gas to the surface. Larger 6.36-mm-diameter tubing and a 1-L purge volume were used in winter sampling to minimize vacuum-induced icing, and 3.18-mm-diameter tubing was used in spring sampling to minimize purging requirements. A 6.36-mm-diameter Nalgene line transferred 2 L of soil gas to Tedlar bags. A drop in gas flow registered by the flow meter signaled the onset of water clogging drawn from the capillary fringe and effectively stopped profiling at a given location.

The total hydrocarbon vapor pressure was measured by connecting the Tedlar bag to a battery-powered Bacharach TLV combustible hydrocarbon meter calibrated with hexane to a vapor pressure, p_V, of 500 parts per million (ppm). The meter had three scales to a maximum capacity of 10,000 ppm. A 2-L/min pump built into the meter pulled gas from the Tedlar bag through the inline filter into a catalytic combustion chamber for destructive sampling of the flow. The catalytic combustion required sufficient oxygen for meter accuracy, so that pressures were underpredicted for oxygen vapor pressures (p_{VO}) below 5 percent. Relative humidity and, to some extent, molecular weight of the hydrocarbons may have also introduced error into the readings (*16*). The oxygen partial pressure of the soil gas in the Tedlar bag was measured by a Bacharach Model 302 meter equipped with a potentiometric cell and a 2-L/min pump. The meter was calibrated with ambient air (presumed to be 20.9 percent oxygen) before and after each reading. A few heavily contaminated, low oxygen samples were diluted by injecting 0.50 L of soil gas into a second Tedlar bag, to which 1.5 L of compressed air was added (*1,16*). Thirty-nine depths at 8 paved locations were profiled using the drill rig on December 28, 1993, and 159 depths were sampled with the rig at 15 paved locations June 1–3, 1994.

Soil gas tubing clusters were installed in 19 boreholes drilled by 11.5-cm-diameter hollow-stem augers during field trips in October 1993, December 1993, and June 1994. The clusters consisted of 6.36-mm-diameter steel tubing cut in 0.50- or 1-m intervals to depths as great as 3 m (Figure 3). The tube ends were capped with 40-μm sintered stainless steel filters and set in a 2-mm-diameter sand pack with the augers raised slightly. Cuttings were backfilled into the borehole as the flight was pulled to the next cluster depth. Up to six tubes were emplaced in each cluster, which was finished with a cast iron cover set in concrete. The top of each tube was coupled to a Swagelok fitting to facilitate soil gas sampling. The Tedlar bag protocol was followed in the latter regard, with a Swagelok-equipped Nalgene transfer line coupling the cluster tube to the vacuum pump.

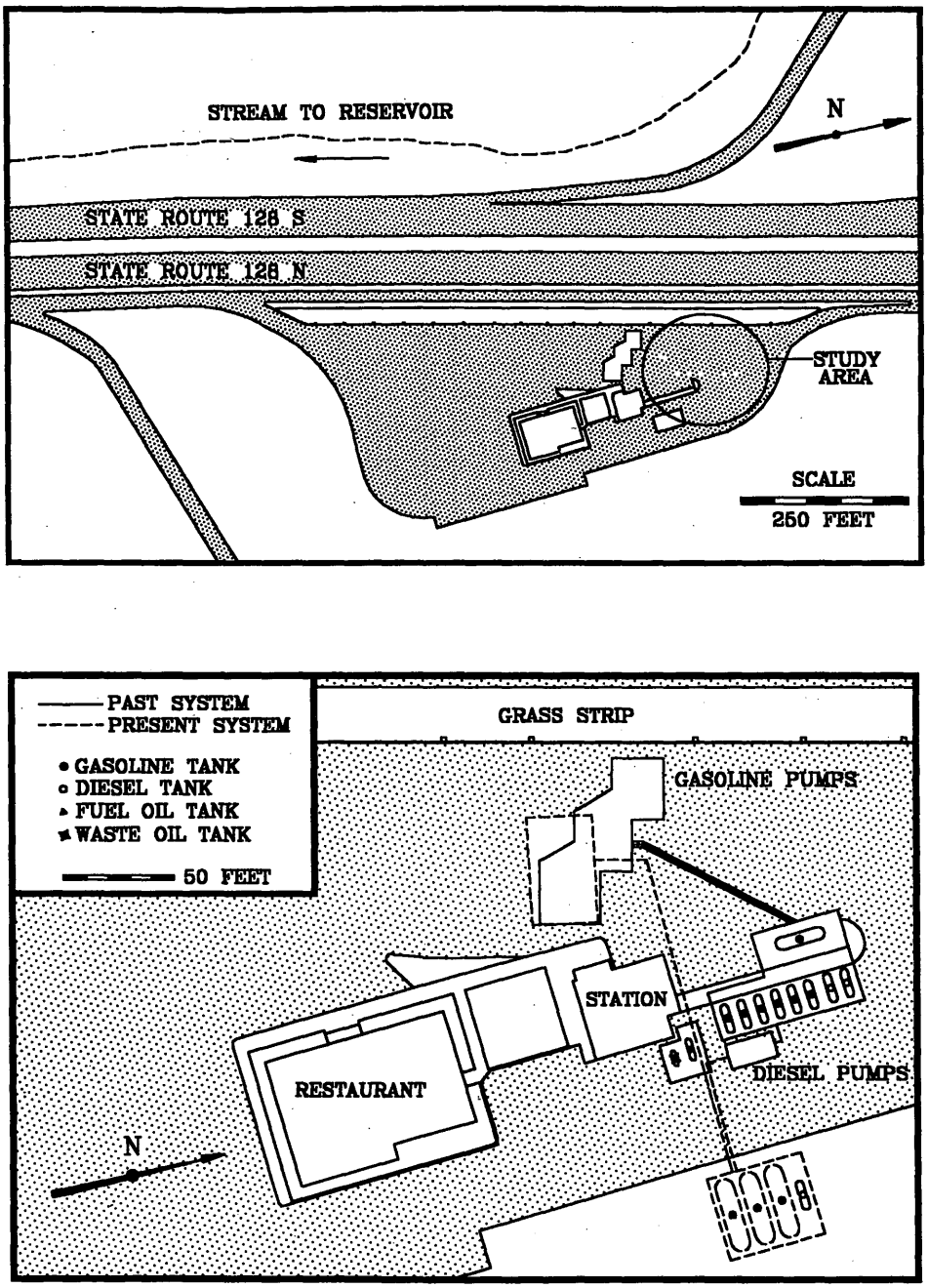

FIGURE 1 Location sketch: *top*, SR-128/I-95; *bottom*, service area.

Selected Tedlar bag samples were analyzed by gas chromatograph as well. A 250-μL Hamilton Gastight syringe with a 26-gauge bevel-tipped needle withdrew soil gas from the Tedlar bag for subsequent direct injection into an HNU System Model 311 portable gas chromatograph, equipped with a DB-5 capillary column of 0.53-mm diameter, 30-m length, and 0.5-μm film thickness. The injector and column temperatures were 200 and 50°C, respectively, and a 10-mL/min flow of research grade nitrogen carried the injection from the column to a 10.2 eV photoionization detector. The data were captured on HNU Peakworks software. Separate phase petroleum sampled from one of the MHD monitoring wells in May 1993 served as a standard for analysis. The standard was allowed to equilibrate with headspace in a 40-mL sample vial sealed with a Teflon-faced silicone septum.

APPROXIMATE COMPOSITION OF HYDROCARBON VAPORS

An analysis was performed on the UMASS Hewlett Packard 5898/5890 gc/ms to identify compounds and estimate the (saturated) vapor pressure of the headspace standard. Table 1 gives the 27 compounds in the headspace, obtained by matching observed electron impact spectra sensed by the gc/ms with library spectra.

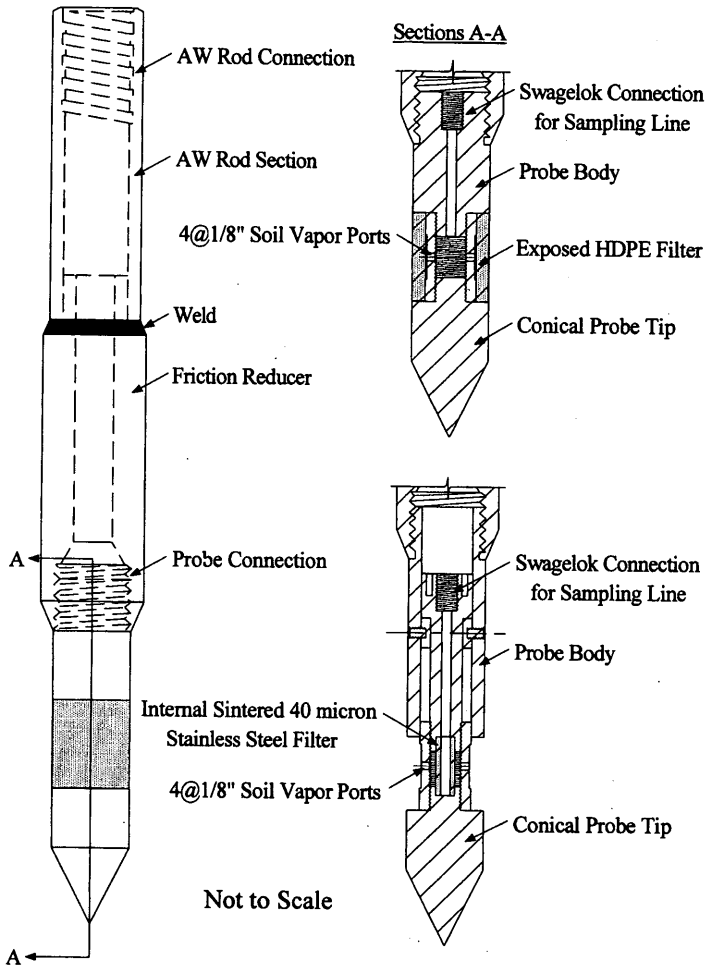

FIGURE 2 Stainless steel soil vapor probes with friction reducer and AW drill rod: *top*, HDPE filter probe; *bottom*, retractable probe with shield.

The vapors consisted primarily (93.7 percent) of alkanes with a small (6.3 percent) aromatic fraction. The most abundant compounds were 2 methylpentane (13.8 percent of the chromatographic area) and hexane (12.2 percent of the area). This composition was used to estimate the saturated vapor pressure of the standard, so that total hydrocarbon vapor pressures could be inferred from the chromatograms of the portable gc.

The saturated vapor pressure p_{VS} of the headspace is the sum of saturated partial pressures p_{VSI} of all the hydrocarbon constituents in equilibrium with the liquid petroleum in the sample vial

$$p_{VS} = \sum_I p_{VSI} \tag{1a}$$

$$p_{VSI} = p_{VSATI}\chi_I \tag{1b}$$

Equation 1b is Raoult's law (*22*) equating each compound's saturated partial pressure to the product of its mole fraction in the liquid petroleum in the sample vial χ_I and its saturated vapor pressure p_{VSATI} in equilibrium with pure liquid. Reid et al. (*23*) present an empirical equation for the latter parameter,

$$p_{VSATI} = p_C \exp\left(\frac{C_1\tau + C_2\tau^{1.5} + C_3\tau^3 + C_4\tau^6}{1 - \tau}\right) \tag{2a}$$

$$\tau = 1 - \frac{T}{T_C} \tag{2b}$$

where

T = temperature (°K),
τ = relative temperature,
T_C = characteristic temperature,
p_C = characteristic pressure, and
C_N = coefficient tabulated for a large number of organic compounds.

The standard compounds given in Table 1 had computed 20°C saturated vapor pressures ranging from 1,300 to 760,000 ppm. The table presents the compounds by their elution order, which coincides closely with their volatility.

Equation 1 yielded an expression for the ratio ϵ_I of an individual constituent vapor pressure to the total vapor pressure under equilibrium conditions:

$$\epsilon_I = \frac{p_{VSI}}{p_{VS}} \tag{3a}$$

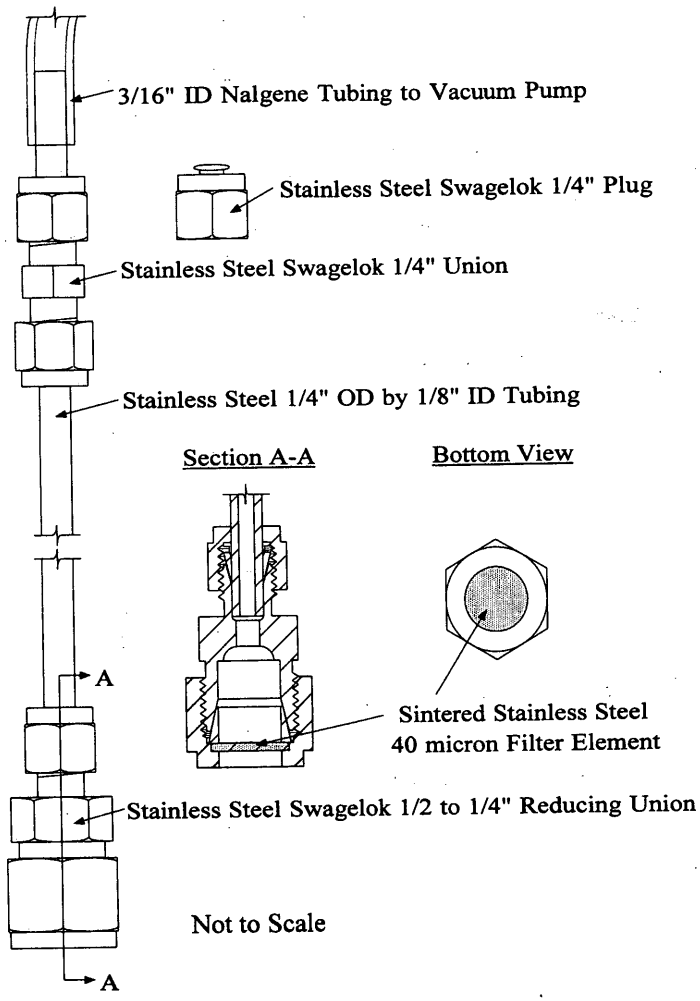

FIGURE 3 Stainless steel tubing cluster tube with sintered filter element and Swagelok coupling.

$$\epsilon_I = \frac{p_{VSATI}\chi_I}{\sum_I p_{VSATI}\chi_I} \tag{3b}$$

The ratio was assumed to be proportional to the reconstructed chromatographic area fraction A_I observed in the mass spectrometer, so that ϵ_I was known for each constituent (Table 1)

$$\epsilon_I = \frac{\left(\frac{A_I}{m_I}\right)}{\sum_I \frac{A_I}{m_I}} \tag{4}$$

with molar mass m_I for constituent I. Equation 4 presumed that the area fraction was equal to the mass fraction (rather than the pressure fraction) of the compound.

The liquid mole fraction was unknown, so Equation 3b was solved for this variable with the result

$$\chi_I = \frac{\epsilon_I}{p_{VSATI}} \sum_I p_{VSATI}\chi_I \tag{5}$$

The ratio of a constituent I mole fraction to a second constituent (J) mole fraction followed simply from Equation 5

$$\frac{\chi_I}{\chi_J} = \frac{\epsilon_I}{p_{VSATI}} \cdot \frac{p_{VSATJ}}{\epsilon_J} \tag{6a}$$

$$\chi_I = \frac{\epsilon_I}{p_{VSATI}} \frac{p_{VSATJ}}{\epsilon_J} \chi_J \tag{6b}$$

A set of equations similar to 6b was constructed by holding J fixed while varying I over all the constituents. These equations were added together and solved for χ_J with the result

$$\chi_J = \frac{\epsilon_J}{p_{VSATJ}} \frac{\sum_I \chi_I}{\sum_I \frac{\epsilon_I}{p_{VSATI}}} \tag{7a}$$

$$\sum_I \chi_I = 0.42 \tag{7b}$$

The chromatographic area fractions from the headspace analysis were substituted into Equation 4 to compute ϵ_I, and the empirical

TABLE 1 GC/MS Headspace Analysis and Saturated Vapor Estimates[a]

Compound[b]	m_I, kg/mole	$PVSATI$, ppm[c]	ε_I[d]	$PVSI$, ppm	χ_I, %
2 Methylbutane	0.0722	755,000	0.035	500	0.0668
Pentane	0.0722	556,000	0.009	130	0.0244
2 Methylpentane	0.0862	225,000	0.152	2,230	0.995
3 Methylpentane	0.0862	201,000	0.088	1,260	0.631
Hexane	0.0862	159,000	0.134	1,970	1.25
Methylcyclopentane	0.0842	144,000	0.044	630	0.437
2 Methylhexane	0.100	67,600	0.074	1,070	1.58
2,3 Dimethylpentane	0.100	71,100	0.074	1,070	1.51
3 Methylhexane	0.100	63,200	0.044	640	1.02
2,2,4 Trimethylpentane	0.114	50,700	0.075	1,070	2.12
Heptane	0.100	46,200	0.018	260	0.570
Methylcyclohexane	0.0982	47,400	0.032	450	0.961
2,3,4 Trimethylpentane	0.114	27,300	0.022	320	1.17
2,3,3 Trimethylpentane	0.114	27,400	0.014	200	0.716
2,3 Dimethylhexane	0.114	23,400	0.034	490	2.09
2 Methylheptane	0.114	20,300	0.025	350	1.74
3 Methylheptane	0.114	19,300	0.034	490	2.53
2,2,4 Trimethylhexane	0.128	14,200	0.006	90	0.613
Octane	0.114	13,700	0.017	240	1.79
Ethylbenzene	0.106	9,350	0.008	100	1.11
p Xylene	0.106	8,550	0.016	210	2.45
Nonane	0.128	4,050	0.005	540	1.34
Propylbenzene	0.120	3,310	0.003	30	1.05
Trimethylbenzene	0.120	2,080	0.012	170	8.35
Decane	0.142	1,290	0.001	20	1.53

[a]Weathered petroluem liquid sample from MHD monitoring well, analyzed at 20°C.

[b]Compounds listed in elution order.

[c]$PVSATI$ values computed per Reid *(23)*.

[d]ε_I computed from gas chromatograph/mass spectrometer and Equation 4.

Equation 2 was used to estimate p_{VSATI}. The sum of volatile mole fractions $\sum_I \chi_I$ appearing in Equation 7b was estimated from a companion gc/ms estimate of the separate phase petroleum. The large number of compounds in the latter sample precluded precise estimates of individual mole fractions, however. The large amount of heavier hydrocarbon constituents implied by the χ_I values suggested that at least part of the petroleum spill consisted of diesel fuel or fuel oil (or both).

In view of Equation 1a and Table 1, the saturated headspace pressure was estimated to be

$$p_{VS} = 14{,}800 \text{ ppm} \qquad (293°\text{K}) \tag{8}$$

Saturated headspace standards at 293°K were injected into the portable gc in the field and the resulting total chromatographic area set equal to 14,800 ppm to calibrate the instrument response. In this way, the gc was used to corroborate the combustible hydrocarbon meter readings. Figure 4 (*left*) displays 21 oxygenated (>5 percent p_{VO}) Tedlar bag samples analyzed by both methods, agreement was reasonable over three orders of magnitude. Figure 4 (*right*) suggests that the ratio of gc to meter hydrocarbons increased with decreasing oxygen below the 5 percent level, presumably because of incomplete combustion in the catalytic chamber for hydrocarbon-rich, oxygen-poor soil gas. A calibrated empirical adjustment was accordingly applied to the organic vapor meter data

$$p_V = p_V(\text{meter})\left[C_7 + (C_8 - C_7)\frac{p_{VO}}{5}\right] \qquad (p_{VO} < 5\%) \tag{9a}$$

$$p_V = C_8\, p_V(\text{meter}) \qquad (p_{VO} > 5\%) \tag{9b}$$

$$C_7 = 2.83 \qquad (p_{VO} \text{ in } \%) \tag{9c}$$

$$C_8 = 0.905 \tag{9d}$$

Equation 9 is sketched as straight lines on Figure 4; the fitted C_8 value implies that the blend of petroleum hydrocarbon vapors burns more efficiently than the hexane used to calibrate the meter.

LATERAL PETROLEUM DISTRIBUTION AND BIODEGRADATION POTENTIAL

Table 2 and Figure 5 summarize depth-averaged soil gas vapor pressures for total hydrocarbon and oxygen observed in tubing clusters and vapor probe samples in the service area parking lot during the December 1993 and June 1994 field trips. A 10-m radius area downgradient of the original tank pad contained saturated soil gas, with p_V values dropping off rapidly beyond a 20-m radius. Elevated hydrocarbons were found over the two separate phase contaminated MHD wells in the parking lot study area, which were gauged on May 13, 1994. Two other MHD wells without product were overlain by lower hydrocarbon vapor pressures.

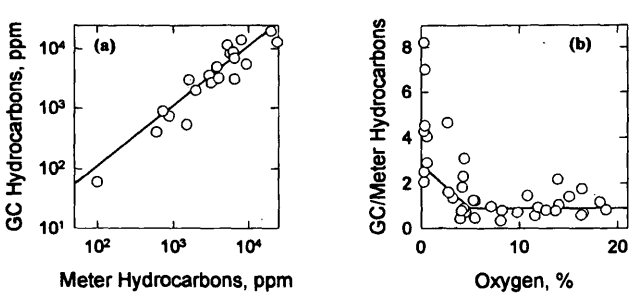

FIGURE 4 Combustible hydrocarbon meter and portable gas chromatogram data: *left*, oxygenated samples; *right*, gc/meter hydrocarbon readings versus oxygen content.

The data were simply modeled to assess the aerobic biodegradation potential of the soil microbes. The hydrocarbon vapors were assumed to mineralize completely in accordance with the following reaction

$$C_7H_{16} + 11O_2 \xrightarrow{\text{microbes}} 7CO_2\uparrow + 8H_2O \tag{10a}$$

$$\gamma = 3.52 \tag{10b}$$

The assumed hydrocarbon molecular weight, m, of 0.10 kg/mole was close to the headspace average value of 0.0985 kg/mole; Equation 10a suggests that 3.52 kg of oxygen was required to degrade every kilogram of hydrocarbon, giving rise to the mass ratio γ cited in Equation 10b.

A radially symmetric, depth-averaged balance of presumably homogeneous diffusion and reaction was taken to describe the variation of hydrocarbon H and oxygen O vapor concentrations

$$-\frac{D_H}{r}\frac{d}{dr}\left(r\frac{dH}{dr}\right) - k(H_S - H) = -V \qquad (r < R) \tag{11a}$$

$$H = 0 \qquad (r > R) \tag{11b}$$

$$-\frac{D_O}{r}\frac{d}{dr}\left(r\frac{dO}{dr}\right) = -\gamma V \qquad (r < R) \tag{11c}$$

$$-\frac{D_O}{r}\frac{d}{dr}\left(r\frac{dO}{dr}\right) = 0 \qquad (R < r < R_A) \tag{11d}$$

$$O = O_A \qquad (R_A < r) \tag{11e}$$

where

r = radial distance,
H_S = saturated hydrocarbon vapor concentration, and
D_H, D_O = hydrocarbon and oxygen gaseous diffusivities, respectively.

A first-order source term with strength k modeled the evaporation of liquid petroleum from the source radius R into the unsaturated zone. A zero-order reactive term V was assumed, predicated on the abundance of the electron acceptor oxygen and the electron donor hydrocarbon. Hydrocarbon vapors and the degradation reaction were assumed to be negligibly small beyond the separate phase petroleum source, and the oxygen vapors were assumed to attain a background value O_A at radius R_A. The molecular diffusivities were assumed (*24*) to be given by

$$D_H = 2.50 \times 10^{-6}\ \frac{m^2}{s} \tag{12a}$$

$$D_O = 1.77 D_H \tag{12b}$$

The higher oxygen diffusivity cited in Equation 12b reflected the inverse dependence of diffusivities on molecular weight (*23*).

TABLE 2 Borehole Averaged Soil Vapor Pressures and Radial Distances

Designation	Depths	Date	p_{VO}, %	p_V, ppm	r,[a]
Probe 1	2	28Dec93	3.6	31,800[b]	9.54
Probe 2	2	28Dec93	9.8	13,800[b]	2.64
Probe 3	6	28Dec93	11.9	4,440[c]	14.8
Probe 4	3	28Dec93	8.0	180[c]	27.0
Probe 5	2	28Dec93	11.4	140[c]	21.7
Probe 6	1	28Dec93	13.9	11,300[b]	13.5
Probe 7	1	28Dec93	2.8	12,900[b]	13.9
Probe 9	2	1Jun94	15.8	1,670[b]	16.0
Probe 10	11	1Jun94	17.8	110[c]	31.1
Probe 11	12	1Jun94	2.2	4,500[c]	15.6
Probe 12	10	1Jun94	3.0	7,530[c]	11.9
Probe 13	1	1Jun94	13.7	3,130[b]	23.5
Probe 14	10	1Jun94	13.7	100[c]	22.9
Probe 18	9	3Jun94	15.8	200[c]	27.2
Probe 19	12	3Jun94	3.6	11,400[c]	23.2
Cluster 1AA	2	2Jun94	5.2	190[c]	34.2
Cluster 2AC	4	11Jul94	1.3	11,800[b]	6.32
Cluster 2AA	3	11Jul94	2.0	20,700[b]	10.2
Cluster 3AA	3	2Jun94	9.3	100[c]	36.2
Cluster 7AA	3	1Jun94	7.4	120[c]	16.3
Cluster 7AB	1	11Jul94	4.3	2,300[b]	21.3
Cluster 12AB	1	2Jun94	11.2	90[c]	28.3
Cluster 14AA	1	2Jun94	13.5	90[c]	27.0
Cluster 16AA	2	2Jun94	17.3	80[c]	47.7
Cluster 16AC	4	2Jun94	15.6	80[c]	59.1

[a]Distance from equivalent source origin, sketched in Figure 5.

[b]Measured with gas chromatograph.

[c]Measured with total hydrocarbon meter and adjusted in accordance with Equation 9.

The equidimensional differential equation for oxygen and the Bessel equation for hydrocarbons (*25*) yielded the following solution

$$H = \left(H_S - \frac{V}{k}\right)\left\{1 - \frac{I_0\left[r\left(\frac{k}{D_H}\right)^{1/2}\right]}{I_0\left[R\left(\frac{k}{D_H}\right)^{1/2}\right]}\right\} \qquad (r < R) \qquad (13a)$$

$$O = \frac{\gamma V r^2}{4D_O} \qquad (r < R) \qquad (13b)$$

$$O = \frac{\gamma V R^2}{2D_O}\left[\frac{1}{2} + \ln\left(\frac{r}{R}\right)\right] \qquad (r > R) \qquad (13c)$$

with modified Bessel function of the first kind of order zero I_0. Equation 13c ensured continuous oxygen and oxygen fluxes at the

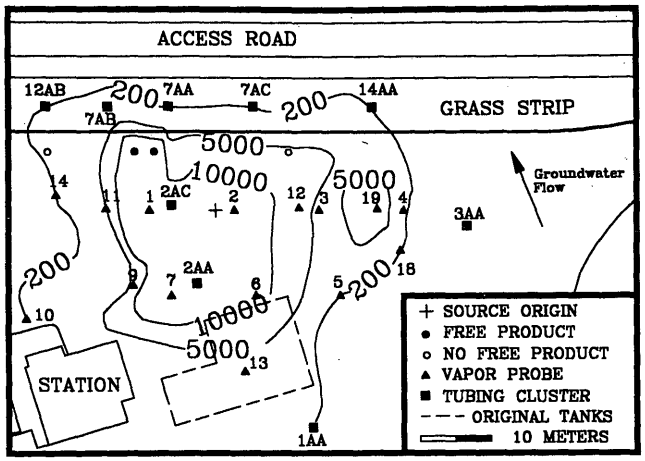

FIGURE 5 Depth-averaged total hydrocarbon vapor pressure isopleths (ppm) and equivalent source origin.

edge of the hydrocarbon spill, and Equation 13a was consistent with Equation 11b. The hydrocarbon vapor profile was also finite at the source origin.

A Fibonnaci search was conducted to fit Equations 13b and 13c to the borehole averaged oxygen data for an assumed source radius R of 20 m and a source origin sketched on Figure 5, with radial distances cited in Table 2. The ideal gas law (*22*) was used to convert gaseous partial pressures to concentrations

$$O = \frac{p_{VO}\, m_O}{R_U\, T} \qquad (m_O = 0.032 \text{ kg/mole}) \tag{14a}$$

$$H = \frac{p_V\, m}{R_U\, T} \qquad (m = 0.100 \text{ kg/mole}) \tag{14b}$$

$$R_U = 8.31\ \frac{\text{Pa} - m^3}{\text{mole} - {}^\circ\text{K}} \tag{14c}$$

where R_U is the universal gas constant and m_O is the molecular weight of oxygen. The maximum reaction rate was varied to minimize the model error standard deviation with the results given by

$$V = 1.54 \times 10^{-9}\ \frac{\text{kg}}{m^3 - s} \tag{15}$$

Figure 6 (*left*) displays the calibration and oxygen data. The saturated hydrocarbon vapor concentration and the source strength were fit to the hydrocarbon data with the following result

$$H_S = 0.127\ \frac{\text{kg}}{m^3} \tag{16a}$$

$$k = 5.98 \times 10^{-8}\ s^{-1} \tag{16b}$$

Figure 6 (*right*) shows the hydrocarbon data, computed from Table 2 and the ideal gas law, and the model calibration. It is important to note that the oxygen and hydrocarbon models were coupled through the stoichiometry of a common reactive term. The observed trend of increasing oxygen and decreasing hydrocarbon vapor concentrations with distance away from the origin was recovered by the model. Physically speaking, petroleum constituents diffuse radially

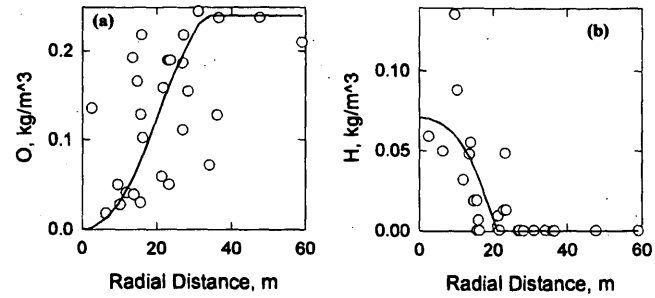

FIGURE 6 Observed (symbols) and calibrated (curves) soil vapor profiles: *left*, oxygen concentrations; *right*, total hydrocarbon concentrations.

away from the center of contamination. This origin also serves as a biological sink due to aerobic degradation, so that oxygen diffuses toward the center.

DISCUSSION OF RESULTS

Ostendorf et al. (*24*) analyzed aviation gasoline evaporation out of intact core samples from an Environmental Protection Agency (EPA) field research site with a detailed data base and mathematical model. The evaporative source strength k^* from that model was equated to the present source term with the theoretical result

$$k \approx \frac{k^* L}{10b} \tag{17}$$

where L is the thickness of the contaminated soil and b is the thickness of the unsaturated zone. The aviation gasoline source strength k^* varied from 10^{-6} to $10^{-5}\ s^{-1}$ in the EPA cores. This range, along with a parking lot L/b estimate of 0.1, were inserted into Equation 17 to get a k range of 10^{-8} to $10^{-7}\ s^{-1}$, which compared favorably with Equation 16b. Richards et al. (*26*) measured maximum reaction rates in soil microcosms from the 4.5-m depth in soil at the EPA research site. The soil microbes degraded a blend of alkane and aromatic vapors representative of aviation gasoline under aerobic conditions, and a V of about 2×10^{-9} kg/m^3-s was observed. This value, which compares reasonably well with Equation 15, is an order of magnitude smaller than the V-levels near the ground surface at the EPA site. The calibrated H_S value (Equation 16a) is considerably higher than the headspace value of 0.0306 kg/m^3 implied by Table 1 constituents at a soil temperature of 281.6°K; it is likely that volatile fractions are underrepresented in Table 1 because of weathering of the separate phase standard during storage.

The hydrocarbon evaporation rate F_E out of the separate phase petroleum was estimated from the calibrated source strength and saturated concentration (Equation 16)

$$F_E = \pi R^2\, b\theta_A\, kH_S \tag{18a}$$

$$F_E = 6.18 \times 10^{-6}\ \frac{\text{kg}}{s} \tag{18b}$$

with an unsaturated zone thickness of 2.5 m. A measured petroleum density of 810 kg/m^3, in view of Equation 18b, implied a natural evaporative diffusion of 63 gal/year from the service area parking lot.

Further model refinements for transience, heterogeneity, measured degradation kinetics, density-driven advection, sorption, and the actual source distribution implied by separate phase coring data would doubtless reduce the scatter of the data about the calibrated curves of Equation 5. MHD and UMASS researchers are pursuing a program consisting of tubing cluster monitoring, solid core sampling, and soil microcosm studies to document these model improvements and improve the estimates of evaporation, degradation, and distribution of soil gas constituents. Nonetheless, the simple analysis and sparse data of Table 2 suggest that aerobic degradation occurs naturally in the subsurface of the parking lot. Furthermore, the separate phase petroleum under the lot is likely to be confined to a 20-m radius centered downgradient of the original storage tanks. The preponderance of diesel range organic constituents suggests that at least part of the spill is diesel or fuel oil.

Equipment and labor costs are associated with this delineation of a petroleum spill and preliminary assessment of its remediation potential. Basic field equipment needed for an elementary soil gas survey include the following items (with 1994 cost estimates cited): (*a*) total hydrocarbon vapor meter ($2,500), (*b*) soil gas oxygen analyzer ($1,500), and (*c*) electric hammer ($1,500). Commercial kits containing drill rods and vapor probes are available for about $1,000, but caution should be exercised when deploying these systems in compacted soils or cobble layers. A rig-driven hammer with thicker rods and customized probes may be needed under these adverse conditions, which are likely to be encountered in the compacted soils of highway rights of way. The labor associated with soil gas sampling depends largely on the character of the unsaturated zone as well. If drill rigs are required, it is possible to profile 10 depths at one vapor probe location each hour under favorable conditions, using a two-person rig crew and a three-person sampling team. Lower labor and a more rapid sampling rate are required for manually driven probes in less resistive soil.

The meter-based technology, with its reasonable costs and a modest level of training, yields qualitative distributions of total hydrocarbon and oxygen partial pressures in the soil gas. The abrupt drop of hydrocarbon levels signals the lateral extent of underlying liquid petroleum contamination, whereas the coincidence of high hydrocarbon and low oxygen concentrations implies an aerobic biodegradation potential. Further quantitative conclusions require more elaborate equipment (gas chromatographs) and sophisticated laboratory analysis (gc/ms).

CONCLUSIONS

The lateral distribution, approximate composition, and aerobic biodegradation potential of vapors from a petroleum hydrocarbon spill in an MHD right of way were inferred from soil gas sampling technology and analyses. Stainless steel vapor probes and stainless steel tubing clusters yielded Tedlar bag samples for on-site analysis by a combustible hydrocarbon meter, an oxygen analyzer, and a portable gas chromatograph. The hydrocarbon data delineated the horizontal extent of the petroleum spill and, with the observed oxygen, calibrated a simple coupled transport model that confirmed the aerobic biodegradation potential of naturally occurring microbes in the site soil.

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PART 5

Natural Resources

Wetland Functions and Values: Descriptive Approach to Visualizing and Assessing Wetland Systems

ROBERT S. DE SANTO AND THERESA A. FLIEGER

The environmental assessment process is a cornerstone of the National Environmental Policy Act (NEPA) of the United States, and part of that policy of environmental conservation includes protection of the nation's wetland resources. The U.S. Army Corps of Engineers (USACOE) has jurisdiction over the federal permit required by the Clean Water Act concerning wetland impacts (Section 404). As a consequence, the Regulatory Division of the USACOE New England Division promulgated a highway methodology to guide the preparation of assessments required as part of its permit process in New England. The methodology emphasizes the function and value of wetlands. That determination can be most efficiently accomplished by using computer-aided drafting and design and geographic information systems, although neither of these computer techniques is essential to the procedure. It is adapted to help describe complex wetland systems and their interrelationships without bias because it does not weight functions. Such weighing of functions by other methods has created difficulty in assessing wetlands as resources in light of other cultural, natural, and socioeconomic issues that are also considered by the NEPA process. The present methodology is consistent with NEPA, recognizing sensitivity to habitat preservation on the one hand and socioeconomic development, on the other. It has been used to clarify impacts associated with large and small transportation related projects in New England. Examples of resource mapping and checklist and forms to guide wetland function and value assessment are based on projects in which the authors have participated individually or collectively.

From the perspective of applied ecology in the transportation industry, environmental regulation of large projects in the United States requires the development of tools and methods that can be used to assess both social (i.e., cultural) and natural (i.e., ecological) resources. Such assessments are intended to help weigh benefits and impacts likely to be associated with development projects. In that sense, the goals of environmental protection are dependent on the practical application of environmental management to link science, engineering, socioeconomics, and law (*1,2*). The evolution of such environmental management has taken many pathways, one of which began in the United States at the first Earth Day on April 22, 1970. That event was sponsored by the then new movement of environmental activists who vowed to pursue political action against those in government who did not match their environmental protection rhetoric with action. That growing and dedicated movement for environmental protection is clearly accomplishing its 1970 goal.

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A negative consequence of adopting laws and regulations that focus on preserving natural resources is the growing estrangement between natural resource protection and socioeconomic resource management. These antagonistic aspects of environmental management are not balanced evenly in the law because the broad reach of present environmental laws generally is biased toward natural environment preservation, such as wetlands, and laws that pertain to socioeconomic issues (i.e., human issues related to quality of life and lifestyle) do not provide the same measure of impact quantification. A valid comparison of the costs and benefits of natural resources and those of human resources is still being sought. Such issues are complicated further by the diversity of the professional competence of individuals who must deal with them. Such skill requires a wide range of technical proficiency as well as diplomatic and social cognizance and competence. These important issues will not be explored here because they are all well-summarized and reviewed elsewhere (*3–5*).

Because of the usually mutually exclusive nature of social and economic development versus natural resource preservation, genuine conflicts arise when project alternatives are assessed in light of cultural and socioeconomic resource management as opposed to environmental conservation. These conflicts can be resolved when the consideration of alternatives is faithful to the scientific method, thus defining resources based on objective, unbiased, and appropriately detailed standardized methods. During the linear projects associated with highways and railroads, such methods help to avoid the entanglement of regulatory gridlock that otherwise tends to delay or prevent conclusion of the permit process. Such deadlocks prevent definitive choices and project implementation. Often an evaluation of the impacts on resources caused by the alternatives of a particular project is required for a USACOE permit to construct within a wetland.

For example, a USACOE permit is likely to be required for proposed highway or railroad projects. Discharges of dredged or fill material in waters of the United States, including wetlands, require a permit under Section 404 of the Clean Water Act; coastal and certain inland projects may also require a permit under Section 10 of the Rivers and Harbors Act. These requirements are in addition to state and local permits (*6–11*). In 1987 the USACOE Regulatory Division, New England Division, promulgated its highway methodology, which it subsequently published as a booklet (*11*). It serves as a means to integrate highway, railroad, or other planning and design projects with (*a*) the requirements of the USACOE permit regulations, (*b*) the National Environmental Policy Act, and (*c*) FHWA funding approval requirements.

The highway methodology is consistent with the principles of overlaying land use and geographic constraints advocated by

McHarg (*12*). In that process, maps of such resources as wetlands, soil types, habitats, structures, roads, and other features of the landscape are combined. The composite picture illustrates the geography of landscape features and includes socioeconomic factors, such as neighborhoods, that help reviewers make objective judgments about those resources and the consequential impacts and benefits to regional interrelationships caused by using (i.e., changing or removing) these diverse features as part of a proposed project. The highway methodology is one defined and tested procedure to assemble resource characteristics that are needed in order to proceed with the USACOE environmental permit process. Its principles organize and prioritize resources such that project planning incorporates the appropriate avoidance of impacts, the minimization of unavoidable impacts, and the compensation of impacts in order to offset those minimized, yet still residual, impacts.

This approach to environmental management is important to all objectives of good environmental stewardship. It guides a significant government environmental permit process (i.e., Section 404 of the Clean Water Act) that affects habitats and species both directly and indirectly. The better the analytical tools on which it is based and the better it serves to support environmental stewardship, the better it can help conserve, manage, and restore habitat values for both nonhuman and human populations.

The highway methodology continues to be tested, modified, and adapted each time it is used. As an oversight of its primary goal, it advocates tools and methods that qualify and, to the extent practical, quantify various aspects of environmental assessment that may then be used to facilitate permit decisions. Although a central consideration of the USACOE is to avoid harming the functions and values of wetlands, it is also charged with weighing other environmental impacts and societal issues when reaching its decisions. These issues include habitat fragmentation, community cohesion, and socioeconomics. For the purpose of this paper, however, only the New England Division approach to wetland functions and values assessment will be addressed. Those other evolving methods and tools of environmental impact assessment are left for papers in preparation.

ITEMIZED FUNCTIONS AND VALUES OF WETLANDS

A major emphasis of the highway methodology concerns wetlands because they are at the center of the Clean Water Act Section 404 regulatory program. For this reason, considerable research has been contributed to this field; this paper focuses on nontidal wetlands and is largely dependent on that literature—for example, see the review by Mitsch and Gosselink (*13*). Wetlands contribute to water quality and quantity management, wildlife management, recreational resources, and habitat stability. In particular, the web of wetland ecology functions to restore and protect water quality through biofiltration—that is, wetlands are living filters that help renovate storm water by "digesting" or adsorbing pollutants, sediments, and nutrients (*14*). These important attributes lend further importance to the consideration of wetland functions and values in the protection of habitat as interpreted by the procedures of the USACOE.

The wetland assessment approach in the USACOE New England Division Highway Methodology diverges from the Wetland Evaluation Technique II (WET II) (*15*), because the highway methodology places no weightings on evaluation factors of those functions that guide wetland inspection criteria. The purpose of this assessment procedure is threefold: (*a*) to report the presence or absence of 13 generally accepted wetland functions, (*b*) to report which one or more of these 13 functions are predominant in each wetland studied, and (*c*) to provide descriptive information, including photographs, to help reviewers make informed judgments, whether or not those reviewers can conduct their own direct field inspections.

This approach identifies the 13 wetland functions listed in the following. The rationale that defines each category is contained in Appendix A. Although these categories are not necessarily the only wetland functions possible, nor are they necessarily precisely defined, they do represent the best working "pallet" of descriptors that can be used to paint a useful and objective representation of the wetland resources associated with a proposed project.

1. *Groundwater interchange (recharge/discharge).* This function considers the potential for a wetland to serve as a groundwater recharge or discharge area (or both). It reflects the fundamental interaction between wetlands and aquifers, regardless of the size or importance of either.
2. *Flood flow alternation (storage and desynchronization).* This function considers the effectiveness of the wetland in reducing flood damage by water retention for prolonged periods following precipitation events. It adds to the stability of the wetland ecological system or its buffering characteristics and provides social and economic value relative to erosion and flood control.
3. *Sediment and shoreline stabilization.* This function represents the effectiveness of a wetland to stabilize stream banks and shorelines against erosion.
4. *Sediment, toxicant, and pathogen retention.* This function reduces or prevents degradation of water quality. It relates to the effectiveness of the wetland as a trap for sediments, toxicants, or pathogens in runoff water from surrounding uplands, or upstream eroding wetland areas.
5. *Nutrient removal, retention, and transformation.* This function represents the effectiveness of the wetland to trap nutrients in runoff water from surrounding uplands or contiguous wetlands, and the ability of the wetland to convert these nutrients into other chemical forms or tropic levels. One aspect of this function is to prevent the ill effects of nutrients from entering aquifers or surface waters such as ponds, lakes, streams, rivers, and estuaries.
6. *Production export (nutrient).* This function represents the effectiveness of the wetland to produce food or usable products for man and other living organisms.
7. *Fish and shellfish habitat.* This function represents the effectiveness of seasonal or permanent water courses associated with the wetland in question as fish and shellfish habitat.
8. *Wildlife habitat.* This function represents the effectiveness of the wetland as habitat for various types and populations of animals typically associated with wetlands and the wetland edge. It also represents the use of the wetland as habitat for migrating species and species dependent on the wetland at some time in their life cycles. Species lists or observed and potential animals should be included in the wetland assessment as documentation of this function.
9. *Threatened or endangered species habitat.* This function represents the suitability of the wetland to support threatened or endangered species whose survival has been officially acknowledged as being threatened or endangered.

10. *Visual quality and aesthetics.* This function represents the visual and aesthetic quality or usefulness of the wetland.

11. *Educational and scientific value.* This function considers the suitability of the wetland as a site for an "outdoor classroom" or as a location for scientific study or research.

12. *Recreation (consumptive and nonconsumptive).* This function represents the suitability of the wetland and associated water courses to provide recreational opportunities such as canoeing, boating, fishing, hunting, and other active or passive activities. Consumptive opportunities consume or diminish the plants, animals, and other wetland resources. Nonconsumptive uses do not consume or diminish the wetland or its resources.

13. *Uniqueness/Heritage.* This function represents the wetland or its associated water bodies for certain special characteristics. These may include archaeological sites, critical habitat, overall health and appearance, role in the ecological system of the area, or relative importance as a typical wetland class for its geographic region. Such functions are clearly important wetland attributes relative to aspects of public health, recreation, and habitat diversity.

From consideration of these 13 wetland functions and values, wetland assessment is intended to document, without bias, as much hydrologic, biologic, and cultural information as is practically possible and necessary in order for reviewers to judge potential impacts and select from among imperfect project choices. The necessarily biased judgments of these reviewers are expected to consider the data presented in a straightforward format, which is the basis on which such subjective judgments can be made. The presentation of these data is, therefore, intended to allow a reviewer to envision the subject wetland and consider its characteristics from whatever perspective that the reviewer deems appropriate. It is assumed that those subjective (i.e., biased) judgments would be explained and discussed in open forum in order to ensure that all parties can represent their particular concerns and solutions. When those conditions are met and carried out in good faith, the debate of priorities and choices is open and productive. Although consensus is an admirable goal in this process, the USACOE is the ultimate decision maker in this Clear Water Act Section 404 permit process (although a Section 404(c) veto process can be initiated by the Environmental Protection Agency). It weighs all comments, facilitated by an orderly and unbiased presentation of such key factors as wetlands functions and values. Therefore, consistent with the objective of making the best overall choice and with the requirements of the regulatory program, documentation of each resource (i.e., wetland) is unweighted and thus unbiased. Figure 1 is one example of the format that guides wetland functions and values assessments. The top portion of the form reports the physiographic characteristics of the subject wetland, including its size, type, location in the watershed, habitat characteristics, aquatic and vegetative diversity, and anticipated impacts. The lower portion of the form focuses on specific functional characteristics of the subject wetland, annotated by numbers in the "Rationale Why" column. These reference numbers are a shorthand to identify specific and important characteristics from the accompanying checklists in Appendix A. Comments may be added for special emphasis, and space is provided for a USACOE *Confidence Level* of reported findings made by the evaluator.

The "Principal Valuable Function(s)" column is used to identify dominant functions. Space is provided at the bottom of the form for a narrative of the wetland in order to record unusual or noteworthy conditions, or to add comments helpful in defining unique aspects of the wetland being studied. This form continues to evolve with its use. Data, therefore, may be recorded in different formats, provided that the format is clear, unambiguous, and appropriately comprehensive.

After these procedures, each wetland involved in a Phase 2 study (*10*) is evaluated for 13 possible functions and values all derived from the evolving literature (*15–20*). That literature provides documentation of the functions being evaluated and helps ensure uniformity and objectivity in guiding field inspections. Each wetland is inspected and photographed to illustrate potential impact areas, unusual aspects of the wetland, or other significant features. A generalized sketch of each wetland is also prepared to summarize shape, vegetative interspersion, cover type, interconnections, number and types of inlets and outlets, cross sections, bank height, open water, vegetation zonation, and the location of each photograph. The dominant plant species and observed or signed wildlife is also recorded. All this information is collected in data files, an example of which is shown in Figures 1 and 2.

GRAPHICAL REPRESENTATION

A graphical representation of the functions and values of each wetland involved with the overall assessment of a project is important as a means of providing both technical and lay reviewers with an intuitive perspective of the "big picture." Once a study area is defined and resources are identified at scales such as U.S. Geologic Survey quadrangle maps (24,000 scale), a Phase 1 assessment leads to screening candidate alignments. This process results in a manageable number of three to five for Phase 2 study. The Phase 1 screening is the first step in recognizing interrelationships, indirect and direct impacts, and the significance of choices between alternative alignments of a project plan. Increasing detail is developed during Phase 2 when functions and values are represented more graphically. Figure 3 illustrates the graphical means of summarizing wetland functions and values developed during the Nashua-Hudson Circumferential Highway project in New Hampshire and the Route 6 project in Connecticut. It represents all the basic characteristics of each wetland investigated using symbols (i.e., icons) that, when taken together, represent complex ecological and sociological relationships. The specific and complete documentation of each such relationship appears to be beyond the need for agencies to make initial choices between the project alternatives that are the subject of USACOE jurisdictional requirements. Refinement of that initial choice and the final issuance of a Section 404 permit to allow project construction requires that this initial information be augmented. The augmentation includes detailed delineation of wetlands and project construction monitoring specifications. Both are needed to ensure that contract stipulations be present to protect important resources to the extent that they are defined and their functions and values are recognized and conserved through the permit process.

Once the characteristics of each wetland are identified by an icon box, a map is prepared to show the geographic relationship between each such wetland and the alternative alignments of the proposed project. Figure 4 is a sample of a portion of such a map that shows part of one alternative alignment.

NASHUA-HUDSON CIRCUMFERENTIAL HIGHWAY
WETLANDS EVALUATION

FUNCTION-VALUE ASSESSMENTS
42 45.82 Lat.
71 23.23 Long.

WETLAND I.D. EF3A WP28
Prepared by: KLS, LDC, DMM
Date: 10-10-91

TOTAL AREA OF WETLAND: NWI 1.15 acres SCS None MAN MADE? No IS THE WETLAND PART OF A WILDLIFE CORRIDOR? Yes
OR A "HABITAT ISLAND"? No ADJACENT LAND USE Deciduous forest DISTANCE TO NEAREST ROADWAY OR OTHER DEVELOPMENT 300'-400'
DOMINANT WETLAND SYSTEMS PRESENT PFOIE CONTIGUOUS UNDEVELOPED BUFFER ZONE PRESENT No

IS THE WETLAND A SEPARATE HYDRAULIC SYSTEM? No IF NOT, WHERE DOES THE WETLAND LIE IN THE DRAINAGE BASIN? Upper
HOW MANY TRIBUTARIES CONTRIBUTE TO THE WETLAND? 1 AQUATIC DIVERSITY/ABUNDANCE Y/N VEGETATIVE DIVERSITY/ABUNDANCE Y/Y
WILDLIFE DIVERSITY/ABUNDANCE N/N ANTICIPATED IMPACTS Cut and fill - eliminate
WETLAND IMPACTED: NWI 1.15 acres SCS None

FUNCTION	Function Occurrence Y	Function Occurrence N	Rationale Why (Number)	Principal Valuable Function(s)	Comments	ACOE Confidence Level
Groundwater Interchange Recharge/Discharge	X		1, 2, 6, 7, 11-13, (15)	→	Underlain by bedrock and till. Occurs along base of slope.	
Floodflow Alteration (Storage & Desynchronization)	X		5-9, 11, 12, 14, 16	→	Wetland is in upper watershed & protects downstream low density residential area. Flood storage/detention. Soil stabilized by vegetation in this wetland.	
Sediment/Shoreline Stabilization	X		1, 4, 6, 8, 9, 12-15			
Sediment/Toxicant Retention	X		1-4, 6, 9-12	X		
Nutrient Removal/Retention/ Transformation		X	3, 5-9, 11, 12, (13)	→	Runoff enters from roads & upstream trailer park. Sediment trap function. Diffuse flow thru herb. veg. enhances filtration.	
Production Export (Nutrient)		X	1, 2, 5, 7, 8, 10, 14	→	Some export but primary function is nutrient attenuation.	
Fish & Shellfish Habitat	X		1, 2, 4, 7-10, 14-17	→	Food, cover, spawning possible, but small & shallow limits value. Linked by watercourse to other wetlands.	
Wildlife Habitat	X		1-9, 11, 13-15, 18, 19	→	Stratified vegetation. Corridor, not nesting or feeding habitat.	
Endangered Species Habitat		X	6, 7	→	No known T&E species present.	
Visual Quality/Aesthetics		X	3-5, 7, 10, 11	→	Homogeneous and inconspicuous structure.	
Educational Scientific Value		X	2, 4, 9-11, 13	→	Limited value. Small & near houses.	
Recreation (Consumptive and Non-Consumptive)		X	4, 6	→	Hunting incompatible. Hiking possible. Nature watching limited by small area.	
Uniqueness/Heritage		X	6-8, 10, 11, 15, 16, 18, (19), 22			

NOTES: Wetland in upper limits of Second Brook tributary. Alternately diffuse and defined channel and associated flat, vegetated flood plain. Wetland width varies. Windthrows produce discontinuous tree canopy. Shrub layer patchy, interspersed with open herbaceous flats. Runoff enters from near roads and an upstream trailer park. Evidence of siltation present.

FIGURE 1 Guide for field inspectors in using descriptive categories to document characteristics for judging environmental impacts on wetland systems.

CONCLUSIONS

The USACOE wetlands functions and value assessment approach is intended to avoid any hidden weighing of evaluation criteria. It holds promise as a tool in planning transportation projects, as well as for other projects that require an evaluation of wetland resources. The approach is used primarily to facilitate determination of potential impacts and to compare project alternatives with respect to the functions and values of wetlands. It can also be used to select sites in the landscape where wetland creation would compensate for wetland takings, and to assist in the evaluation of wetland monitoring activities where it serves to document whether specified functions were indeed realized after the subject wetlands were created.

The wetland assessment approach defined here permits biasing to take place in an open forum where agencies or other interested parties can review and argue their individual perspectives. The raw data that define the resources under consideration are documented in appropriate detail and are easily recoverable. The process thus supports open debate of the scientific methods used, and of the alternatives defined, by the assessment. In that respect, the USACOE can openly solicit input from commentors on the values of each subject wetland. Using the data forms and methods described herein will lead to better informed decisions. Although gaining a consensus on these values of wetlands and the selection of alternatives is an admirable goal, the USACOE remains the decision maker in this process and must arrive at a decision in light of its Section 404 jurisdiction.

Vegetative

Red Maple	*Acer rubrum*
Slippery Elm	*Ulmus rubra*
White pine	*Pinus strobus*
Ash	*Fraxinus sp.*
Yellow birch	*Betula lutea*
Grey birch	*Betula populifolia*
Speckled alder	*Alnus rugosa*
Poison sumac	*Rhus vernix*
Dogwood	*Corunus sp.*
Highbush blueberry	*Vaccinium corymbosum*
Maleberry	*Lyonia ligustrina*
Winterberry	*Ilex verticillata*
Sensitive fern	*Onoclea sensibilis*
Poison ivy	*Rhus radicans*
Skunk cabbage	*Symplocarpus foetidus*
Steeple bush	*Spirea tomentosa*

Wildlife

Black capped chick-a-dee	*Parus atricapillus*
Blue jay	*Cyanocitta cristata*
Green frogs	*Rana clamitans melanota*
Grey squirrel	*Sciurus carolinensis*

DIAGRAM NOT TO SCALE

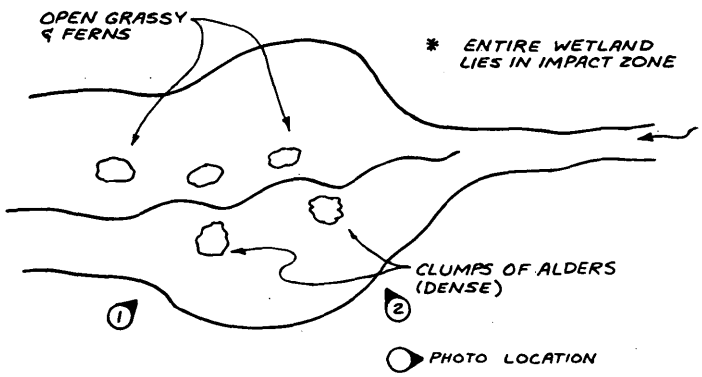

FIGURE 2 Species list based on observed species, or their signs, during site investigations used to provide site-specific detail for Phase 2 planning.

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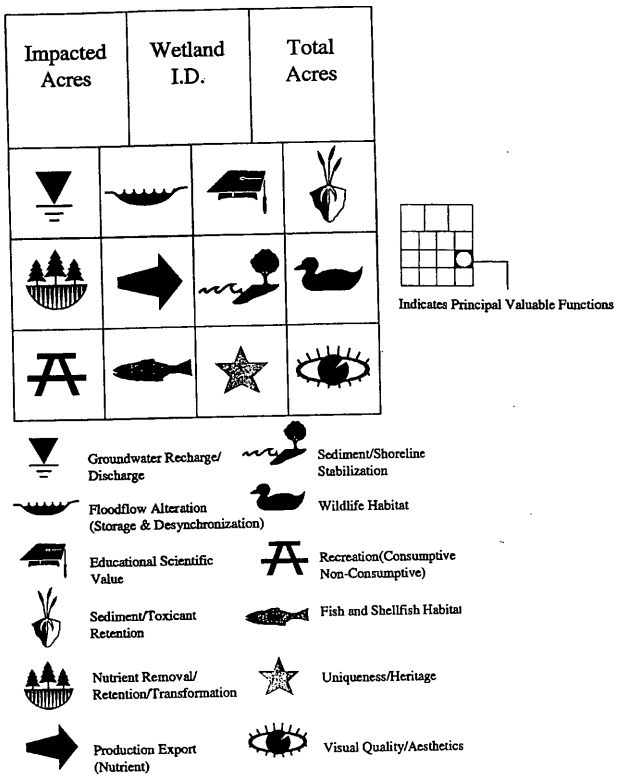

FIGURE 3 Graphical summary of wetland characteristics; endangered species habitat is not illustrated by an icon, so 12 icon possibilities are shown.

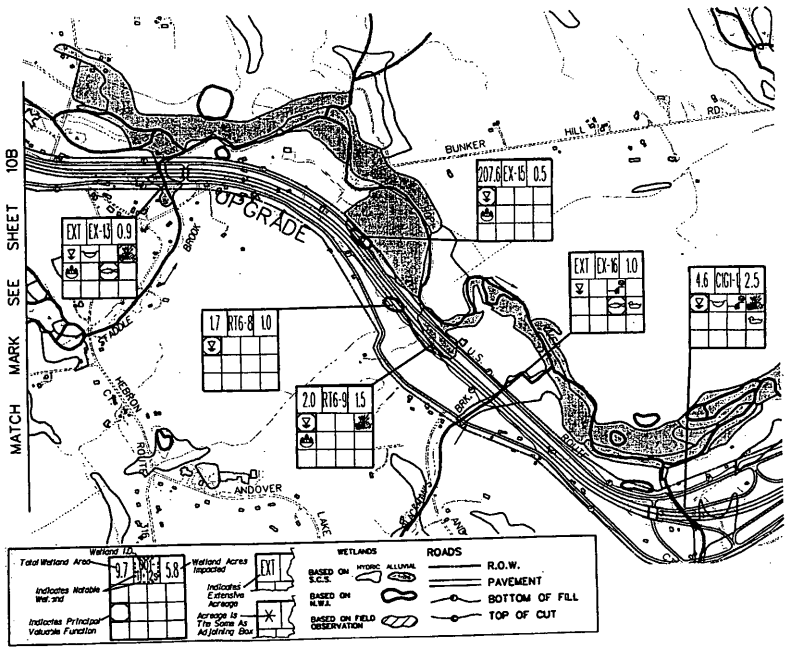

FIGURE 4 Icon boxes summarizing functions and values for each wetland investigated.

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APPENDIX A

GROUNDWATER INTERCHANGE (RECHARGE/DISCHARGE)

1. Public or private wells occur downstream of wetland.
2. Potential exists for public or private wells downstream of wetland.
3. Wetland is underlain by stratified drift.
4. Gravel or sandy soils are present or adjacent to wetland.
5. Fragipan does not occur in wetland.
6. Fragipan, impervious soil, or bedrock does occur in wetland.
7. Wetland is associated with a perennial or intermittent water course.
8. Signs of groundwater recharge are present or piezometer data demonstrate recharge.
9. Wetland is associated with a water course but lacks a defined outlet or contains a constricted outlet.
10. Wetland contains only an outlet.
11. Groundwater quality of stratified drift aquifer within or downstream of wetland meets drinking water standards.
12. Quality of water associated with wetland is high.
13. Signs of groundwater discharge are present (e.g., springs).
14. Water temperature suggests that it is a discharge site.
15. Wetland shows signs of variable water levels.
16. Gravel or sandy soils are present in or adjacent to wetland.
17. Piezometer data demonstrate discharge.
18. Other.

FLOOD FLOW ALTERNATION (STORAGE AND DESYNCHRONIZATION)

1. Area of wetland is large relative to its watershed.
2. Wetland occurs in the upper portions of its watershed.
3. Effective flood storage is small or nonexistent upslope of or above wetland.
4. Wetland watershed contains a high degree of impervious surfaces.
5. Wetland contains hydric soils that are able to absorb and detain water.
6. Wetland exists in a relatively flat area that has flood storage potential.
7. Wetland has an intermittent outlet or ponded water, or signs are present of variable water level.
8. During flood events, wetland can retain higher volumes of water than under normal or average rainfall conditions.
9. Wetland receives and retains overland or sheet flow runoff from surrounding uplands.
10. In the event of a large storm, wetland may receive and detain excessive floodwater from a nearby water course.
11. Valuable properties, structures, or resources are located in or near the floodplain downstream from wetland.
12. Watershed has a history of economic loss due to flooding.

[Stop here if this wetland is not associated with a water course.]

13. Wetland is associated with one or more water courses.
14. Wetland water course is sinuous or diffuse.
15. Wetland outlet is constricted.
16. Channel flow velocity is affected by wetland.
17. Land uses downstream are protected by wetland.
18. Wetland contains a high density of vegetation.
19. Other.

SEDIMENT AND SHORELINE STABILIZATION

1. Indications of erosion, siltation are present.
2. Topographical gradient is present in wetland.
3. Potential sediment sources are present up-slope.

[Stop here if this wetland is not associated with a water course.]

4. No distinct shoreline or bank is evident between the waterbody and wetland or upland.

5. A distinct step between the open water body or stream and the adjacent land exists (i.e., sharp bank) with dense roots throughout.
6. Wide wetland (> 10 ft) borders water course, lake, or pond.
7. High flow velocities exist in wetland.
8. Potential sediment sources are present upstream.
9. The watershed is large enough to produce channelized flow.
10. Open water fetch is present.
11. Boating activity is present.
12. Dense vegetation borders water course, lake, or pond.
13. High percentage of energy-absorbing emergents or shrubs borders water course, lake, or pond.
14. Vegetation is composed of large trees and shrubs that withstand major flood events or erosive incidents and stabilize the shoreline on a large scale (feet).
15. Vegetation is composed of a dense resilient herbaceous layer that stabilizes sediments and the shoreline on a small scale (inches) during minor flood events or potentially erosive events.
16. Other.

SEDIMENT, TOXICANT, AND PATHOGEN RETENTION

1. Potential sources of excess sediment are in the watershed above wetland.
2. Potential or known sources of toxicants are in the watershed above wetland.
3. Opportunity for sediment trapping by slow-moving water or deepwater habitat are present in wetland.
4. Mineral, fine-grained, or organic soils are present.
5. Long-duration water retention time is present in wetland.
6. Public or private water sources occur downstream.
7. Wetland edge is broad and intermittently aerobic.
8. Wetland is known to have existed for more than 50 years.
9. Drainage ditches have not been constructed in wetland.

[Stop here if wetland is not associated with a water course].

10. Wetland is associated with an intermittent or perennial stream or a lake.
11. Channelized flows have visible velocity decreases in wetland.
12. Effective floodwater storage in wetland is occurring. Areas of impounded open water are present.
13. No indicators of erosive forces are present. No high water velocities are present.
14. Diffuse water flows are present in wetland.
15. Wetland has a high degree of water and vegetation interspersion.
16. Dense vegetation provides opportunity for sediment trapping or signs of sediment accumulation are present by dense vegetation.
17. Other.

NUTRIENT REMOVAL, RETENTION, AND TRANSFORMATION

1. Wetland is large relative to the size of its watershed.
2. Deep water or open water habitat exists.
3. Overall potential for sediment trapping exists in wetland.
4. Potential sources of excess nutrients present in the watershed above wetland.
5. Wetland is saturated for most of the season. Ponded water is present in wetland.
6. Deep organic and sediment deposits are present.
7. Slowly drained mineral, fine-grained, or organic soils are present.
8. Dense vegetation is present.
9. Emergent vegetation or dense woody stems are dominant.
10. Aquatic diversity and abundance are sufficient to use nutrients.
11. Opportunity for nutrient attenuation exists.
12. Vegetation diversity and abundance are sufficient to use nutrients.

[Stop here if wetland is not associated with a water course.]

13. Waterflow through wetland is diffuse.
14. Water retention and detention time in wetland is increased by constricted outlet or thick vegetation.
15. Water moves slowly through wetland.
16. Other.

PRODUCTION EXPORT (NUTRIENT)

1. Wildlife food sources grow within wetland.
2. Detritus development is present within wetland.
3. Economically or commercially used projects found in wetland.
4. Evidence of wildlife use found within wetland.
5. Higher trophic level consumers use wetland.
6. Fish or shellfish develop or occur in wetland.
7. High vegetation density is present.
8. Wetland exhibits high degree of plant community structure and species diversity.
9. High aquatic diversity and abundance are present.
10. Nutrients exported in wetland watercourses (permanent outlet present).
11. "Flushing" of relatively large amounts of organic plant material occurs from wetland.
12. Wetland contains flowering plants that are used by nectar-gathering insects.
13. Indications of exports are present.
14. High production levels occur; however, there are no visible signs of export (assuming export is attenuated).
15. Other.

FISH AND SHELLFISH HABITAT

1. Forest land is dominant in the watershed above wetland.
2. Abundance of cover objects are present.

[Stop here if this wetland is not associated with a water course.]

3. Size of wetland is able to support large fish and shellfish populations.
4. Wetland is part of a larger, contiguous watercourse.
5. Wetland has sufficient size and depth in open water areas so as not to freeze and retains some open water during winter.

6. Stream width (bank to bank) is more than 50 ft.
7. Quality of the watercourse associated with wetland is able to support healthy fish and shellfish populations.
8. Streamside vegetation provides shade for the water course.
9. Spawning areas are present (submerged vegetation or gravel beds).
10. Food is available to fish and shellfish populations within wetland.
11. Barrier(s) to anadromous fish (such as dams, including beaver dams, waterfalls, and road crossing) are absent from the stream reach associated with wetland.
12. Evidence of fish is present.
13. Wetland is stocked with fish.
14. Water course is persistent.
15. Man-made streams are absent.
16. Water velocities are not too excessive for fish usage.
17. Defined stream channel is present.
18. Other.

WILDLIFE HABITAT

1. Wetland is not degraded by human activity.
2. Water quality of the water course, pond, or lake associated with wetland meets or exceeds Class A or B standards.
3. Wetland is not fragmented by development.
4. Upland surrounding this wetland is undeveloped.
5. More than 40 percent of wetland edge is bordered by upland wildlife habitat (i.e., brushland, woodland, active farmland, or idle land) at least 500 ft wide.
6. Wetland is contiguous with other wetland systems connected by water course or lake.
7. Wildlife overland access to other wetlands is present.
8. Wildlife food sources are within wetland or nearby.
9. Wetland exhibits a high degree of interspersion of vegetation classes and open water.
10. Two or more islands or inclusions of upland with wetland are present.
11. Dominant wetland class includes deep or shallow marsh or wooded swamp.
12. More than 3 acres of shallow permanent open water (less than 6.6 ft deep), including steams in or adjacent to wetland, is present.
13. Density of wetland vegetation is high.
14. Wetland exhibits a high degree of diversity in plant species.
15. Wetland exhibits a high degree of diversity in plant community structure (e.g., trees, shrubs, vines, grasses, mosses, etc.).
16. Plant and animal indicator species are present.
17. Animal signs are observed (tracks, scats, nesting areas, etc.).
18. Seasonal uses vary for wildlife, and wetland appears to support varied population diversity and abundance during different seasons.
19. Wetland contains or has potential to contain a high population of insects.
20. Wetland contains or has potential to contain large population of amphibians.
21. Wetland contains or has potential to contain high avian utilization.
22. Indications of less disturbance-tolerant species are present.
23. Signs of wildlife habitat enhancement are present (birdhouses, nesting boxes, food sources, etc.).
24. Other.

ENDANGERED SPECIES HABITAT

1. Wetland contains or is known to contain threatened or endangered species.
2. Wetland contains critical habitat for a state or federally listed threatened or endangered species.
3. Wetland is a national natural landmark or recognized by a state natural heritage or similar agency noting exemplary nature of the site.
4. Wetland has local significance because it has biological, geological, or other features that are locally rare or unique.
5. Wetland is known to be a study site for scientific research.
6. Little disturbance has occurred in and around wetland.
7. A large area of undeveloped land surrounds wetland.
8. Other.

VISUAL QUALITY AND AESTHETICS

1. Multiple wetland classes are visible from primary viewing locations.
2. Emergent marsh and open water are visible from primary viewing locations.
3. Diversity of vegetation species is visible from primary viewing locations.
4. Wetland is dominated by flowering plants or plants that turn vibrant colors in different seasons.
5. Land use surrounding the wetland is undeveloped as seen from primary viewing locations.
6. Visible surrounding land use form contrasts with wetland.
7. Wetland views are absent of trash, debris, and signs of disturbance.
8. Wetland is considered to be a valuable wildlife habitat.
9. Wetland is accessed easily.
10. Noise level is low at primary viewing locations.
11. Unpleasant odors are absent at primary viewing locations.
12. Relatively unobstructed sight line exists through wetland.
13. Other.

EDUCATIONAL AND SCIENTIFIC VALUE

1. Wetland contains threatened, rare, or endangered species.
2. Little or no disturbance is occurring in wetland.
3. Potential educational site contains a diversity of wetland classes that are accessible or potentially accessible.
4. Potential educational site is undisturbed and natural.
5. Wetland is considered to be a valuable wildlife habitat.
6. Wetland is located within a nature preserve or wildlife management area.
7. Signs of wildlife habitat enhancement are present (bird houses, nesting boxes, food sources, etc.).
8. Off-road parking at potential educational site is suitable for school bus access in or near wetland.
9. Potential educational site is within safe walking distance or a short drive to schools.
10. Potential educational site is within safe walking distance to other plant communities.

11. Direct access to perennial stream at potential educational site is available.
12. Direct access to pond or lake at potential educational site is available.
13. No known safety hazards exist within the potential educational site.
14. Public access to the potential educational site is controlled.
15. Handicap accessibility is available.
16. Site is currently used for educational or scientific purposes.
17. Other.

RECREATION (CONSUMPTIVE AND NONCONSUMPTIVE)

1. Wetland is part of a recreation area, park, forest, or refuge.
2. Fishing is available within or from wetland.
3. Hunting is permitted in wetland.
4. Hiking occurs or has potential to occur within wetland.
5. Wetland is a valuable wildlife habitat.
6. Water course, pond, or lake associated with wetland is unpolluted.
7. High visual and aesthetic quality exists in potential recreation site.
8. Access to water is available at this potential recreation site for boating, canoeing, or fishing.
9. Water course associated with wetland is wide and deep enough to accommodate canoeing or nonpowered boating.
10. Off-road public parking is available at the potential recreation site.
11. Accessibility and travel ease is present.
12. Wetland is within a short drive or safe walk from highly populated public and private areas.
13. Other.

UNIQUENESS AND HERITAGE

1. Upland surrounding wetland is primarily urban.
2. Upland surrounding wetland is developing rapidly.
3. More than 3 acres of shallow permanent open water exist in wetland (less than 6.6 ft deep) including stream.
4. Three or more wetland classes are present.
5. Deep or shallow marsh, or wooded swamp dominate.
6. High degree of interspersion of vegetation or open water occurs wetland.
7. Well-vegetated stream corridor (15 ft on each side of the stream) occurs in wetland.
8. Potential educational site is within a short drive or a safe walk from schools.
9. Off-road parking at potential educational site is suitable for school buses.
10. No known safety hazards exist within this potential educational site.
11. Direct access to perennial stream or lake exists at potential educational site.
12. Two or more wetland classes are visible from primary viewing locations.
13. Low-growing wetlands (marshes, scrub-shrub, bogs, open water) are visible from primary viewing locations.
14. Half an acre or open water of 200 ft of stream is visible from the primary viewing locations.
15. Large area of wetland is dominated by flowering plants or plants that turn vibrant colors in different seasons.
16. General appearance of wetland visible from primary viewing locations is unpolluted or undisturbed.
17. Overall view of wetland is available from the surrounding upland.
18. Quality of the water associated with wetland is high.
19. Opportunities for wildlife observations are available.
20. Historical buildings occur within wetland.
21. Presence of pond or pond site and remains of a dam occur within wetland.
22. Wetland is within 50 yd of nearest perennial water course.
23. Visible stone or earthen foundations, berms, dams, standing structures or associated features occur within wetland.
24. Wetland contains critical habitat for a state or federally listed threatened or endangered species.
25. Wetland is known to be a study site for scientific research.
26. Wetland is a natural landmark or recognized by the state natural heritage inventory authority as an exemplary natural community.
27. Wetland has local significance because it serves several functional values.
28. Wetland has local significance because it has biological, geological, or other features that are locally rare or unique.
29. Wetland is known to contain an important archaeological site.
30. Wetland is hydrologically connected to a state or federally designated scenic river.
31. Wetland is located in an area experiencing a high wetland loss rate.
32. Other.

Responsibility for any errors that may remain in this paper is the authors' alone.

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Mitigation and Compensation of Habitat Fragmentation Caused by Roads: Strategy, Objectives, and Practical Measures

H. D. VAN BOHEMEN

Experiences with the Dutch Second Transport Structure Plan are presented, the strategy is introduced, the general objectives are reviewed, and habitat fragmentation caused by roads is treated as a special case. The general effects of habitat fragmentation on sensitive species and ecosystems will be addressed, and the ecological effects of roads and traffic will be discussed in more detail. Bottlenecks between the existing and planned roads and the National Ecological Network in the Netherlands are analyzed. Finally, examples of mitigation and compensation are given that show how to solve the conflict between planning and building roads and the fragmentation of nature and landscapes caused by roads by various means of ecological engineering.

The Dutch Second Transport Structure Plan is an example of an approach to integrating environmental aspects in a policy document for which an environmental impact assessment is not compulsory. The plan deals with transport in a sustainable society.

STRATEGY OF SECOND TRANSPORT STRUCTURE PLAN

The strategy of the Second Transport Structure Plan consists of the following elements:

1. Tackling problems at their source (e.g., vehicles must be as clean and as safe as possible);
2. Managing and restricting mobility (e.g., reducing the travelling distances between home and work by means of location policy as well as by encouraging a more appropriate use of cars);
3. Improving alternatives to the private car (e.g., facilities for cyclists, standards of public transport, and a more shared use of vehicles);
4. Implementing selective accessibility on the roads (e.g., special corridors for each type of transportation); and
5. Strengthening the foundations with support measures (e.g., better communication, financial planning, and research).

The five elements of the strategy have been translated into 35 policy areas (Figure 1)—air pollution, energy saving, noise nuisance, and so on—and grouped into four categories: environment and amenity (livability), managing and restricting mobility, accessibility, and foundations (means of support). For all the policy areas, qualitative and quantitative targets have been formulated.

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HABITAT FRAGMENTATION

The overall impact of infrastructure on nature is called fragmentation: the partition of ecosystems or habitats of plant and animal populations into smaller, more isolated units. Infrastructure is one of the main causes of habitat fragmentation. Four aspects of fragmentation can be distinguished:

- *Destruction:* absolute loss of a habitat area through the physical presence of the road and associated infrastructural elements.
- *Disturbance:* deterioration of the habitat due to traffic noise, emission of xenobiotic substances, the effects of visual stimuli (artificial lighting), and so on.
- *Barrier action:* separation of functional areas.
- *Collisions:* injury or death of fauna due to motorized traffic.

These aspects can influence the chance of survival of populations of individual species and of essential ecosystem processes.

Isolation can cause subpopulations, or their feeding and breeding habitats, to become separated; then the viability of a population decreases. These aspects may have a strong negative effect on the ecological value of habitats.

To mitigate negative effects of roads on fauna elements, certain measures such as warning signs, wildlife warning reflectors, fences, badger tunnels, and adapted culverts were introduced in the 1970s and 1980s; more recently, ecoducts (overpasses for fauna) have been used to allow animals to move more safely between otherwise isolated habitats.

Activities to mitigate habitat fragmentation caused by infrastructure are now embedded in the policy of the Dutch government. But should the problem be solved?

In the Dutch Second Structure Plan formulated, the target scenario for the short term is to prevent further fragmentation of the countryside; in the long term fragmentation will be reduced. First, an attempt is made to prevent habitat fragmentation by restricting infrastructural development and by integrating the infrastructure into the landscape. Second, the aim is to counteract fragmentation, which can be done by mitigating existing situations (by constructing suitable verges, providing barrier fencing and tunnels for badgers and amphibians, building ecobridges that enable wild animals to cross roads without risking being hit by a vehicle, and reducing speeds and noise levels).

Where the effects of fragmentation cannot be mitigated, it is desirable to take compensatory measures (replacing lost habitats or enhancing marginal habitats through appropriate forms of environmental improvement). Recently, compensation became compulsory in the Netherlands for certain areas with a conservation status.

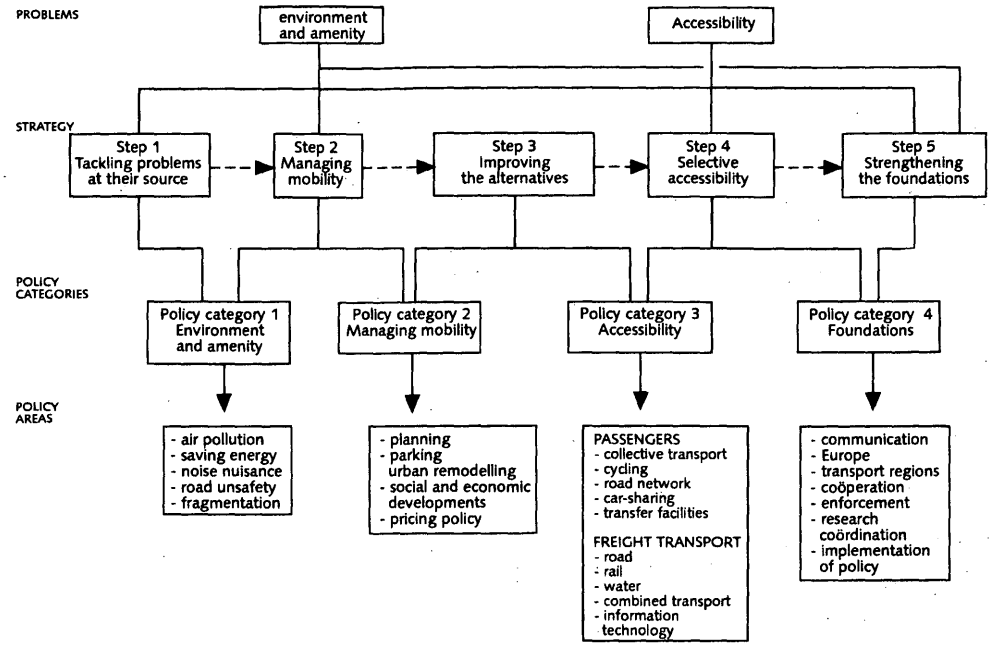

FIGURE 1 Objectives of Second Transport Structure Plan.

There is a growing interest in compensation, motivated by a desire to promote ecological functions and natural values in a given area and to replace those functions and values that have been damaged or have disappeared because of the presence of infrastructure. Examples of such regulations in other countries include Germany's "Eingriffsregelung" (1976) and the no-net-loss principle for wetlands (1986) of the United States and Canada.

The scientific basis of these measures is of major importance. In this respect the author finds it worth mentioning the island biogeographic theory (*1*) and the metapopulation concept (*2*). (A metapopulation is a system of local populations that are linked by dispersal.)

The island biogeographic theory draws attention to the importance of patch size and isolation; the metapopulation concept is important because it makes one realize that landscapes consist of heterogeneous mosaics that are changing continuously over time.

Besides concern for individual species, more attention will soon be given to maintaining ecological processes in highly man-influenced landscapes.

BOTTLENECKS BETWEEN NATIONAL ECOLOGICAL NETWORK AND ROADS

To discover ways to implement measures in concrete situations, the main bottlenecks between roads and wildlife were investigated (*3*). In this study a bottleneck was defined as a situation in which a road (*a*) is located in an actual or potential habitat of a species that is vulnerable to fragmentation, (*b*) is situated in a priority area from a viewpoint of conservation, or (*c*) shows large numbers of dead animals from traffic collisions. Figure 2 shows the bottlenecks that can be resolved by mitigation or compensation:

- Mitigating measures: otter subways, small tunnels or bridges for such species as badger and pine marten, and large tunnels or ecoducts for larger species such as rose deer, wild boar, and red deer.
- Compensating measures: habitat improvement or habitat enlargement along the road (spatial, layout, and management measures).

This study was followed by an investigation of all the locations of intersections between the National Ecological Network and the existing and planned main infrastructure (*4*). The Dutch National Ecological Network comprises habitats of international and national importance in a logical hierarchical structure (*5*). It is a complex of core areas, nature development areas, and corridors (ecological connecting zones). Figure 3 shows the coherent Dutch National Ecological Network of sustainable ecosystems that are of (inter) national importance, and it shows the bottlenecks with the main infrastructure: about 500 km of intersection between the network areas and the highways. Additional information on the ecological functions and species composition of the intersected areas was collected.

The study in Figure 2 is based on species and species composition of ecosystems. It is assumed that the selected species more or less represent the ecosystem concerned. The species were selected on the basis of international nature conservation values as well as their sensitivity to fragmentation caused by roads. Both aspects have been combined in the form of a measure of vulnerability. Figure 3 is the result of the information about the different conservational categories of the Dutch National Conservation Policy Plan, which was confronted with the existing and planned highways.

Later targets for reducing the effects of habitat fragmentation due to roads were based on the evaluation of the Dutch Second Structure Plan:

- In 2000, 40 percent of the bottlenecks will be resolved.
- In 2010, 90 percent of the bottlenecks will be resolved.
- In situations in which mitigation is not possible, compensation measures will be implemented.

FIGURE 2 Map showing bottlenecks from a natural viewpoint (mitigation measures: ⊙ ottertunnels, ○ badger tunnels, and ● ecoducts; compensation measures: M = waterfowl, W = meadow birds, K = birds of small-scale areas, H = heathland birds, and B = woodland birds).

MITIGATION MEASURES

Mitigation can be defined as measures used to stop or reduce negative effects on ecological values caused by building and the use of infrastructure. The measures involve tunnels, underpasses, and overpasses in accordance with the behavior and needs of the species concerned. They include fencing to funnel animals and to prevent road kill.

Badger Pipes and Tunnels

In the Netherlands, 15 percent of the badger population (400 to 450 individuals) is killed by road accidents each year. The total population in summer numbers about 2,200. Some years ago the yearly increase of badgers corresponded with the yearly losses caused by death. The main bottlenecks between badgers and highways have been solved by implementing measures such as badger tunnels and barrier fencing along the road to create safe connections between habitats. During the past few years the reduced mortality has brought about an increase in population size (approximately 100 to 200 net).

Such measures for badgers, and also for amphibians, are mainly species-specific, although other animals can use such provisions.

Tunnels for Amphibians

Besides temporarily closing roads and moving caught amphibians in buckets, special tunnels for amphibians and prefab conducting elements are a successful solution today.

Ecopipes

All kinds of species can use stream culverts (Figure 4) to cross a road, if the culvert is completed with a dry path beside the water. It is important that the ground has a slope beginning below water level (ALWL in figure) and ending above water level (AHWL). This last development is called the so-called ecopipe. There is a growing interest in prefab conducting elements.

Ecoducts

Along with the construction of a new highway (A50) in 1988, two overpasses (cerviducts and ecoducts) were built to enable the red deer (hence cerviduct) to migrate from one side of the highway to the other (Figure 5). Both ecoducts were situated on an old migration track of the red deer. The location is on ground level so the an-

FIGURE 3 Dutch ecological network and highway system.

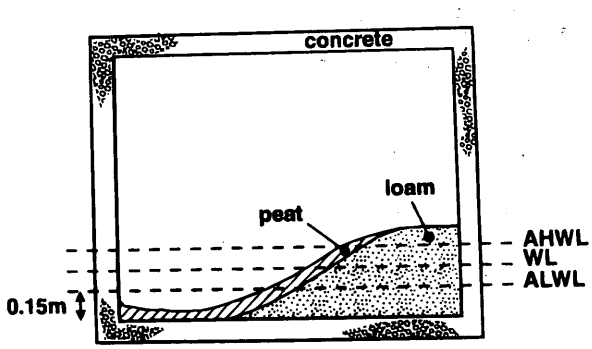

FIGURE 4 Stream culvert: cross section of passage for swamp species.

imals do not have to climb or descend in an unnatural manner (for this reason the highway is built below ground level). The ecoducts are protected against the visual and acoustic influences of the highway by means of a wall and trees.

The northern ecoduct ("Woeste Hoeve") is shaped like a parabola, and the narrowest part is 50 m wide. The traffic drives through three Armco pipes. The southern one ("Terlet") is built like a common viaduct. Both ecoducts are used intensively, not only by red deer, but also by other species such as roe deer, boar, badger, hedgehog, and fox.

The number of passages across Highway A50 through the ecoducts at Terlet and Woeste Hoeve in 1989 is as follows:

	Terlet	*Woeste Hoeve*
Red deer (edelhert)	294	153
Wild boar (wild zwijn)	690	292
Roe deer (ree)	38	43
Fallow deer (damhert)	–	51

Recently a new ecoduct was built over Highway Al near the Dutch town Almelo (Boerskotten). At least seven species of larger mammals use this ecoduct.

So that more can be learned about the effectiveness of ecoducts on population levels, a new monitoring and evaluation program has been set up.

Joint use of Construction

Bridges, viaducts, aqueducts, and culverts can also serve as crossing places for animals. Isolating parts of these constructions from traffic increases these possibilities.

Costs of Mitigation Measures

General figures are given to provide some information about the costs of mitigation measures, these figures are rough, and the real costs involved depend on the local situation.

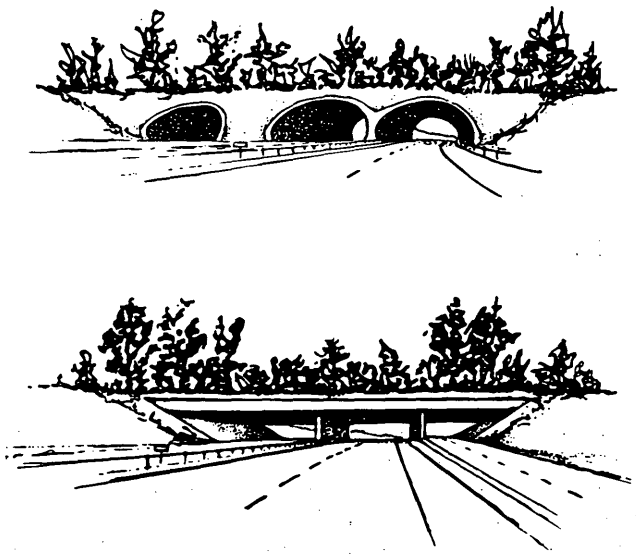

FIGURE 5 Ecoduct: *top*, cerviduct Woeste Hoeve; *bottom*, cerviduct Terlet.

Measure	*Cost (Fl.)*
Ecoduct	3,000,000
Roe deer passage	1,000,000–2,000,000
Adaption of bridge for joint use	100,000–1,000,000
Pipe passage	10,000–100,000

COMPENSATION

Compensation entails that ecological damage, expected to result from human intervention, is repaid financially, the funds being used for the benefit of nature and the environment. In the Netherlands and elsewhere in Europe, interest in compensation has grown recently; it is motivated by a desire to promote ecological functions and nature reserves in a given area and to replace functions and values that have suffered or disappeared because of the presence of infrastructure.

Mitigation and compensation can be defined clearly; these terms can be related to the recovery and replacement, respectively, of ecological functions and natural values. For mitigating measures such as barrier fencing and badger tunnels, the effect of the intervention can be connected to the measure that is implemented. In the case of compensation, however, it is more difficult to establish such a connection.

It is important to give a clear-cut set of criteria to set priorities for the location and nature of compensation and to establish the relationship between compensation and mitigation. A logical order of priority might be to apply compensation first *inside*, then *adjacent to*, and finally *outside* the intervention area, thereby aiming to achieve a higher or (if not possible) equal quality of nature. The product of the area and the quality of nature in the intervention area should remain equal before and after intervention. If the identical replacement of ecological functions and natural values is impossible, the best approach is to aim for similar ecological functions and natural values and, if this is not feasible, for dissimilar ecological functions and nature values.

It is difficult to give detailed figures for compensation measures because little practical experience is available. Clearly costs will involve the acquisition of the site and construction and management.

RESEARCH

The Road and Hydraulic Engineering Division has set up research activities to help determine project priorities and select the best mitigating and compensating measures.

1. Studies on the minimum requirements for population sustainability;
2. Studies on the minimal critical areas for ecosystem processes;
3. Research on dose-effect relations;
4. Effectiveness of mitigating and compensating measures;
5. Comparison of compensation based on species or landscape elements;
6. Studies on the implementation of measures in the policy of national, regional, and local governments; and
7. Evaluation of the defragmentation policy.

CONCLUSIONS

It is important to realize that mitigation and compensation are elements of an integrated landscape conservation strategy to maintain values of natural ecosystems. Moreover, a network of greenways across the landscape can help to achieve the goals of biodiversity conservation. Both are invaluable components of the overall conservation strategy (*6*).

If a road needs to be built, ecological engineering techniques such as mitigation and compensation measures can help to reduce the negative effects on the landscape. Mitigation measures are mainly species-specific, and compensation is aimed at replacing both species and ecosystems (increasing area or improving quality). The species approach involves working with gaps in knowledge, particularly in terms of the dose-effect relationship, and the compensation of landscape elements can make up only partly for overall impact, but it is relatively easy to implement.

Hopefully it has been shown that it is possible to integrate attempts to conserve valuable ecosystems and reduce the negative effects of infrastructure and transportation in planning and building roads.

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Size-Based Fees and Rebates for Reducing Light Vehicle Energy Use and Carbon Dioxide Emissions

JOHN M. DECICCO

Vehicle purchase price incentives in the form of fees and rebates ("feebates") linked to vehicle efficiency are a potential mechanism for reducing U.S. transportation energy consumption and greenhouse gas emissions. General principles for formulating feebates are described, and issues to be addressed in developing a workable feebate program are identified, particularly treatment of light trucks and differential impacts on manufacturers. Size-adjusted feebates are introduced as a way to mitigate the intermanufacturer equity concerns that arise with a system based only on fuel consumption. The impacts of various feebate formulations are examined by a nameplate-level static analysis of the 1990 fleet. By separating cars from light trucks and choosing an appropriate size-adjusted approach, it is possible to develop a feebate system that does not disadvantage U.S. automobile makers. The data base analyzed also reveals a significant variation among different configurations of a given nameplate. Although further analysis is needed, the size-based feebate concepts presented here may serve as a foundation for designing vehicle price incentives to reduce energy use and carbon dioxide emissions.

Concerns about oil imports, greenhouse gas emissions, and other adverse economic and environmental impacts associated with U.S. transportation energy consumption continue to motivate the development of new policies for improving the fuel economy of light vehicles (cars and light trucks). Under market conditions of low gasoline prices and little public apprehension about future oil supply, manufacturers at best improve fuel economy only to the extent that it provides a very short term payback, is achieved as part of a package of other benefits, or appeals to the relatively limited number of new vehicle buyers who highly value fuel economy. The average fuel economy of new light vehicles in the United States has been essentially unchanged for 12 years, averaging 25 (± 1) mpg from 1982 to 1993 (*1*). Further improvements appear unlikely given the market conditions that have prevailed since oil prices fell in 1986.

Fuel pricing, regulation, and vehicle pricing all have their pros and cons as policies for controlling motor fuel consumption. Fuel pricing is directed mainly toward consumers' decision making and can affect both vehicle choice and travel behavior. Vehicle regulation is directed toward manufacturers' planning. Of course, both types of policies involve responses by the other parties in the market. Vehicle pricing policies, such as a variable tax and subsidy (fee and rebate, or "feebate") scheme linked to fuel economy, affect consumers and manufacturers as well as car dealers. In any case, the long-term fuel economy response, which is of most interest for policy development, is dominated by technology improvements in vehicles rather than changes in consumer choice among vehicle size class. This understanding is based on examination of historical changes in the light-duty market as well as on detailed modeling of prospective feebate systems (*2,3*). For a policy change of given magnitude (e.g., percentage change in current pricing), feebates are likely to be more influential than higher fuel taxes in reducing overall motor fuel consumption (*4*). Summaries of existing or proposed feebate programs, policy issues, and energy savings estimates are given in recent reports sponsored by the U.S. Department of Energy (*3,5*). The recent study by Davis et al. (*3*) is the most comprehensive analysis to date of the likely market response to feebates.

In the United States, feebates can be viewed as an extension of the existing gas guzzler tax, which has an observable but small effect on new car fuel economy. Among the reasons that the coverage of the U.S. gas guzzler tax has been limited to a small portion of new cars was concern about effects on the market position of U.S. automobile makers. This concern motivates the exploratory analysis reported here, which is based on a longer technical report (*6*). Since adjusting fees and rebates according to vehicle size can change their impacts on manufacturers, the effects of varying formulations of size-adjusted feebates were examined. A data base was assembled containing vehicle characteristics and sales volumes for 224 nameplates covering the market in model year 1990. The analysis of various feebate schemes was static, that is, the authors did not attempt to evaluate market response (changes in manufacturer designs or consumer choice). However, given the dominance of technology change over shifts among vehicle types in achieving fuel economy improvements, a static analysis is valuable in revealing the likely manufacturer impacts of various feebate designs and identifying the issues that need to be addressed to develop a workable program.

CONSUMPTION-BASED FEEBATES

Generally, a feebate is defined as the product of a feebate rate and the difference between a factor representing a vehicle's energy consumption and some reference level relative to which vehicles are judged:

$$\text{Feebate} = -\text{feebate rate} \times (\text{energy factor} - \text{reference level}) \quad (1)$$

This convention yields negative fees and positive rebates. In the most straightforward formulation, the energy factor would be given in gallons per mile or liters per 100 km, and a vehicle's feebate would be proportional to the location of its fuel consumption above or below some reference fuel consumption. For example, the refer-

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ence level could be the fleet average fuel consumption rate. The reference level is also called the zero point since vehicles having an energy factor at this level have zero fee or rebate in a revenue-neutral program.

Examining a consumption-based feebate reveals issues that need to be addressed in developing a workable proposal. A fuel consumption–based feebate is also equivalent to a carbon dioxide (CO_2) emission–based feebate for gasoline vehicles. For illustrative purposes, a consumption-based feebate can be constructed by extending the existing U.S. gas guzzler tax. The tax schedule is shown as the step function in Figure 1, with the resulting consumption-based feebate extension shown as the curve. Plotted against fuel consumption rather than fuel economy, the tax would follow a straight line with slope $749/Liter/100 km and intercept 9.56 L/100 km (24.6 mpg) (this line is shown for reference in Figures 2 and 3). The mpg-based feebate (longer dashed line) is tangent to the consumption-based feebate curve at the zero-feebate intercept of 24.6 mpg with a slope of $291/mpg. The CAFE fine rate ($5/mpg) is shown as the shallow dashed line, relative to the 1991 CAFE standard of 27.5 mpg for automobiles.

Table 1 gives top-selling 1990 light vehicles by decreasing nameplate average fuel economy along with other statistics. These vehicles had just over half of light duty vehicle sales and an average fuel economy of 24.7 mpg, close to the 24.8 mpg average of all 1990 light vehicles. Except for the Cadillac Fleetwood/Deville, all of these models are untouched by the gas guzzler tax, which does not apply to trucks. The "consumption-only" columns list feebates calculated on the basis of fuel consumption, with cars and light trucks treated together relative to a single reference level. Under this scheme, 21 of the 35 vehicles have rebates and 14 have fees on a nameplate average basis. Feebates are also given as a percentage of vehicle sales price. The sales-weighted mean absolute value of the feebates in this example is $1,153, or 8.0 percent of the average new vehicle price of $14,500. This percentage is called the *leverage* of the feebate, since it represents the average vehicle price influence exerted by the feebate. Leverage is useful as a dimensionless indicator of the strength of the probable effect on decision making.

The outcome of a consumption-based feebate scheme depends strictly on fuel economy, favoring smaller economy vehicles over larger, more powerful or luxurious vehicles. In this example, the range is from fees of 28 percent for the Ford Econoline van to a rebate as high as 23 percent for the Ford Escort, as a percentage of price. Two-thirds of the feebates fall within ±10 percent of the vehicle price. The Chrysler minivans had fuel economies near the light-duty fleet average, implying a negligible net rebate on a nameplate average basis. Not shown in this table is the fact that different configurations of a nameplate can have significantly different fuel economies. For example, different configurations of the 1990 Taurus were rated from 24 to 27 mpg, implying feebates ranging from −$230 (fee) to $580 (rebate) compared with the nameplate average of a $305 rebate. The domestic vehicles with the second and third highest sales are the Ford and Chevy pickup trucks. With sales-rated average fuel economies just under 18 mpg, these vehicles have average fees of about $2,800, 22 percent of their nameplate average sales price. Table 1 thus reveals one issue for developing feebate schemes, namely, the low fuel economy of light trucks. The 1990 light truck standard was 20.0 mpg—lower than the guzzler tax threshold of 22.5 mpg. In short, most light trucks are gas guzzlers relative to cars.

Table 2 presents the impact of consumption-only feebates by manufacturer. The outcome corresponds to the manufacturers' respective corporate average fuel economy (CAFE) levels. The U.S.

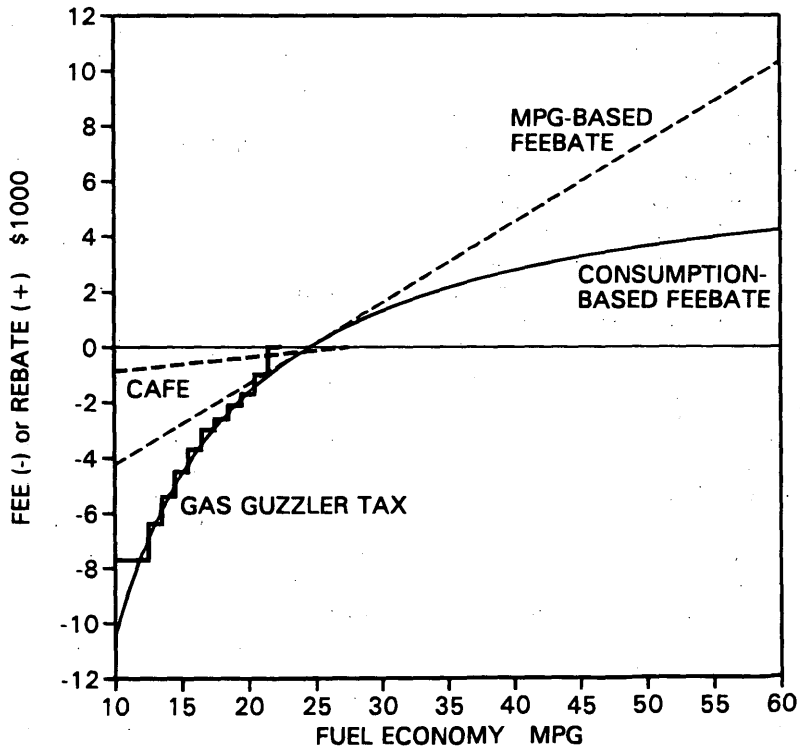

FIGURE 1 Fee and rebate levels extrapolated from federal gas guzzler tax.

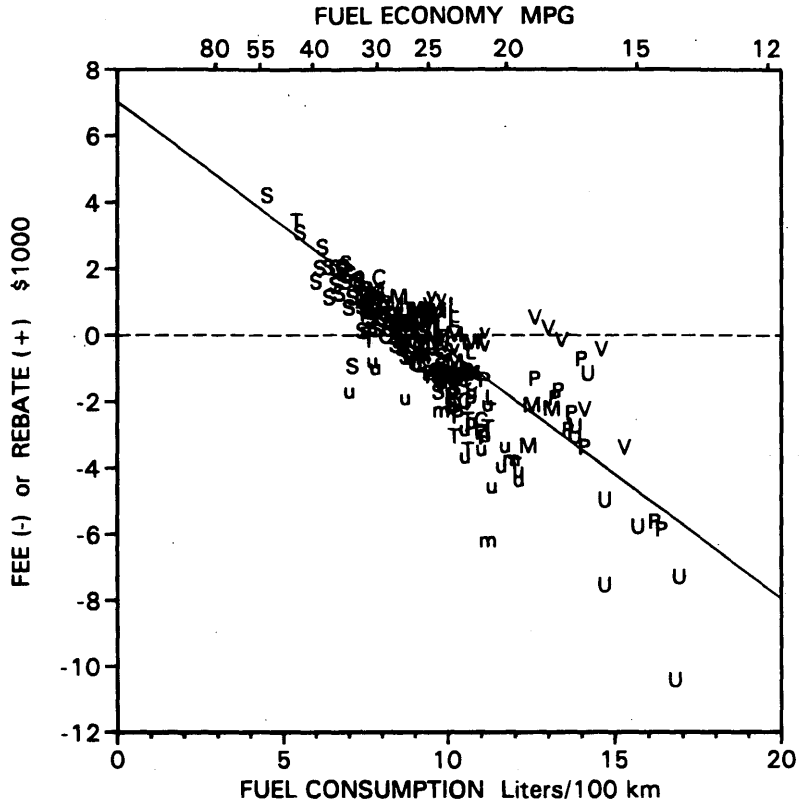

FIGURE 2 Footprint-normalized consumption feebates (all classes together) versus nameplate fuel consumption. C = compact, L = large, M = midsize, S = subcompact, m = minicompact, T = two-seater, P/p = large/small pickup, U/u = large/small utility, V/v = large/small van.

"Big Three"—Chrysler, Ford, and General Motors—accounted for 69 percent of all light-duty vehicle sales in 1990. These manufacturers are the "D3" group. The automobile makers with the next highest sales are five Japanese firms—Toyota, Honda, Nissan, Mazda, and Mitsubishi—the "J5" group. It accounted for 25 percent of 1990 sales. The D3 and J5 groups together comprised 94 percent of the market. Table 3 summarizes static feebate outcomes for these major manufacturer groupings. With the consumption-only feebate, the D3 members all pay net fees, amounting to $3.1 billion in aggregate for the 1990 model year sales mix. The J5 members receive net rebates amounting to $2.7 billion. This highlights a second major issue: the "domestic versus import" problem of net fees for the Big Three and net rebates for most Asian manufacturers. The domestic versus import problem is linked to the light truck problem, since light trucks are an important part of D3 market share.

Besides these concerns, several others would need to be addressed in developing a workable feebate program:

1. Ways to deal with light trucks;
2. Domestic versus import problem;
3. More generally, equitable treatment of manufacturers ensuring that all have incentive to improve their fleets without creating an unfair competitive advantage because of particular fleet characteristics;
4. Leverage needed to effect a desired fuel economy improvement;
5. Consumer equity;
6. Understandability to consumers;
7. Administrative costs and government revenue impacts; and
8. Alternatively fueled vehicles.

This paper introduces size-based feebates as a way to address Issues 1 through 3. Discussions of the remaining issues may be found elsewhere (*3,5,6*).

SIZE-BASED FEEBATES

Some of the drawbacks of a consumption-only formulation may be addressed by incorporating other vehicle characteristics into the calculation of the incentive. Vehicle size, pollutant emissions, and crashworthiness have all been proposed for formulating feebate proposals. Other attributes that could be considered are domestic content, payload weight, power or power/weight ratio, and alternative fuel use. Considering the variation in vehicle size among different manufacturers has also been proposed for reforming fuel economy standards (*7*). Overall, average vehicle size has been fairly stable, despite CAFE standards and changes in fuel prices. Since 1976, the average interior volume of new cars dropped only 3 percent and wheelbase dropped 7 percent, compared with much larger changes in fuel economy.

Interior volume is the basis of the size classifications used to group vehicles in the Environmental Protection Agency's (EPA's) *Gas Mileage Guide* (*8*). However, it is difficult to compare interior

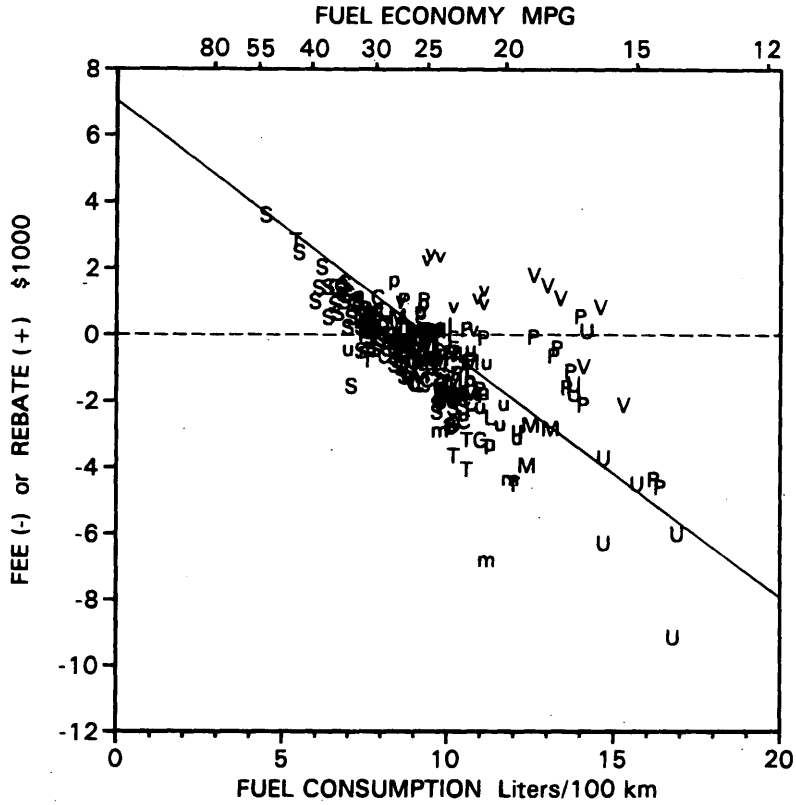

FIGURE 3 Footprint-normalized consumption feebates, (with separate car and light-truck reference levels) versus nameplate fuel consumption. Codes are as given in Figure 2; reference levels are 87.40 g/(km m²) for cars and 102.48 g/(km m²) for light trucks.

volume among different passenger vehicle types (e.g., cars, station wagons, vans), and it is even less valuable for comparing light trucks (pickups, sport utilities, cargo vans). Payload weight might be considered, but it is not defined for regulatory purposes. Defining payload weight in a consistent and reliable way across vehicle classes would be difficult. Exterior dimensions provide a more universal measure of vehicle size. For example, one could use vehicle "shadow," the product of overall length times overall width. A difficulty with exterior dimensions is that they are easily affected by cosmetic changes to vehicles.

Wheelbase (the distance between the front and rear axles) is a universal measure of vehicle size for which trend data are available (*9*). Track width is the distance between the right and left tire centerlines. Track width often differs slightly between the front and rear wheels, but it can be averaged readily. Footprint is defined as the product of wheelbase and average track width and has units of area. Wheelbase and track width are widely reported vehicle specifications related to vehicle structure and are not changed except during major redesigns. Neither is currently considered for regulatory purposes. In contrast with payload weight or interior volume, footprint is well-defined for all major classes of light-duty vehicle. Footprint is selected as a basis for this analysis for reasons of its convenience, universality, and likely stability. Nameplate average footprints for top-selling 1990 vehicles are given in Table 1. The 1990 sales-weighted average values are 3.86 m² for cars, 4.45 m² for light trucks, and 4.05 m² overall.

For light trucks, there is less certainty about the probable design response to incentives based on footprint. Light trucks have a wide variety of characteristics, and their market segment has evolved rapidly over the years. Track width varies little among the configurations of a given model (although some heavy-duty pickups have twin rear wheels, resulting in a wider rear track). However, pickups and vans often have a range of wheelbases. For example, in 1990 Ford F-series pickup wheelbases ranged from 117 to 208 in.; the Chevrolet standard pickup wheelbases ranged from 118 to 169 in. A concern for footprint-based incentives is the possibility of shifting sales to versions with larger wheelbases. However, a larger wheelbase can incur a weight penalty, lowering fuel economy. The relative manufacturing cost trade-offs will merit further investigation if a footprint-based incentive is pursued.

A size-adjusted feebate scheme can be developed by defining an energy factor as the ratio of fuel consumption rate to footprint. For a given fuel, this is equivalent to the ratio of greenhouse gas emissions rate to footprint, which is the formula used for this analysis, anticipating extension to alternatively fueled vehicles. For gasoline vehicles as considered here, energy factors are calculated using a full fuel cycle CO_2-equivalent emissions rate of 12 $kgCO_2$/gal and a fuel economy shortfall of 20 percent. For example, a vehicle rated at 30 mpg with a 4-m² footprint would have an energy factor of 78 gCO_2/(km m²). Dropping the units, average footprint-based energy factors are 87 for cars, 102 for light trucks, and 92 overall for the 1990 new fleet.

TABLE 1 Feebates for Top-Selling 1990 Light-Duty Vehicles Using Consumption-Only and Size-Adjusted Formulations

MAKE	MODEL[a]	CLASS[b]	MPG	Footprint (m^2)	CONSUMPTION-ONLY Feebate ($)	CONSUMPTION-ONLY price change	SIZE-ADJUSTED Feebate ($)	SIZE-ADJUSTED price change
Nissan	SENTRA	S	34.8	3.49	2,044	-21%	1,334	-14%
Ford	ESCORT	C	34.4	3.59	1,985	-23%	1,471	-17%
Honda	CIVIC	S	34.3	3.63	1,970	-19%	1,558	-15%
Toyota	COROLLA	S	31.7	3.45	1,549	-15%	255	-2%
GM	Geo PRIZM	S	31.4	3.45	1,496	-13%	173	-2%
GM	Chev. CAVALIER	C	30.9	3.62	1,405	-16%	497	-6%
GM	Pont. GRAND AM	C	30.0	3.70	1,234	-10%	413	-3%
Honda	ACCORD	C	29.6	4.02	1,155	-8%	1,128	-8%
Toyota	CAMRY	C	28.9	3.81	1,011	-7%	346	-2%
GM	Chev. CORSICA	M	28.3	3.70	881	-9%	(213)	2%
Ford	PROBE	C	27.5	3.67	700	-5%	(606)	5%
GM	Olds.CUTLASS CIERA	M	27.0	3.92	582	-4%	(86)	1%
GM	Buick CENTURY	M	26.9	3.90	557	-4%	(165)	1%
GM	Pont. GRAND PRIX	M	26.1	4.08	357	-2%	(21)	0%
GM	Chev. LUMINA	M	26.1	4.08	357	-3%	(21)	0%
Ford	TEMPO	C	26.0	3.62	331	-3%	(1,435)	14%
Ford	TAURUS	M	25.9	4.17	305	-2%	141	-1%
GM	Chev. S-10	p	25.7	3.76	252	-3%	755	-8%
GM	Buick LESABRE	L	25.0	4.29	60	-0%	59	-0%
Chrysler	Dodge CARAVAN	v	24.8	4.57	3	-0%	2,499	-17%
Chrysler	Plym. VOYAGER	v	24.8	4.57	3	-0%	2,499	-16%
Ford	MUSTANG	S	24.3	3.68	(143)	1%	(2,077)	15%
Ford	RANGER	p	24.2	3.83	(173)	2%	245	-2%
Ford	Linc. TOWN CAR	L	23.0	4.77	(553)	2%	307	-1%
GM	Chev. CAPRICE	L	23.0	4.58	(553)	3%	(134)	1%
GM	Chev. BLAZER S-10	u	22.4	3.62	(758)	5%	(1,533)	10%
Ford	BRONCO II/EXPLORER	u	22.0	4.00	(901)	6%	(413)	3%
GM	Cadi.FLTWD/DEVILLE	L	22.0	4.40	(901)	3%	(1,098)	3%
GM	Chev. ASTRO	v	21.5	4.65	(1,087)	7%	1,159	-7%
Chrysler	Jeep CHEROKEE	u	21.2	3.78	(1,203)	8%	(1,717)	11%
Ford	AEROSTAR	v	21.1	4.68	(1,243)	9%	1,012	-7%
GM	Chev. C/K-1500	P	17.8	4.87	(2,791)	22%	(619)	5%
Ford	F150	P	17.7	4.98	(2,847)	22%	(399)	3%
Ford	F250	P	16.8	5.66	(3,380)	26%	560	-4%
Ford	ECONOLINE	V	16.1	6.05	(3,836)	28%	850	-6%

[a]The 35 top-selling 1990 nameplates (50.3% of light duty sales), listed by decreasing sales-weighted fuel economy (unadjusted EPA composite rating) as given by the ORNL MPG and Market Shares Report (8).

[b]Class codes: C=Compact, L=Large, M=Midsize, S=Subcompact, P/p=Large/Small pickup, U/u=Large/Small utility, V/v=Large/Small van.

The resulting feebates, computed relative to a single reference level for the 224 nameplates analyzed here, are plotted in Figure 2. This graph shows the variation created by footprint adjustment compared with feebates based on fuel consumption alone, which follow a straight line. Feebates are calculated as on-road CO_2 emissions rate divided by footprint, using a conversion constant of 9321 (mpg g/km), a rate of $124 per unit difference in energy factor, and a single reference level of 92.36 g/(km m^2) for both cars and light trucks. For comparison, the line shows a consumption-only feebate extension of the gas guzzler tax. Size adjustment alone does not eliminate the efficiency gap between cars and light trucks, which accounts for much of the disparity between the D3 and J5 fleets. The residual imbalance is shown in the second line of Table 3. Aggregate D3 fees are halved compared with the consumption-only case, but a substantial net transfer remains.

The next step is to analyze a scheme with separate reference levels for cars and trucks, using the average car and light-truck energy factors noted earlier. The feebate rate is kept the same for both fleets, maintaining a common incentive level per unit of size-adjusted fuel consumption. The resulting feebates are plotted in Fig-

TABLE 2 Fuel Consumption–Based Feebates, Fixed 1990 Fleet Outcome by Manufacturer

MANUFACTURER	FLEET MPG	GHG[a] (g/km)	DIFFER[b] FROM AVG	NET FEEBATES[c] (Million $)	AVG. PER[d] MODEL ($)
BMW	21.9	425	13%	-53	-922
Chrysler	23.8	392	4%	-527	-306
Daihatsu	37.8	247	-34%	41	2445
Ford	23.0	406	8%	-1835	-567
GM	24.3	384	2%	-726	-150
Honda	30.4	306	-19%	1121	1320
Hyundai	33.3	280	-26%	256	1818
Isuzu	22.1	421	12%	-95	-851
Jaguar	21.3	438	16%	-22	-1165
Mazda	26.9	346	-8%	197	562
Mercedes	21.2	439	17%	-75	-1192
Mitsubishi	27.7	336	-11%	140	746
Nissan	27.3	342	-9%	402	651
Porsche	21.9	426	13%	-9	-949
Rover	16.0	583	55%	-18	-3904
Saab	25.9	360	-4%	8	299
Subaru	28.9	323	-14%	108	1007
Suzuki	33.0	283	-25%	39	1762
Toyota	28.1	331	-12%	881	846
VW	28.9	322	-14%	160	1011
Volvo	24.6	379	1%	-5	-51
Yugo	33.0	282	-25%	13	1768
OVERALL	24.8	376		0	1153

[a]Fleet average full fuel cycle greenhouse gas emissions, based on an emissions factor of 3.2 kg/liter (CO_2-mass equivalent) for gasoline and 20% fuel economy shortfall.

[b]Difference of each manufacturer's fleet average GHG emissions rate relative to the 1990 light duty vehicle average of 376 g/km.

[c]Manufacturer's net outcome [Fees (-), Rebates (+)] assuming a fixed 1990 sales mix and a feebate rate of $18.90 per g/km .

[d]Manufacturer's net outcome divided by sales; the overall average per model is the sales-weighted mean absolute value of all feebates.

ure 3, with the straight line of a consumption-only feebate again shown for comparison. It turns out that a footprint-based system results in no net fee transfer from light trucks to cars. There is still a net D3 to J5 transfer, as shown in the third line of Table 3. However, with net D3 fees of $0.5 billion and net J5 rebates of $1.1 billion, the transfer is mitigated greatly compared with the consumption-only case.

Separating the car and light-truck fleets results in a marked difference in the treatment of vehicles, as shown in the last two columns of Table 1. Rebates on subcompacts are reduced. Some cars that received rebates when compared with the overall light-vehicle average now get fees, since their adjusted fuel consumption is above average for cars. For example, the "m" outlier below the line in Figure 3 at 11 L/100 km is the Porsche 911, a high-powered luxury sportscar classified as a minicompact. Its fee is over $6,000 since it is so inefficient for its size relative to other passenger cars. The largest fees among the top-selling 1990 car nameplates fall on the Ford Mustang and Tempo. Light trucks in general and vans in particular fare much better under this system. Rebates for the Chrysler minivans rise to 16 to 17 percent of their price, and even the Ford Econoline now shifts to a rebate. This is also illustrated in Figure 3, which shows van rebates well above the line. There are still large fees on the sport utilities; for example, nameplate average fees are 10 to 11 percent of price for the Chevy Blazer and Jeep Cherokee. In contrast, some minivans (plotted by small "v") earn rebates of more than $1,000, because their footprints are much larger and they are compared with the class of all light trucks.

TABLE 3 Summary of Outcomes for Various Feebate Formulations with Static 1990 Fleet Mix

Type of Feebate Formulation	Aggregate rebates (fees) billion (10^9) dollars	
	D3	J5
Consumption only, treating all light vehicles together	(3.089)	2.741
Footprint-adjusted, treating all light vehicles together	(1.446)	1.852
Footprint-adjusted, with separate reference levels for cars and light trucks	(0.452)	1.118
Separate formulas, volume-adjusted for cars and footprint-adjusted for light trucks	0.798	(0.231)

One way to improve the outcome for U.S. domestic manufacturers is with a hybrid feebate system, using volume adjustment for cars and footprint adjustment for light trucks. Further details on such a system are given elsewhere (*6*). In this case the range of size-based feebates for vehicles having the same fuel economy becomes quite large, as much as ±$7,000. For example, there would be a $14,000 difference between a minivan and a relatively inefficient sports or luxury minicompact. A hybrid system using the 1990 fleet mix results in aggregate net rebates of $0.8 billion for the D3 and gives all of the domestics a net positive outcome. The J5 groups end up slightly negative, with aggregate net fees of $0.2 billion. Thus, by separating cars from light trucks and choosing an appropriate size adjustment procedure, it is possible to develop a feebate system that would not disadvantage U.S. automobile makers on the basis of a recent fleet mix.

OTHER ISSUES

It is beyond the scope of this paper to probe all of the issues raised when considering the design of feebate programs for the United States. The data base does permit brief examination of two additional issues: the variation of feebates with respect to vehicle configuration and the question of setting the rate (or "slope") of a feebate system.

Configuration Choice

A nameplate-level analysis masks the way in which feebates might affect choices among different configurations (submodels) of a nameplate. Configuration refers to the exact specification of a vehicle regarding attributes that affect emissions and fuel economy, such as engine displacement and transmission type. Table 4 presents fuel economy ratings and hybrid size-based feebate values for various configurations of several top-selling 1990 nameplates. For each nameplate, the most efficient configuration is 10 to 40 percent more fuel efficient than the least efficient configuration. Lacking size (volume or footprint) data by configuration, nameplate average sizes are used for these estimates, so that the feebate variability by configuration in Table 4 depends entirely on fuel economy variability. This limitation may overstate feebate variability, particularly for light trucks if more efficient confirmations have wheelbases smaller than the nameplate average.

The subcompact Geo Prizm, for example, was available in configurations ranging from 31 to 35 mpg in 1990. Its nameplate average was 31.4 mpg, implying an average rebate of $332. However, the Prizm's most efficient configuration, rated at 35 mpg, would earn a substantially larger rebate of $1,421. There is a similarly large variability among different configurations of nearly every model. Various configurations of the Ford Taurus, for which the nameplate average is near the reference level for cars, range from a fee of $578 to a rebate of $700. Even the Jeep Cherokee qualifies for a $948 rebate in its most efficient configuration, while its least efficient gets a $1,852 fee.

Ford pickup trucks are an important example of the way that a feebate would influence configuration choice. The Ford F150 series full-size pickup trucks were the top-selling light vehicle in 1990 and had a nameplate average fuel economy of 17.7 mpg. The fuel economy of various F150 configurations ranges from 15 to 21 mpg. With a separate footprint-normalized scale for light trucks, some of the F150s get rebates, as indicated in Table 4. Thus, a customer might opt for a small-displacement engine for his or her chosen make and model. For many customers, four-wheel drive and a large engine might be superfluous (but marketable) niceties, not warranted by their use of the truck, since most light trucks are used strictly for personal transportation. A feebate would make it more likely that buyers would forego unnecessary options detrimental to fuel economy. In aggregate, many such decisions could compound the positive response to a feebate program. Nevertheless, a configuration-level analysis is unlikely to substantially affect manufacturers' net fee and rebate burdens, as examined here without modeling market response.

Rationales for Feebate Rate

A key question in designing a feebate program is how to set the feebate rate, which determines the relative magnitude of fees and rebates. Several rationales might be used (Table 5).

A federal program could be designed as an extension of the gas guzzler tax, as in the examples presented earlier. Figure 1 illustrated such a feebate curve, which yields a feebate rate equivalent to $1.17/gal over 120,000 mi of vehicle usage (undiscounted). The corresponding feebate leverage is 8 percent. Similarly, a state program could be derived from an existing sales tax (e.g., by converting a flat 5 percent tax to a sliding scale between 0 and 10 percent tax). This would have a lower leverage, roughly 2 percent.

TABLE 4 Feebates for Selected Configurations of 1990 Models Based on Fuel Consumption (*18*)

Make Division MODEL / Class	Engine liters	cyl	Trans/ drive	MPG	Size[a]	ENERGY FACTOR	FEEBATE $
GM Geo	1.6	4	M5	35	83	76.64	1,421
PRIZM	1.6	4	M5	32	83	83.82	530
Subcompact	1.6	4	L4	31	83	86.53	195
FORD	1.9	4	M4	42	85	62.36	3,192
ESCORT	1.9	4	M5	36	85	72.76	1,903
Compact	1.9	4	A3	34	85	77.04	1,372
	1.9	4	M5	31	85	84.49	448
GM Buick	2.5	4	L3	30	98	75.72	1,535
CENTURY	3.3	6	L4	27	98	84.14	491
Midsize	3.3	6	L3	26	98	87.37	90
Ford	3.0	6	L4	27	100	82.46	700
TAURUS	2.5	4	A3	26	100	85.63	307
Midsize	3.8	6	L4	25	100	89.05	(118)
	3.0	6	M5	24	100	92.76	(578)
Chrysler Dodge	2.5	4	M5	28	4.57	72.84	3,675
CARAVAN	2.5	4	L3	26	4.57	78.44	2,981
Small van	3.0	6	L4	25	4.57	81.58	2,592
	2.5	4	A3	24	4.57	84.98	2,170
	3.3	6	L4	24	4.57	84.98	2,170
GM Chevrolet	2.5	4	L4	28	3.76	88.53	1,730
S10 PICKUP	2.5	4	M5	29	3.76	85.48	2,108
Small pickup	2.8	6	M5	25	3.76	99.15	412
	4.3	6	L4	23	3.76	107.78	(657)
	4.3	6	M5	23	3.76	107.78	(657)
Chrysler Jeep	2.5	4	M5 4wd	26	3.78	94.84	948
CHEROKEE	2.5	4	M5	26	3.78	94.84	948
Small utility	2.5	4	M5 4wd	24	3.78	102.74	(32)
	2.5	4	L4 4wd	23	3.78	107.21	(586)
	4.0	6	M5 4wd	22	3.78	112.08	(1,190)
	4.0	6	L4 4wd	21	3.78	117.42	(1,852)
Ford	4.9	6	M5	21	4.98	89.12	1,656
F150 PICKUP	4.9	6	L4	20	4.98	93.58	1,104
Large pickup	4.9	6	L4 4wd	19	4.98	98.51	493
	4.9	8	L4	18	4.98	103.98	(186)
	4.9	6	A3 4wd	17	4.98	110.09	(944)
	5.8	8	L4	16	4.98	116.97	(1,797)
	4.9	8	A3 4wd	15	4.98	124.77	(2,764)
	5.8	8	L4 4wd	15	4.98	124.77	(2,764)

[a] Size is passenger volume (ft^3) for cars and footprint (m^2) for light trucks (assumed the same for all configurations).

Another approach would be to estimate the rate needed to achieve a specified fuel economy improvement. This question is the inverse of estimating the expected market response to a feebate. Little experience is available to guide such estimation. Vehicle choice modeling indicates that consumption-based feebates with a leverage of about 2 percent would improve new fleet fuel economy by 12 percent (average of cars and light trucks) over a 20-year period (*3*).

The dominant effect of a feebate is expected to be manufacturers' making technology-based efficiency improvements across the fleet. Thus, guidance can be inferred from the estimated cost of technology improvement, which partly underlies the estimates of Davis et al. (*3*). The improvements in miles per gallon achieved over the past two decades were estimated to have cost $30 to $60/mpg (*10,11*). The cost of future improvements is a controversial subject. Independent estimates range from $40 to $110/mpg for a 30 to 40 percent improvement over 10 or 15 years (*12,13*). Automobile manufacturers give much higher cost estimates (*14*). As indicated in Table 5, implied feebate leverages range from 2 to more than 10 percent.

A fourth rationale for setting the feebate rate is based on the externalities of fuel consumption. Feebates can be viewed as a way to front-load external costs that occur over the life of a vehicle (*15*). For example, assuming an undiscounted externalities cost of $1/gal over a vehicle lifetime implies a leverage of 6.8 percent. A green-

TABLE 5 Leverage Values Implied by Various Rationales for Setting Feebate Rate

Rationale	Equivalent $/gallon[a]	Implied Leverage[b]
Extension of existing taxes		
U.S. Gas Guzzler Tax	1.17	8%
A state 5% sales tax	0.30	2%
For a 12% new fleet fuel economy improvement, from Davis et al. (3)	0.30	2%
Technology cost:		
Industry/SRI (13)	2.00+	13%
Greene and Duleep (11)	0.70	5%
DeCicco and Ross (12)	0.30	2%
Externalities:		
per $1/gal valuation	1.00	6.8%
$100/tonne carbon tax	0.33	2.3%
CA DRIVE+ (15)	0.13	0.9%
Manufacturer sales rebates	1.05	7%

[a]Based on undiscounted lifetime fuel consumption, assuming 120,000 miles and a 20% shortfall between rated and on-road fuel economy.

[b]Sales-weighted mean absolute value of fees and rebates.

house gas emissions tax of $100/T (carbon mass basis) would imply a leverage of 2.3 percent. This type of rationale was also used in the design of California's DRIVE+ proposal, which had a carbon emissions component as well as components based on external costs of tailpipe criteria pollutant emissions (*16*).

Finally, rebates used by automobile makers to promote sales range from 4 to 12 percent of new vehicle price. The median of a sample is 7 percent of price, suggesting that feebates with such a leverage would be influential; however, public information on the response to manufacturer rebates is unavailable. In January 1992 the Monsanto Company offered its employees a $1,000 incentive for buying a North American–made car; this program reportedly generated $53 million in new car sales (*17*). Rebates are used by electric utility companies to encourage consumers to purchase more efficient appliances. In incentive programs for efficient refrigerators, rebates typically range from $50 to $100, or 8 to 15 percent of new product price. These rebates have been successful in influencing manufacturer product planning and dealer marketing strategies as well as consumer purchasing decisions (*18*).

Thus, the information at hand leaves a large uncertainty about how to set the feebate rate. Modeling analyses and modest externality values suggest relatively low rates (e.g., a 2 percent leverage). Larger leverages, comparable to that of an extended gas guzzler tax, are implied by rebates used in other sales promotions. Further analysis is needed to develop better guidance on this critical design element of a feebate program.

CONCLUSION

Feebates—new vehicle purchase fees and rebates linked to fuel consumption—would provide a market incentive favoring greater energy efficiency and are an appealing approach to improving fleetwide fuel economy and reducing CO_2 emissions. This paper identified a variety of issues that should be addressed in developing a feebate program for the United States. A feebate system is an inherently flexible mechanism that can provide many programmatic options for addressing the issues at hand.

Examining a straightforward consumption-based feebate scheme served to highlight a number of these issues, particularly the car versus truck effects and the relative burdens on different manufacturers. Size-based feebates were introduced as a way to address intermanufacturer equity. Computing feebates as the ratio of fuel consumption to vehicle footprint and assigning separate reference levels for cars and light trucks substantially mitigates the domestic versus import revenue transfer problem and has the advantage of providing consistent treatment across vehicle classes. There are large variations in the feebates among different configurations of the same model, which would motivate consumers to choose the more efficient models among those having similar size and style.

The energy-saving and emission-reduction effects of a feebate program are difficult to estimate; a review of existing studies shows that the effects are dominated by manufacturers' responses in designing vehicles for higher efficiency. The response depends mainly on the feebate rate and should be independent of classifications and size adjustments used to address manufacturer equity issues. This analysis examined hypothetical feebate schemes having a rate based on an extension of the existing U.S. gas guzzler tax. Other bases for the rate were also identified, including the level estimated to produce a desired fleetwide fuel economy improvement; the cost of technology improvement; the value of avoided fuel consumption, including externalities; and comparability to manufacturers' sales rebates.

Despite uncertainties about the response, the feebate concept is flexible enough that it should be possible to design a system providing a strong incentive to improve the fuel economy of all classes of cars and light trucks while addressing the issues that arise. Thus, feebates appear to be a promising way to help reduce gasoline use

and CO_2 emissions by the U.S. light-vehicle fleet. Better quantifying the likely effects of feebate programs, especially manufacturer responses, is a worthy subject for ongoing study.

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