tion by cell. Marc Kaplan contributed methodological assistance, support, and direction to the development of the final form of DVSAM. Sarah LaBelle assisted in early documentation of DVSAM and provided a valuable editorial critique of early drafts of this paper. To these persons the authors extend their gratitude. The work reported in this paper was sponsored by the Office of Environmental Analyses, U.S. Department of Energy.

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# Projection of Typical Characteristics of Automobiles and Transit Vehicles for Policy Analysis

CHARLES L. HUDSON and EVELYN S. PUTNAM

ABSTRACT

In this paper the characteristics of three future automotive technology sets are described, starting from historical data and projected forward in time along paths suggested by given alternate future socioeconomic environments. The characterizations include quantified projections of automobile and transit vehicle weight, performance, fuel economy, consumer price, operating cost, materials of construction, fuels and environmental residuals associated with their manufacture, operating pollutants, and infrastructure-related energy expenditures, emissions, and cost. Brief descriptions of rationale and calculational procedures are also given, and selected results are presented. The breadth of the vehicle characterizations permits the effects of policy options on most facets of the urban transportation section to be examined. The methodologies developed in this work are generalized, and hence can be used with alternate assumptions in a variety of investigations. For purposes of the Technology Assessment of Productive Conservation in Urban Transportation (TAPCUT) policy analysis, each technology set consisted of six sizes of personal automobiles, each propelled by conventional

> Otto, stratified-charge Otto, turbocharged Otto, diesel, Brayton, or Stirling heat engines; and lead-acid, nickel-zinc, or lithium-sulfide battery-electric systems. The characteristics of 13 types of urban transit vehicles and systems were also projected for each technology set. Thirty-one current and potential materials of vehicular construction were identified. From the bills of materials developed for each vehicle, the amounts of 6 types of fuels used and 31 kinds of residuals produced in their production were also projected for each set, and then disaggregated into extraction, manufacturing, and recycling-production phases.

The characteristics of vehicles and the cost of fuels influence consumer choice and hence the composition of the vehicle fleet. In turn, fleet characteristics are major determinants of the fuel consumed in transportation, and they influence the effectiveness and direction of policies designed to encourage productive conservation. In this paper the methods used and the results obtained in projecting the technical characteristics of future vehicles as they might evolve under the conditions embodied in three alternative socioeconomic environments are described. The resulting technology data sets are expressed in terms of the performance, price, fuel efficiency, and other technical characteristics of alternative future vehicle stocks. These data sets were used as input data for the policy analysis models.

Materials of manufacture, vehicular manufacturing practices, and construction of infrastructure also influence energy consumption and the production of environmental residuals. These variables also were characterized for each technology data set, thus providing a basis for making alternative projections of direct and indirect urban transportation energy consumption and concomitant environmental effects.

## APPROACH

Figure 1 shows how the vehicle characterization task was organized. First, to provide a manageable data base, the enormous existing number of personal and transit vehicle types were aggregated into typical vehicle size classes. The U.S. Environmental Protection Agency (EPA) size classification system (1) was used for personal automobiles, and predominate existing sizes were used for transit vehicles. Then 1980 model automobiles were characterized by using sales-weighted average values for nonspecialty domestic and foreign vehicles in the selected size classes. Baseline transit vehicle characteristics were estimated by averaging available data in the appropriate size categories.

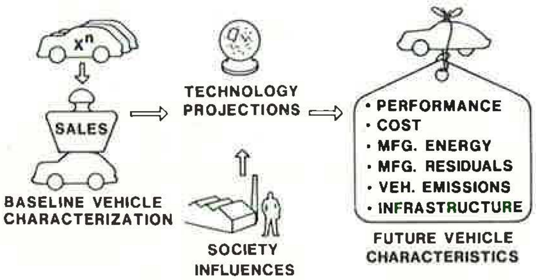

FIGURE 1 Major vehicle characterization tasks.

Qualitative judgments were made on how the alternative socioeconomic environments, including the projected fuel prices, might influence consumer demand and how industry might respond. Next, based partly on published estimates and partly on engineering judgment, the type of change in automotive technology that might take place in each alternative environment was quantified. By using these projections of technological change for vehicle subsystems, the technical characteristics of personal and transit vehicles comprising three potential vehicle stocks were defined.

## BASELINE VEHICLE CHARACTERIZATION

The baseline vehicle characteristics are given in Table 1 and were calculated from published statistics (2). Engine weights were estimated from the following equations derived from Dowdy et al. (3):

$$\text{Otto engine weight (lb)} = 11.878(\text{hp})^{0.761}.$$

$$\text{Generic diesel engine weight (lb)} = 9.659(\text{hp})^{0.888}.$$

The calculated generic diesel engine weights may be somewhat heavier than actually installed in 1980 automobiles because many of these are modified-Otto engines and are slightly lighter than generic diesels. Transit vehicle electric motor weights were estimated from published technical data. The body weights given in Table 1 represent the difference between curb weight and the calculated engine and motor weight.

Total automobile operating costs were not estimated because they depend on fuel cost, which was allowed to vary in the policy analysis. However, fuel efficiencies were characterized, and major repair, maintenance, and tire-replacement costs were estimated by using curb weight and price-related equations derived from Liston (4). Estimates were also made of engine-specific service costs.

Although generic diesels are expected to require less repair and maintenance, the modified-Otto diesels and generic diesels in the fleet are trouble prone (5). Therefore, the same repair and maintenance equation was used for both vehicle types.

Transit operating costs were estimated from statistical data (6) and personal interviews with several transit operators.

## ALTERNATE SOCIOECONOMIC ENVIRONMENT INTERPRETATION

To initiate the characterization it was necessary to project the kinds of vehicular performance likely to emerge in the given socioeconomic environments. In each of these environments fuel costs were projected to be considerably higher than experienced today, thus providing a major driving factor in the vehicle characterization. Specific fuel prices were projected for each scenario, whereas the amount of tax was varied by policy. The forecast prices are described in separate reports (7, and paper by Moses, LaBelle, and Bernard elsewhere in this Record). A dynamic, competitive society was interpreted to result in consumer demand for high performance and the best possible fuel efficiency. It was also interpreted to result in a business and industrial climate conducive to investment in research and development. As a result, satisfaction or consumer demands by the automobile industry was premised through the use of advanced materials, engine technology, and design methods. The vehicles characterized under these societal conditions were referred to as technology set A (the best vehicles) in the policy analysis.

In contrast, the community-oriented spirit of an

TABLE 1 Baseline (1980) Vehicle Characterization

| Engine, Motor Type, and Size Class | Engine and Motor Weight (lb) | Body Weight (lb) | Curb Weight (lb) | Power (hp) | Performance[a] (hp/lb) | Fuel Efficiency[b] (miles/gal) | Price[c,d] ($) | Operating Cost[c] ($/mile) |
|---|---|---|---|---|---|---|---|---|
| Automobile | | | | | | | | |
| Otto | | | | | | | | |
| Mini[e] | 330 | 1,826 | 2,156 | 79 | 0.032 | 28 | 3,495 | 0.032[f] |
| Small[e] | 343 | 2,026 | 2,369 | 83 | 0.031 | 24 | 4,002 | 0.034[f] |
| Medium[e] | 425 | 2,686 | 3,111 | 110 | 0.032 | 19 | 4,918 | 0.039[f] |
| Large[e] | 468 | 3,235 | 3,703 | 125 | 0.031 | 16 | 6,215 | 0.045[f] |
| Van[e] (15 passengers) | 491 | 3,197 | 3,688 | 133 | 0.033 | 14 | 4,930 | 0.038[f] |
| Van[g] (9 passengers) | 291 | 2,884 | 3,175 | 67 | 0.019 | 16 | 7,013 | 0.049[f] |
| Diesel | | | | | | | | |
| Small[h] | 305 | 1,549 | 1,853 | 48 | 0.022 | 40 | 4,597 | 0.037[f] |
| Medium[e,i] | 561 | 2,859 | 3,420 | 97 | 0.026 | 25 | 5,554 | 0.043[f] |
| Large[j] | 602 | 3,479 | 4,081 | 105 | 0.024 | 20 | 6,779 | 0.049[f] |
| Diesel buses | | | | | | | | |
| 25-28 ft | 713 | 12,087 | 12,800 | 127 | 0.010 | 7 | 62,600 | 1.76[k] |
| 35-40 ft | 1,112 | 22,388 | 23,500 | 210 | 0,009 | 3.5 | 115,000 | 1.76[k] |
| Rail, heavy electric | 5,500 | 76,000 | 81,500 | NA | NA | 8.4[l] | 500,000 | 2.00 |

[a] 300-lb load.
[b] Automobiles, EPA urban cycle; transit vehicles, experienced.
[c] Price and cost in 1975 dollars.
[d] Basic vehicle with automatic transmission.
[e] Sales-weighted data.
[f] Less fuel cost.
[g] Volkswagon van.
[h] Volkswagon Rabbit.
[i] 1980 Oldsmobile diesel price (deflated).
[j] 1980 Olds 98 data (deflated).
[k] Approximate; depends on labor costs.
[l] kWh/car mile.

environmentally concerned and family-centered society would cause consumers to be willing to sacrifice performance for improved fuel economy and reduced emissions. This inferred extremely light, low-power vehicles designed to maximize internal volume at the expense of styling. Nevertheless, intensive research and development would be required to attain maximum engine efficiency and weight reduction. In this consensus society automobile manufacturers would attain the same technological success in achieving these goals as in the competitive society, but would select different materials and promote greater material recycling. The resulting vehicle stock is referred to as technology set B (the conservation vehicles) in the policy analysis.

In a divisive society characterized by a lack of national purpose and sharply stratified economic classes, consumer automobile demands might split into prestige vehicles with high-performance, fair-to-good fuel economy at a high price, and utilitarian vehicles with good fuel economy at a low price. In this uncertain and socially inefficient climate an aversion to risk taking would develop within industry, thereby resulting in substantially lower technological achievement. In general, technological progress might range from 50 to 75 percent of that projected for the other alternative socioeconomic environments, with most of that progress driven by the federal fuel economy laws now in effect (Energy Policy and Conservation Act of 1975). This vehicle stock projection is referred to as technology set C (the expected vehicles) in the policy analysis.

Transit vehicle technology was judged less sensitive to socioeconomic pressures because of traditional industry conservatism; thus it was projected to follow slow evolutionary trends. No radical designs would be offered, but relevant technology improvements from the automobile industry would be adopted.

## TECHNOLOGY PROJECTIONS

In projecting characteristics of future urban transportation technologies, the market entry of new engine types [program combustion (PROCO) and Texico control combustion system (TCCS) stratified charge, Brayton, and Stirling] and lead-acid, nickel-zinc, and lithium-sulfide battery-electric and hybrids was considered in addition to existing Otto and diesel engines. Intrinsic engine-efficiency improvements were projected separately from improvements gained through engine weight reduction. Body weight reductions were considered as the sum of downsizing and material substitutions. Improvements in timing and technology entry dates were driven by industry capacity and other considerations appropriate to the alternate-socioeconomic, environment-derived technology sets. Figure 2 shows the projection method, and Figures 3-10 show anticipated changes in engine and body technology for each technology set. In Figures 3-10 curves derived from published estimates are presented as solid lines. Curves generated in the course of this study are shown as dashed lines. Rationale and supporting bases for these subsystem projections are described in the following subsections.

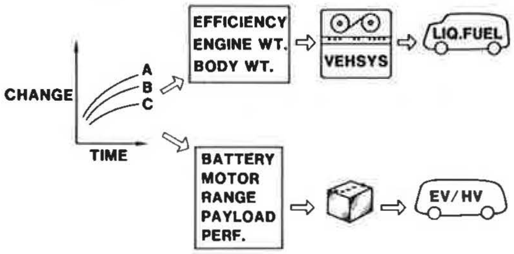

FIGURE 2 Projection method.

### Specific Horsepower

In Figure 3 the 10 percent improvement in specific horsepower by 1985 and the 15 percent improvement projected by 1990 for technology sets A and B are estimates given by Renner and Siegel (8) for the uniform-charge Otto engine. The 15 percent improvement correlates with the projections given by Ciccarone (9). It was estimated that technology set C, in 2000, would approach the 1990 efficiency of sets A and B. Although few such specific projections for other engine technologies were located, it was assumed that competitive forces would generally result in similar efficiency improvement curves for all technologies in a specific technology set.

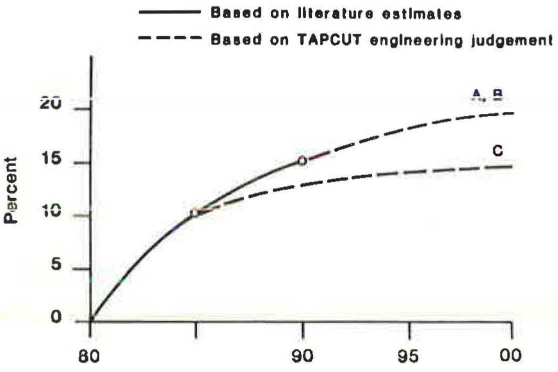

FIGURE 3 Increase in engine-specific horsepower, percentage by year and technology set.

Otto-engine efficiency improvements are expected to result from modifications such as closed-loop combustion control, low-friction lubricants, fuel injection, combustion-chamber shape, knock sensing, and improved power train matching. Diesel engine efficiencies are projected to improve from higher speed [revolutions per minute (rpm)] capabilities, better injector and combustion chamber design, increased structural rigidity, and improved power train matching. Although Brayton and Stirling engines are currently under development, efficiencies should improve over current estimates by the percentages given in Figure 3 when improved understanding of combustion dynamics, hydrodynamic flows, and high-temperature management techniques is achieved. Electric motors may show a substantial shift to alternating current (ac) operation and control. Turbocharging was considered in this study as a load-leveling add-on (see Figure 5), but it is not included in Figure 3.

## Uniform-Charge, Otto-Engine Weight

The technology set A and B curve in Figure 4 represents the total estimated weight reduction that could be achieved through design improvements and substitution of lighter materials. The 1980 baseline weight includes data presented by Bryant (10).

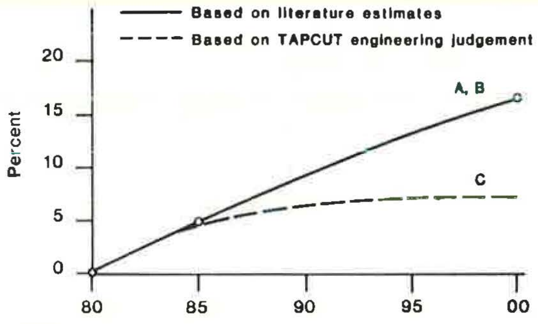

FIGURE 4 Reduction in uniform-charge Otto-engine weight, percentage by year and technology set.

The estimated 5 percent weight reduction by 1985 for Otto engines in all technology sets represents a continuation of the trend to replace cast-iron cylinder heads with aluminum (11), and to replace other lightly loaded parts with either aluminum or plastic materials. The year-2000 weight reduction for technology sets A and B (shown in Figure 4) is based on an estimate that a 12 to 15 percent weight reduction can be achieved by using all-aluminum engines and perhaps magnesium as a crankcase material (12,13). Increased use of high-temperature plastics is also projected.

A recent study reviewed contemporary engines and found that advanced engine power-to-weight ratios were 16 to 17 percent better than in 1978 (note that these data were from a 1981 unpublished draft report by C.L. Hudson of Hudson Associates on an updated aluminum-air vehicle cost procedure; this report was prepared for Lawrence Livermore National Laboratory). This correlates well with the sum of the efficiency and weight percentage projections given in Figures 3 and 4 when extrapolated to 1978. In the same study naturally aspirated advanced diesel engines were found to be about 20 percent heavier than Otto engines of equivalent horsepower in 1981 versus 45 percent heavier in 1980. These data support the estimates shown in Figure 6.

In contrast to the optimized engines projected for technology sets A and B, the engines in set C represent only minor weight-reducing changes after 1985, such as the use of aluminum and plastic radiators, filter housings, and nonstructural bracketing, with no major additional changes to the engine.

## Turbocharged, Uniform-Charge, Otto-Engine Weight

The curves in Figure 5 are mostly conjectural and based on 1980 data, which indicate that turbocharging can boost peak horsepower nearly 50 percent (2). If the turbocharger were considered a load-leveler, then the engine could be downsized. However, a weight penalty might be incurred, and the overall weight reduction might be about 35 percent. The shape of the curves reflects the projections of Shackson and Leach (14) that the use of turbocharging will increase significantly between 1987 and 1990.

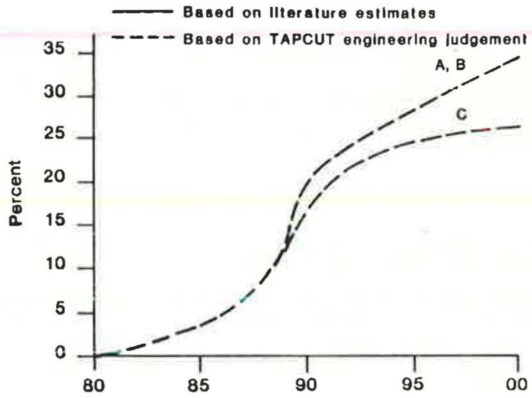

FIGURE 5 Weight reduction in uniform-charge Otto engine with turbochargers, percentage by year and technology set.

## Diesel Engine Weight

Domestic (and some foreign) diesel engines are modified production Otto engines designed expressly to attain corporate average fuel economy (CAFE) standards. The durability of these engines is not yet proved. If diesel emission-control technology permits the eventual 0.4 g per mile $NO_x$ and other potential standards for emissions unique to the engine to be met, then a decision is likely to be made before 1990 to aggressively pursue diesel technology (14). Under these conditions generic diesels would probably be developed for domestic automobiles in all three technology sets but for different reasons. In technology set C the underlying cause might be liability reduction, and in sets A and B the cause might be the pursuit of maximum efficiency and reliability.

To obtain Otto-engine weight equivalence, turbocharging of generic diesels may be required (15). This judgment is reflected in the 1990 crossover point in the diesel weight-reduction curve for sets A and B shown in Figure 6. In addition to turbocharging, an estimated weight reduction of about 30 percent for advanced (adiabatic) diesels is also projected (15). However, the less-optimistic estimate of a 20 percent weight reduction made by Dowdy et al. (3) is more realistic and was adopted for the characterization.

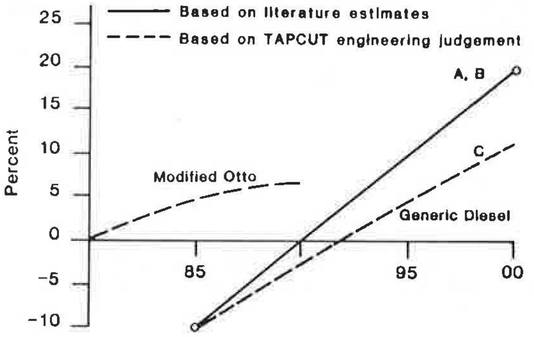

FIGURE 6 Reduction in diesel engine weight relative to 1980 Otto engine, equivalent horsepower, percentage by year and technology set.

## Stratified-Charge, Otto-Engine Weight

The PROCO or TCCS type of stratified-charge engine incurs a weight penalty compared to Otto engines (3,15). Nevertheless, the fuel efficiency is considered nearly the same as the diesel (14). The estimates of future weight reduction shown in Figure 7 are conjectural, but follow the same slope as weight-reduction projections for the Otto engines because similar weight-saving techniques might also apply.

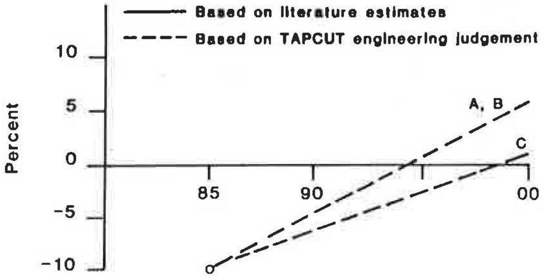

FIGURE 7 Weight reduction in stratified-charge Otto engine, relative to 1980 Otto engine, equivalent horsepower, percentage by year and technology set.

## Brayton-Engine Weight

The curve for technology sets A and B in Figure 8 represents average single-shaft and free turbine estimates, adjusted for low and high horsepower. The 1985 datum point is taken from Dowdy et al. (3), and the 2000 datum point is taken from the Jet Propulsion Laboratory (JPL) (15).

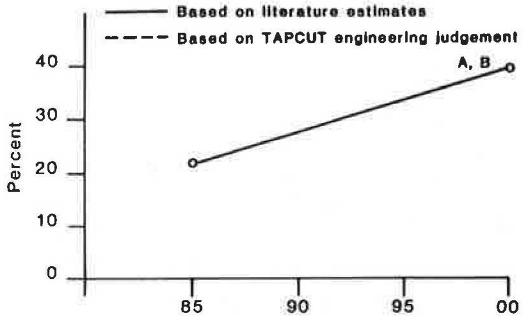

FIGURE 8 Weight reduction in Brayton engine, relative to 1980 Otto engine, equivalent horsepower, percentage by year and technology set (set C may see only limited use).

Introduction of Braytons around 1993 for technology sets A and B at about 1 percent per year appears possible (14), although low-horsepower applications may not be viable because of fluid-dynamics limitations. As indicated in Figure 8, Brayton engines probably would not be introduced in set C (except for the possibility of a specialized, very high performance vehicle) because consumer cost would be twice that of an equivalent horsepower Otto (14).

## Stirling-Engine Weight

Sources indicate that the specific weight of the Stirling engine is likely to be much greater than that of the Otto engine (3,15). The 2000 datum point in Figure 9 (15) would require extensive use of high-temperature ceramics. Optimism varies as to whether this degree of weight reduction can be attained. Renner and Siegel (8) are optimistic because the thermal efficiency of the engine approaches an ideal Carnot cycle. However, their optimism is tempered when the technological achievements necessary to realize this goal are taken into account. Nevertheless, the potential for reduced emissions is considered excellent.

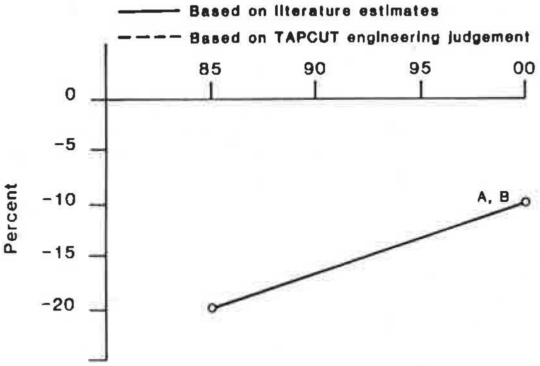

FIGURE 9 Weight reduction in Stirling engines, relative to 1980 Otto engine, equivalent horsepower, percentage by year and technology set.

Shackson and Leach (14) project fleet introduction of the engine at a low market penetration rate, with consumer costs at 2.5 times the Otto engine of equivalent horsepower. These forecasts were adopted for technology sets A and B. Given these technical requirements and cost implications, the Stirling engine was not introduced in technology set C.

### Body Weight Reduction

The term body in Figure 10 refers to all components of the vehicle other than the engine; that is, it includes the transmission and drive train. The majority of the vehicle weight is in the vehicle body; the degree of body-weight reduction was an important factor in the vehicle characterization. Many data sources were considered in determining the shape of the curves shown in Figure 10. However, the results of the analyses were fairly summarized by the estimates of Shackson and Leach (14). Therefore, the data points shown reflect their work. The uppermost curve for technology sets A and B represents the maximum weight-reducing effects of downsizing, design changes, and materials substitution. Body-weight reduction for technology set C results primarily from downsizing and design changes; curve C approaches the Shackson and Leach projections for these techniques. The lowest curve applied to vans in all technology sets.

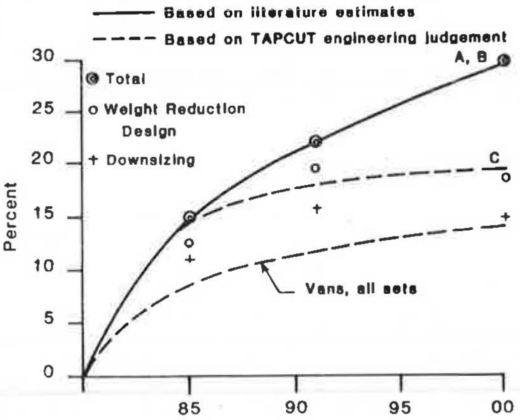

FIGURE 10 Body weight reduction, percentage by year and technology set.

## FUTURE VEHICLE PERFORMANCE AND COST CHARACTERISTICS

### Performance and Weight Calculations

A computerized iterative procedure (program VEHSYS) was used to calculate the performance and weight of all liquid-fueled automobiles projected for each technology set. Starting with a baseline vehicle of appropriate size, VEHSYS first uses the relationships given in Table 2 to calculate the engine and body weight of a future vehicle with the desired power-to-weight ratio based on 1980 technology.

The technological improvements projected in Figures 3-10 are then used to calculate the new relationship between horsepower and engine weight for the future vehicle. Then the engine and body weight of the future vehicle with the desired body power-to-weight ratio is computed, taking weight-propagation factors into account.

Electric and hybrid automobile weights were computed as a function of performance, vehicle size, battery characteristics, and design range by using a closed-form equation (16). Transit vehicle weight and performance projections were also estimated for each vehicle class and alternate socioeconomic environment (16).

**TABLE 2 Relationships Between Horsepower and Engine Weight (lb) Used in Estimating the Initial Performance and Weight Characteristics of Future Vehicles**

| Engine Type | Equation |
|---|---|
| Uniform-charge Otto | $WT = 11.878\ (hp)^{0.761}$ |
| Stratified-charge Otto | $WT = 15.750\ (hp)^{0.721}$ |
| Diesel | |
| Naturally aspirated | $WT = 9.659\ (hp)^{0.888}$ |
| Turbocharged | $WT = 6.232\ (hp)^{0.931}$ |
| Brayton | $WT = 55.4 + 2.265\ (hp)$ |
| Stirling | $WT = 66.667 + 4.333\ (hp)$ |

### Fuel-Efficiency Calculations

The equations derived to estimate automobile fuel consumption are based on empirical data accumulated by the General Motors Corporation (17). These data confirm a previously demonstrated linear relationship between fuel consumption and trip time, namely,

$$FC_w = a + b\,\bar{T} \tag{1}$$

where

$FC_w$ = fuel consumption, fully warmed engine;
$\bar{T}$ = trip time per unit distance; and
$a,b$ = constants related to the characteristics of the vehicle.

An expression was derived relating constants a and b to vehicle characteristics. Empirical cold-start fuel-consumption data (17) were then used as a basis for deriving factors that were applied to fully warmed fuel-efficiency estimates to project total fuel consumption for various trip distances.

The final form of the fuel-efficiency equation for fully warmed vehicles is

$$\begin{aligned} FC_w &= (0.0304W/B\eta_a) + (0.0753W/B\eta_c) + [(0.0269W)(1 - \eta_c)/B\eta_c] \\ &= [(11.33C_d A/B\eta_c) + 0.098e_i + 0.140e_b]\,\bar{T} \end{aligned} \tag{2}$$

where

$FC_w$ = fuel consumption, fully warmed engine (gal/mile);
$\bar{T}$ = trip time per unit distance (min/mile);
$W_t$ = vehicle curb weight (lb);
$B$ = energy content of the fuel (Btu/gal);
$\eta_a$ = system efficiency, acceleration (decimal expression);
$\eta_c$ = system efficiency, cruise (decimal expression);
$C_d$ = drag coefficient;
$A$ = frontal area (ft²);
$e_i$ = fuel flow rate, idling (gal/min); and
$e_b$ = fuel flow rate, braking (gal/min).

The overall system efficiencies ($\eta_a$ and $\eta_c$) are important contributors to the measure of fuel consumption; their estimation included improvements to transmissions, tires, accessories, and lubricants as well as other factors such as average engine efficiency in the urban driving regime.

The data in Tables 3 and 4 present the engine-specific and vehicle-specific values used in evaluating Equation 2. The data in Figure 11 compare the results of the calculated fuel-consumption relationships to trip time per unit distance (dotted lines) and empirical values for selected fully warmed vehicles.

**TABLE 3 Engine-Specific Values Used in Estimating Vehicular Fuel Consumption, Technology Set A**

| Engine Type | Fuel Flow[a], $e_i$ and $e_b$ (gal/min) | Running Efficiency (acceleration and cruise) | |
|---|---|---|---|
| | | Year | $\eta$ |
| Otto, uniform charge | $3.78 \times 10^{-3} + [8.9 \times 10^{-5} (hp-40)]$ | 1980 | 0.14 |
| | | 1990 | 0.18 |
| | | 2000 | 0.18 |
| Otto, stratified charge | $2.43 \times 10^{-3} + [6.2 \times 10^{-5}(hp-40)]$ | 1980 | 0.15 |
| | | 1990 | 0.19 |
| | | 2000 | 0.19 |
| Otto, turbocharged | $3.78 \times 10^{-3} + [8.9 \times 10^{-5} (hp-40)]$ | 1980 | 0.13 |
| | | 1990 | 0.17 |
| | | 2000 | 0.17 |
| Diesel | $1.2 \times 10^{-3} + [2.4 \times 10^{-5} (hp-40)]$ | 1980 | 0.17 |
| | | 1990 | 0.21 |
| | | 2000 | 0.21 |
| Brayton | | | |
| Diesel fuel | $5.05 \times 10^{-3} + [8.66 \times 10^{-5} (hp-40)]$ | 2000 | 0.28 |
| JP-4 fuel | $5.24 \times 10^{-3} + [8.98 \times 10^{-5} (hp-40)]$ | | |
| Stirling | $2.16 \times 10^{-3} + [5.53 \times 10^{-5} (hp-40)]$ | 2000 | 0.25 |

[a] Data from Dowdy et al. (*3*).

**TABLE 4 Vehicle-Specific Values Used in Estimating Vehicular Fuel Consumption, Technology Set A**

| Size Class | Year | Frontal Area, A (ft$^2$) | Coefficient of Drag, $C_d$ |
|---|---|---|---|
| Mini (2 passengers) | 1980 | 16.9 | 0.50 |
| | 1990 | 18.0 | 0.35 |
| | 2000 | 18.0 | 0.35 |
| Small (4 passengers) | 1980 | 18.8 | 0.50 |
| | 1990 | 20.0 | 0.35 |
| | 2000 | 20.0 | 0.35 |
| Medium (5 passengers) | 1980 | 21.8 | 0.50 |
| | 1990 | 23.0 | 0.35 |
| | 2000 | 23.0 | 0.35 |
| Large (6 passengers) | 1980 | 25.5 | 0.50 |
| | 1990 | 26.0 | 0.35 |
| | 2000 | 26.0 | 0.35 |
| Van (9 and 15 passengers) | 1980 | 28.2 | 0.55 |
| | 1990 | 30.0 | 0.40 |
| | 2000 | 30.0 | 0.40 |

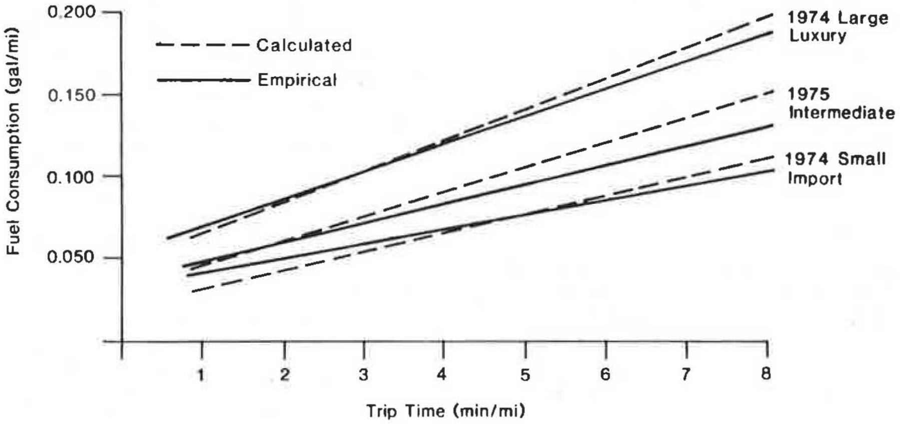

**FIGURE 11 Calculated versus empirical relationship between fuel consumption (fully warmed vehicle) and trip time per unit distance.**

The cold-start fuel-consumption data (17) result from experiments where short-trip consumption was measured for four vehicles, two with V-8 and two with 4-cylinder engines, both with and without fuel injection. By using these data, it was found that the instantaneous cold-start factor ($CSF_i$) could be characterized with sufficient accuracy for all engine sizes in all time periods by the following relationship:

$$CSF_i = 1 + 1.83e^{(-1.4D)} \qquad (3)$$

where $CSF_i$ is the instantaneous cold-start factor, and D is the trip distance (miles). The cumulative cold-start factor was then defined as

$$CSF_i = \left[\int_0^D (FC_w)d(D)\right] / \left[\int_0^D (CSF_i)(FC_w)d(D)\right] \qquad (4)$$

By using the distance and speed characteristics of the city cycle (LA-4) EPA test procedure (18), the fully warmed fuel consumption of each of the vehicles and the cold-start factor for each of the three trip segments was calculated. Finally, the overall trip fuel consumption was calculated according to the following equation:

$$FC = [0.35/(FE_1)(CSF_1)] + [0.37/(FE_2)(CSF_2)] + [0.27/(FE_3)(CSF_3)] \qquad (5)$$

where

$FC$ = trip fuel consumption,
$FE_1$ = fuel efficiency (miles/gal), first trip segment, and
$CSF_1$ = cumulative cold-start factor, first trip segment.

Figure 12 shows the benchmark fuel economy for new Otto-engine automobiles. A constant new car sales distribution of 50 percent small, 30 percent medium, and 20 percent large Otto-engine automobiles was used for all technology sets to illustrate the effects of technological change. The resulting harmonically averaged fuel economy for new car fleets approximates or exceeds the CAFE required value of 27.5 miles per gallon in 1985.

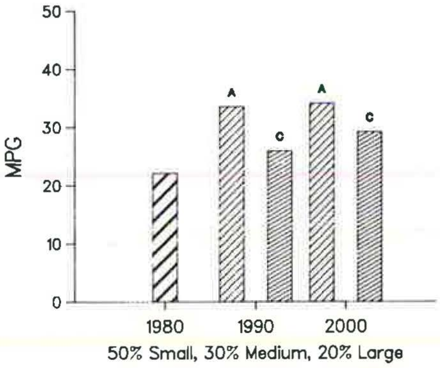

**FIGURE 12 Benchmark fuel economy for new Otto-engine cars in two technology sets used for TAPCUT policy analysis.**

### Purchase Cost Calculations

The methodology used to estimate liquid-fueled automobile purchase cost (in 1975 dollars) was based on the methodology devised for another study (19). It entailed applying regression analyses to historical data to develop equations relating the weight of vehicular components to a vehicle characteristic (e.g., horsepower) and subsequently developing equations relating the manufacturing cost of the components to either their weights or horsepower. The sum of the vehicle manufacturing and assembly costs was then converted to purchase cost (price) by a relationship derived from the difference between actual list prices and computed manufacturing costs of actual vehicles in a given model year. A simple extrapolation of prices derived from regression analyses does not necessarily account for competition-driven improvements in production processes. However, relative price differences influence a household's choice among new vehicles more than absolute price (see paper by Saricks, Vyas, and Bunch elsewhere in this Record). Because of the importance of relative price, this simplification of the price-determination process based on historically traceable data was used for automobiles.

Transit vehicle costs were judgmentally derived from past trends and adjusted for improvements from the use of lighter but more expensive materials. Electric and hybrid vehicle prices were computed by using material percentages by material type and projected costs on a per unit weight basis. A relationship between material cost and consumer price was used to compute final vehicle price (16).

### Operating Cost Calculations

Operating costs, less fuel (which was a policy variable), were estimated for repair and maintenance, replacement tires, and lubricating oil. The same operating cost relationships derived for the baseline vehicles represented those costs for future liquid-fueled vehicles except for the cost of lubricating oil changes for the Brayton engine, which was less than conventional engines. The cost of Otto-engine lubricating oil changes was used as a surrogate for that of the Stirling engine.

### Selected Cost and Performance Results

The data in Table 5 give the performance and cost characteristics that were projected for medium-sized liquid-fueled vehicles in 2000 for each technology set. The data in Table 6 indicate similar projected characteristics for selected battery-electric automobiles and transit vehicles.

The data in Table 5 indicate that horsepower for vehicles in set A is much higher than in sets B and C. The interpretation of the socioeconomic scenario leading to set A assumed that high-performance vehicles would be demanded by a highly competitive society. Power-to-weight ratios for the average automobile would be considerably higher than current averages, but not beyond the range of the highest performance automobiles now available. [For comparison, a better-than-average 1980 BMW 320I has 101 hp at a curb weight of 2,500 lb (2). Thus 132 hp in a 2,200-lb vehicle as shown in the table is not an extreme increase.] Conversely, the medium-sized vehicle in set C was designed for the segment of that society for which high performance was of little necessity. Further, in set C little attention was given to efficiency improvements even though fuel costs forced a moderate improvement over current conditions. Set B reflects the demand for the utmost in fuel economy. Thus vehicle efficiency was high and performance was deemed unimportant. Therefore, the low power-to-weight set B vehicles gained a significant fuel-economy improvement with respect to the other two sets.

As noted earlier, prices were computed from an extrapolation of regression analyses of current data. Recall that relative prices within a set were a major factor in vehicle choice. However, the only slightly lower price for the set A Otto-engine vehicle, as compared to its weight, is also a function of several observed factors. The regression analyses and comparison with actual list prices indicated that as vehicle weight is lowered, fixed manufacturing costs and return-on-investment expectations assumed a greater proportion relative to variable manufacturing costs, thus resulting in a higher price per pound of vehicle. In set A this effect drove the calculated price upward more than might be expected from its low curb weight. In set B this

TABLE 5 Future Vehicle Characteristics: Medium-Sized Class, 2000

| Vehicle and Technology Set | Engine Weight (lb) | Body Weight (lb) | Curb Weight (lb) | Power (hp) | Urban Cycle Fuel Efficiency (miles/gal) | Price[a] ($) |
|---|---|---|---|---|---|---|
| Otto engine, uniform charge | | | | | | |
| Set A | 358 | 1,832 | 2,190 | 132 | 27 | 5,240 |
| Set B | 131 | 1,826 | 1,957 | 35 | 35 | 5,258 |
| Set C | 198 | 2,100 | 2,298 | 52 | 26 | 5,321 |
| Otto engine, stratified charge | | | | | | |
| Set A | 413 | 1,847 | 2,260 | 135 | 30 | 5,256 |
| Set B | 149 | 1,831 | 1,979 | 35 | 37 | 5,262 |
| Set C | 214 | 2,105 | 2,319 | 52 | 28 | 5,333 |
| Otto engine, turbocharged | | | | | | |
| Set A | 198 | 1,792 | 1,990 | 123 | 28 | 5,551 |
| Set B | 75 | 1,812 | 1,887 | 34 | 33 | 5,619 |
| Set C | 140 | 2,082 | 2,222 | 51 | 27 | 5,622 |
| Diesel engine | | | | | | |
| Set A | 322 | 1,820 | 2,141 | 130 | 42 | 5,864 |
| Set B | 119 | 1,822 | 1,942 | 35 | 47 | 5,765 |
| Set C | 182 | 2,095 | 2,277 | 51 | 37 | 5,708 |
| Brayton engine | | | | | | |
| Set A | 214 | 1,791 | 2,006 | 124 | 41 | 7,018 |
| Sets B and C | - | - | - | - | - | - |
| Stirling engine | | | | | | |
| Set A | 426 | 1,842 | 2,268 | 136 | 42 | 6,896 |
| Set B | 173 | 1,837 | 2,010 | 36 | 54 | 6,160 |
| Set C | - | - | - | - | - | - |

[a] Price in 1975 dollars.

TABLE 6 Future Selected Medium-Sized Electric Automobile and Transit Vehicle Characteristics

| Vehicle and Technology Set | Engine or Motor/Controller Weight[a] (lb) | Battery Weight (lb) | Curb Weight (lb) | Urban Cycle Fuel Efficiency (kWh/mile) | Price[b] ($) | Range (mile) |
|---|---|---|---|---|---|---|
| Electric (Ni-Zn) | | | | | | |
| Set A | 306 | 830 | 3,294 | 0.36 | 7,295 | 125 |
| Set B | 276 | 761 | 2,969 | 0.33 | 7,198 | 125 |
| Set C | 365 | 886 | 3,476 | 0.42 | 8,084 | 125 |
| Transit | | | | | | |
| Bus, 35-40 ft (diesel) | | | | | | |
| Set A | 1,000 | - | 22,000 | 2.8[c] | 115,000 | - |
| Set B | 1,100 | - | 23,400 | 2.7[c] | 125,000 | - |
| Set C | 1,112 | - | 21,388 | 3.0[c] | 130,000 | - |
| Light rail (electric) | | | | | | |
| Set A | 3,400 | - | 61,600 | 5.7 | 370,000 | - |
| Set B | 3,400 | - | 61,600 | 5.7 | 370,000 | - |
| Set C | 3,400 | - | 62,500 | 6.2 | 370,000 | - |

[a] Motor/controller applies to electric vehicles only.

[b] Price in 1975 dollars.

[c] Miles per gallon.

effect was slightly more pronounced. In addition to the cost-versus-weight function, the manufacturing cost of an engine was found to be a fairly weak function of its power. This finding was partly substantiated by the observation that optimal high-powered engine prices listed by some manufacturers for some vehicles were less than $100 higher than for the lower-powered counterpart. Thus the high horsepower of the set A vehicle did not substantially contribute to its price. The combination of these factors and other subtle influences resulted in the rather narrow range of prices given in Table 5.

## CHARACTERISTICS OF FUELS AND RESIDUALS ASSOCIATED WITH THE MANUFACTURE OF VEHICLES

The energy and environmental consequences of vehicle production in each technology set was estimated by quantifying changes in material and vehicle production methods implicit in each of the alternative socioeconomic environments. Result highlights are presented in the following subsections.

### Method

A modularized data base was prepared for each material used in baseline and projected vehicles. Then the types and amounts of fuels required to produce these materials in extraction, production, and recycling processes were obtained from many sources (16). These data were then expressed in British thermal units (Btu) per fuel type per pound of material. A similar approach was used to formulate the data base on air and water residuals and solids resulting from the production of 1 lb of material in extraction, manufacture, and recycling phases.

Next a baseline bill of materials was prepared for each major component of each 1980 vehicle (engines, motors, batteries, and bodies). Then projections were made of future vehicles' bills of materials based on interpretation of the probable material substitutions implicit in each alternative socioeconomic environment. Finally the weight percentage of each material in a component was estimated, and component weights derived from the vehicle characterization were converted to weights of materials associated with a specific vehicle, the amounts of fuels consumed, and residuals produced in extraction and manufacturing.

An important aspect of this characterization was that only fuels used and residuals produced in the United States were associated with the production of a vehicle. Estimates of the percentage of imported materials in each alternate socioeconomic environment were made. Estimates of recycled material percentages (i.e., steel, aluminum) were also made, and these had significant impacts because recycling is less energy intensive and environmentally degrading than production from virgin materials.

The amount of fuel consumed (by fuel type) and the extraction and manufacturing residuals was calculated by using a computer program (VEHFR). The program data files contain estimates by technology set of the amount of fuel consumed and residuals produced by type per pound for 31 materials, disaggregated into extraction, manufacture, and recycling, and included assembly plant fuels and residuals. Output data include vehicle technology set, vehicle component and component weight, Btu by fuel type (coal, petroleum, natural gas, electricity, hydroelectricity, and miscellaneous), total Btus, weight of 11 air and 20 water residuals, and total solids. These data are also disaggregated into extraction and manufacture.

### Alternate Socioeconomic Environment Influences on Materials Production and Manufacturing Practices

For technology set A, the major effect of socioeconomic conditions and government policies was to increase exports and to initally relax environmental control on manufacturing. Production processes greatly improved and quickly replaced outmoded ones. Imports of ores and fabricated materials were reduced, and recycling increased moderately over 1980 levels. The use of coal would increase, and the use of petroleum would bottom out in 1985. Purchased electricity for use in some materials processing and in-plant operation increased.

The primary effect of socioeconomic conditions on technology set B was to sharply increase the recycling of materials. The conservation ethic resulted in reduced requirements for products and energy. Some ores were imported to reduce environmental degradation. Strict environmental controls were retained, but plant productivity had some improvement, despite controls, and there was a moderate amount of new plant construction. The use of coal increased slowly, with natural gas taking up the slack. Manufacturing sector requirements grew slowly.

For technology set C, little improvement was made over 1980 in conserving either energy or the environment. Lack of environmental control enforcement resulted in some transitory increases in plant productivity. However, few new plants were constructed, and the faltering economy required increased material imports. The amount of recycling also decreased. There was little change in the distribution of fuels used from the 1980 era.

### Materials and Residuals of Production: Characterization Highlights

In the area of materials substitution, the projected year-2000 bills of materials show light materials (aluminum, plastics, and magnesium) increasing in Otto engines from 8.5 to 52 percent for technology set A, to 54 percent for set B, and to 35 percent for set C. The use of lighter materials in bodies (aluminum, plastics, and carbon and graphite composites) follows the same pattern, increasing from 8.3 percent in the 1980 base year to 22 percent for technology sets A and B, and to 15 percent for set C.

A somewhat surprising result is shown in Figure 13, where manufacturing energy expenditures per pound of a medium-sized Otto-engine automobile are shown for each technology set. In set A energy use dips slightly between 1980 and 1990 as lighter vehicles are produced and plant efficiency improves. However, energy use rises sharply from 1990 to 2000 as more energy-intensive materials, such as aluminum and magnesium, are substituted and material imports are reduced to gain a favorable balance of trade.

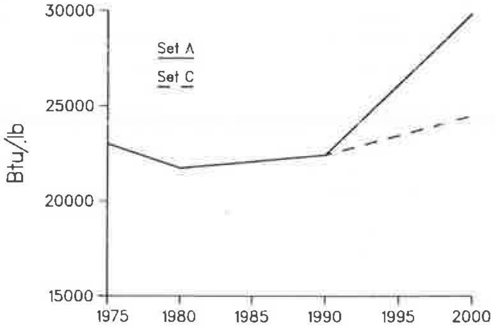

FIGURE 13 Comparison of weight-specific vehicle production energy for a medium-sized automobile with Otto engine in two technology sets.

Technology set B, with its emphasis on conservation and environment, is level between 1980 and 1990, even though plant efficiencies increase marginally and substitution of energy-intensive materials is instituted at an earlier date. Projected increases in recycling is the major reason for energy saving. However, increased use of light materials causes a slight rise in total energy from 1990 to 2000. Manufacturers reduced vehicle operating energy use (the greatest energy expenditure) and, as a result, incurred some increased energy use in production.

For technology set C, increased energy use after 1980 occurs as plant efficiency increases only slowly and productivity decreases. However, the situation is turned around after 1990, when substitution of energy-intensive materials has not been aggressively pursued and increasing material imports shift the energy expenditure and residuals burden outside the United States. The result is that energy use per pound of vehicle in 2000 in technology set C is the same as expended in set B. The difference is that in technology set C the favorable energy expenditure was at the expense of unfavorable trade balances, whereas set B gained it through recycling.

As an example to illustrate how residuals of production change with respect to technology sets, $NO_x$ air residuals associated with the production of a medium-sized automobile in technology set A (2000) decreased 47.5 percent over baseline levels, whereas in set B the decrease is 51.8 percent. The general vigor of the alternate socioeconomic environment leading to the characterization of technology set A resulted in substantial environmental benefits, even though priority research was delayed until late in the century. Technology set C improved 35 percent in spite of an indifferent attitude toward the environment. Here, again, much of the residual burden was shifted outside of the United States.

## ON-ROAD EMISSIONS CHARACTERIZATION

It was assumed that the most stringent 50,000-mile standards now proposed by the EPA at the time of this study for future implementation are the maximum practicable. Therefore, for currently regulated pollutants, future motor vehicle emissions were projected in accordance with the phase-in rate for each technology set. New emission standards for CO and $NO_x$, originally scheduled for 1981, were postponed in all technology sets until 1985. These CO and $NO_x$ standards were projected to remain in force through 1987 for technology sets A and C, with the more stringent, but not final, standards then in effect through 2000. In set B these more stringent standards became effective in 1983 with the final 0.4 g per mile $NO_x$ standard for Otto engines taking effect in 1988.

Diesel HC emissions from 1983 to 1987 were estimated to be 0.41 g per mile for technology sets A and C and 0.2 g per mile for set B. Only nonleaded gasolines were used in all technology sets in 1988, with set B implementing a faster phase-out of leaded fuels.

Among engine-specific projections, Stirling emissions were quite low in all emission categories for all potential fuels. Brayton-engine emissions were projected to be similar to Otto-engine emissions in 2000, with the best emission performance realized from use of diesel and alcohol fuels. Total suspended particulates were projected to be in the 5.2 g per mile range for all engines in all technology sets, except for the diesel to 1987 (about 5.9 g per mile for sets A and C, and 5.3 g per mile for set B), and zero for alcohol-fueled Stirling and Brayton engines. Aldehydes were projected to be within the rather close range of 0 to 0.04 g per mile, except for early technology sets A and C diesels, which were 0.07 g per mile.

## INFRASTRUCTURE CHARACTERIZATION

The capital cost, energy cost, and air and water emission burdens attendant to the construction of rights-of-way were assessed. A modularized data base was developed where structures related to light rail, commuter rail, expressway and freeway, and express busway transportation systems were typified according to architecture and other pertinent characteristics. A bill of materials was developed for each typical structure, and tabulations were made of the energy consumed and residuals associated with the production of those materials, the fuels used and emission produced in the construction process, and the capital cost of construction.

This data base permitted a desired infrastructural element to be conceptually constructed and the energy expenditure, emission, and cost of construction to be rapidly calculated. Other than the use of energy and residual projections for materials characterized in vehicular analysis, no attempt was made to relate the infrastructural projections to alternate socioeconomic environments.

## SUMMARY

The characterizations presented in this paper describe future automotive technology sets for policy analysis, starting from a baseline vehicle characterization derived from historical data. The baseline characterization was projected forward in time along paths suggested by given alternate future socioeconomic environments supported, where possible, by projections of other researchers in the field. The breadth of the vehicle characterizations permits the effects of policy options on most facets of the urban transportation sector to be examined, including transit, although detailed transit characterizations are not described here. The methodologies developed in this work are generalized, and hence can be used with alternate assumptions in a variety of other investigations.

## ACKNOWLEDGMENT

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# Energy-Conservation Strategies and Their Effects on Travel Demand

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## ABSTRACT

The types of impacts on urban travel demand that might be expected from two broad, multifaceted energy-conservation strategies are described. Based on sketch-planning travel demand modeling conducted for three case study regions and generalized extrapolation of these results to national totals, illustrative travel impact results are presented. Five different types of impact are considered: (a) mode choice by trip purpose (work versus nonwork), (b) variations in transit travel by city type, (c) vehicle miles of automobile travel for work and nonwork purposes, (d) variations in trips per capita and per trip length by purpose, and (e) distributional differences in terms of household (central city, suburban, exurban). The in-place policy, marked by a sharp rise in automobile out-of-pocket costs, had no increase in per capita automobile travel by 2000, although aggregate energy consumption was lowered. The individual travel strategy, which lowered automobile operation cost relative to the in-place policy by improvements to automobile fuel economy, achieved noticeable energy savings with negligible impact on choice of travel mode. The group travel strategy, on the other hand, significantly altered mode choice and saved transportation energy in this way. Significant improvements in transit service and strong automobile travel disincentives yielded dramatic shifts to group travel modes for nonwork travel. Work travel mode choice was affected to a lesser extent, with increases of 30 to 40 percent in transit and shared-ride modal splits.

Meaningful analysis of the many different supply- and demand-oriented strategies for conserving urban transportation energy is a complex undertaking. Not only is the range of available conservation options a wide one, but the applicability of such options within urban areas varies greatly by urban area size and density (1-3). When the potential impact of technology-oriented options (e.g., alternate fuels, engine technology advances, and greater fuel efficiency from the vehicle mix) is considered, another layer of complexity is added (see papers by Hudson and Putnam, and by Saricks, Vyas, and Bunch elsewhere in this Record). Even more complications arise when the analysis tools available for the examination of travel demand impacts are considered, together with the necessary behavioral assumptions that are associated with them (see paper by Kaplan, Gur, and Vyas elsewhere in this Record).

Consequently, because of these complications the analysis results presented in this paper are illustrative only. In order to permit a systematic yet wide-ranging analysis to move forward, a host of reasonable (but still limiting) assumptions has been made. For example, only two scenarios regarding the future socioeconomic characteristics of urban regions [household size, income, energy price, gross national product (GNP)] were considered. Among the many different combinations of energy-conserving actions that could be devised, only two--one emphasizing group travel options (transit and shared ride) and another emphasizing greater efficiency in individual vehicle travel--were investigated (to-