



Year 2005

UCD—ITS—RR—05—17 (1)

AVCEM: Advanced-Vehicle Cost and Energy Use Model Overview of AVCEM

Mark A. Delucchi

AVCEM: ADVANCED-VEHICLE COST AND ENERGY-USE MODEL

AVCEM DOCUMENTATION PART 1: OVERVIEW OF AVCEM

UCD-ITS-RR-05-17 (1)

Mark A. Delucchi

Institute of Transportation Studies
University of California
Davis, CA 95616

madelucchi@ucdavis.edu
www.its.ucdavis.edu/people/faculty/delucchi

October 2005

AVCEM DOCUMENTATION REPORTS

The documentation to AVCEM is published in six parts:

- 1) AVCEM Documentation Part 1: Overview of AVCEM
- 2) AVCEM Documentation Part 2: Model of Vehicle Cost and Weight
- 3) AVCEM Documentation Part 3: Model of Vehicle Energy Use
- 4) AVCEM Documentation Part 4: Periodic Ownership and Operating Costs
- 5) AVCEM Documentation Part 5: References and Parameter list
- 6) AVCEM Documentation Part 6: Appendix A, Modeling Battery and Drivetrain Efficiency

Documentation reports are published on Delucchi's faculty web page, www.its.ucdavis.edu/people/faculty/delucchi.

ACKNOWLEDGMENTS

The California Air Resources Board (CARB), the University of California Energy Institute (UCEI), the Hydrogen Pathways Program at the Institute of Transportation Studies at the University of California Davis, the Energy Foundation, Sierra Research,

and the U. S. Postal Service provided funding for this research. Of course, none of these sponsors necessarily endorse any of our methods or findings, and we are solely responsible for the material herein.

TABLE OF CONTENTS

INTRODUCTION	1
Overview of AVCEM and documentation.....	1
WHAT AVCEM DOES	2
Types of vehicles in AVCEM.....	2
Output of AVCEM.....	3
DISCUSSION OF MODELING INPUTS AND METHODS.....	5
Vehicle manufacturing and retail cost	5
The battery	7
The fuel cell and reformer system	8
The fuel-storage system.	10
Energy use: overview	10
Energy use: vehicle efficiency	11
Energy use: vehicle performance.....	11
Other ownership and operating costs.....	12
External costs and other social-cost components	15
Financial parameters for vehicle purchase.....	15
AN EXAMPLE OF HOW AVCEM WORKS	16
The fuel cell.....	16
The battery	17
Other systems	18

OVERVIEW OF AVCEM, ADVANCED-VEHICLE COST AND ENERGY-USE MODEL

INTRODUCTION

AVCEM is an electric and gasoline vehicle energy-use and lifetime-cost model. AVCEM designs a motor vehicle to meet range and performance requirements specified by the modeler, and then calculates the initial retail cost and total private and social lifetime cost of the designed vehicle. It can be used to investigate the relationship between the lifetime cost -- the total cost of vehicle ownership and operation over the life of the vehicle -- and important parameters in the design and use of the vehicle.

Overview of AVCEM and documentation

There are three major parts to AVCEM and the AVCEM documentation:

- the model of vehicle cost and weight
- the model of vehicle energy use
- periodic ownership and operating costs.

The **model of vehicle cost and weight** consists of a model of manufacturing cost and weight, and a model of all of the other costs -- division costs, corporate costs, and dealer costs -- that compose the total retail cost. The manufacturing cost is the materials and labor cost of making the vehicle. In our analysis, material and labor cost is estimated for all of the nearly 40 subsystems that make up a complete vehicle. We also perform detailed analyses of the manufacturing cost of the key unique components of electric vehicles: batteries, fuel cells, fuel-storage systems, and electric drivetrains.

The **model of vehicle energy use** is a second-by-second simulation of all of the forces acting on a vehicle over a specified drive cycle. The purpose of this model is to accurately determine the amount of energy required to move a vehicle of particular characteristics over a specified drivecycle, with the ultimate objective of calculating the size of the battery or fuel-cell system necessary to satisfy the user-specified range and performance requirements. (The cost of the battery or fuel-cell system is directly related to its size; hence the importance of an accurate energy-use and performance analysis within a lifetime cost analysis.) The energy-use simulation is the standard textbook application of the physics of work, with a variety of empirical approximations, to the movement of motor vehicles.

Periodic ownership and operating costs, such as insurance, maintenance and repair, and energy, are *in toto* about the same magnitude as the amortized initial cost, and hence an important component of the total lifetime cost of ownership and use. Because of this, and because these costs can vary with the vehicle technology, it is helpful to estimate them accurately. We develop detailed estimates of the most important of these costs, which are maintenance and repair and insurance. Note that in

the AVCEM documentation, periodic ownership and operating costs include external costs, such as the cost of air pollution, and financial parameters, such as interest rates.

The AVCEM documentation also contains an appendix that details some aspects of our modeling of battery and drivetrain parameters.

WHAT AVCEM DOES

Types of vehicles in AVCEM

AVCEM calculates the performance and cost of the following kinds of light-duty motor vehicles:

- gasoline internal-combustion-engine vehicles (ICEVs);
- methanol ICEVs; ethanol ICEVs;
- compressed natural-gas (CNG) ICEVs;
- liquefied natural-gas (LNG) ICEVs;
- liquefied-petroleum-gas (LPG) ICEVs;
- liquefied-hydrogen (LH₂) ICEVs;
- hydride-hydrogen ICEVs;
- compressed-hydrogen (CH₂) ICEVs;
- battery-powered electric vehicles (BPEVs);
- hydrogen fuel-cell-powered EVs (with or w/out peak-power device) (FCEVs);
- methanol FCEVs (with or w/out peak-power device); and
- hybrid ICE-electric vehicles.

As noted above, the fuel-cell vehicles may be hybridized with a peak power device, such as a high-power battery. AVCEM has over 1000 input variables (not counting “low-case” inputs separate from “high-case” inputs, and not counting optional multiple inputs of the same variable [e.g., for fuel-cell optimization]). It occupies several megabytes of storage space, and takes a minute to run on a personal computer. AVCEM is detailed and integrated: all vehicle components are linked analytically to vehicle weight, power, cost, and energy use, and the resulting computational circularity is solved by iterative calculations. The overall performance of the fuel-cell and the battery are calculated from second-by-second simulations that are the equivalent of simplified engine maps for ICEVs.

We emphasize that AVCEM is a vehicle-design *and* vehicle lifetime-cost model: it designs vehicles that satisfy range and performance requirements over a particular drive-cycle, specified by the user, and then calculates the initial and lifetime cost of that vehicle over the specified drive cycle.

AVCEM allows users to specify up to seven different kinds of vehicles for detailed analysis. As discussed more below, the user specifies parameters relating to energy use, weight, and manufacturing cost. The energy-use parameters describe the engine (e.g., engine size and number of cylinders), the transmission (e.g., gear ratios), the tires (e.g., tire size and rolling resistance), the body (e.g., drag coefficient), and more.

The weight and manufacturing cost parameters describe each of nearly 40 subsystems of the vehicle (e.g., suspension, seats, and emission control system).

There also are five different drive cycles, characterized by beginning and ending velocity, grade, and wind speed by time interval. The user selects one vehicle type and drivecycle from the among the five.

AVCEM presently has input specifications for a midsize vehicle (based on the Ford Taurus), a compact vehicle (based on the Ford Escort), a postal service delivery vehicle, a mini-car (mainly of our design), and an SUV (based on the Ford Explorer). There is an input file for two other vehicles, which can be anything from a motor scooter to a transit bus. Of course, AVCEM can be expanded structurally to accommodate more vehicle types.

Output of AVCEM

AVCEM calculates the following outputs:

- Vehicle characteristics:

- the peak power of the electric vehicle (a BPEV, HEV or FCEV) and the baseline ICEV
- the acceleration performance of the EVs and the baseline ICEV (the user specifies the starting and ending speed, grade, and wind speed in the test
- the weight of all of the vehicles types; the volume of the fuel-storage system and/or battery (EVs and baseline ICEVs only)
- the gasoline-equivalent fuel economy of all of the vehicle types (in miles/gallon, mi/kWh, and liters/100 km)
- the life of all of the vehicle types, in kilometers
- the gross peak power of the fuel cell (a key user-input design variable)
- battery cycle life, energy density, and retail-equivalent cost
- and the coefficient of drag for all of the vehicle types.

- Vehicle and subsystem manufacturing cost and weight: this includes the variable manufacturing cost, division cost, corporate cost, profit, dealer cost, and shipping cost; and the curb weight and loaded in-use weight, of the complete vehicle. AVCEM also summarizes the cost, the weight, and (in some cases) the volume of the following vehicle subsystems: the chassis, body, and interior; the powertrain and emission control system; the traction battery, tray, and auxiliaries, if any; the fuel storage system, including valves, regulators, & fuel lines; and the fuel cell stack and associated auxiliaries, if any; and the methanol reformer and associated auxiliaries, if any. These detailed results are calculated for the baseline ICEV and the EVs, but not for the eight alternative-fuel ICEVs (AFICEVs). All subsystems of the vehicle are sized to meet the requirements of any drive-cycle and performance test specified by the user.

We emphasize that AVCEM estimates the *full production and retail cost* of the vehicle, which will not necessarily be the same as the *actual selling price* of the vehicle. The actual selling price depends on marketing strategies and other factors as well as on the production and selling costs.

Manufacturing costs are estimated as a continuous function of production volume. The cost vs. volume functions are fit to point estimates for low (typically 1,000 to 2,000 units/year), medium, and high (generally 100,000 units/year or more) production runs of electric drivetrains, batteries, fuel cells, reformers, high-pressure hydrogen storage cylinders, heating and air conditioning systems for EVs, and home recharging stations. We also estimate maintenance and repair costs, hydrogen fuel costs, and hydrogen fueling station costs as a function of the vehicle production volume.

- Fuel cost: this is the gasoline-equivalent cost of the fuel, in \$/gallon-gasoline equivalent. The cost of gasoline, hydrogen and methanol is broken down by: feedstock cost, fuel-production cost; fuel-storage and distribution costs; and retail-level costs. AVCEM also estimates the cost of fuel used to heat battery EVs.

- The private and social lifetime cost per-mile (or per km): this is the levelized present-value cost per mile. The levelized present value, which is the conceptually correct expression of the lifetime cost per mile, is calculated in three steps. First, AVCEM calculates the present value (at specified interest rates) of every cost stream. Then, this present value is annualized (or levelized) over the life of the cost stream. Finally, the annualized present value is divided by the calculated annual average mileage.

The lifetime cost is shown for all vehicle types, and is broken down into the following components:

Private or consumer cost components:

- Purchased electricity (accounts for battery heating and regen from fuel cell)
- Vehicle, excluding battery, fuel cell, and hydrogen storage
- Battery and tray and auxiliaries
- Space heating fuel for EVs
- Motor fuel, excluding excise taxes
- Fuel-storage system
- Fuel-cell system, including reformer, if any
- Home battery-recharging station
- Insurance (calculated as a function of VMT and vehicle value)
- Maintenance and repair, excluding oil, inspection, cleaning, towing
- Oil
- Replacement tires (calculated as a function of VMT and vehicle weight)
- Parking, tolls, and fines (assumed to be the same for all vehicles)

- Registration fee (calculated as a function of vehicle weight)
- Vehicle safety and emissions inspection fee
- Federal, state, and local fuel excise taxes
- Accessories (assumed to be the same for all vehicles)

External and other social-cost components:

- Dollar value of external costs of air pollution, noise, and energy security (this can be excluded from the analysis)
- Deduction of fuel taxes (a social transfer, not a social resource cost)
- Deduction of producer surplus on fuel (a social transfer, not a social resource cost)

The social lifetime cost is equal to the private or consumer cost plus the external and other social-cost components.

AVCEM can display the cost-per-mile results for three different driving ranges for each of the three types of EVs (BPEV, HEV, FCEV) – a total of nine cases. (Of course, the user actually can analyze an unlimited number of cases; if one wants to do more than nine cases, one must write down the results or copy them to another file. The point is that AVCEM will show nine EV cases simultaneously.) AVCEM displays one case only for the baseline ICEV and each of the AFICEVs.

- The break-even price of gasoline: The breakeven price is that price of gasoline, including all excise taxes, at which the lifetime cost-per-mile of the alternative-fuel or electric vehicle equals the lifetime cost-per-mile of the baseline gasoline vehicle. This statistic is produced along with the lifetime cost statistic discussed above, and is shown in the same six output columns for EVs and individual output columns for the ICEVs. The breakeven price is shown on a private-cost basis and a social-cost basis.

- Cost summary: these include the gasoline-equivalent fuel retail price, excluding excise taxes (\$/equivalent gallon); the full retail price of the vehicle, including dealer costs, shipping cost, and sales taxes (\$); levelized annual maintenance cost (\$/year); the total private and social lifetime cost (cents/km); the difference between the present value of the EV lifetime cost and the present value of the gasoline-vehicle lifetime cost; and the break-even gasoline price (\$/gallon) (private-cost and social-cost basis). This is shown for all vehicle types.

DISCUSSION OF MODELING INPUTS AND METHODS

This section summarizes the cost parameters and methods used in AVCEM. Subsequently, we give an example of how AVCEM works.

Vehicle manufacturing and retail cost

The initial cost of the EVs and gasoline ICEV is calculated by a vehicle-manufacturing sub-model. This sub-model breaks a complete vehicle into nearly 40 parts, according to the "Uniform Parts Grouping" system used by the automobile industry. The major groups (or divisions) in this system are the body, the engine, the transmission, and the chassis. For each of the part groups, the model-user enters the weight of the material user, the cost per pound of the material, the amount of assembly labor time required, the wage rate for labor, and the overhead on labor.

The material cost plus the overhead-burdened labor cost equals the total variable manufacturing cost. To this variable manufacturing cost are added fixed costs at the division and the corporate level: buildings, major equipment, executives, engineers, accountants, corporate advertising, design and testing, legal, and so on. Finally, corporate profit, dealer costs, and shipping costs are added to produce the Manufacturers' Suggested Retail Price (MSRP).

Parts data for two baseline gasoline ICEVs -- a Ford Taurus and a Ford Escort -- are from cost analyses done by experienced automotive consultants. (Another consultant provided helpful data for the SUV.) The baseline weight and cost data for the approximately 40 subparts sum up to the actual weight and MSRP of the Taurus and the Escort. For other ICEVs, and for the EVs and the AFICEVs, the cost and weight of each sub-group is modified as appropriate. For, example, in the BPEV and FCEV sub-models, the cost and weight of the emission-control system and of the exhaust system are zero, but the frame and suspension are heavier and costlier in order to support the heavy battery (the extra reinforcement is calculated by a weight-compounding factor). To accommodate the components of the EV drivetrain, we have added three alternate subgroups to the conventional ICEV grouping: the electric motor, the electric motor controller, and other electric drivetrain components. (As mentioned next, the traction battery, the fuel-cell, and the hydrogen-storage system are handled outside of the basic parts grouping.) We develop cost functions for the motor and controller, on the basis of a detailed review and analysis of available information. For the EVs, we include a complete heating and cooling system, an onboard charger (with offboard charging equipment accounted separately), regenerative braking, battery thermal management, and fuel-cell auxiliaries, including air compression and water management.

The manufacturing cost of the battery, the fuel cell, and the methanol or hydrogen fuel-storage system (for FCEVs) are calculated separately elsewhere in the lifetime cost model (and discussed elsewhere in this overview), and then added as an additional subsystem to the manufacturing cost of the vehicle.

The division cost is equal to a fixed cost plus an additional cost assumed to be proportional to the manufacturing cost. The corporate cost is equal to a fixed cost plus an additional cost assumed to be proportional to the manufacturing-plus-divisions cost, plus the opportunity cost of money invested in manufacturing. The corporate profit is taken as a percentage of the factory invoice. The dealer cost is equal to a fixed cost plus an additional cost assumed to be proportional to the factor invoice to the dealer, plus the cost of money to the dealer. The shipping cost is assumed to be proportional to vehicle weight.

The initial cost of the AFICEVs is calculated as the cost of the baseline gasoline vehicle plus any cost differences between the AFICEV and the baseline gasoline vehicle in fuel storage (e.g., CNG tankage), powertrain, emission control, fuel economy improvements, chassis support, or vehicle body and interior.

The battery

The lifetime cost of the battery is calculated from the following parameters:

- The \$/kg manufacturing cost, estimated as a function of the Wh/kg specific energy of the battery (see discussions below). The specific energy of the battery is estimated on the basis of a function that relates specific energy to specific power. The specific power is estimated on the basis of the maximum power required over the drive cycle. These functions (\$/kg vs. Wh/kg, and Wh/kg vs. W/kg) represent real tradeoffs in battery design and manufacturing, and allow AVCEM to optimize the battery for the specified range and performance requirements.
- the weight of the battery, estimated as a function of the specific energy, the driving range, and the vehicle efficiency.
- A recycling cost coefficient (\$/kWh).
- The life of the battery, estimated as the shorter of the calendar life and the cycle life. The cycle life is estimated as a function of the depth of discharge, and the capacity of the battery when it is discarded. The average daily depth of discharge is estimated as a function of the driving range of the BPEV.
- The efficiency of the battery, estimated second-by-second over the specified drive cycle as a function of the battery resistance, voltage, and power.
- the weight and size of the battery tray, tie downs, electrical auxiliaries (such as bus bars), thermal management systems, and on-board charger. These are estimated as a function of battery parameters, temperature, and other factors.
- the time it takes the fuel cell/reformer system to warm up (in minutes), during which an supplementary power source, such as a peak-power battery, drives the vehicle

The battery is designed in AVCEM to be as light as possible for the user-specified range and performance mission. The calculation procedure is as follows. First, the battery is required to have the amount of power necessary to exactly meet the performance requirement -- and no more. Given the required power, the power density is calculated. With the calculated power density, the corresponding energy density is calculated, from functions that characterize the tradeoff between power density and energy density in design. The lower the required power density, the higher the energy

density; hence, by having only as much power as is required by the performance standard, the energy density of the battery and hence the efficiency of the vehicle is maximized.

AVCEM calculates the amount of heat loss from a high-temperature battery and the amount of energy required to heat the battery to maintain its operating temperature when it is not in use. The user can specify that the electrical resistive heating energy come either from the wall outlet or, if the vehicle has a fuel cell, from the fuel cell. If the user specifies that the fuel-cell system is used to maintain the temperature of a high-temperature battery, AVCEM re-sizes the fuel tank so that the vehicle can store enough energy to heat the battery and still satisfy the range requirement. The re-sizing of the fuel tank circularly and iteratively affects vehicle weight, efficiency, and power. Thus, whether one heats a battery from the fuel cell ultimately affects such thing as the cost of structural support material in the rest of the vehicle, because all vehicle components are linked in design via the performance, weight, and energy consumption of the vehicle.

The user also specifies the upper limit on the power density (W/kg) for the particular technology chosen. If the performance and range demanded of the vehicle necessitate a peak power density in excess of the maximum allowable, AVCEM generates a warning statement.

AVCEM does *not* account for any loss of interior storage capacity due to the bulk of the battery.

The fuel cell and reformer system

The lifetime cost of the fuel cell is calculated from a detailed set of material and labor cost inputs, and an “engine-map” type representation of the efficiency of the fuel cell.

Cost. In the analysis of fuel-cell cost, the material and labor cost inputs include: membrane price (\$/ft²-total membrane); total membrane area per active membrane area; total electrode area per active membrane area; catalyst price (U. S./troy-oz); total catalyst loading at the cathode (mg/cm²-electrode area); total catalyst loading at the anode (mg/cm²-electrode area); the cost of the flow-field(\$/lb); the volume of the flow-field (cm³/cm²-active membrane area); the density of the flow-field (g/cm³); other areal materials cost (\$/cm²-active membrane area); total cost of materials for the air compressor (\$/kW_{peak}-compressor); total cost of materials for the water pump, the hydrogen pump, and the fans (\$/kW_{peak}-stack); total cost of materials for control of the reformer and the level of CO (\$/kW_{peak}-stack); total cost of vehicle electronics needed specifically for the fuel-cell system, in addition to those needed in a pure BPEV, if the fuel-cell system is hybridized with a peak-power device (\$-MSRP/kW_{peak}-stack); assembly and installation of the fuel cell, water pump, hydrogen pump, and fans (hrs-labor/kW_{peak}-stack); assembly and installation of the air compressor (hrs-labor/kW_{peak}-stack); assembly and installation of the reformer system (hrs-labor/kW_{peak}-stack); the wage rate, excluding overhead, for fuel-cell assemblers (\$/hr); the overhead on labor (benefits, operating costs, supervisor salaries, and main plant costs, expressed as a wage multiplier); specific weight of the fuel-cell stack

(kg/kW_{peak-stack}); specific weight of the heat, air, and water management systems for the fuel cell (kg/kW_{peak-stack}); specific weight of the reformer and associated CO-control systems (kg/kW_{peak-stack}); fuel-cell salvage value (fraction of initial cost including taxes); ratio of fuel-cell calendar life to vehicle calendar life; volumetric power density of the fuel cell (ft³/kW_{peak-stack}); volumetric power density of all fuel-cell auxiliaries (ft³/kW_{peak-stack}); and the volumetric power density of the reformer and associated auxiliaries (ft³/kW_{peak-stack}).

Efficiency. The fuel-cell efficiency is calculated from user-input data on the current density (I) (milli-amps/cm²-active area) of the fuel cell at different fuel-cell voltage levels (V). The user can specify up to six of these V-I series, corresponding to six different air-compression regimes and air-fuel ratios. At each point in each of the six V-I series, AVCEM calculates the net power output of the fuel-cell system, by deducting from the gross power the energy required for air compression and for other system auxiliaries. This results of in six series of voltage versus net power. Then, at each voltage level, AVCEM reads across the six voltage-power series and selects the maximum calculated net power output. This results in a power-vs.-voltage series with the "optimal" -- i.e., efficiency maximizing -- combination of air compression and air-fuel ratio at each voltage point. The fuel cell then "follows" this optimal voltage-power path over the drive cycle: for each segment of the drive cycle, AVCEM calculates the power required from the fuel cell, and then uses the optimal power-voltage path to find the voltage associated with the required power. Finally, this optimal voltage is used to calculate the voltaic efficiency of the fuel cell. (Note that AVCEM interpolates between input data points (i.e., does not simply choose the closest data point.)

The user can specify that the fuel cell be used with or without a supplemental peak-power device. If the user specifies a supplemental peak power device (such as an ultra-capacitor or battery), she or he first characterizes the device with the same input data described under "battery". Then, the user runs a macro command to find the most economical fuel-cell power level for the given vehicle. The macro inputs a series of trial fuel-cell gross-power levels, starting at 5 kW. For each input gross fuel-cell peak power, AVCEM calculates the net peak-power output from the fuel-cell system, the peak power required of the peak-power device in order to satisfy the performance requirement of the vehicle, and, through a series of iterations, the lifetime cost of the fully equilibrated vehicle design. The user then notes the fuel-cell power level that, in combination all of the other input parameters, results in the lowest lifetime cost subject to constraints on power, range, and the power density of the peak-power device.

If the user chooses to use the fuel cell alone, without a peak-power device, AVCEM automatically calculates the gross power needed to fulfill the performance and range requirements. In this case there is no regenerative braking, and vehicle efficiency, performance, fuel storage, weight, and so on are recalculated accordingly.

An example of calculations involving the fuel-cell system is given below.

The fuel-storage system.

The cost of liquid-fuel tanks for gasoline or alcohol, high-pressure CNG tanks, low-pressure LPG tanks, cryogenic tanks for LH₂ and LNG, and hydrogen-hydride systems is calculated by multiplying the amount of tankage required per unit of fuel (lb/lb) by the cost of the container per lb.

The cost of high-pressure hydrogen storage is calculated in more detail. On the basis of size, weight, and cost data in the literature, we estimate three parameters – $\$/\text{ft}^3/1000 \text{ psi}$, $\text{lb}/\text{ft}^3/1000\text{psi}$, and the outer:inner volume ratio – as a nonlinear function of storage pressure. We use these estimated functions to calculate the cost, weight, and size of the high-pressure hydrogen storage vessels at the user-specified storage pressure, as a function of the volume of production.

Energy use: overview

Energy use is a central variable in economic, environmental, and engineering analyses of motor vehicles. The energy use of a vehicle directly determines energy cost, driving range, and emissions of greenhouse gases, and indirectly determines initial cost and performance. It therefore is important to estimate energy use as accurately as possible.

The drivecycle energy-use submodel calculates the energy consumption of EVs and ICEVs over a particular trip, or drivecycle. The energy consumption of a vehicle is a function of trip parameters, such as vehicle speed, road grade, and trip duration, and of vehicle parameters, such as vehicle weight and engine efficiency. Given trip parameters and vehicle parameters, energy use can be calculated from first principles (the physics of work) and empirical approximations.

In the energy-use submodel, the drivecycle followed by the EVs and ICEVs consists of up to 100 linked segments, defined by the user. For each segment, the user specifies the vehicle speed at the beginning, the speed at the end, the wind speed, the grade of the road, and the duration in seconds. Given these data for each segment of the drivecycle, and calculated or user-input vehicle parameters (total weight, coefficient of drag, frontal area, coefficient of rolling resistance, engine thermal efficiency, and transmission efficiency), AVCEM uses the physics equations of work and empirical approximations to calculate the actual energy use and power requirements of the vehicle for each segment of the drivecycle. The equations can be found in physics and engineering textbooks, books on vehicle dynamics, and papers on estimating the fuel consumption of motor vehicles.

Given a drive cycle along with total vehicle range and a maximum fuel-cell net power output, AVCEM calculates the total amount of propulsion energy consumed when the required power is less than the fuel-cell maximum power, and the amount consumed when the required drive power exceeds the fuel-cell maximum. These calculated energy data are used to size the peak-power device and the fuel-storage system. (The size of these is important because lifetime cost is directly and indirectly a function of component size.)

Energy use: vehicle efficiency

The vehicle efficiency is calculated from the efficiency or energy consumption of individual components (the battery, the fuel-cell and reformer system, the engine, the transmission, the motor controller, and vehicle auxiliaries), the characteristics of the drive cycle (see discussion above), the characteristics of the vehicle (see above), the requirements of battery thermal management, and the requirements of cabin heating or cooling. (In the base case, we assume year-round “average” heating and cooling needs, but these conditions can be varied in AVCEM.)

The efficiency of the battery, fuel cell, electric motor, motor controller, and transmission are not input as single values over the entire drive cycle, but rather are calculated second by second. Vehicle efficiency is circularly related to many components and parameters via weight: for example, if the driving range is increased, the amount of battery needed increases, which in turn increases the amount of structural support. The extra battery and structure make the vehicle heavier and less efficient, so that even more battery is needed to attain a given range, and so on, iteratively. AVCEM resolves these circularities and converges on mutually consistent set of values through iterative calculations. Regenerative braking is represented explicitly and in complete detail. An example of the circular involvement of vehicle efficiency in many areas of the lifetime cost calculation is given below.

Energy use: vehicle performance

AVCEM designs the EVs to satisfy performance requirements specified by the user. The user specifies the desired amount of time for the EV to accelerate from any starting speed to any ending speed, over any grade, and AVCEM then calculates the required motor power (using calculated or input data on vehicle weight, component efficiency, drag, air density, rolling resistance, and so on). As an option, the user can specify that the EV have the same acceleration time, for any particular starting and ending speed and grade, as has the baseline gasoline ICEV. (The peak horsepower of the baseline gasoline ICEV is an input variable. Given this input power, and other vehicle and drive-cycle characteristics, AVCEM can calculate the acceleration time for the baseline gasoline vehicle.) The formulas used in the performance design calculation are the same as those used in the drive-cycle energy-use calculations.

In AVCEM, the maximum power of the EV is circularly related to every component that (in vehicle design) really is related to vehicle performance. Thus, AVCEM captures effects that one might overlook but which really do relate to performance. For example, if (in vehicle design) one changes the expected storage pressure of hydrogen in an FCEV, then the strength and hence the weight of the container needed to attain a given range will change. When the weight of the vehicle thus changes, the amount of power required to attain a given performance relative to the gasoline ICEV changes. This in turn changes the size and weight of the motor and battery. These changes in weight change the vehicle efficiency, which in turn changes the amount of battery and fuel-storage required to attain a given range. The change in weight again affects the amount of power required, and so on. The circularities are

resolved by iterative calculations. (Note that the peak power is calculated in this way for the EVs only; the AFICEVs are assumed to have the same performance as the baseline gasoline ICEV.)

Other ownership and operating costs

Insurance. The lifetime cost model handles insurance payments in some detail. We begin with an estimate of the monthly premium for comprehensive physical-damage insurance and liability insurance for a reference vehicle. Then, we formulate a relationship between the liability and physical-damage insurance premiums, and the value and annual travel of a vehicle. Generally, we assume that premiums are nearly proportional to VMT and vehicle value. With this relationship, and an estimate of the value of the modeled vehicle relative to the value of the reference vehicle, and of the VMT of the modeled vehicle relative to the VMT of the reference vehicle, we calculate the insurance premiums for the modeled vehicle relative to the estimated premiums for the reference vehicle.

We also specify the number of years that physical-damage insurance is carried, in order to accurately calculate the lifetime cost.

Home recharging. The cost of home recharging is estimated as a function of the initial cost of a home recharging system (high-power circuit, and charger box), the interest rate, and the amortization period of the investment. AVCEM calculates the length of time required to fully recharge the battery given a voltage and current input by the user, and the size of the battery required to satisfy the input vehicle range and power. If the user specifies that the battery in an FCEV be recharged by the outlet, AVCEM deducts from the total recharging requirement the amount of energy returned to the battery by regenerative braking over the specified drive cycle, when the vehicle is operating on the fuel cell. If the user specifies that the battery in the FCEV be recharged by the fuel-cell instead of by the outlet, then the home recharging cost is assumed to be zero.

The retail cost of fuel or electricity. AVCEM calculates the cost of gasoline, methanol, and hydrogen on the basis of user-specified feedstock costs, fuel-production costs, distribution costs, and retail costs. The cost of a hydrogen refueling station is calculated in detail, as discussed below. The cost of electricity is entered directly as an input variable. Federal and state fuel excise taxes are handled separately (see below).

The hydrogen refueling station. The hydrogen refueling station is characterized in detail, on the basis of cost estimates developed by industry specifically for a high-pressure hydrogen refueling station. AVCEM takes the following input variables: the fixed cost of the compressor (\$/hp); the compressor cost per unit of power (\$/hp; calculated as a function of the compressor power); the compressor cost per unit of output (\$/hp/million standard ft³ [SCF] of hydrogen/day); the cost of electricity in the commercial sector (\$/kWh); the annual cost of service, labor, and new parts (fraction of initial cost); the salvage value of the compressor (fraction of initial cost); the initial temperature and pressure of hydrogen; the compressor output pressure divided by vehicular storage pressure; the factor increase in compression ratio per compressor

stage; the efficiency of compression; the efficiency of the electric motor and auxiliaries; the cost of storage cascade, including manifolding, support, safety equipment, and transportation from the factory to the job site (\$/SCF/1000-psi storage); the storage capacity of station (in SCF) divided by total SCF demanded during peak period; the amount of gas deliverable from storage at the maximum vehicular storage pressure (fraction of total SCF of storage); the cost of refueling equipment, including meters and safety equipment (\$/refueling line); the salvage value of storage and refueling (fraction of station initial cost); the annual cost of servicing, labor, and new parts (fraction of initial station cost); other station capital and engineering cost (fraction of cost of compressor, storage and refueling equipment); the cost of buildings (\$); the cost of hook up to gas line (\$); the price of land (\$/acre); the amount of land required for buildings, exits and entrances (ft²); the amount of land required per refueling bay (ft²/bay); land required for gas storage (ft² land/1000 SCF storage x 1000 psi pressure); number of refueling lines (or bays); rate of delivery of gas to vehicle (SCF/minute [SCFM]); average length of time spent pulling in and out of refueling bay, removing and replacing pump, and paying (minutes); ratio of average non-peak demand to peak demand (assume peak demand = station capacity); hours of peak (maximum) demand rate; hours open per day; days open per year; fraction of tank filled per refueling; wage rate (\$/hr); average number of shifts per hour; overhead on salaries (multiplier); other station operating cost: supplies, water, sewage, garbage, etc. (\$/yr); and corporate financial parameters (discussed next).

A complete set of financial parameters are used to calculate a real-world capital recovery charge: insurance and property tax (as an annual fraction of the total investment, every year); the real rate of return on investment, after income taxes; the real rate of interest on a loan, before taxes (we assume that the loan period is the life of the equipment); the amount of the loan taken out to finance the project (as a fraction of the total required initial investment); the corporate income tax rate; the life of the building and the equipment at the service station; and the real rate of change in the value of land (fraction of original cost per year).

The cost of a CNG and an LNG station is calculated from a similar but less detailed set of input parameters.

Maintenance and repair. The cost of maintaining and repairing a motor vehicle is one of the largest costs of operating a motor vehicle, on a par with the cost of fuel and the cost of insurance. Because the maintenance and repair (m & r) cost is relatively large, and is different for EVs than for ICEVs, it is important to estimate it accurately.

We define a relevant set of m & r costs (net of costs covered by automobile insurance), estimate a year-by-year m & r schedule for the baseline gasoline light-duty ICEV, and then estimate m & r costs for EVs and AFICEVs relative to the estimated m & r costs for the baseline gasoline ICEV. In order to facilitate an accurate estimate of m & r costs relative to those for gasoline ICEVs, we distinguish three kinds of m & r costs:

i) those that are the same for all vehicles, regardless of the fuel or drivetrain (e.g., costs related to the body);

- ii) those that are unique to ICEVs (e.g., those related to the emission control system);
- iii) those that are common to but not the same for all vehicles (e.g., those related to the transmission).

Our analysis of costs in these categories for the baseline gasoline vehicles is based mainly on the comprehensive data on sales of motor-vehicle services and parts reported in the Bureau of the Census' quinquennial *Census of Service Industries* and *Census of Retail Trade*. We use the Census' data to estimate m & r costs per LDV per year, and then compare the results with estimates based on other independent data. We then consider estimates by FHWA to transform the Census' estimates into a year-by-year m & r cost schedule.

The adjusted year-by-year maintenance and repair cost data series are converted to a net present value, which is then levelized to produce an equivalent uniform annual cost series over the life of the vehicle. Costs for the EVs and AFICEVs are estimated relative to costs for the baseline gasoline vehicle in each of the three cost categories.

Replacement tires. The cost per mile of tires is calculated as a function of the initial cost of the tires, the life of the tires and the interest rate. The life of the tires on the gasoline ICEV is specified in miles, and is calculated by AVCEM for the other vehicle types on the basis of the weight of the other vehicle type relative to the weight of the gasoline vehicle. Thus, if an EV or AFICEV weighs more than the baseline ICEV, then its tires will be replaced sooner and hence will have a higher lifetime cost. AVCEM does not replace the tires if the last replacement interval is near the end of life of the vehicle.

Vehicle registration. AVCEM replicates the practice in most states and calculates the registration fee as a function of vehicle weight (heavier vehicles pay a higher fee).

Safety- and emissions-inspection fee. The user enters the annual fee for the baseline gasoline vehicle, and the fee for the other vehicle types relative to the gasoline vehicle fee. (For example, EVs would be subject to a safety-inspection only, not an emissions inspection, and so would have a lower fee.)

Parking, tolls, fines, and accessories. These are input by the user, and are assumed to be the same for all vehicles.

Federal, state, and local excise taxes. AVCEM calculates the cost per mile of the current government excise taxes on gasoline, and then calculates the cost-per-mile for the other vehicles relative to this by using a scaling factor (0.0 to 1.0) specified by the user. In the base case, we assume that all vehicles pay the same tax per mile, so that government revenues from highway users (for the highways) would be the same regardless of the type of vehicle or fuel.

Year-by-year mileage schedule. AVCEM requires as inputs a year-by-year mileage accumulation schedule for the ICEVs and AFICEVs, and a separate schedule for the EVs. This schedule is created from a continuous function that relates age to mileage; the user specifies the value of the coefficients in this function in order to produce the desired mileage schedule. AVCEM has coefficients for several functions specified: one replicates a mileage-accumulation schedule derived from the Residential Transportation Energy Consumption Survey of the U.S. Department of Energy; a

second produces a schedule of more intensive use, in which more miles are driven in the early years of the a vehicle's life; a third is a general low-lifetime mileage schedule; and a fourth is a low-lifetime mileage schedule specifically for mini-cars.

External costs and other social-cost components

AVCEM includes the external cost-per-mile of air pollution, climate change (greenhouse-gas emissions), noise, and oil use. It also includes adjustments for cost items, such as fuel taxes, that are costs to the private consumer but are transfers and hence not costs from the standpoint of society. These external costs and adjustments are added to the private lifetime cost per mile to produce an estimate of the total lifetime *social* cost per mile.

In the external-cost analysis, the basic inputs are \$-per-gram damages and gram-per-mile emission rates in the case of air pollution and climate change, \$-per-mile damages in the case of noise, and \$-per-gallon damages in the case of oil use. AVCEM does not include any other nonmonetary environmental or consumer benefits or disbenefits, such as the disadvantage of a short driving range or the convenience of home recharging.

Financial parameters for vehicle purchase

AVCEM characterizes a "weighted-average" or "typical" vehicle purchase by calculating or taking as input a detailed set of financial parameters: the fraction of new car buyers who take out a loan to buy a new vehicle; the amount of the average downpayment on the car (input as a fraction of retail cost of the vehicle); the length of financing period for cars bought on loan (in months); the real annual interest rate on loans taken out to buy a new car, before taxes; the real annual interest rate foregone on cash used for transportation expenditures, before taxes (the opportunity cost of cash used for downpayment or outright purchase); the effective (average) income tax paid on banking interest earned; after deductions; the annual discount rate to apply to yearly mileage, the annual rate of inflation; the base year and the target year for the inflation analysis (if inflation is not zero); and whether or not interest payments be deducted from taxable income. AVCEM treats loan payments as an ordinary cost, to be discounted by the personal opportunity cost of money.

As noted above, the user can specify a "discount rate" to be applied to the annual mileage. This allows the user to perform a quasi cost-benefit analysis, in which miles of travel are the "benefit" of travel, and are be discounted (or annualized) in the same way that the costs are. (It turns out that if one assumes different mileage schedules for different vehicles, then whether or not one treats VMT as a benefit and applies a discount rate can make a large difference in the overall cost-per-mile results.)

The financial-cost sub-model also performs a highly simplified macro-economic simulation: it assumes that the interest rate, the fraction of new car buyers who take out a loan, the downpayment fraction, and the length of the financing period are a nonlinear function of the real cost of the vehicle.

AN EXAMPLE OF HOW AVCEM WORKS

Here is an illustration of the level of detail and integration of AVCEM. As mentioned above, the user specifies characteristics of the drive cycle. The following illustrates what happens if the user changes one parameter that affects the drive cycle -- say, the grade or wind speed or road roughness.

The fuel cell

First, AVCEM re-calculates the power required for each segment of the drive-cycle. Then, AVCEM goes to the fuel-cell submodel and, using the estimated optimal voltage-power path for the fuel cell (see the discussion above), calculates the optimal (efficiency-maximizing) fuel-cell voltage associated with the power required for the drive-cycle segment. Given the calculated voltage and associated optimal air-compression regime, AVCEM calculates the efficiency of the fuel cell and the energy use of the air compressor for the drive-cycle segment. (The energy requirement of the air compressor is based on an engineering calculation of the energy requirements of adiabatic air compression.)

The efficiency of the fuel system over the entire drive-cycle then is re-estimated on the basis of the new efficiency results for each drive-cycle segment. This change in overall drive-cycle efficiency changes the amount of energy required to achieve the user-specified driving range, which, in turn, changes the size (and hence cost) of the energy-storage system. (As discussed above, the weight, bulk, and cost of high-pressure hydrogen storage is a nonlinear function of the storage pressure.) The change in the weight of the fuel-storage system affects the efficiency of the vehicle and, eventually, changes the amount of storage required to achieve the desired range. Furthermore, the change in the weight of the storage systems changes the amount and cost of structural material needed to support the storage system. This again affects vehicle efficiency, and again feeds back to affect the size of the fuel-storage system. In addition, these changes in weight change the amount of power required to achieve the desired performance (discussed above), and this in turn changes the required maximum output of the peak-power device, motor, and controller. These changes in peak power again affect weight, efficiency, fuel-storage, weight (again), peak power (again), and so on, until the circularities are resolved by convergent iterations.

The battery

The new drive cycle and (if pertinent) the new associated fuel-cell power output change the amount of energy that the peak-power device (say, a high-power battery) or traction battery must provide. The change in the required energy storage capacity of the battery changes the weight of the battery. This change in weight, combined with the changes in the weight of the fuel cell, fuel-storage system, and vehicle, change the amount of maximum power needed to achieve a given performance (see the discussion of performance). The change in peak power and the change in weight change the specific power (W/kg) of the battery, which, via the battery design function in AVCEM, changes the specific energy (Wh/kg) of the battery. The new specific energy changes the amount of battery required to supply the [new] amount of drive energy not supplied by the fuel-cell system; this change in weight feeds back to affect specific power and specific energy, and so on, until AVCEM converges iteratively. The change in battery weight also affects vehicle efficiency and ultimately the weight of other components, and these effects also come back around to affect the amount of battery needed to supply the driving energy not covered by the fuel cell.

The change in the segment-by-segment power output of the fuel cell changes the required segment-by-segment power output of the battery, because the battery provides any difference between power required and power provided by the fuel cell. This change in power output leads ultimately to changes in the voltaic efficiency and overall efficiency (equal to voltaic efficiency multiplied by a constant coulombic efficiency) of the battery, for each segment. The new overall battery efficiency changes vehicle efficiency, which changes the amount of battery, fuel-storage, and so on, needed to attain the given range, which changes the amount of peak power needed, and so on, as discussed above.

Ultimately, the changes in battery weight and power change the initial cost of the battery, according to the battery cost equations (see discussion of battery cost above). There actually are two effects here: the change in Wh/kg changes the \$/kg coefficient itself, and the change in total kg changes the total amount of battery to be paid for. The change in battery power and weight also change the initial cost of the EV motor and controllers, which are input as a function the peak power (kW_{peak}).

The change in vehicle efficiency and battery characteristics change the calendar lifetime of the battery, which in turn affects the annualized cost per mile of the battery. Of course, the change in vehicle efficiency (due to the changes in the segment-by-segment power output of the battery and fuel cell, and to the changes in weight) directly affects the cost per mile of fuel and electricity consumption.

If the battery is recharged and, if necessary, heated by the fuel cell rather than from electricity from the outlet (the user can specify how the battery is heated and recharged), then a change in the size of the battery changes the heat loss rate and amount of stored energy, which in turn change the amount of fuel needed on board for heating and recharging, which changes the amount of fuel-storage equipment, which changes the weight of the vehicle, which changes the efficiency and the power requirement, which then feedback to the size of the battery and fuel-storage system.

Other systems

Returning again to the original change in the drive cycle: this also changes the cycle-average efficiency of the electric drivetrain, which is characterized in AVCEM by maps of efficiency vs. power (torque and rpm). The change in drivetrain efficiency changes overall vehicle efficiency, weight, and required power. The change in the required power of the motor changes the drivetrain efficiency with respect to the drive cycle, and so on.

The changes in weight affect the rate at which tires wear out, which affects the tire replacement interval, which in turn affects the annualized cost of the tire. The changes in the cost of the fuel-cell, fuel-storage system, battery, motor, vehicle, etc., change the value of the vehicle, which in turn changes the cost of physical-damage insurance. The change in vehicle weight changes the annual registration fee.

Finally, the changes in the value of the vehicle (due to changes in the amount and cost of fuel-storage, battery, vehicle material, etc.) actually change the financial terms of vehicle purchase. In AVCEM, as vehicles get more expensive, more people take at loans to buy them, and the cost of borrowing money goes up. These changes are calculated in AVCEM and affect the amortized initial cost of the vehicle.