ADVISOR

Users Conference

Proceedings

August 24–25, 2000
Costa Mesa, CA

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Posters

2000 ADVISOR Users Conference Opening Address

Keith Wipke

Senior Engineer, Vehicle Systems Analysis Task Leader, National Renewable Energy Laboratory

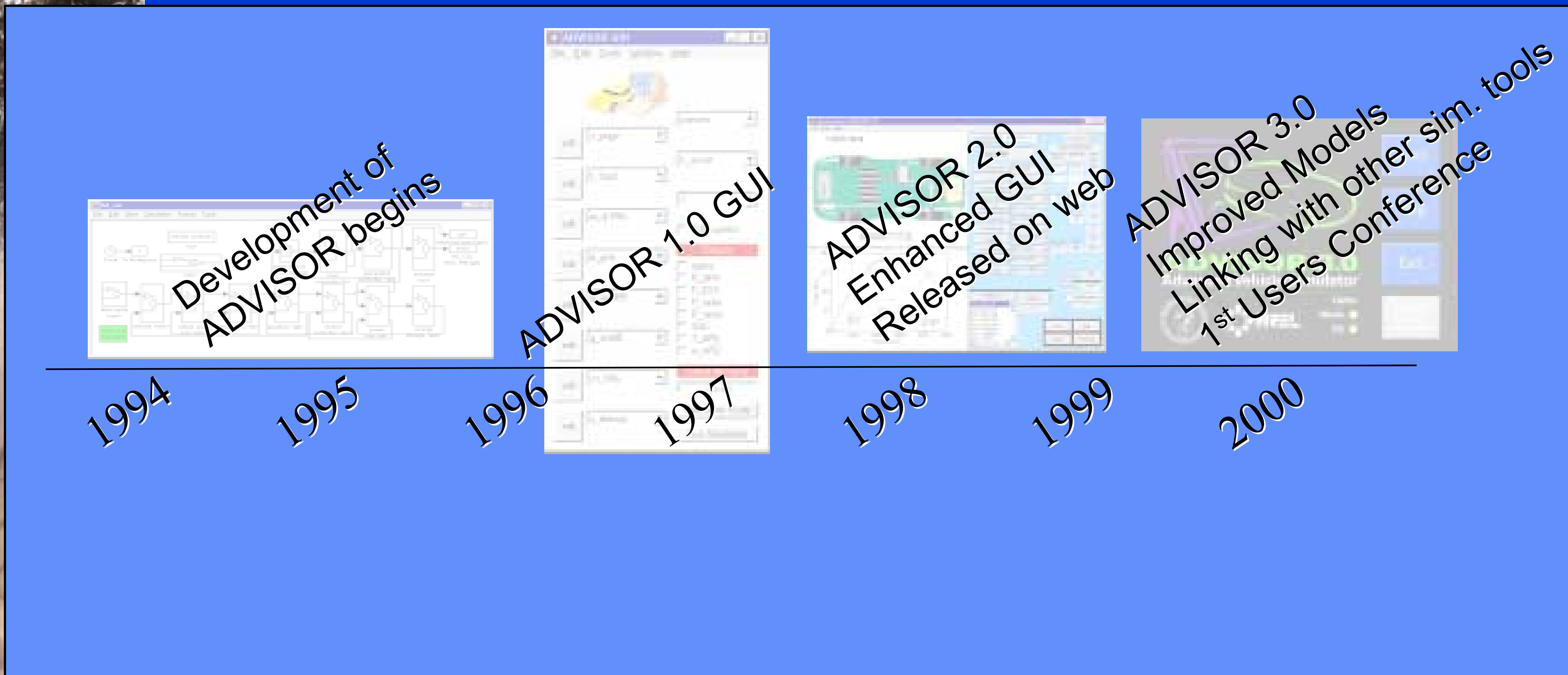
Outline

- NREL/DOE goals of conference
- Historical Perspective
- Demographics of ADVISOR Users
- Sneak-preview of ADVISOR 3.0

NREL/DOE Goals of ADVISOR Conference

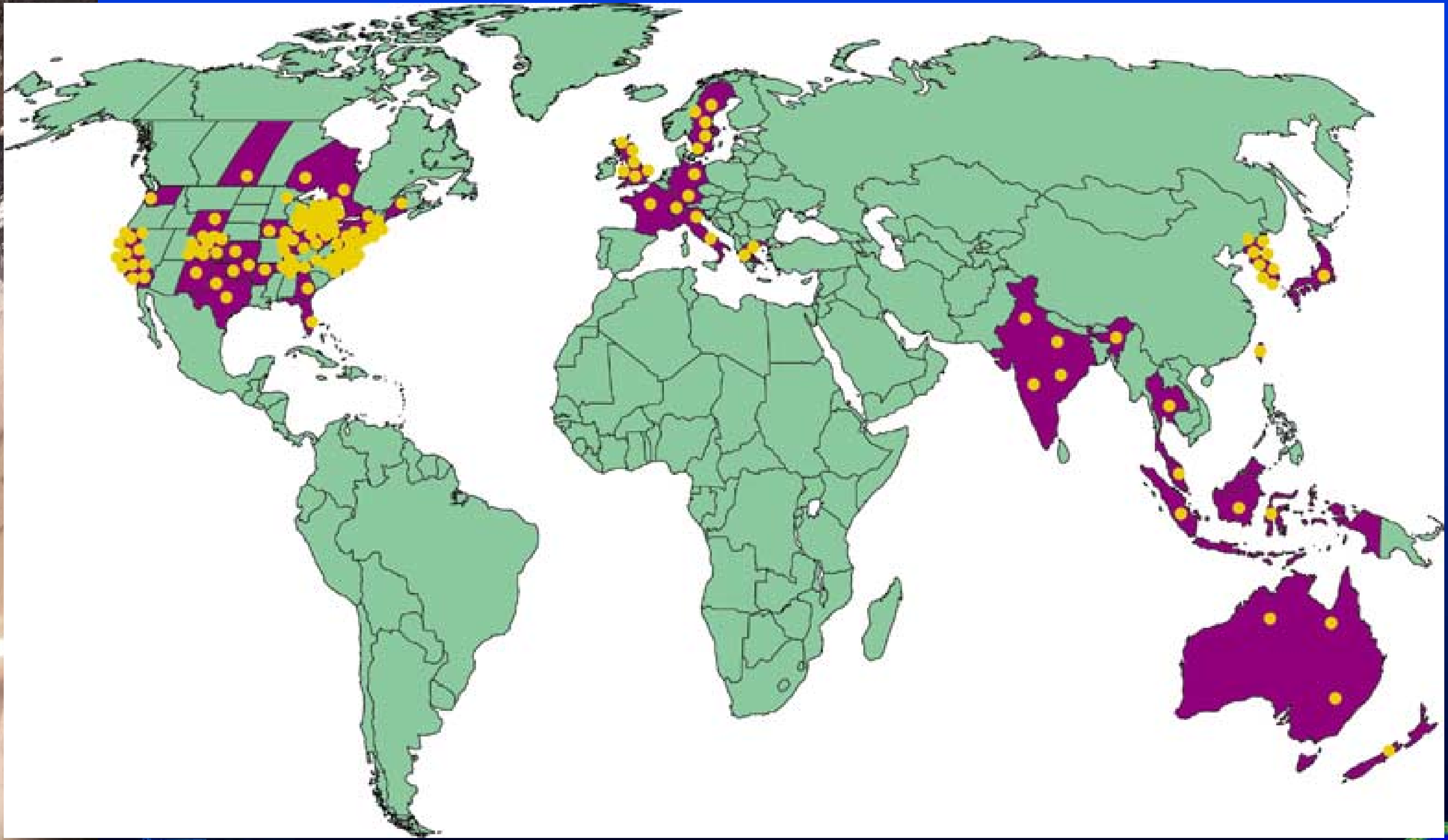
- Bring together users from around the world to…
- Share information, models, techniques, experiences
- Foster a sense of community, elevate the visibility of the virtual community that already exists
- Celebrate successes and identify opportunities for improvements
- Get feedback on future direction for ADVISOR and the Digital Functional Vehicle process

Historical Perspective: Evolution of ADVISOR in 6 Years

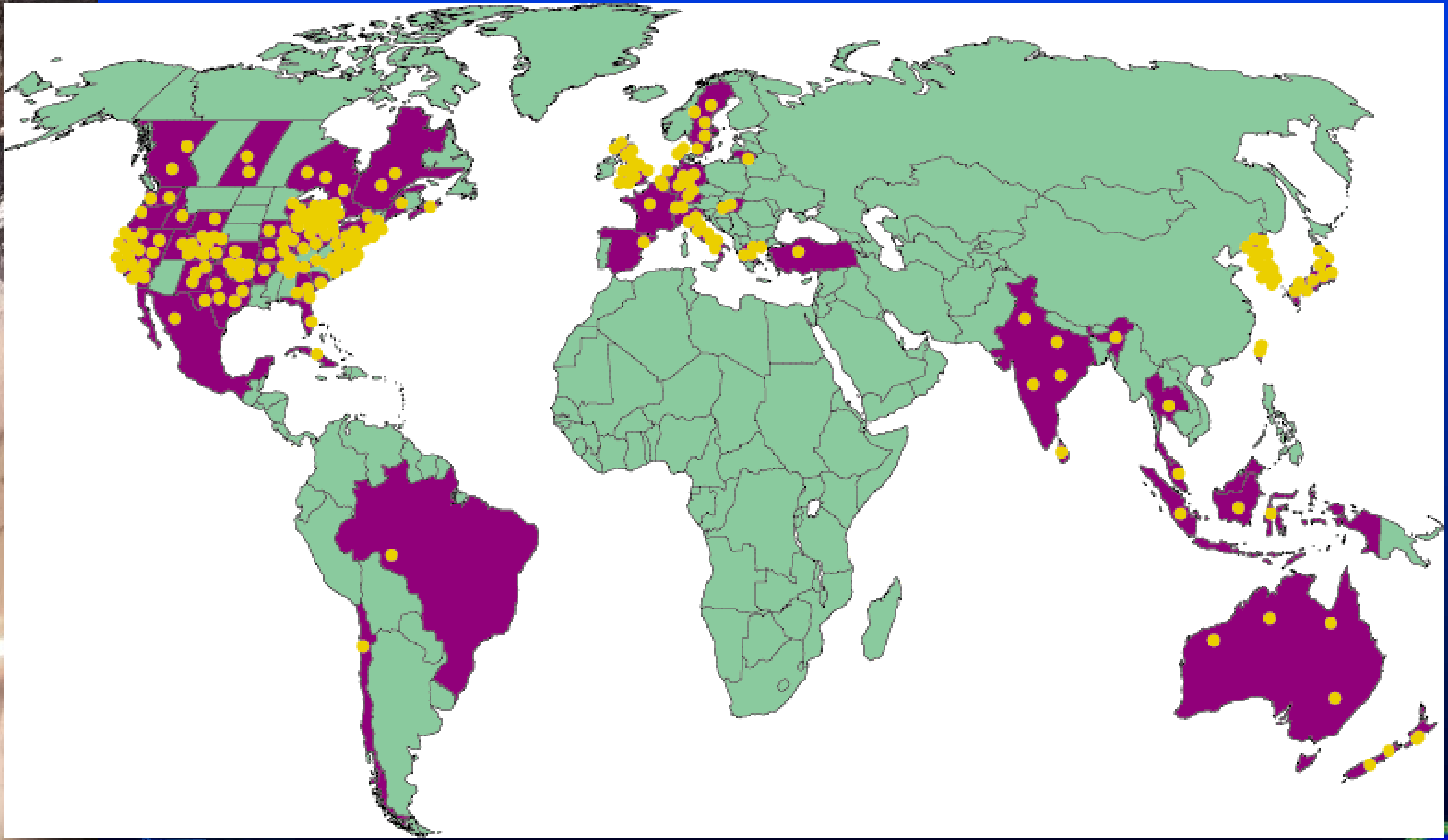


ADVISOR User Demographics

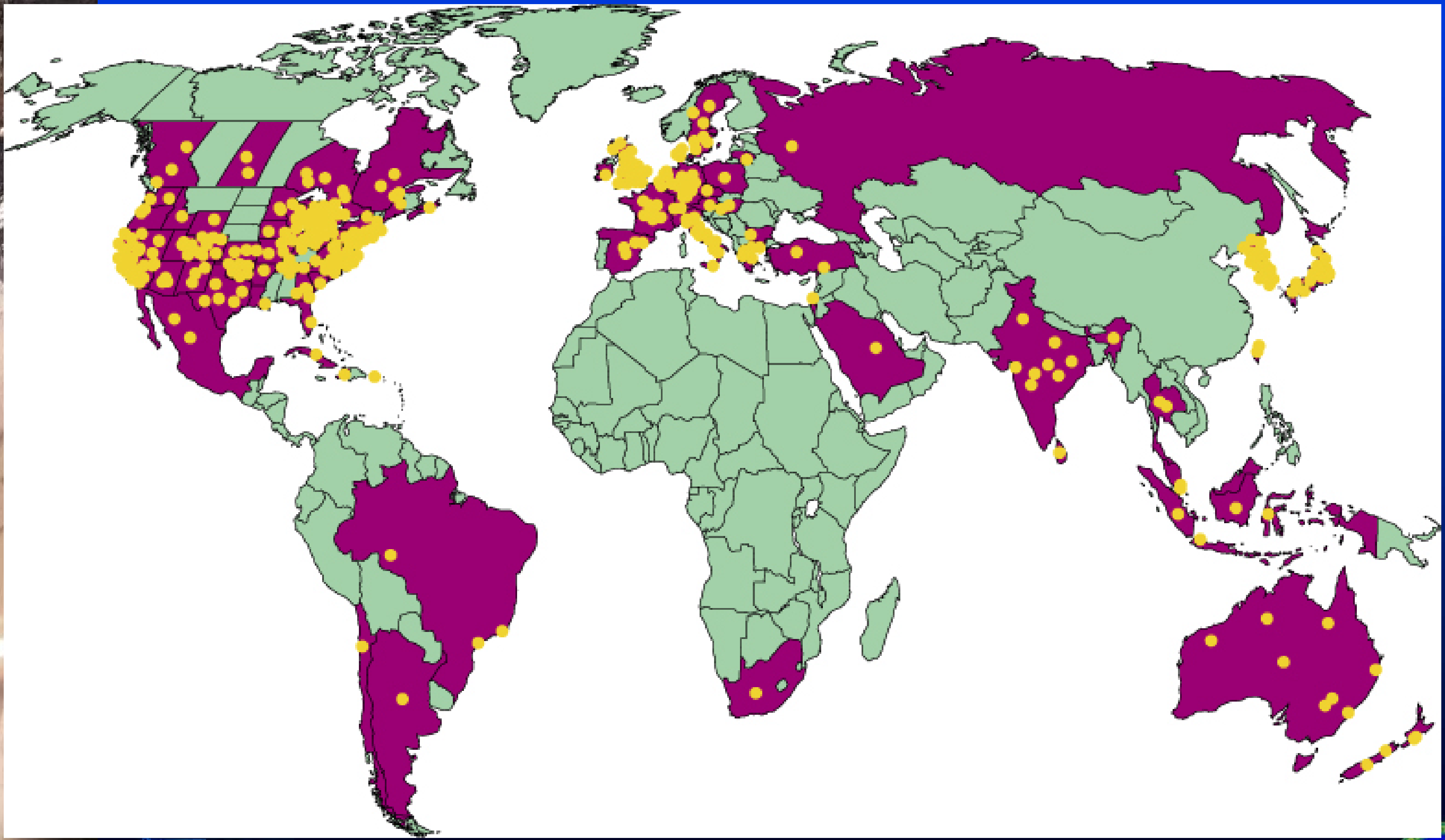
ADVISOR Being Used Globally November 1998: ~130 users



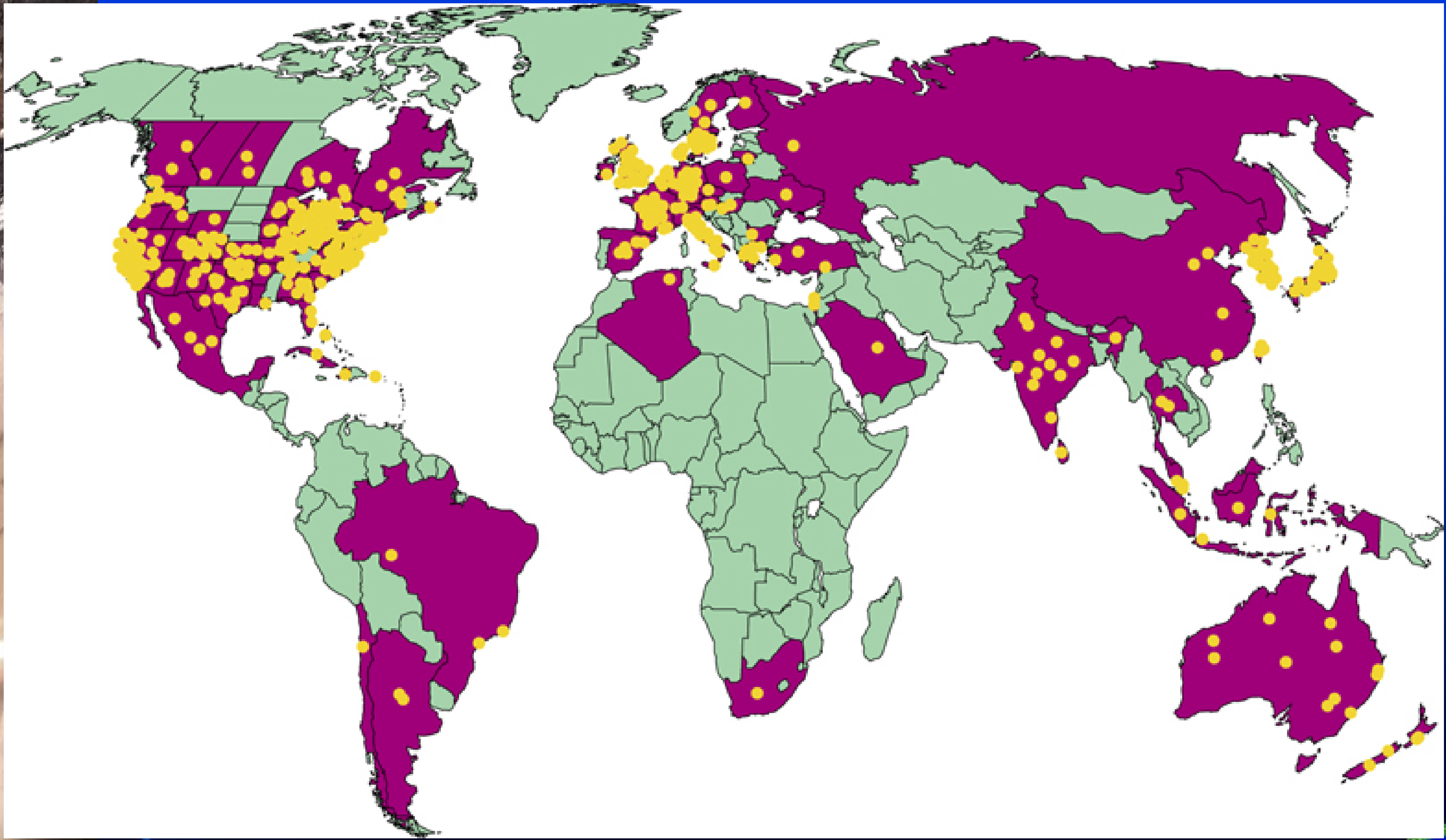
ADVISOR Being Used Globally
January 1999: ~330 users



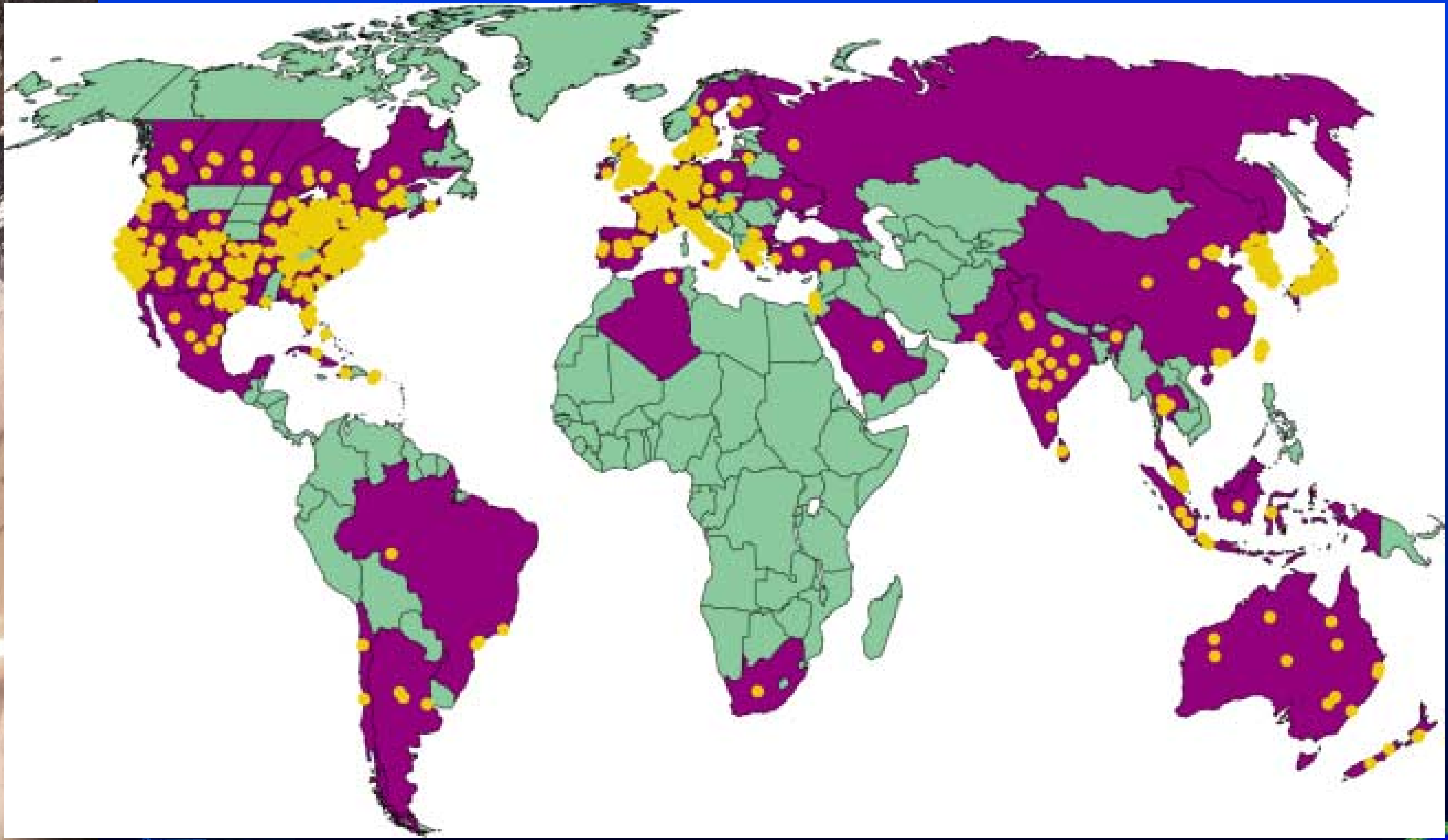
ADVISOR Being Used Globally
March 1999: ~500 users



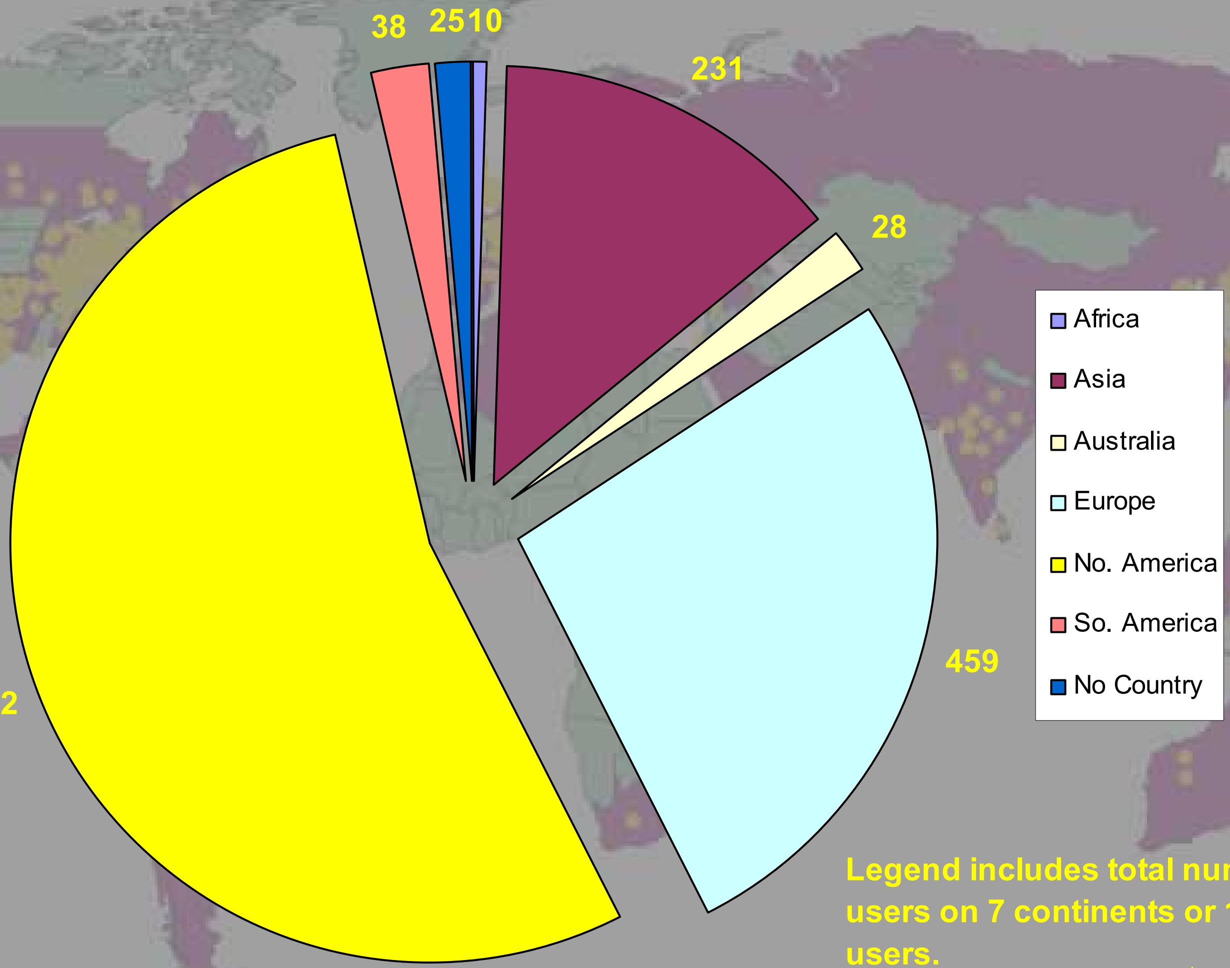
ADVISOR Being Used Globally
August 1999: ~800 users



ADVISOR Being Used Globally
August 2000: >2000 users



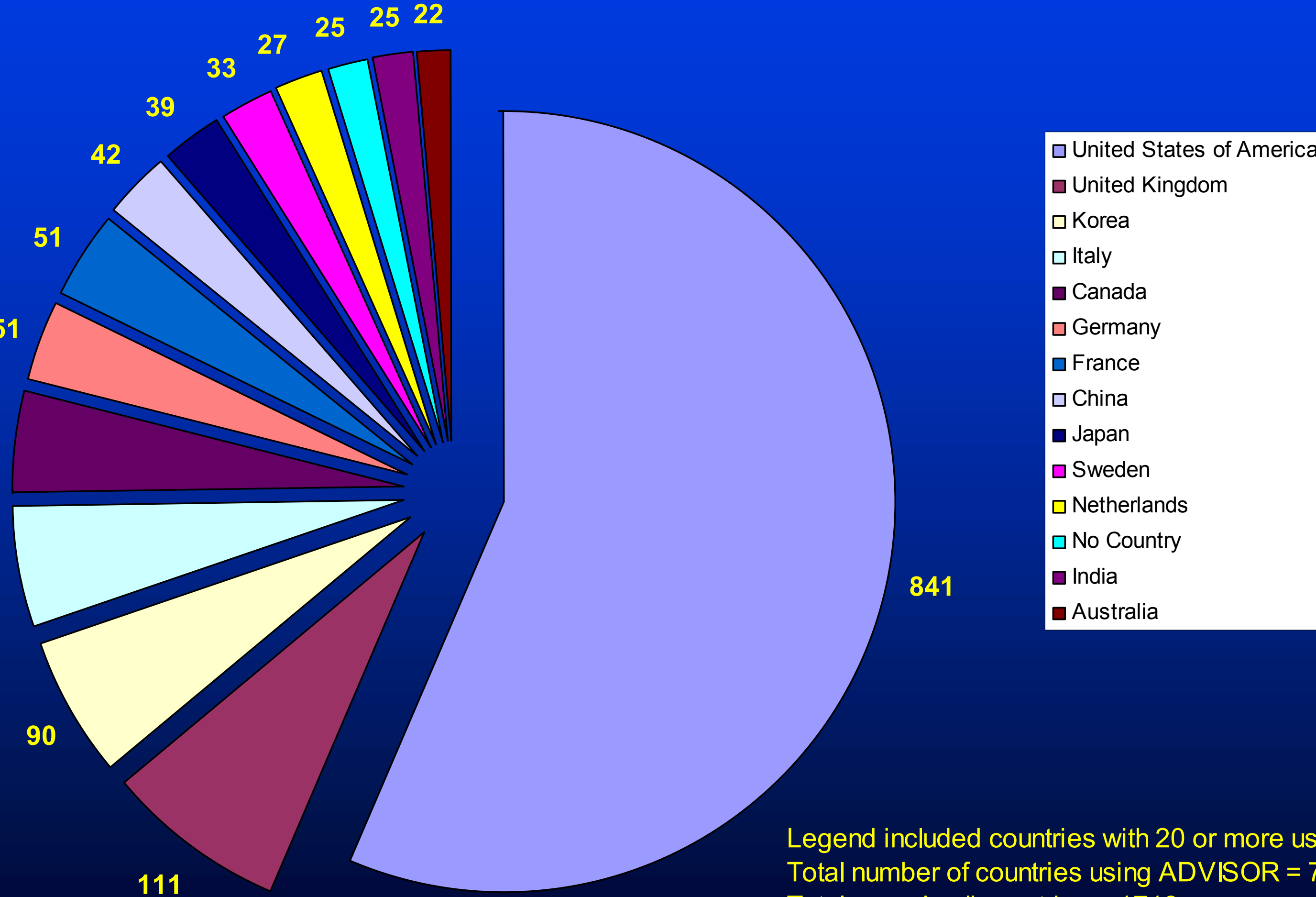
ADVISOR Downloads by Continent



Legend includes total number of users on 7 continents or 1713 users.

As of 6/9/00

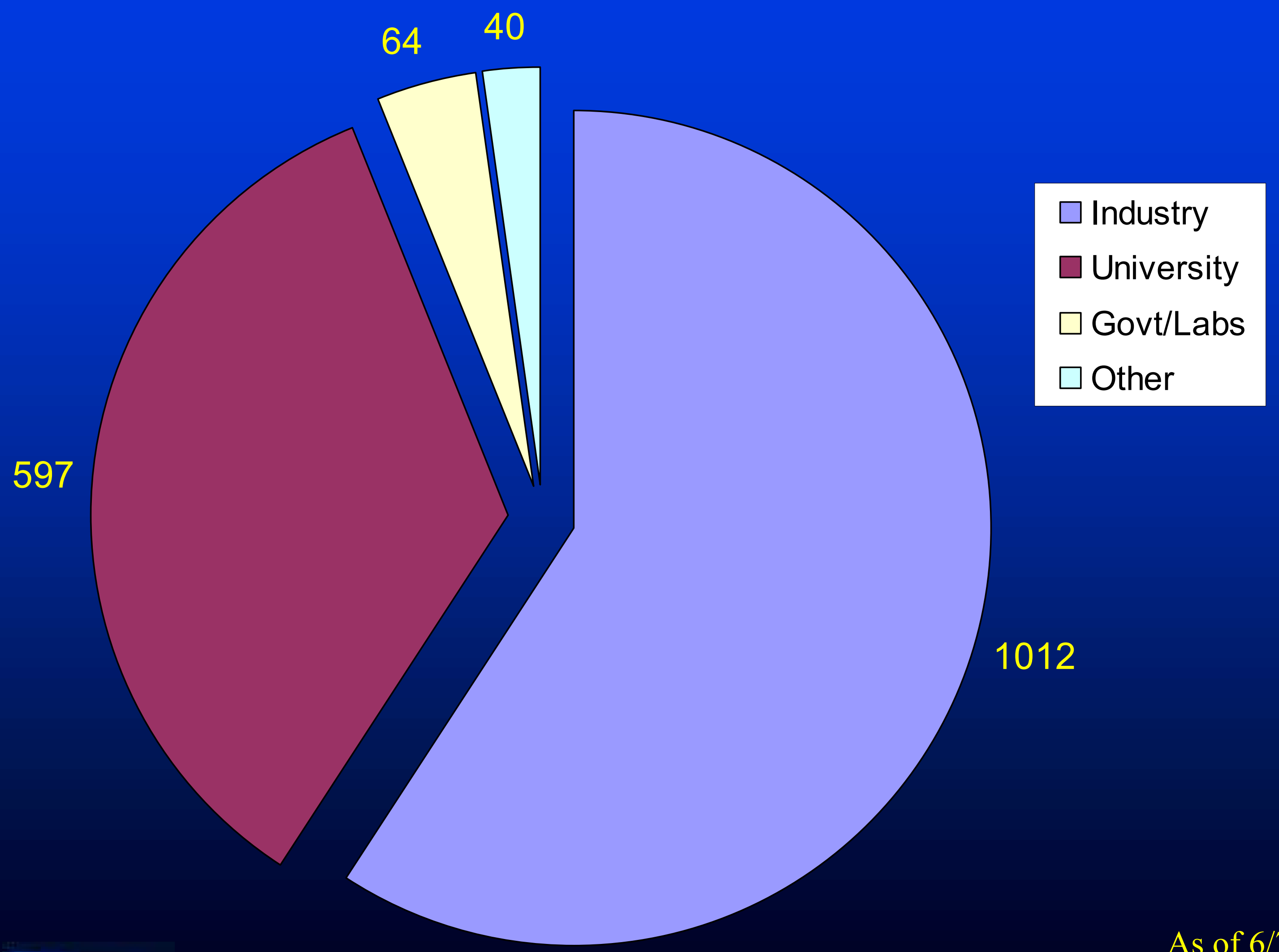
ADVISOR Downloads by Country



Legend included countries with 20 or more users
Total number of countries using ADVISOR = 70
Total users in all countries = 1713

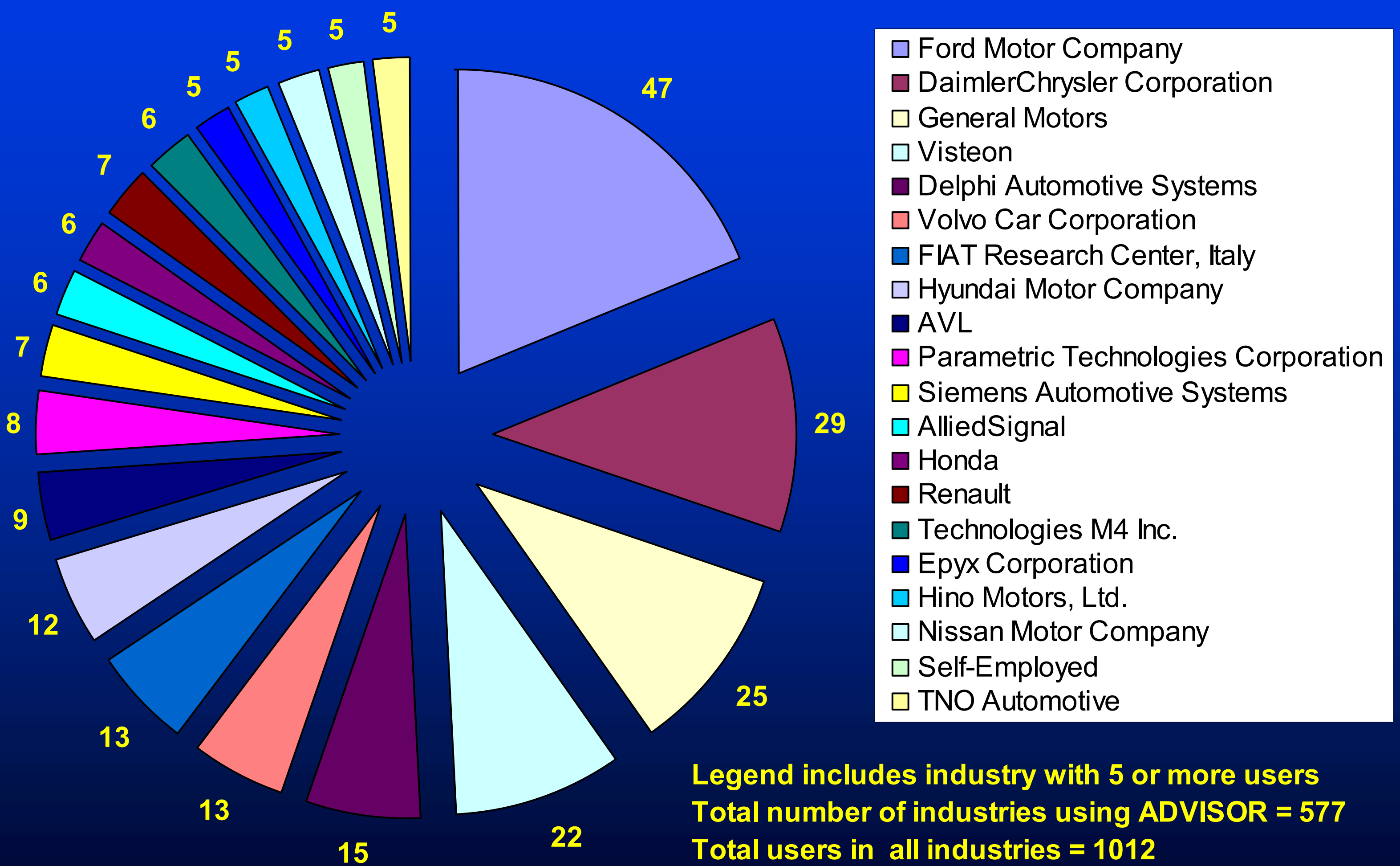
As of 6/7/00

ADVISOR Downloads by Type of Organization



As of 6/7/00

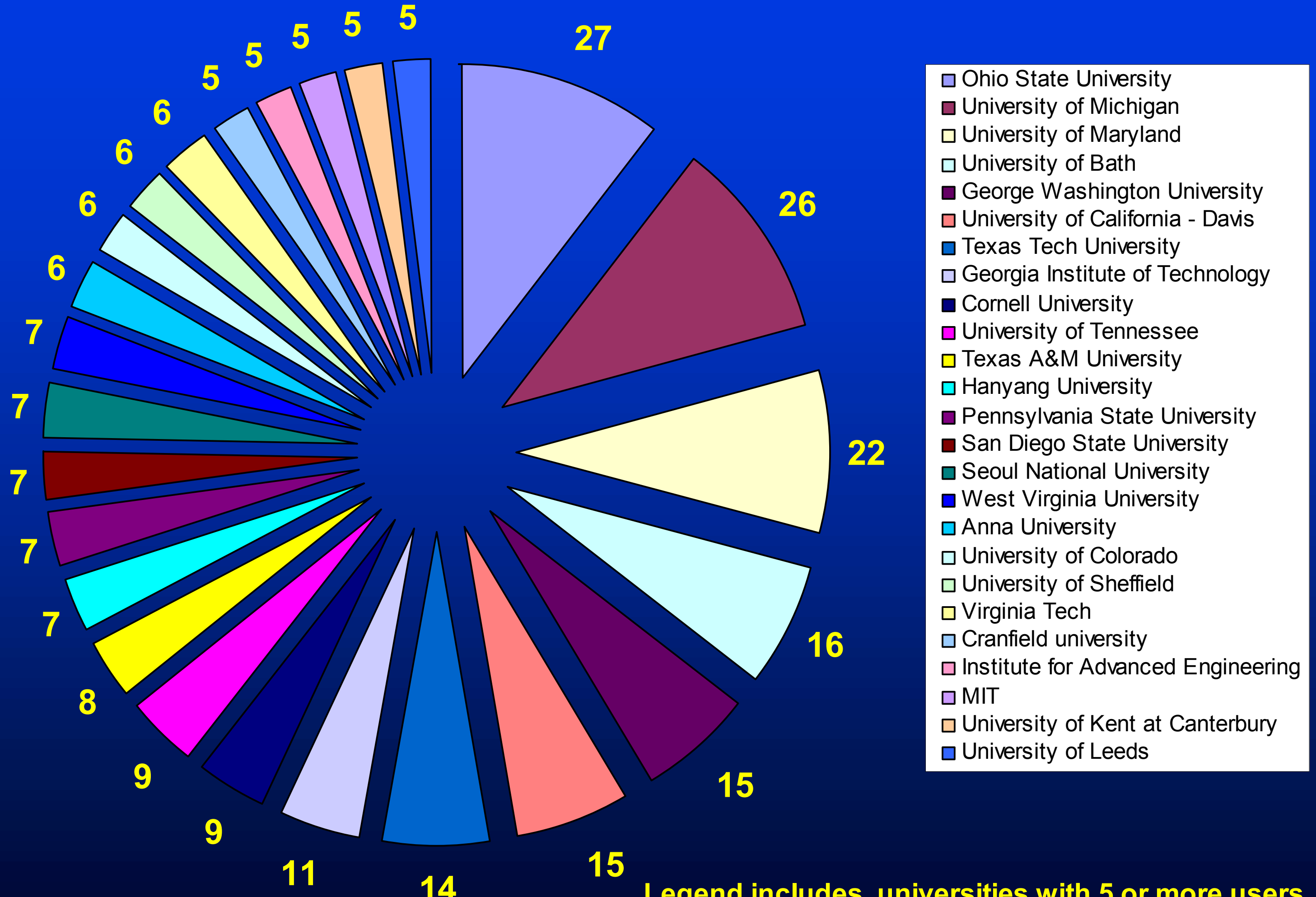
ADVISOR Downloads by Industry



Legend includes industry with 5 or more users
Total number of industries using ADVISOR = 577
Total users in all industries = 1012

As of 8/18/00

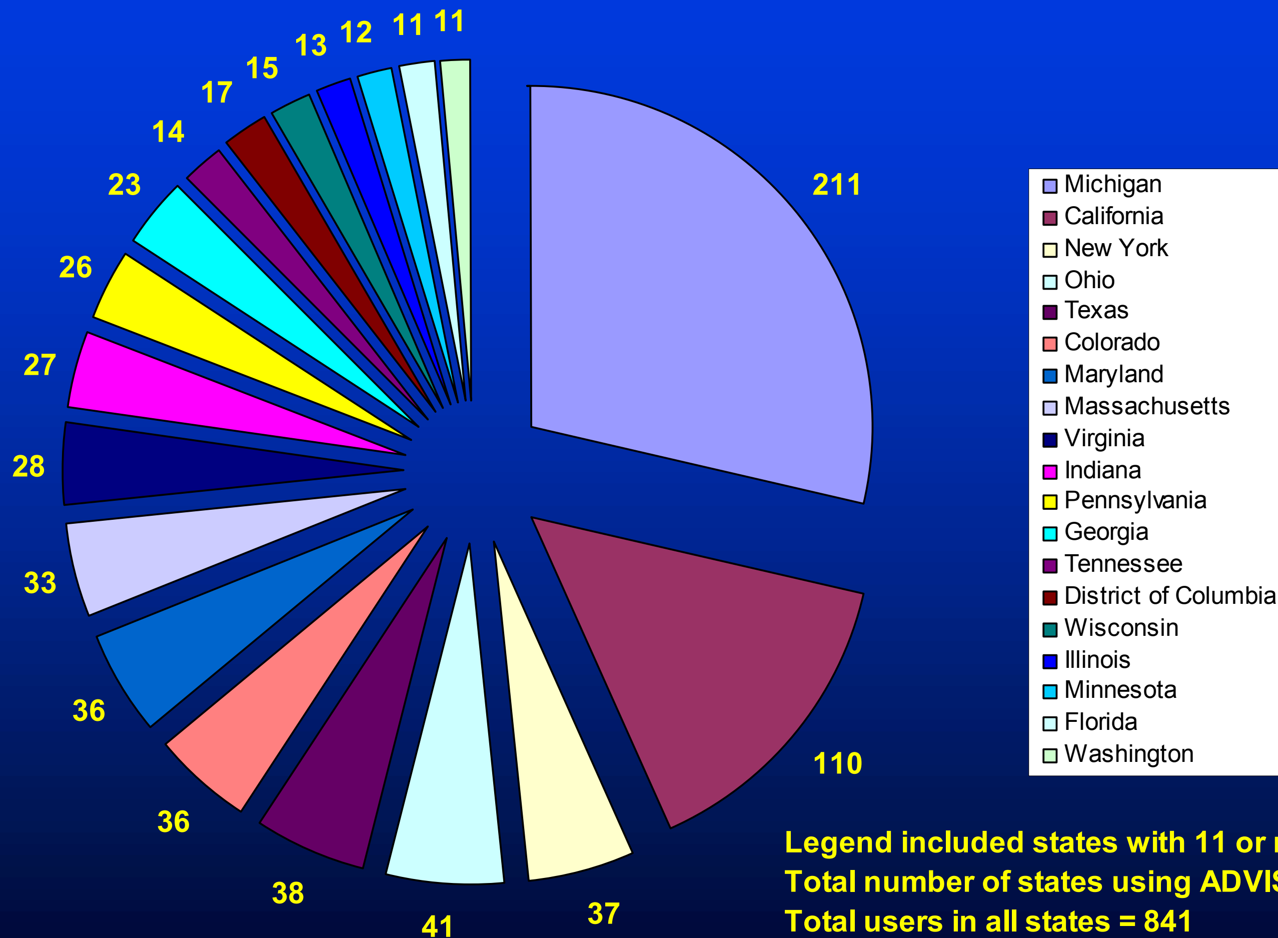
ADVISOR Downloads by Universities



Legend includes universities with 5 or more users
Total number of universities using ADVISOR = 277
Total users in all universities = 597

As of 6/7/00

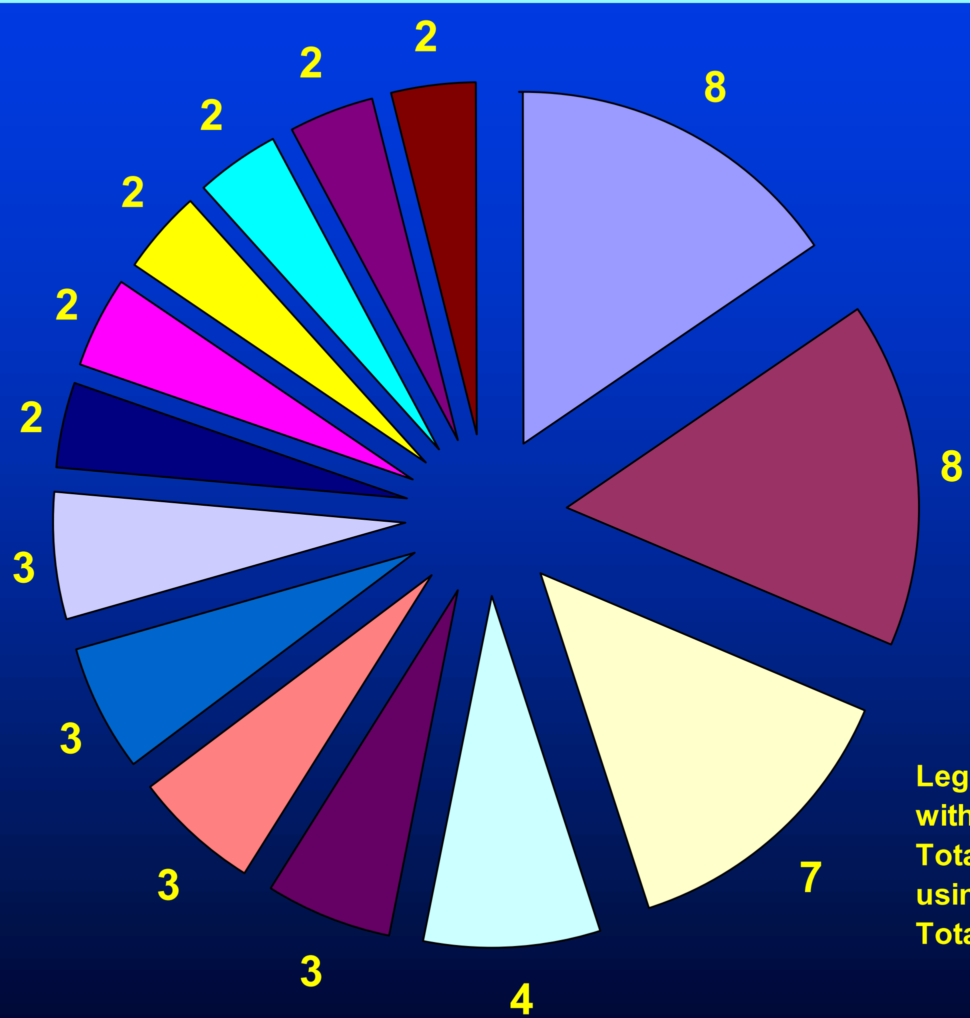
ADVISOR Downloads by State



Legend included states with 11 or more users
Total number of states using ADVISOR = 45
Total users in all states = 841

As of 6/7/00

ADVSIOR Downloads by Government Agencies/Labs



Legend includes government agencies/labs with 2 or more users

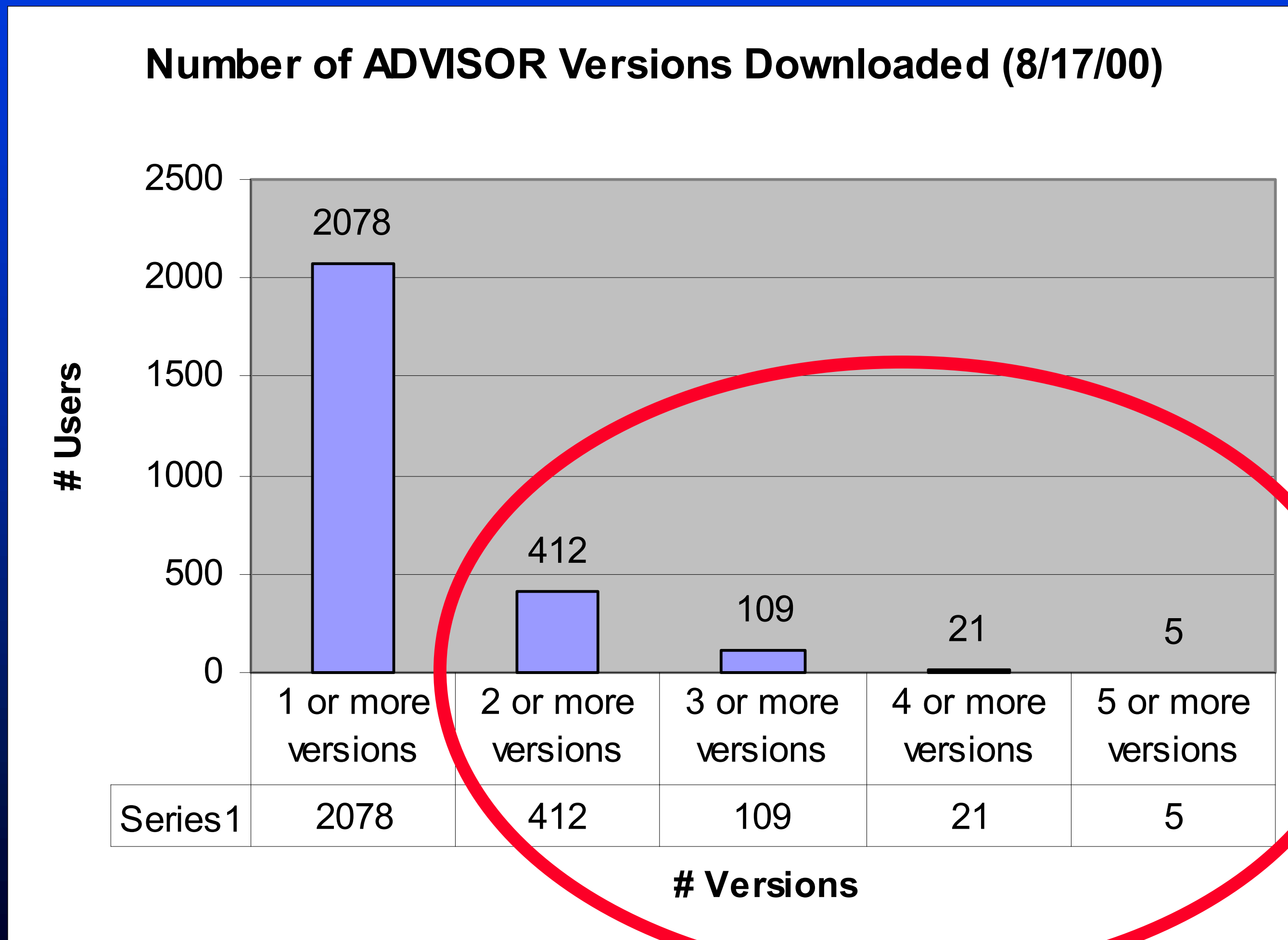
Total number of government agencies/labs using ADVISOR = 64

Total users in all agencies/labs = 27

As of 6/7/00

Multiple Versions Downloaded as one Indicator of "Active" Users

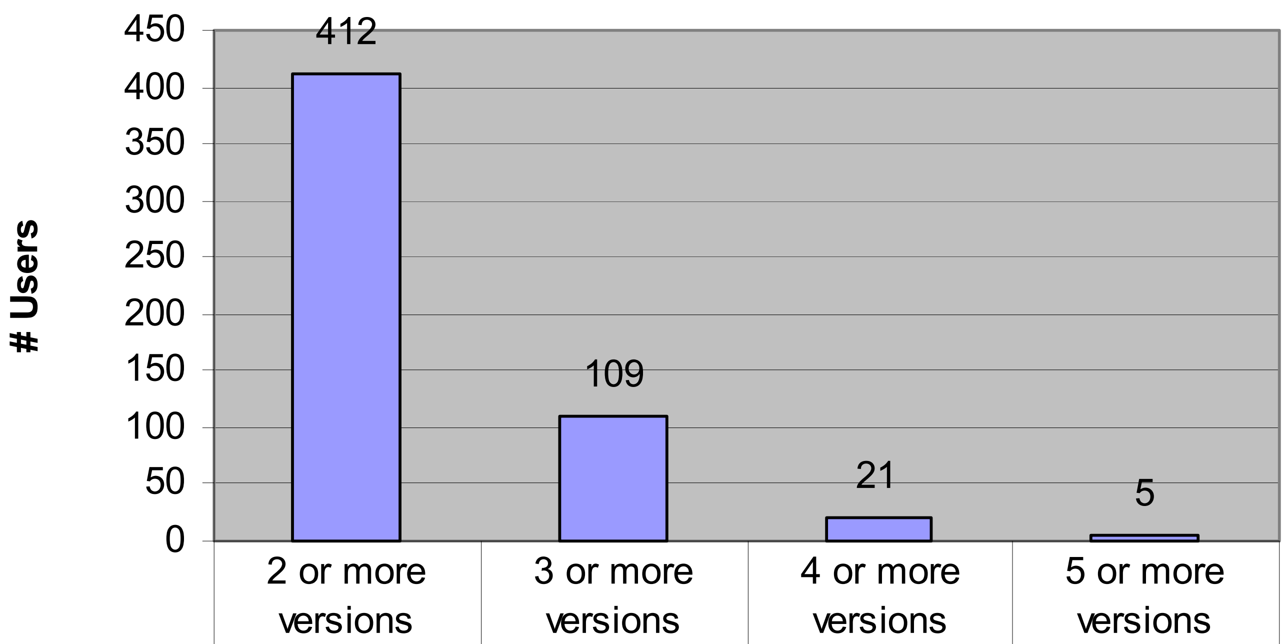
- ~20% appear to be "active" with ADVISOR



Multiple Versions Downloaded as one Indicator of "Active" Users

- ~20% appear to be "active" with ADVISOR

Number of ADVISOR Versions Downloaded (8/17/00)

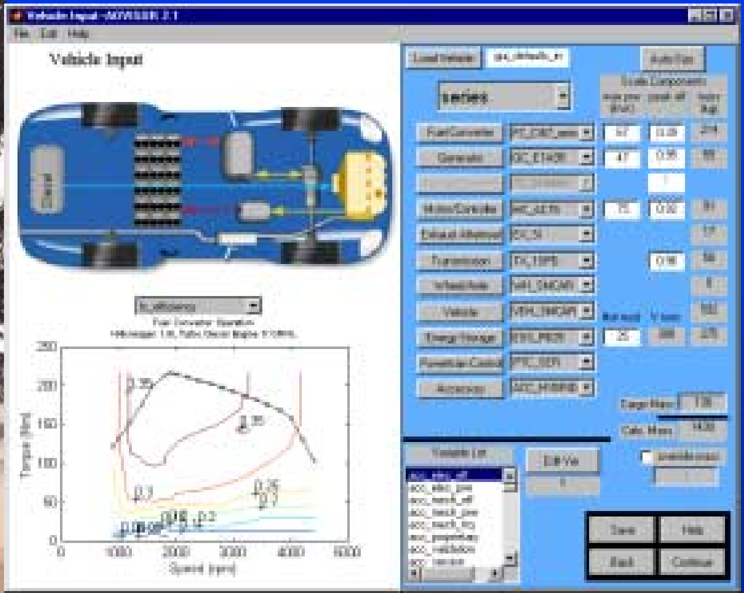


	2 or more versions	3 or more versions	4 or more versions	5 or more versions
Series1	412	109	21	5

 # Versions

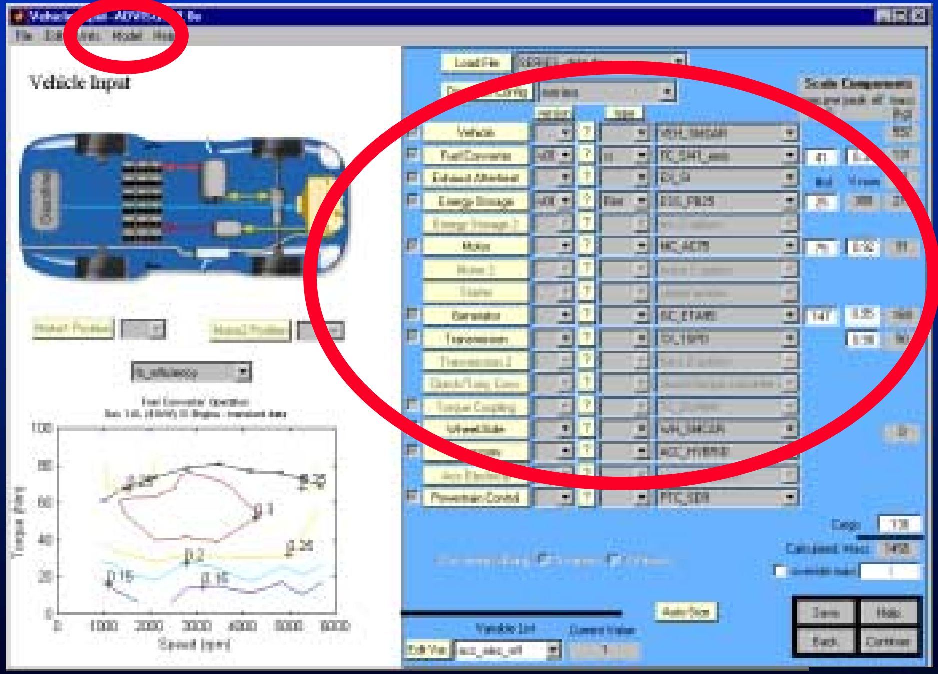
Preview of ADVISOR 3.0

Vehicle Input Screen

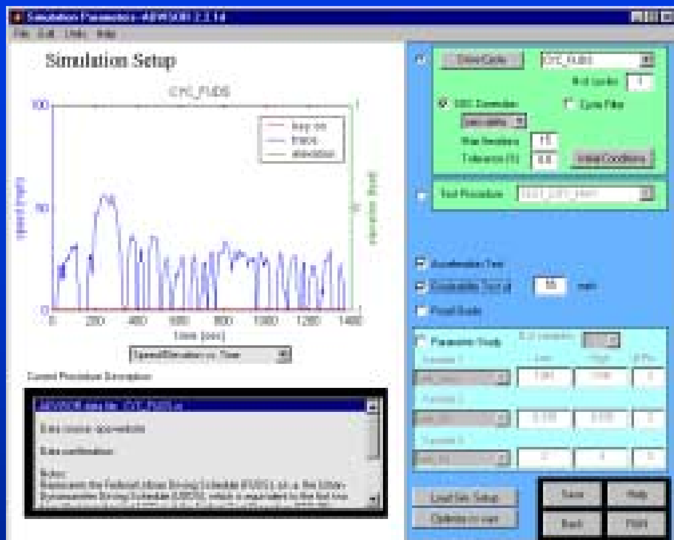


2.2.1

3.0

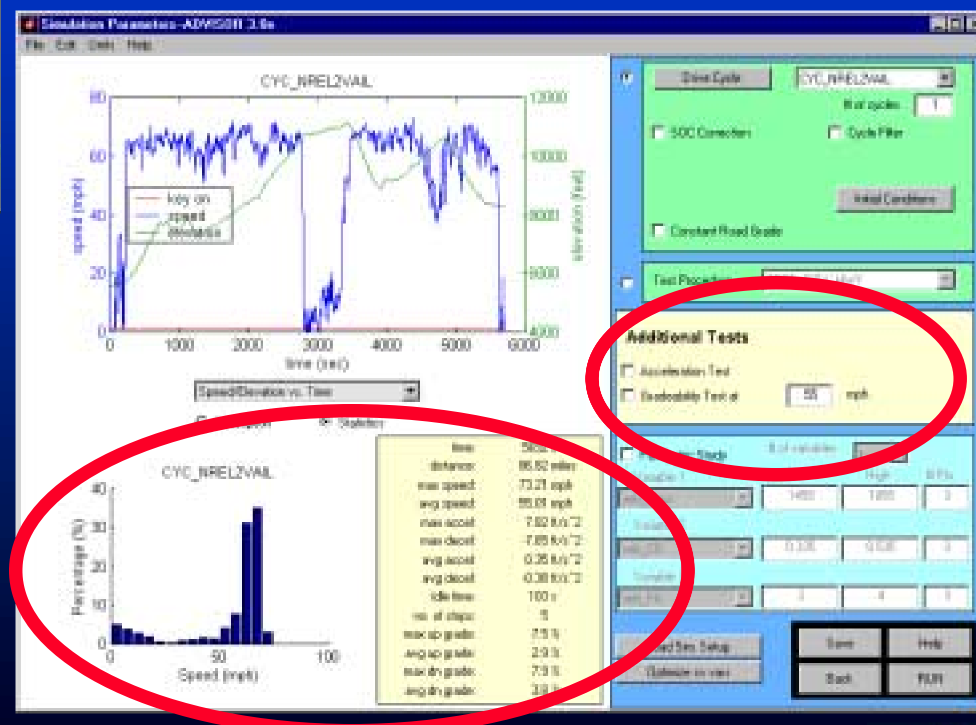


Simulation Setup Screen

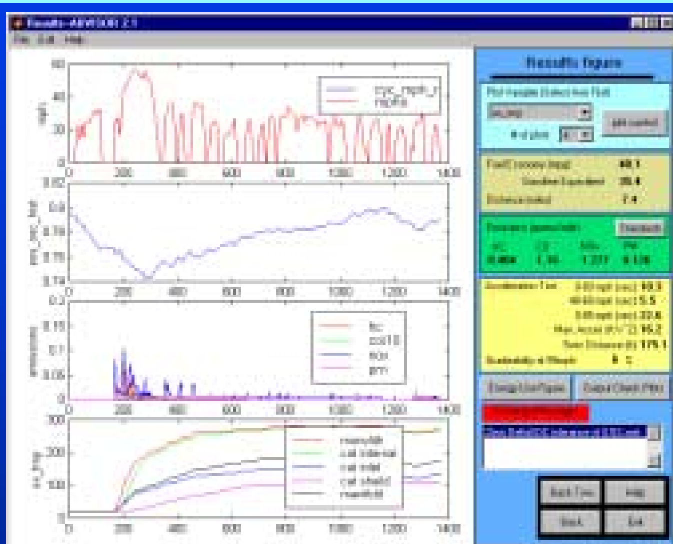


2.2.1

3.0

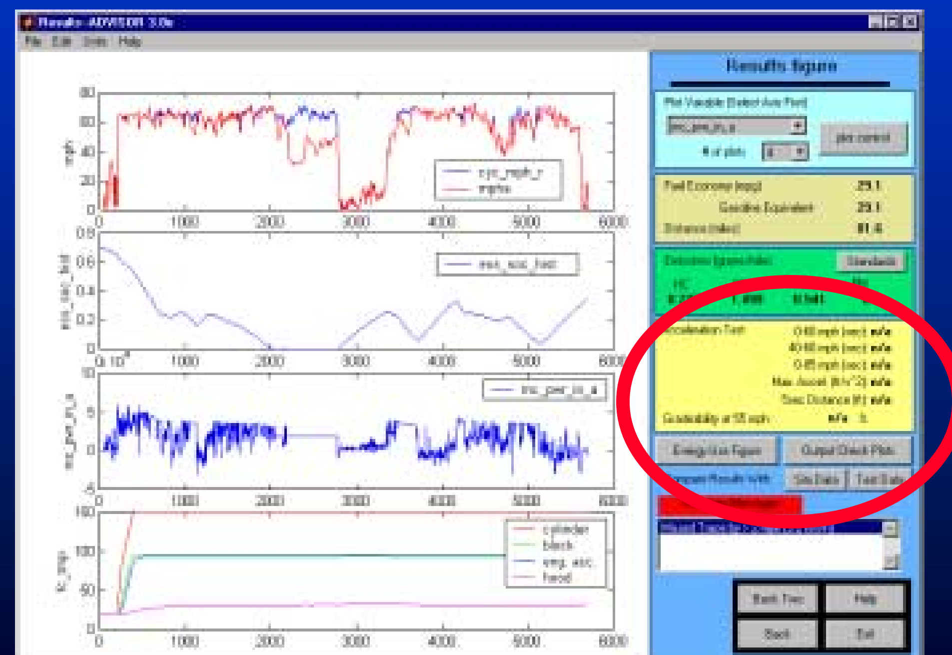


Cycle Results Screen

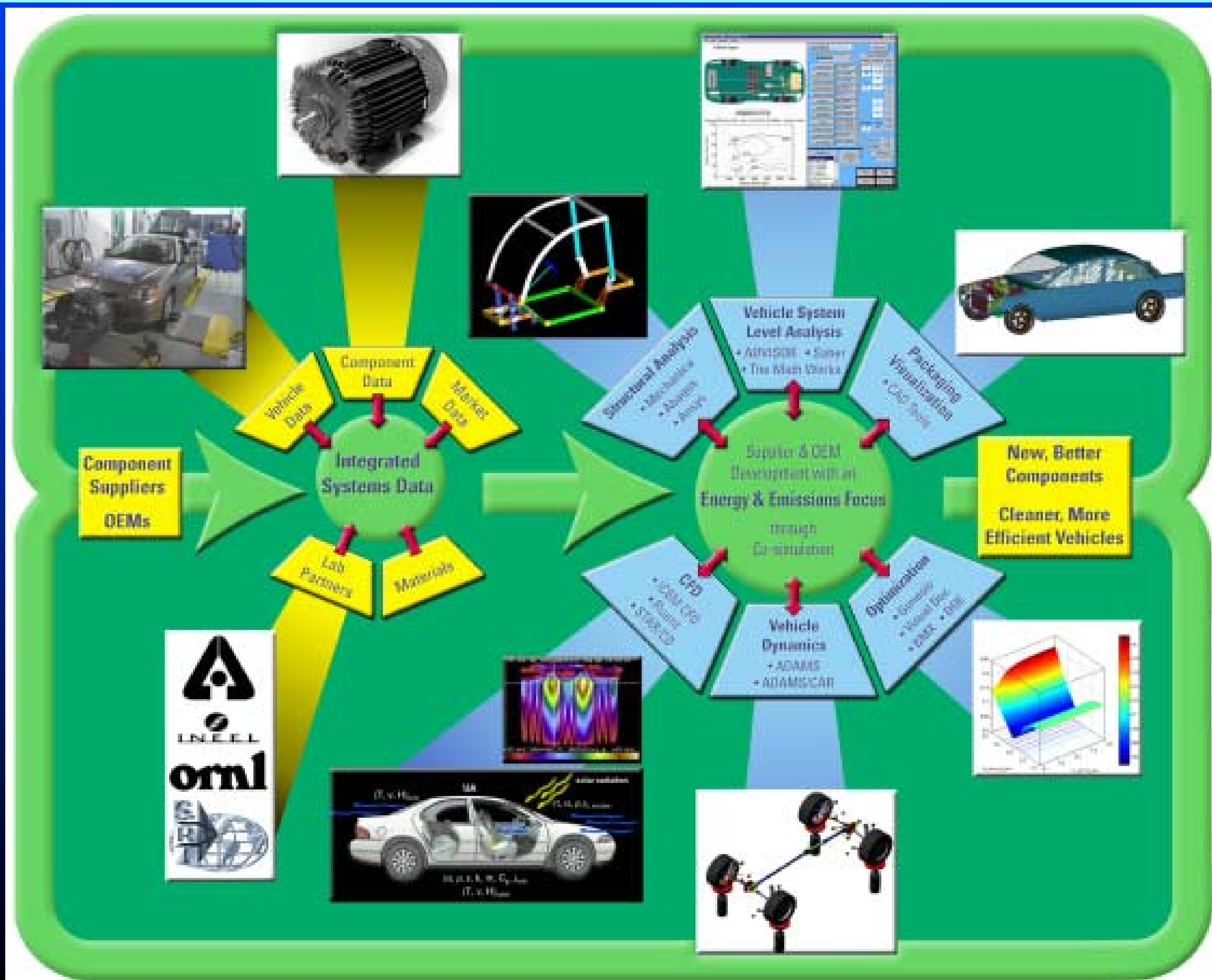


2.2.1

3.0



Future Direction: Digital Functional Vehicle



Special Thanks...

- You, Our Users, for making it possible
- Valerie Johnson, Barbara Ferris (NREL) for organizing conference
- ADVISOR Development Team

Clockwise: Ken Kelly, Sam Sprik, Keith Wipke, Tony Markel, Valerie Johnson, Aaron Brooker, Terry Hendricks (not pictured: Michael O'Keefe)

Special Thanks...

- Our ADVISOR Users Conference 2000 Sponsors:

DELPHI Automotive Systems

Mechanical Dynamics

The MATH WORKS

FLOWMASTER INTERNATIONAL·LTD

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The Rapid Development of an Electric Vehicle

Andreas Vlahinos, Advanced Engineering Solutions, LLC
David Rush,Teamwork's Inc.

Co-Simulation of ADVISOR and Saber: A Solution for Total Vehicle Energy Management Simulation

Presentation

Paper

John MacBain, Delphi Automotive Systems

Comparison of Fuel Efficiencies and Fuel Flexibility of Small Automotive Vehicles

Presentation

Paper

John Reuyl and Robert Apter, NEVCOR Inc.

Time For World Class Solutions

National Renewable Energy Laboratory

Advisor User Conference
August 2000

The Rapid Development of an Electric Vehicle

Dr. Andreas Vlahinos, Principle

& David Rush, President & CEO

Advanced Engineering Solutions

& Teamwork's Inc.

Your Virtual Resource for Rapid New Product Development

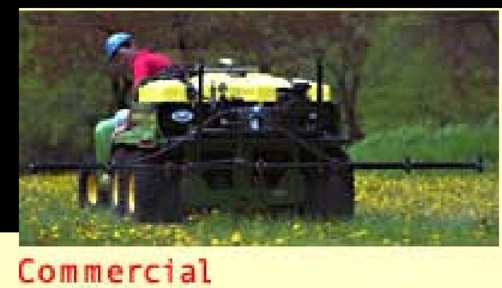
Emerging Electric Personal Mobility

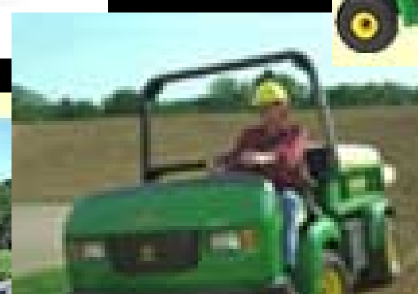
From Electric Bikes

To Electric City Vehicles

Emerging Electric Personal Mobility

To everything in between





Emerging Electric Personal Mobility

To everything in between

So in such a tough competitive emerging market ....

The one that is . . . .

First to market . . . .

with a quality product . . . .

at low cost.

So . . . . how do we get there?

Our Approach……………………

Industry Benefits

Brand name recognition

- Early pricing premiums
- Greater market share
- Reputation as innovator
- Greater profitability

Quality Product

- Product quality is no longer an option, It is a way of life
- Quality is a measure of satisfaction of the customer's requirements & expectations
- Quality is dynamic (changing customer expectations)

Customer Loyalty

- 70 percent of customers bail because of the look/feel/smell/taste of doing business with a company

Shareholder Value

- mission statement " … *to make a profit…"*

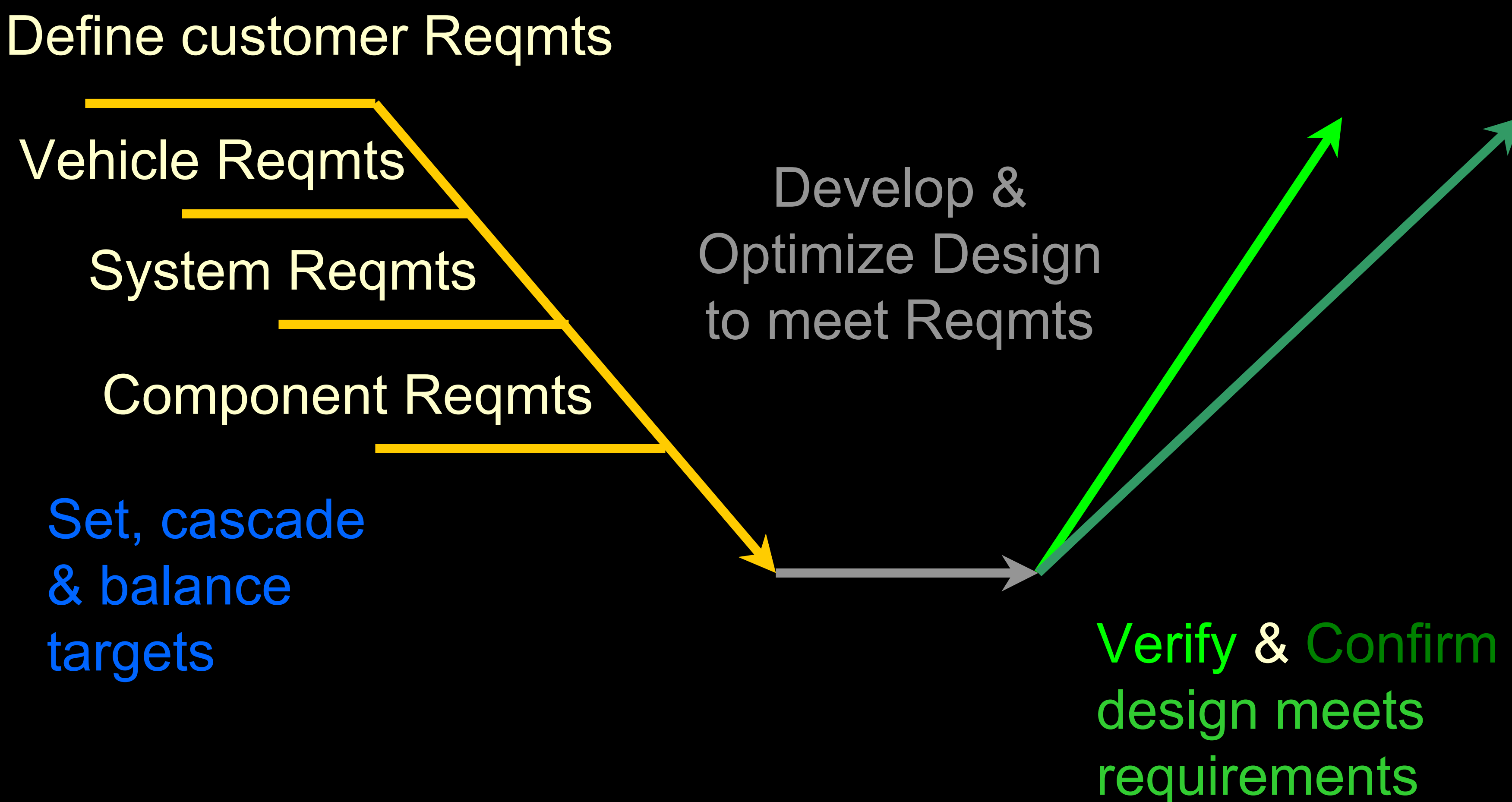
SHAREHOLDER VALUE
BRAND
PRODUCT
CUSTOMER LOYALTY
TECHNOLOGY
METHODS
PEOPLE
EV
PROCESS

The Process

The activities and procedures (and any sub process) that supports the vehicle conceptualization, it’s definition, design and development including :-

- Targets process.
- Quality Operating System.
- Review & decision processes.
- Development process & procedures.
- Sign-off process, etc.

Classic Systems Engineering Process



A Successful Process requires….

- Customer requirements drive the process
- Well defined process is key to rapid product development
- One process – no mavericks
- People must understand and use the process
- Compatible tools
- Integrated methods & techniques
- Web based communication


SHAREHOLDER VALUE
BRAND
PRODUCT
CUSTOMER LOYALTY
TECHNOLOGY
METHODS
PEOPLE
EV
PROCESS

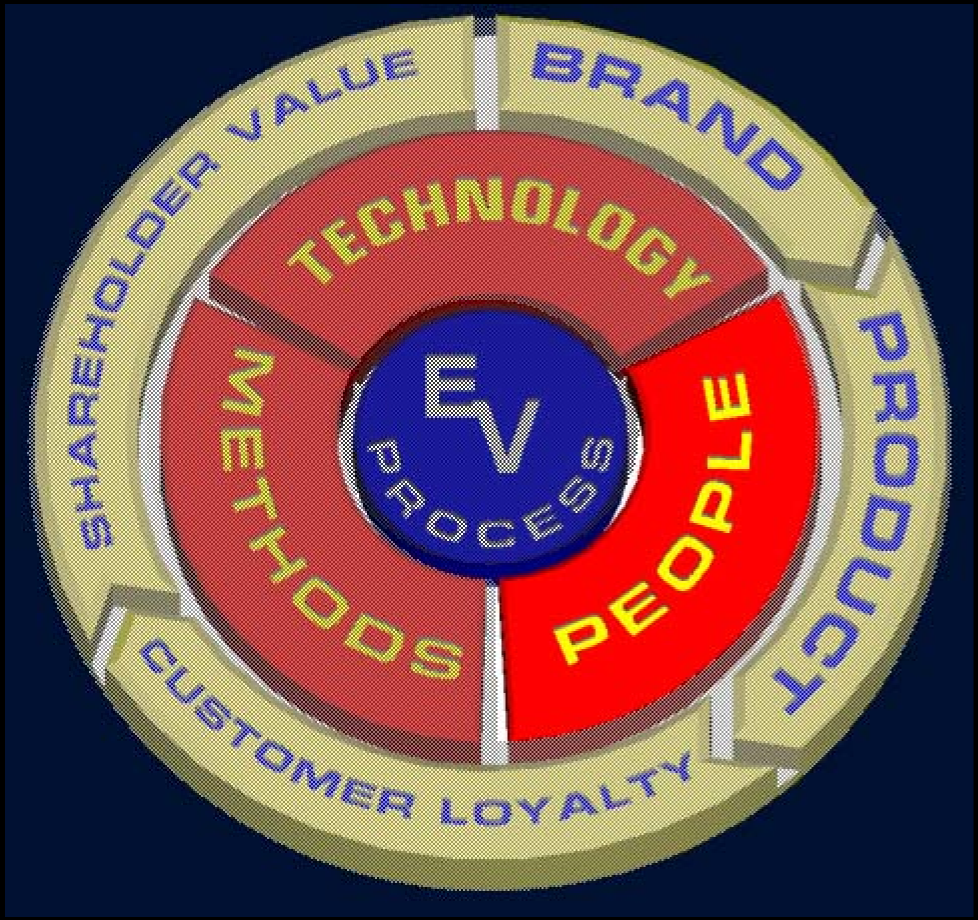
Technology

"**Knowledge** has become the key economic resource and the dominant, if not the only, source of competitive advantage"

Peter Drucker

- Virtual prototypes
- Tool selection for Integration
- Directional indications on time is better than absolute results to late
- Avoid multiple masters - single data base

Tools – Conceptualization


SHAREHOLDER VALUE
BRAND
PRODUCT
CUSTOMER LOYALTY
TECHNOLOGY
METHODS
PEOPLE
EV
PROCESS

The People

" In the digital age, as we move into the quicker and quicker exchanges of information . . . and re-inventions of the world at work, our organizations and our careers in action will become more and more closely aligned with the jazz ensemble . . . we will find ourselves improvising with greater and greater confidence and fearing less and less the imaginative power of the individual committed to enriching the whole."

Stanley Crouch, Forbes

The People

It is in the team environment that all other tools are most effectively used.

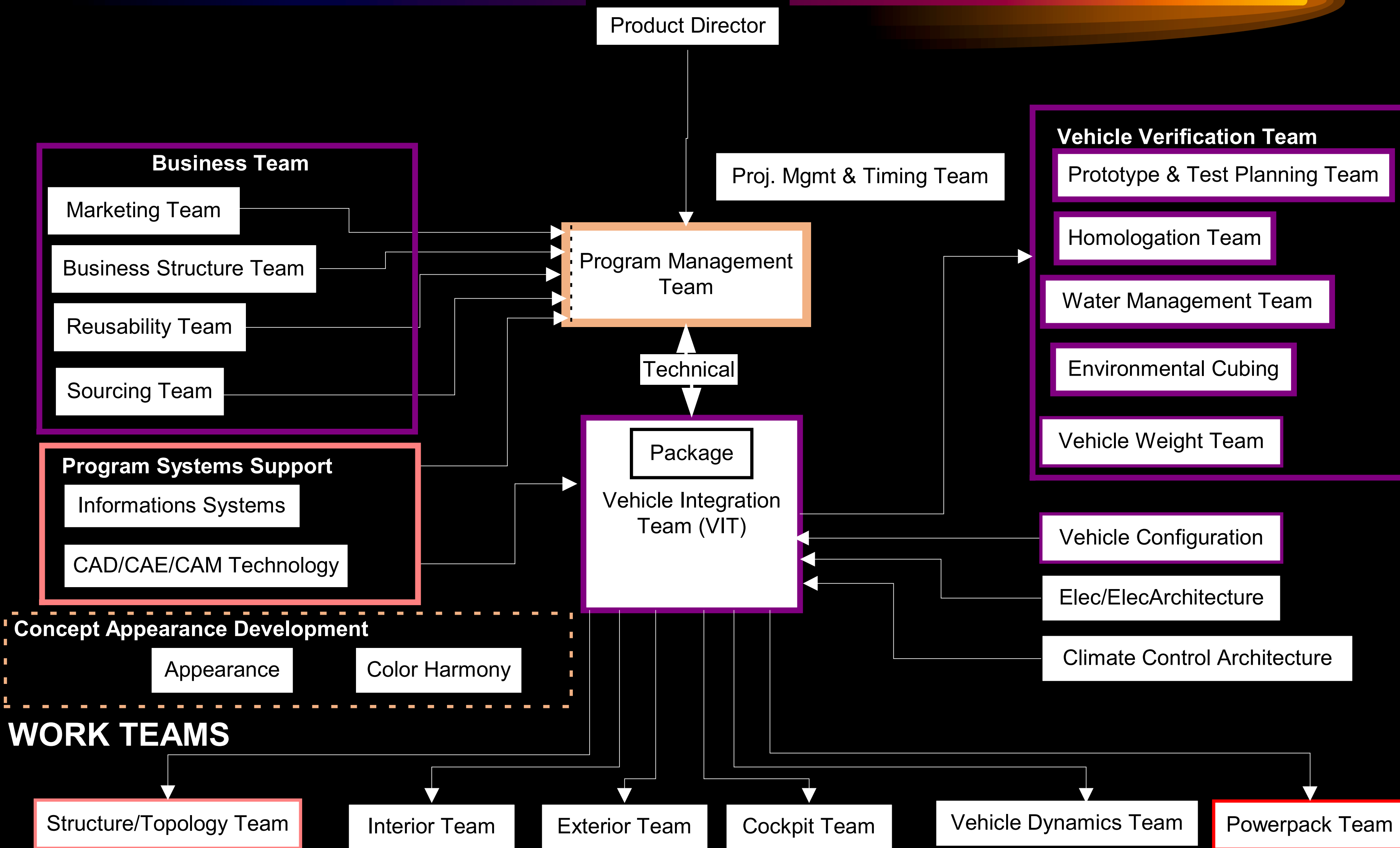
- Team structure.
- Integrate product attributes & system design & release responsibilities.
- Minimize the number of teams required.
- Minimize static data with real time communications.
- Provide central program data access.

The People

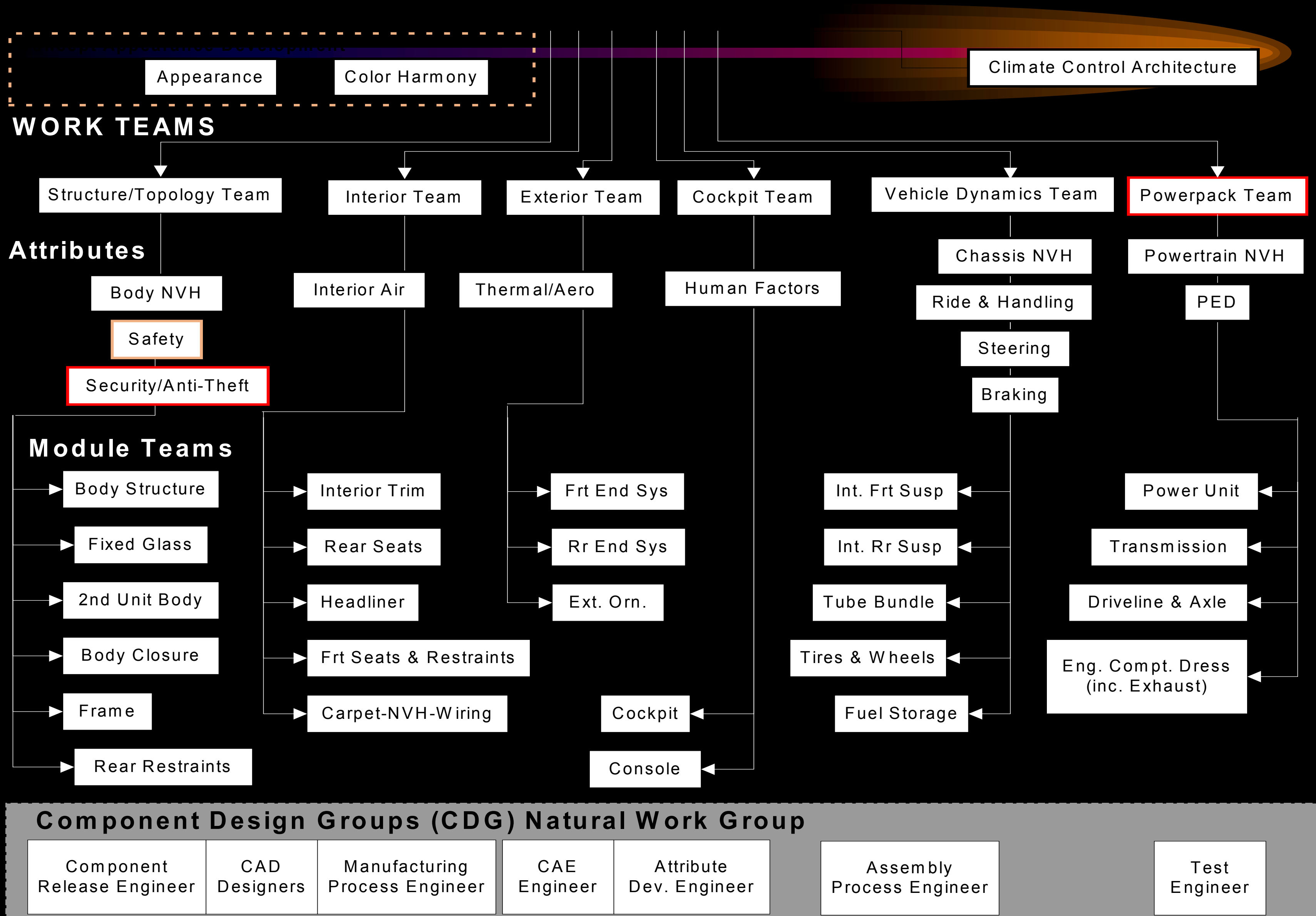
People Skills provide . . .

- **Knowledge of tools and methods.**
- **Skilled in application within the emerging integrated tool sets.**
- **Capability to collaborate through distributed development processes.**
- **Competency to develop new skills in an ever changing technical environment.**

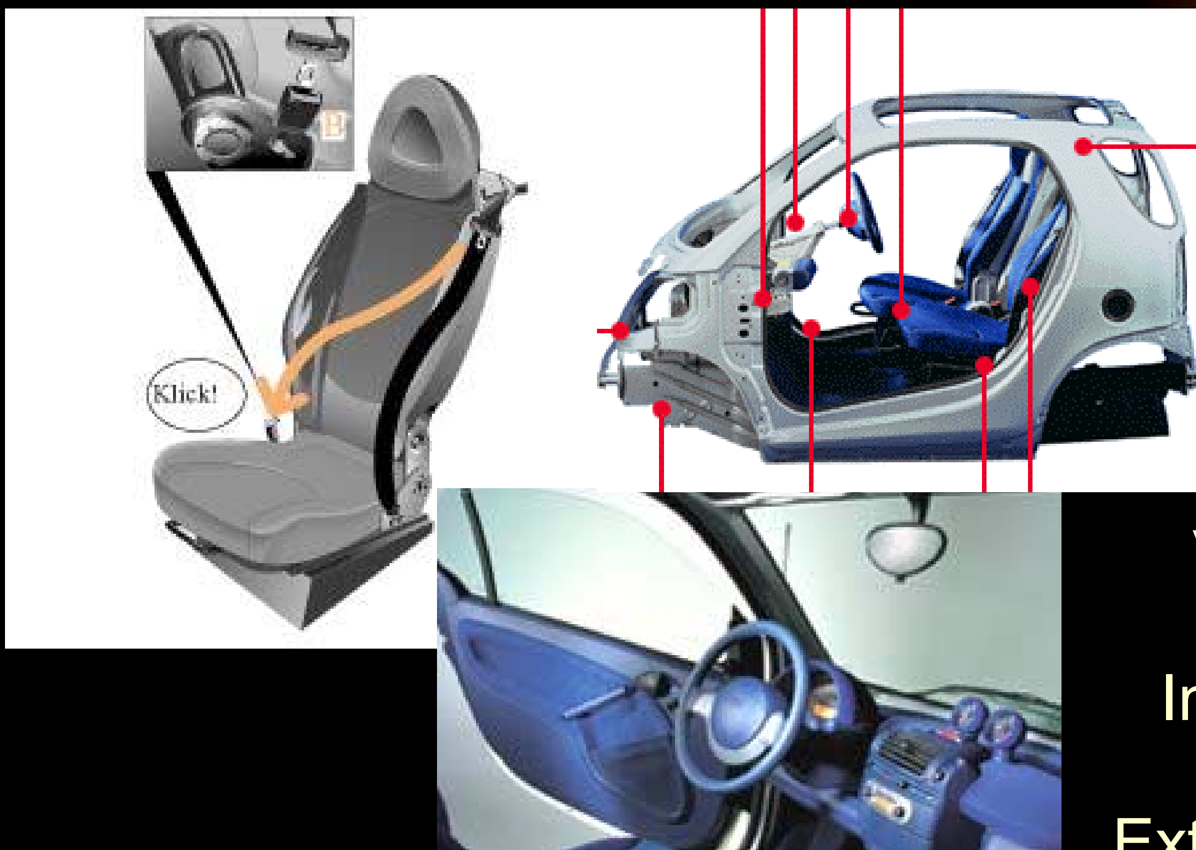
The People – Team Structure



The People – Team Structure



The People & Vehicle Integration



Structure Topology

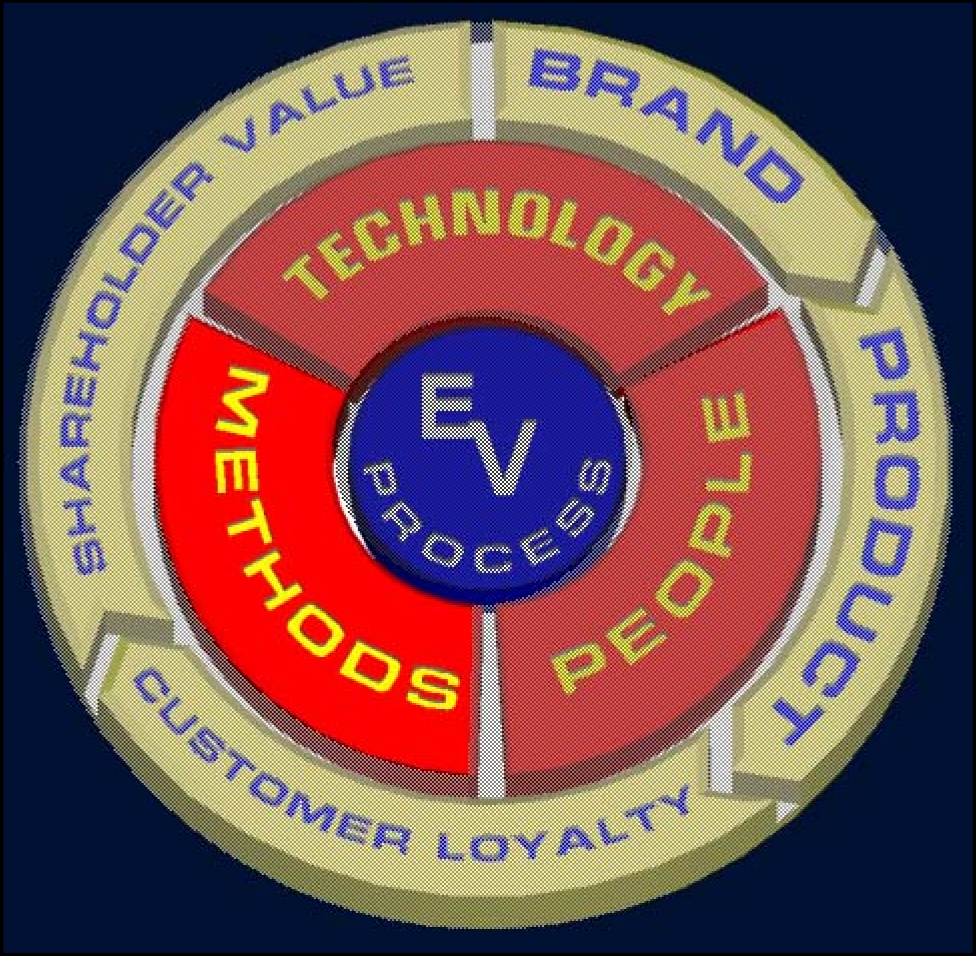
Power Propulsion

Vehicle Dynamics

Interior

Exterior

Cockpit



SHAREHOLDER VALUE
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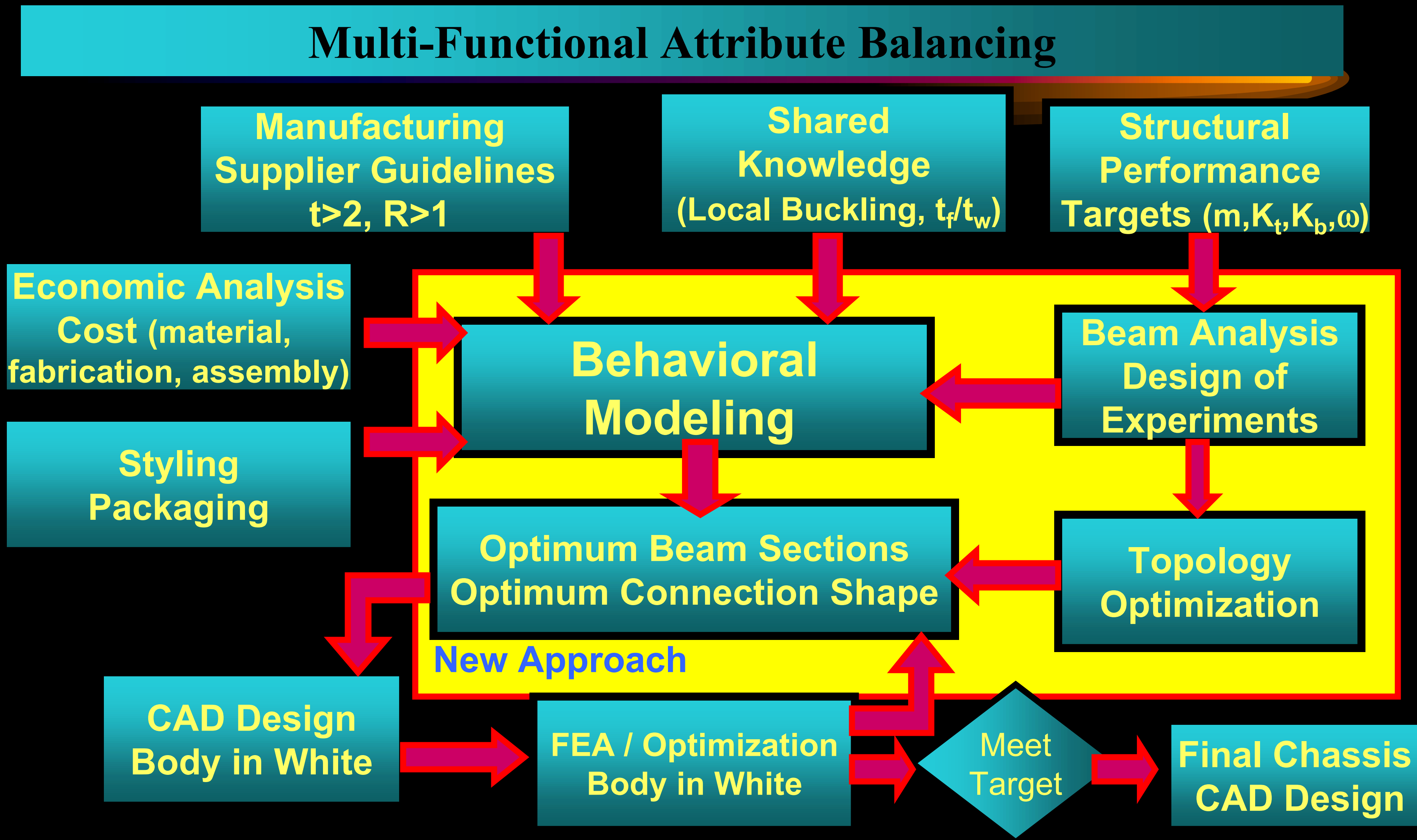
Methods & Techniques



Methods & Techniques

" Product quality requires managerial, technological and statistical concepts throughout all the major functions of the organization ..."

Josheph M. Juran

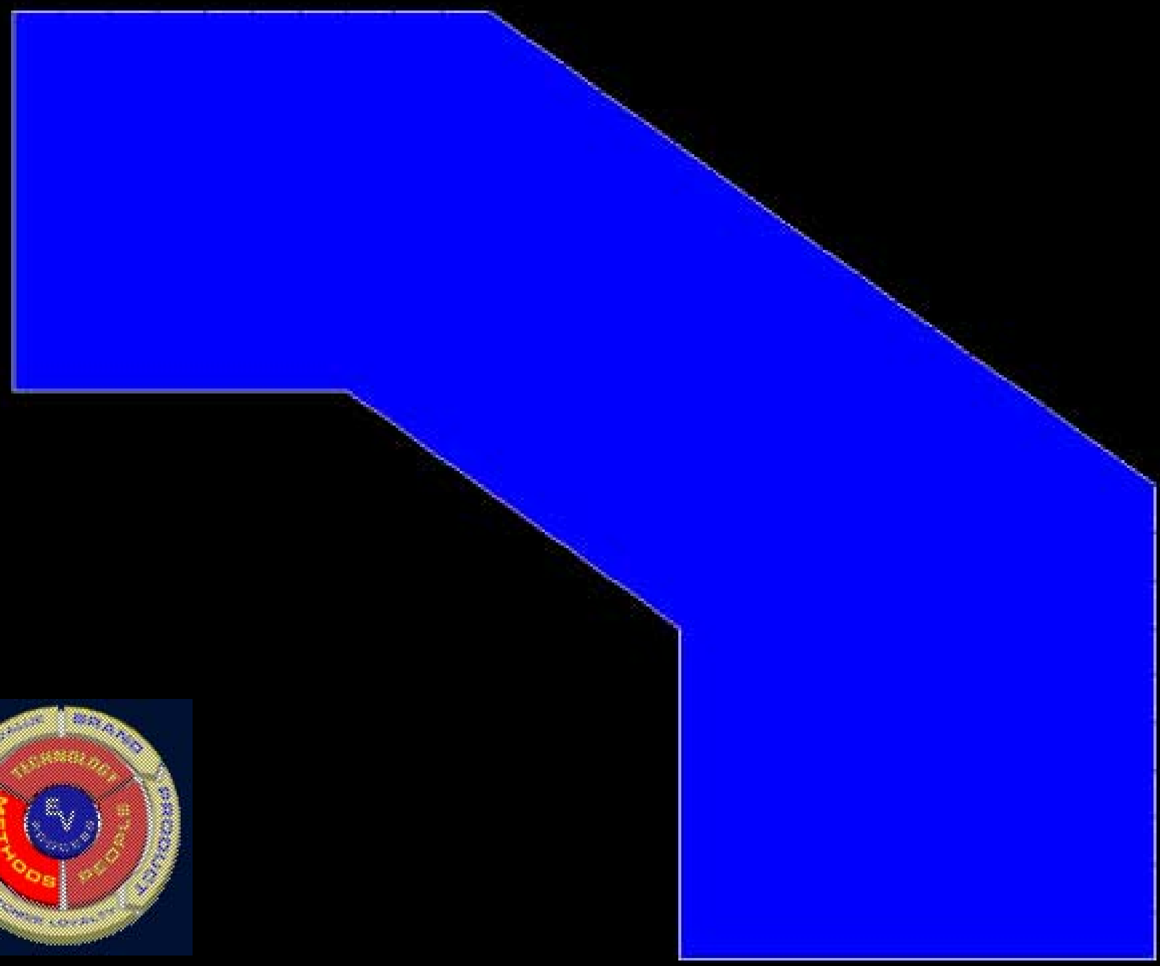
Variation (thickness, properties, surface finish, loads, etc.) is ... *THE ENEMY*

DOE, Six Sigma, Statistical FEA, Behavioral Modeling ... *THE DEFENCE*

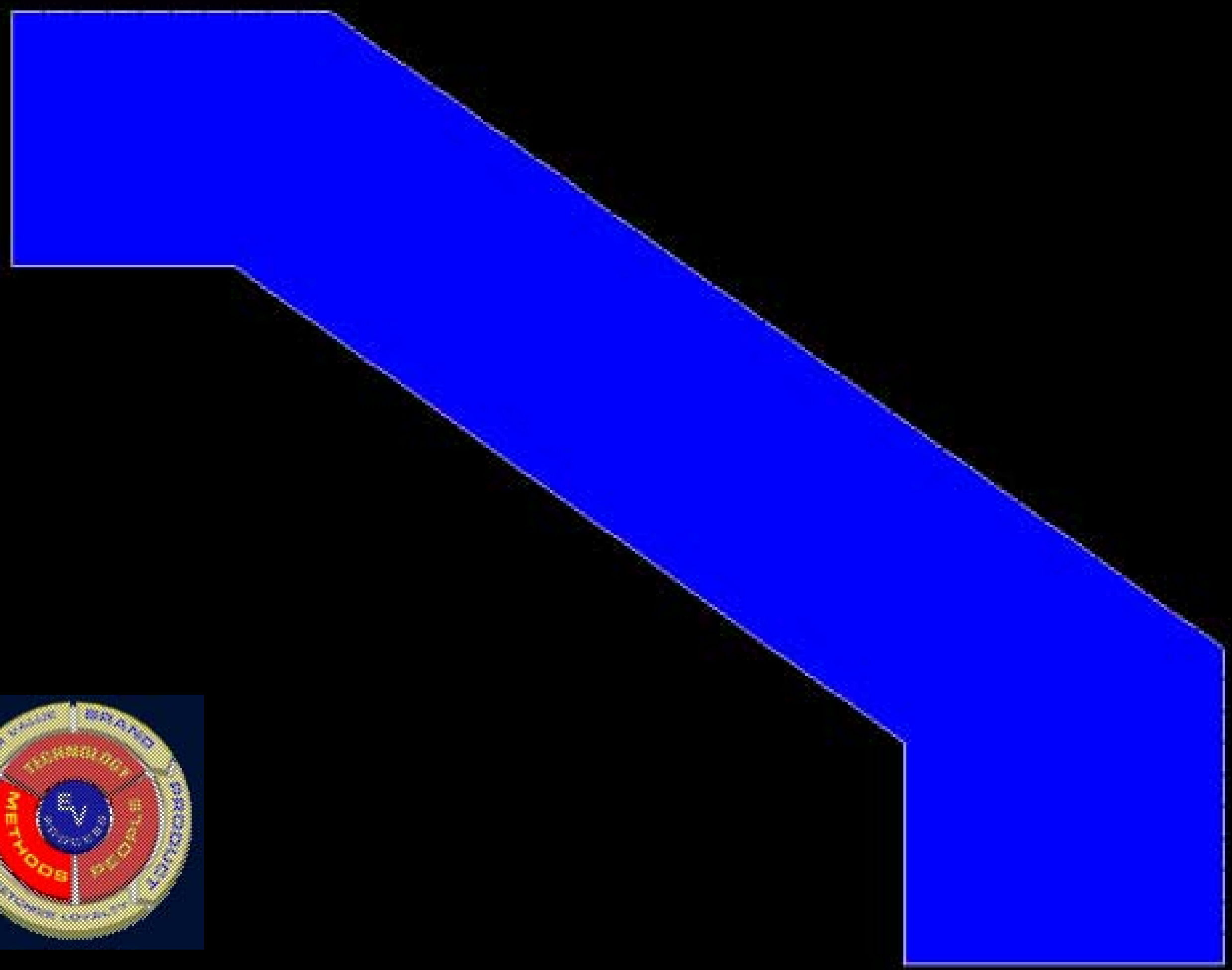
Behavioral Modeling of a Typical Section

- All Sections have the same moment of Inertia
- Find the one that minimizes the cross sectional area (Min Weight) and meet all the manufacturing and stability requirements
- Not a dimension driven CAD model
- Requirement driven design (I_{req})

Topology Optimization Short Section
(finding the best use of material)



Topology Optimization Long Section



Methods & Techniques

Suspension Design Process

Suspension Characteristic Targets
mass, inertia, Global Geometry info

ADAMS/Car

Suspension type &
Hard Point Location

Handling, Ride and
Steer Characteristics

Dynamic Loading

Mechanism Motion
Space Claim Envelop

CAD Design
Suspension

FEA / Optimization
Suspension

Meet
Target
?

Final
Suspension

Solutions for optimal cost without sacrificing ride & handling


SHAREHOLDER VALUE
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DELPHI
Automotive Systems

Energenix Center

Co-Simulation of ADVISOR and Saber

A Solution for Total Vehicle Energy Management Simulation

John MacBain
August 24, 2000

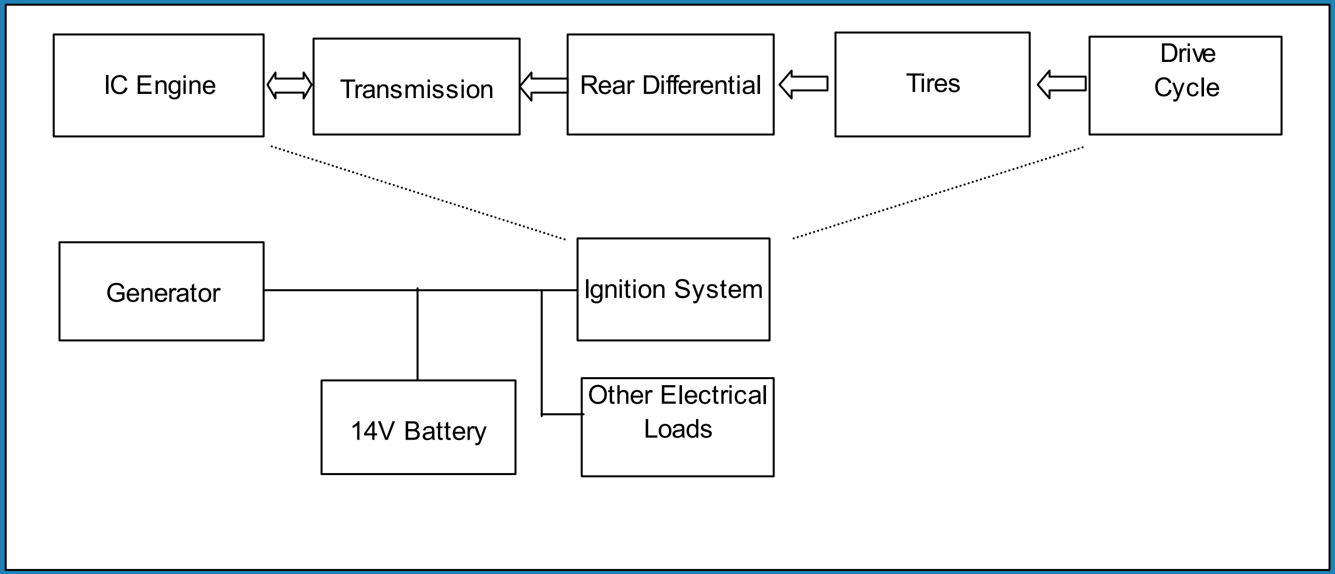
Agenda

- Overview
- Evolution of Automotive Architectures 1
  - Traditional ala 2000 - sizing batteries and generators
  - Traditional with increased electrical power budget
- Co-Simulation Concept
- Evolution of Automotive Architectures 2
  - Dual Voltage Architecture
  - Series Hybrid
  - Parallel Hybrid
- DOE Contract for Co-Simulation of ADVISOR and Saber
  - Status Report

Overview

- Electrical architecture simulation has traditionally been independent from the propulsion system of the vehicle
- Increasing electrical power budgets in traditional vehicles (EVA, EPS, catalytic converter heating, etc.) make consistent solution of the propulsion and electrical systems necessary for accurate results (mpg, sizing of electrical components, macro power flow, etc.)
- Hybrid architectures effectively marry the electrical and propulsion system, making them inseparable from a computational standpoint

Traditional 14V Architecture



ICE rpm determined largely by drive cycle

Generator load largely does not effect ICE rpm

Drive cycle related loads are largely the ignition system

Traditional 14V Architecture

- Sizing of batteries and generators - a key simulation activity at the macro power level

  - Select challenging temperatures and a variety of drive cycles
  - Select minimum battery capability based upon specifications
  - Select the electrical loads for each drive cycle

  - Simulate the propulsion system for the each drive cycle
  - Convert ICE rpm profile to a generator rpm profile
  - Simulate performance of electrical system for each drive cycle
  - Check adequacy of generator to maintain battery charge
  - Adjust size of battery or generator accordingly and repeat the simulation cycle

  - Non-interactive analyses function adequately

Traditional 14V Architecture
Increased Electrical Power Budget

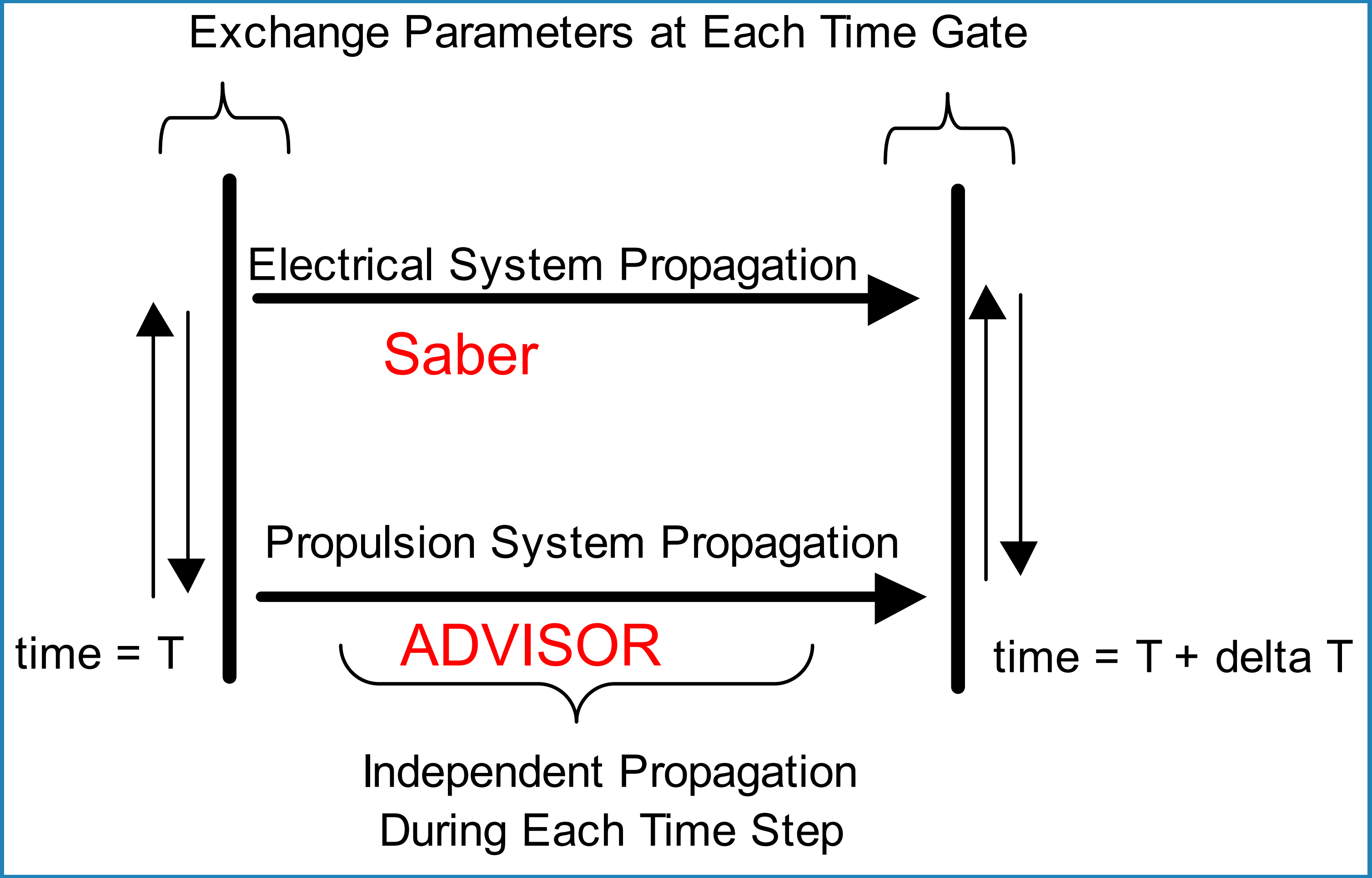
- Three driving factors in future vehicle design
  - Projected generator peak power requirements
    - 1,800 watts in 1990
    - 10,000 watts in 2020
  - Tightening CAFÉ standards
  - Tightening emission standards

- Implications:
  - Events in the propulsion system and electrical system have increasing impact on the other
  - Simulations of the total power system of the vehicle, electrical and propulsion, must be more interconnected as we design to meet stringent requirements requiring system solutions on a broader scope

A Possible Solution

- Potentially Ideal solution - model electrical system in MatLab/Simulink as a part of ADVISOR
- Challenges with the ideal solution
  - Saber and other packages already are developed and focused on the solution of the electrical system
  - Many automotive OEMs are committed to Saber for electrical system analysis
  - Many component models have already been developed in Saber and not in MatLab
  - Saber imports Pspice models
- Thus, it makes sense to connect existing specialized tools rather than re-inventing the wheel

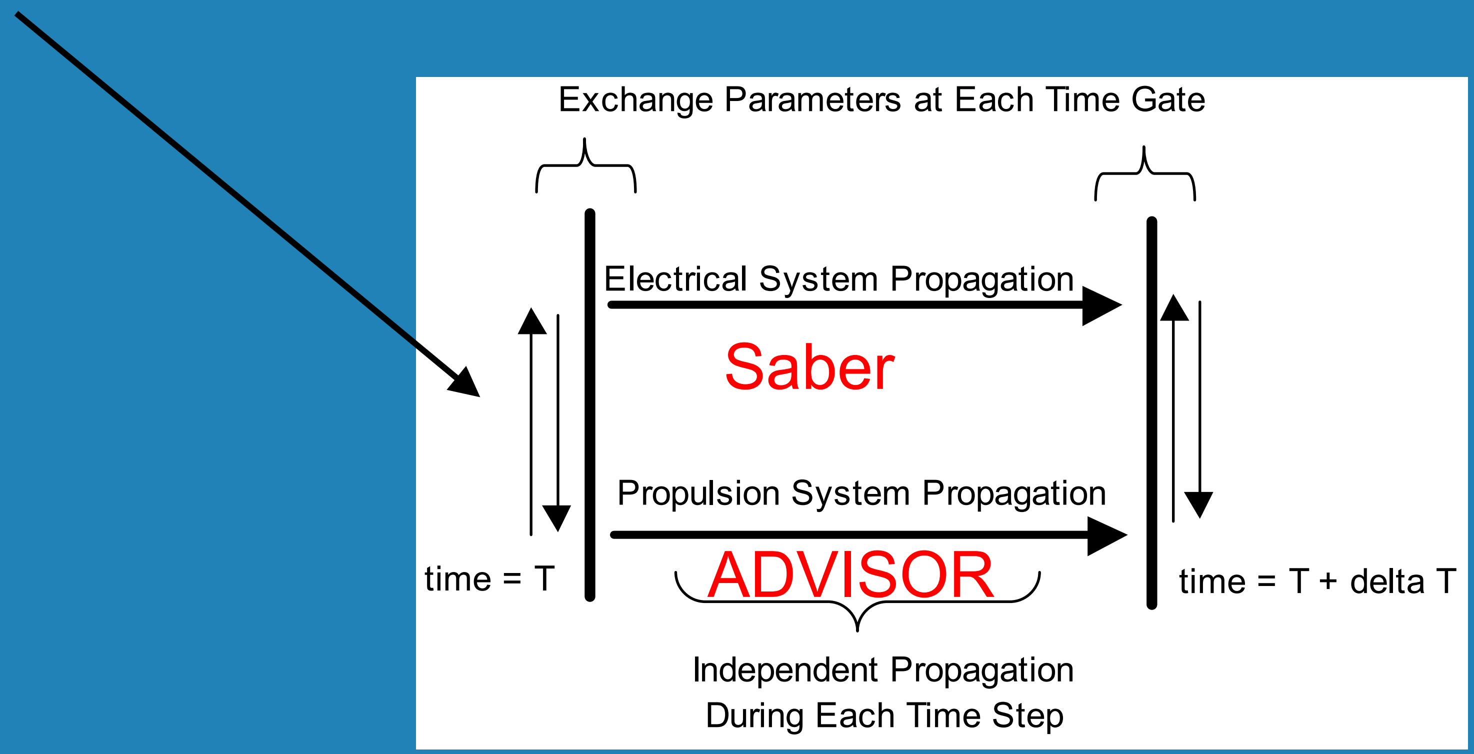
Co-Simulation Concept



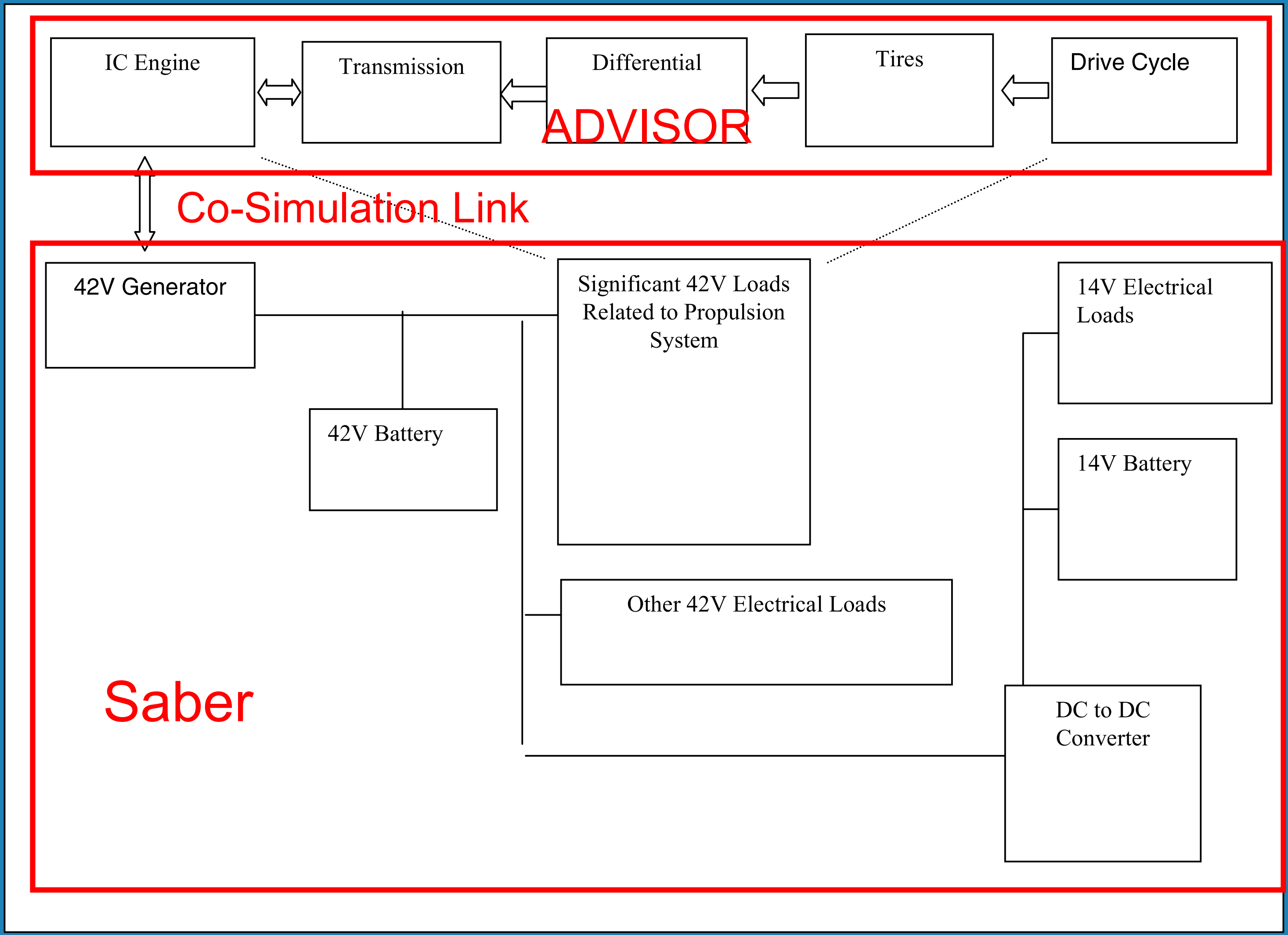
Co-Simulation Concept
Traditional Vehicle Architecture

Potential Parameters to Pass:

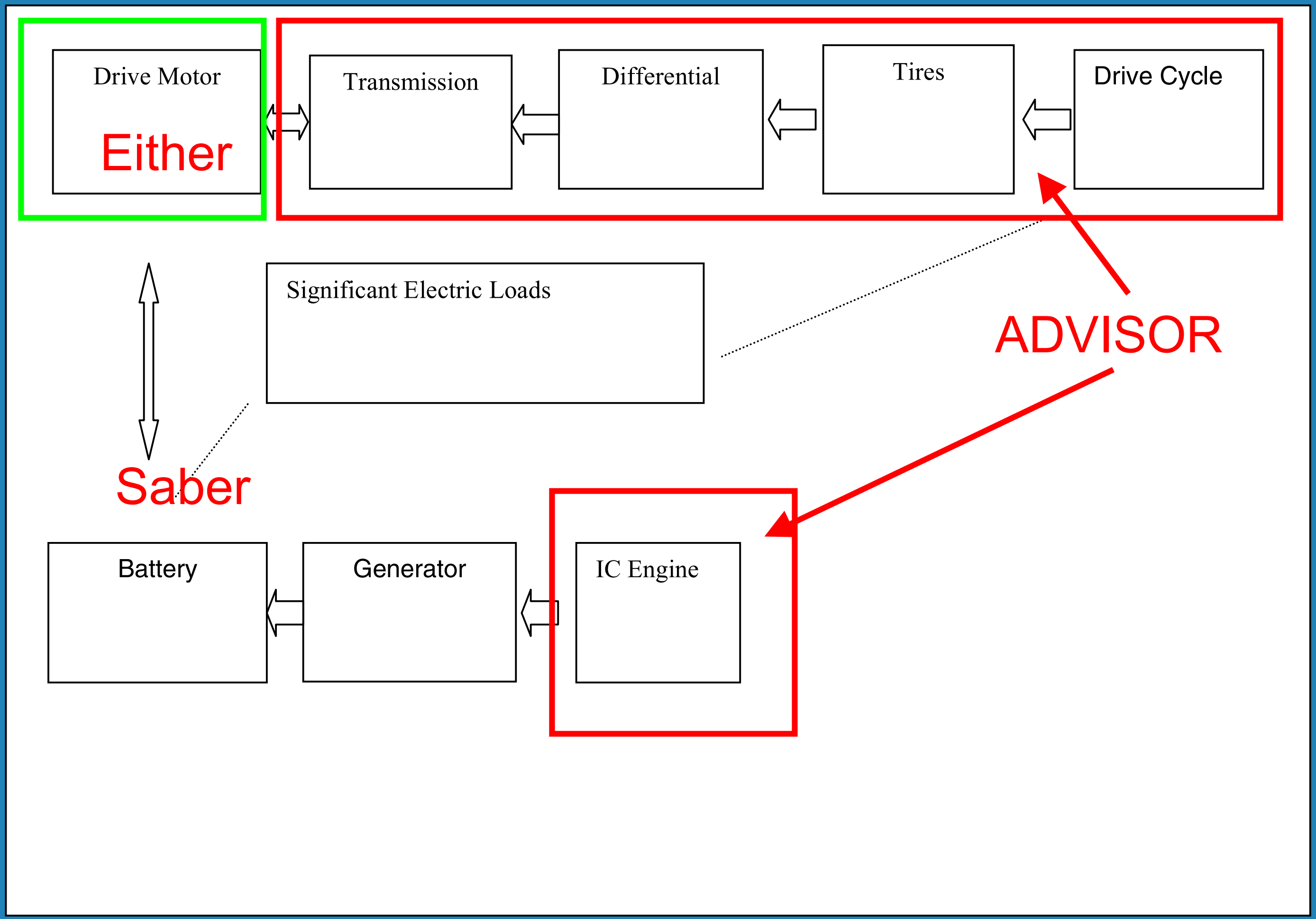
ICE instantaneous rpm
Generator instantaneous required shaft torque



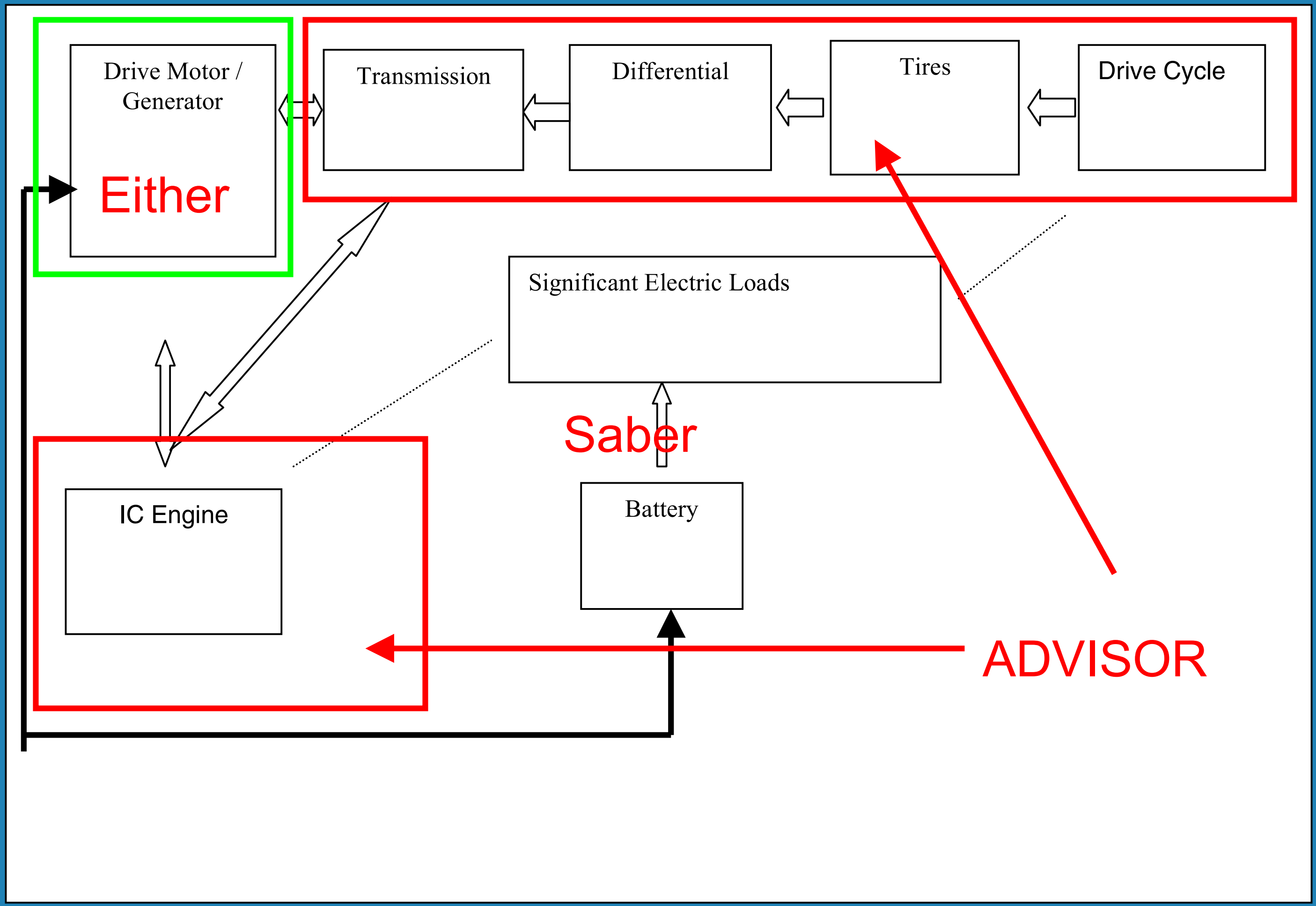
Dual Voltage Architectures



Series Hybrid Architecture



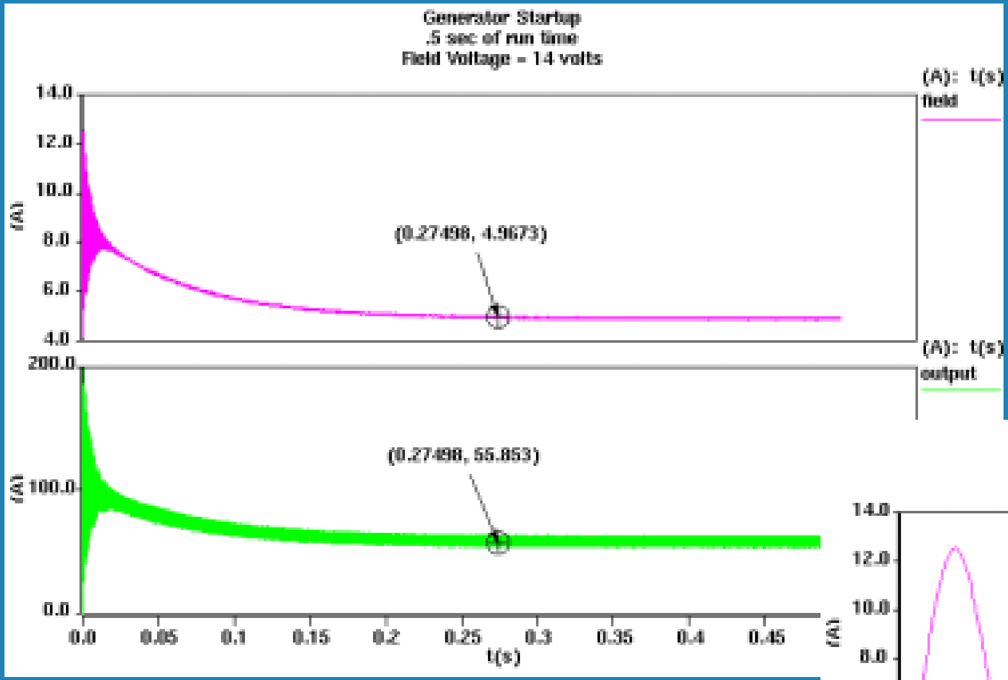
Parallel Hybrid Architecture



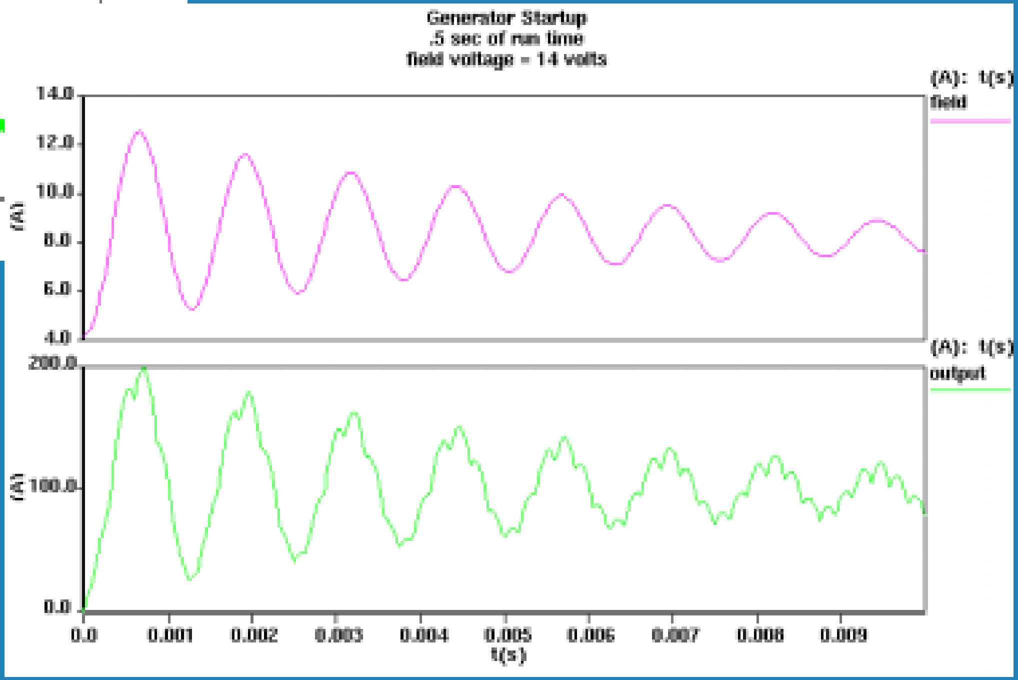
Initial DOE Contract Activities

- Kickoff on June 8, 2000
- Demonstrate restart of Saber with parameter alterations
  - Commands issued within Saber
- Start drafting Saber AIM script for co-simulation as a shell around Saber
  - Commands in effect coming from outside Saber

Restart Demonstration of Saber

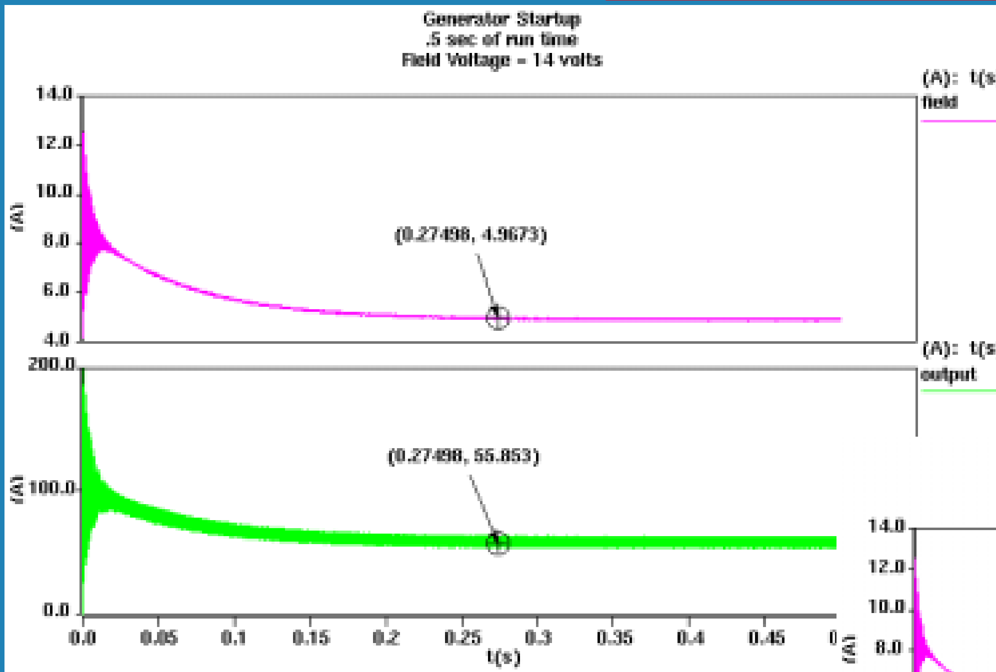


1st .5 seconds



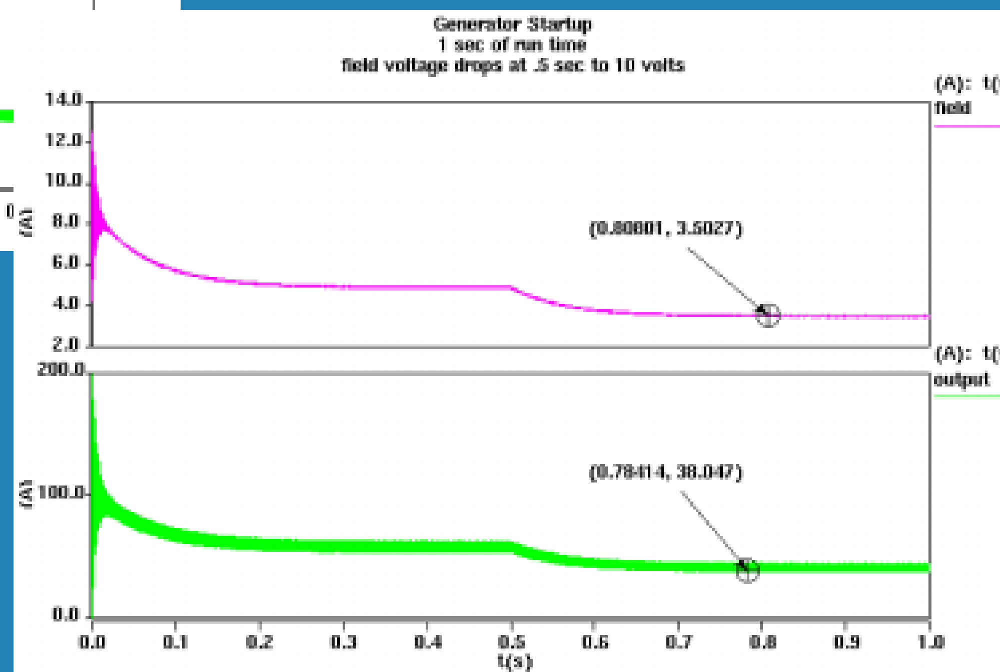
Expanded View of Startup

Restart Demonstration of Saber



1st .5 Seconds

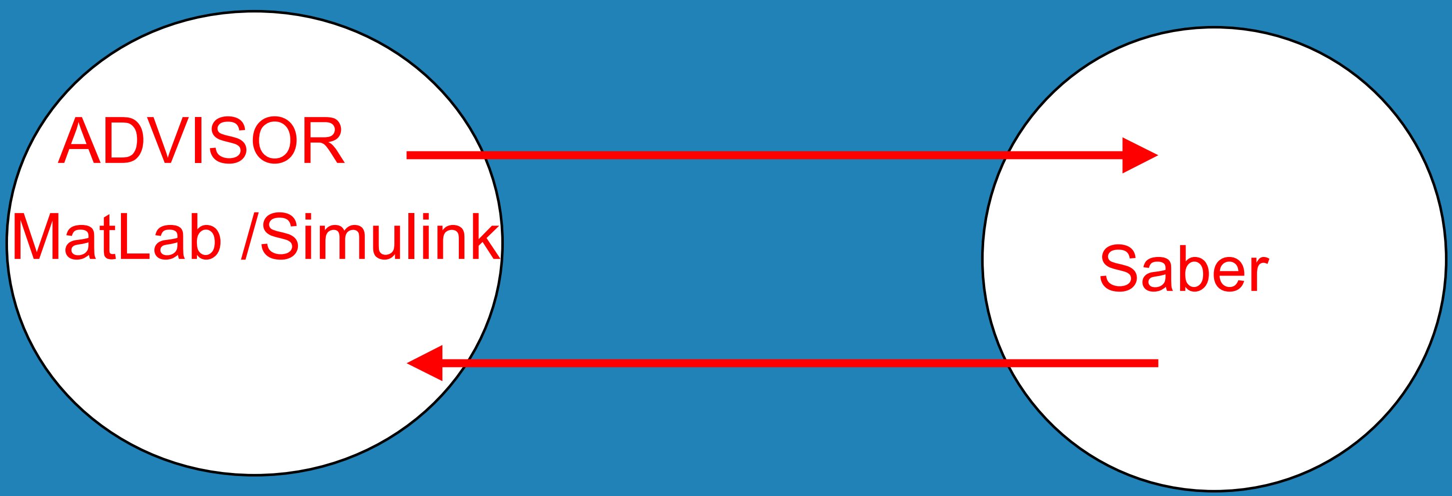
Field Voltage at 14V



Restart Runs to 1 second

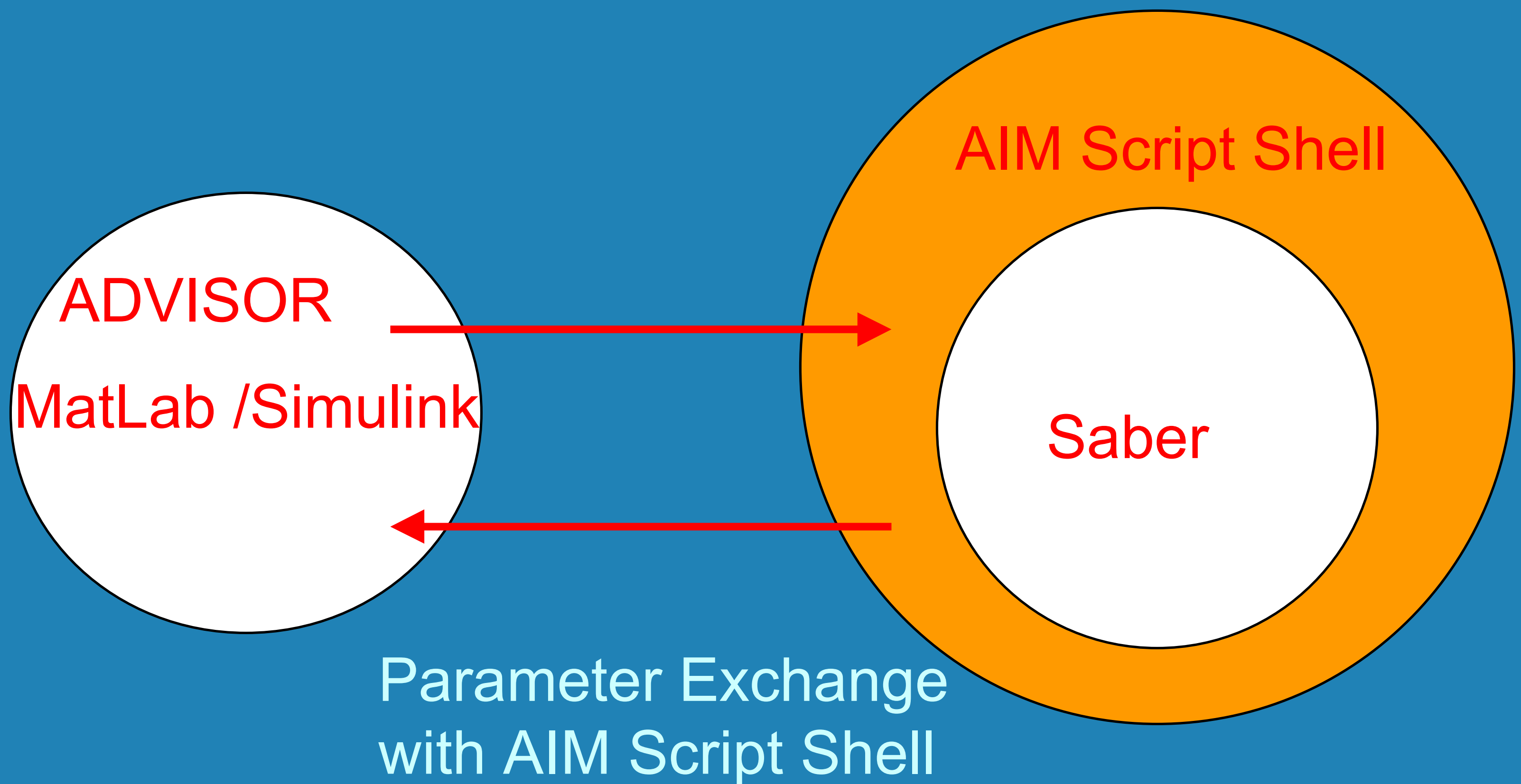
Field Voltage drops to 10V

Ideal Co-Simulation Strategy

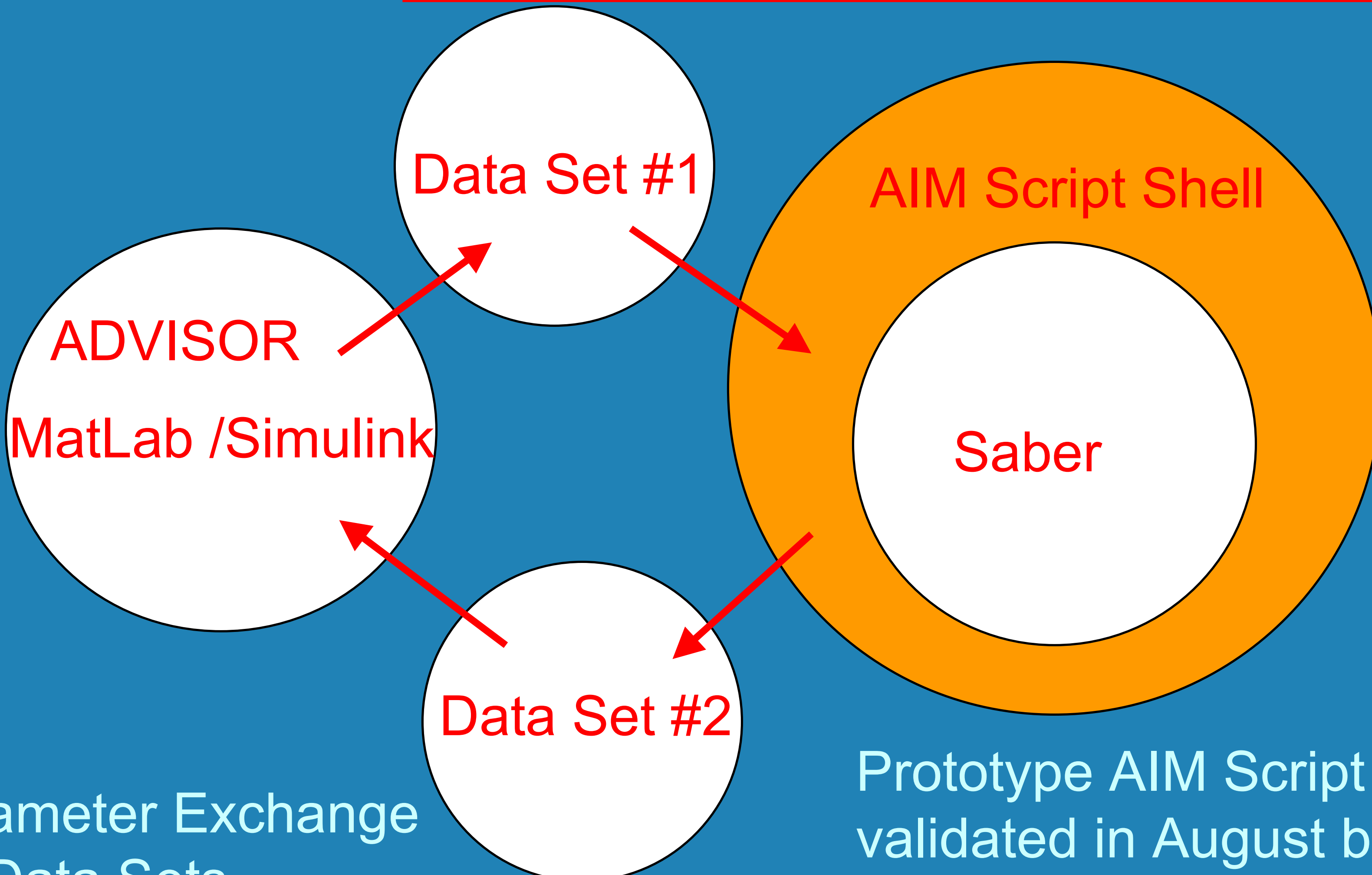


Parameter Exchange
by Direct Communication to
Command Lines

More Realistic Ideal Co-Simulation Strategy



1st Prototype Strategy for Co-Simulation



Parameter Exchange via Data Sets

Prototype AIM Script validated in August by Joe Conover.

Conclusions

- Future evaluation of electrical systems and propulsions systems will require acknowledgement of the codependency of the two systems
- It makes sense to build upon existing specialized software systems
  - Co-Simulation provides a viable method to achieve this by establishing communication between existing software packages
- The DOE contract for co-simulation of ADVISOR and Saber has been started and progress has been made.

Co-Simulation of ADVISOR and Saber - A Solution for Total Vehicle Energy Management Simulation

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Delphi Automotive Systems, Energenix Center

ABSTRACT

Electrical analysis for vehicles with traditional 14V electrical architectures has often been limited to engineering functionality simulation for the components and systems. This level of analysis ignores the impact of the electrical system on the fuel efficiency and emissions of the full vehicle, a much larger system. Even for traditional architecture vehicles that are prevalent today, the computational problems of predicting propulsion system performance and electrical system performance are coupled. As the millennium changes, series and parallel hybrid vehicle concepts are becoming a marketplace reality. These hybrid concepts accentuate the coupling of the propulsion and electrical systems making it less viable to simulate either propulsion or electrical systems independently. This paper explores the various goals of electrical system analysis and how some electrical analyses require acknowledgement of the coupling of the electrical and propulsion systems thus creating a requirement for simultaneous or co-simulation of the propulsion and electrical systems.

This paper will lay out the plans for developing specific co-simulation technologies between NREL's ADVISOR and Saber. This work represents the content of a contract between Delphi Automotive Systems and the Department of Energy that establishes a partnership between the National Renewable Energy Laboratory and Delphi Automotive Systems. The contract is entitled "Modeling and Simulation Development for Advanced Energy Management and Propulsions Systems."

The final product of the contract will be a co-simulation capability tying Saber (for the electrical architecture simulations) and ADVISOR (now for the purely propulsion system simulations) to produce total vehicle energy management system simulations for traditional, series, and parallel hybrid vehicles. The work will provide templates to accommodate both single and dual voltage electrical architectures. The co-simulation capability will be available from NREL to the global automotive engineering community much as ADVISOR is available today with template interfaces for constructing and simulating vehicle energy management systems.

INTRODUCTION

This paper will explore the largely independent requirements on electrical system analysis today. Once this baseline has been established, the paper will move through a progression of vehicle architectures from traditional architectures with higher electrical power budgets to future hybrid concepts with the perspective of requirements for electrical system analysis. This increased electrical power budget comes from the shift of loads from mechanical powered loads to the electrical system (EPS, EVA, etc.), the additional of new loads (catalytic converter heaters), and hybrid vehicle architectures with electric traction motors. The propulsion system and the electrical system become ever more interdependent, moving electrical system analysis from a largely independent activity today to an embedded activity with total vehicle propulsion system performance. The discussion establishes the argument for co-simulation between traditional electrical analysis software and traditional propulsion system analysis software. The paper will end with a discussion concerning the specific plans of the contract between Delphi Automotive Systems and the National Renewable Energy Laboratory (Department of Energy funding) to make co-simulation between ADVISOR and Saber a real and available option in future versions of ADVISOR.

TRADITIONAL 14V VEHICLES – SIZING ELECTRICAL COMPONENTS

A traditional 14V system typical of most passenger car vehicles on the road today has a single voltage electrical system which drives all the electrical loads on the vehicle. A schematic for traditional vehicles is displayed in Figure 1. The energy input to the electrical system is through the shaft of the generator which is turned by the internal combustion (IC) engine. The electrical architecture consists of a generator (including voltage regulator and rectifier), a storage battery, and a series of electrical loads. This section will discuss this electrical architecture with the perspective of performing various electrical analyses often faced in vehicle design.

A variety of electrical system problems are regularly solved without acknowledging the larger vehicle systems, and often this is well justified. Vehicle designers always face the challenge of adequately sizing the generator and the battery to satisfy the electrical power demands of the vehicle. More detailed models of the components are required for analyses which would indicate interference of signals between components and/or the impact of anomalous voltage events triggered by the switching of significant electrical loads. Challenging problems also exist in the choice of the proper cables for the power and signal distribution system. One must carefully choose the cable gauge, insulation class, and circuit fusing methodology (level and fuse/circuit breaker style) to insure proper and safe performance of the electrical system with adequate current and voltage being made available to the various loads in the vehicle. The balance of this section of the paper will elaborate more on the proper sizing of generators and batteries since more awareness of these issues will provide the basis for later topics in the paper. All of these problems are readily addressed as independent electrical system analyses. These analysis technologies have already been created with a high level of sophistication within Delphi Automotive Systems and other companies.

Electrical loads can be categorized as loads which run continuously during vehicle operation, loads which run for prolonged periods, loads which typically run for briefer periods, and key off loads. Loads which run continuously would include the ignition system, the electric fuel pump, electric fuel injection systems, and engine management computers / controls / sensors. Loads which run for prolonged periods would include the windshield wipers, headlights, taillights, side marker lights, instrument panel lamps, entertainment systems, engine cooling fans, and the HVAC blower. Loads with briefer duty cycles include power windows, power door locks, power seats, horn, starting motor, brake lights, backup lights, heated rear window, and the power antenna. These lists have been presented for clarification purposes and are not exhaustive.

When a vehicle is sized for a generator and battery, the engineer must select several typical driving cycles. The engineer also selects several extreme cases such as being stuck in rush-hour traffic. Typical load scenarios are then selected which would cause a strain for the electrical system. For instance, vehicles must continue to perform in the hottest desert environments in Death Valley as well as harsh blizzard conditions in Alaska and Canada. Anticipated driver load choices (AC in summer, etc.) and drive cycle required loads (brake lights, turn signals, etc.) must be included.

The typical analysis methodology proceeds with an independent propulsion system analysis showing the crankshaft rpm required for the vehicle to meet the requirements of the driving cycle. The crankshaft rpm is converted to generator shaft rpm reflecting either a direct mechanical drive system or a belt drive. This generator rpm is the sole input to the electrical system analyses. The electrical system is analyzed for battery and generator adequacy for the various load scenarios coupled with the drive cycles and ignition system electrical loading consistent with the drive cycle.

The engineer adopts a margin of safety for the component specifications and the electrical system typically works quite well. Analysis has played an important role in this engineering methodology for many years, and it has proven to be quite successful. For these purposes, independent electrical system analysis is quite adequate.

As Figure 1 demonstrates, the electrical and propulsion systems are indeed largely autonomous except for the mechanical connection between the IC engine and the generator where the engine speed is largely determined by the drive cycle. The luxury of this relative autonomy is facing extinction. In Figure 1 as with all other figures, the arrows represent flows of information in ADVISOR and between ADVISOR and the electrical simulation.

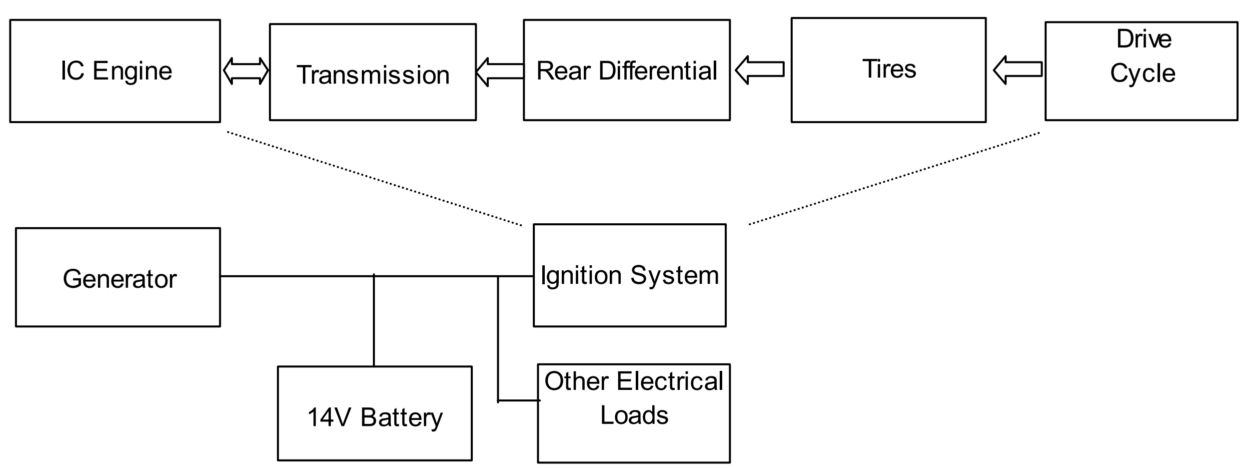

Figure 1: Traditional Vehicle Architecture

TRADITIONAL 14V VEHICLES – VEHICLE EFFICIENCY ANALYSIS MOVING FORWARD

Let us raise the bar for electrical analyses. In addition to designing a well-performing electrical system, we need to ascertain the impact of the electrical system on the overall vehicle fuel efficiency and emissions. Such challenges have become reality in recent years with tightening CAFÉ standards, tightening EPA emission standards, and the perpetually increasing electrical power budgets on vehicles. This electrical power budget has increased from a generator peak power of 1.8kW in 1990 to a projected 10kW in 2020. This increasing demand for electrical power is one of the primary drivers for consideration of dual voltage or high voltage systems for future vehicles; the dual voltage systems permit delivering increased power at reduced current and, therefore, reduced resistive losses and improved efficiency. Can the engineer adequately solve this problem by analyzing the electrical and propulsion systems separately? Let us explore the factors involved in this challenge.

The primary coupling of the propulsion and electrical systems is the transfer of energy from the engine crankshaft to the generator. The energy being supplied to the generator shaft is the only energy input to the electrical system. But, how realistic is the computed rpm profile of the engine crankshaft for a given vehicle on a drive cycle? It is typically computed through an independent powertrain analysis that at best has an average power loss to the generator determining energy consumption. Careful electrical system analysis can compute the actual energy consumption of the electrical system including generator losses. This mechanical loading of the engine can then be iterated back into the propulsion system analyses, thus updating the engine energy consumption. Certainly the fuel consumption profile of the engine will change, and potentially the transmission shift profile and engine rpm profile will change as a result. One can iterate between electrical system analyses and propulsions system analyses, providing updated profiles of the power gain/loss between the two systems until convergence is achieved. Only then will the propulsion system analysis yield the correct fuel economy and emissions for the drive cycle and electrical load assumptions.

Now, let us move five years into the future when the power budget of a typical car has increased substantially. The vehicle architecture may be much the same for low to mid range vehicles. But, now the electrical budget will be much more significant in the total power budget of the vehicle. At this point, there is no alternative to solving the electrical and propulsion problems simultaneously. This would be quite straightforward if all the models and/or differential equations resided in a single piece of software with a single solver.

Today, though, packages tend to specialize in mechanical systems or electrical systems. Two good examples are the ADVISOR® software from NREL that analyzes propulsion system performance and Saber® that is naturally cast towards solving electrical system problems from its roots in the electronics business. From a theoretical perspective, one has a series of coupled models that must be solved simultaneously. However, some models are being solved by software package A and the others are being solved by software package B. The answer is co-simulation. Co-simulation is the closest you can come to simultaneous simulation while maintaining independent solvers.

CO-SIMULATION OF ANALYSIS PACKAGES

Simulation models exist in several distinct classes. Many processes on a vehicle can be described by equations, either differential or algebraic. Other processes are more easily modeled empirically with lookup tables of measured or pre-computed performance. The solution of a simulation problem with time as the independent variable involves stepping a solution forward in time which satisfies all of the models and their respective interactions and interdependencies. As an example consider solving a branched circuit involving resistors, capacitors, and inductors. Kirchoff's laws permit writing the coupled equations for the voltage drops and currents. The subsequent numerical solution comes readily from packages such as Saber® and Pspice® that are designed for solving circuit problems. Or, the differential equations themselves could be modeled in any number of other software packages such as CSSL® (Continuous System Simulation Language) or MatLab/Simulink®.

The problem becomes more complex when the equations cannot be conveniently solved simultaneously by a single solver. This is the challenge faced when a vehicle's electrical system is modeled in Saber® and the propulsion system in MatLab (ADVISOR® from NREL). A good approximation to a simultaneous solution can be achieved with a technique known as co-simulation.

Co-simulation is a computational strategy that repeatedly employs a simple algorithm that is very straightforward to describe. The schematic of co-simulation is depicted in Figure 2. Co-simulation is a process where the two solvers move forward independently through a time step. This time step may be user specified or it may be theoretically controlled depending upon the dynamics of the vehicle system at that point during the drive cycle. The time step must be sufficiently small so that parameters of mutual interest do not experience significant changes. At the end of the time step, key information must be exchanged between the packages to update the coupling or linking of the two solutions. With the electrical analysis updated with refreshed propulsion system parameters (IC engine rpm determining generator rpm) and the propulsion system updated with refreshed electrical system parameters (power drain from the IC engine to drive the generator), a restart capability is exercised for each software package to solve for next time step. This recurring sequence of parallel solutions through a time step followed by an updating of parameters of mutual significance continues until the drive cycle has been completed.

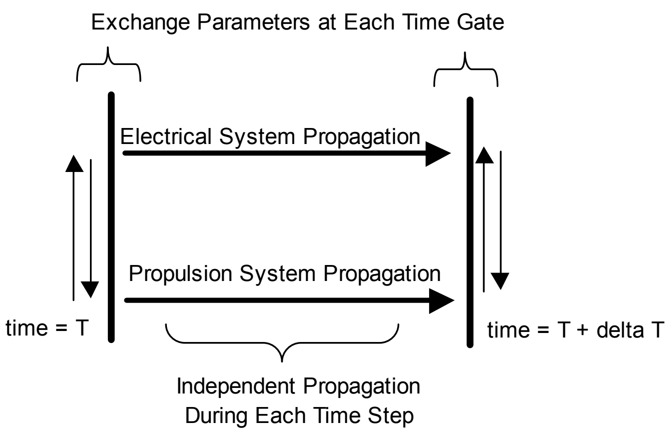

Figure 2: Schematic for Co-Simulation

DUAL VOLTAGE VEHICLES – 42V/14V

Dual voltage electrical architectures face potentially more complex challenges than traditional 14V architectures. The first difference is the obviously more complex electrical system analysis. Figure 3 displays a possible schematic for the electrical system. As a matter of observation, such architectures will often include two batteries, battery control algorithms to enhance battery life and performance, DC to DC converter(s), and a much increased electrical power budget as a proportion of the total vehicle power budget.

The coupling becomes tighter with the 42V/14V vehicle as certain 42V loads are added. Future 42V loads will certainly include electrical valve actuation (EVA), electric brakes, heated catalytic converter, and electric power steering. These subsystems provide further couplings between the propulsion system and electrical systems, representing a shift from traditional mechanically powered subsystems to electrically powered subsystems. The EVA system presents a speed dependent electrical load. Power steering and braking are considered propulsion for this discussion since they traditionally draw power directly from the IC engine. With this migration from mechanical power sources to electrical power sources, the electrical power budget of the vehicle may climb as high as 10 kW. The net result is that independent propulsions system analyses and electrical system analyses will be less representative of reality and the requirement for co-simulation becomes more significant.

SERIES HYBRID ARCHITECTURES

A series hybrid architecture is a propulsion system architecture where energy is created and stored in one form which is then utilized by a separate propulsion unit to create motive power. A potential hardware implementation would have an IC engine running at a highly efficient setting to drive a generator to create and store electricity. The main propulsion unit would be an electrical drive system running from a battery (and generator) power. Figure 4 depicts the architecture of such a vehicle.

The electrical and propulsion systems appear significantly more coupled than for the traditional vehicle because the electrical system now embodies a significant component of the propulsion system. A typical series hybrid will require co-simulation. The control strategy / algorithm may well derive inputs from both the propulsion system and the electrical system. For instance, the control algorithm for the electric drive motor may well have inputs from an automatic transmission to facilitate smooth shift points. Or, a low

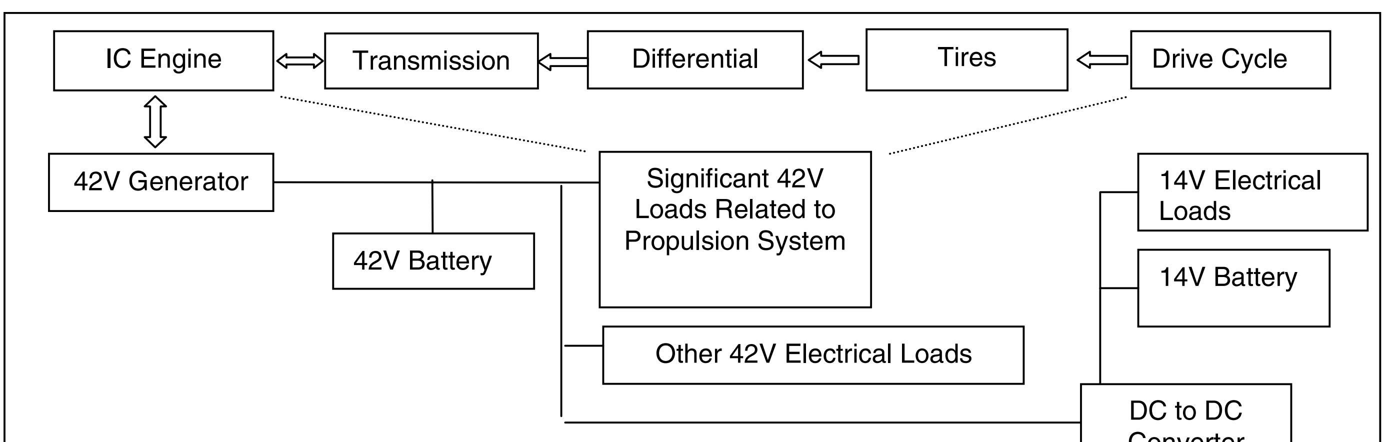

Figure 3: 42V/14V Vehicle Architecture

charge state might force limitations in torque production that would influence the transmission shift points (limp home state). In this case, the coupling of the propulsion and electrical systems requires co-simulation. Other options such as regenerative braking or electric power steering would also dictate co-simulation.

I would be remiss if I did not observe that under certain limiting assumptions, the particular coupling of systems in a series hybrid can amount to complete decoupling of the problems from a computational standpoint. If the control of the IC engine, the generation of electrical power, and the battery control algorithm are dependent solely upon electrical system parameters, and certain electrical loads crossing between the electrical and propulsion sides are not present (electric brakes, electric power steering, etc.), then the problems can be completely decoupled. If one views the propulsion system as everything downstream of the electric drive motor (not including the drive motor), then the necessary speed and torque profile for the electric drive motor can be determined for the vehicle to match a drive cycle. A subsequent and completely independent analysis of the electrical system (including the electric drive motor and the IC engine) can determine the viability of the control algorithm, battery, generator, and IC engine. Please note that co-simulation is still possible, and the results should be very comparable. So, the potential for decoupling would not prevent full integration of the two simulation techniques.

PARALLEL HYBRID ARCHITECTURES

A parallel hybrid architecture is a propulsion system which can draw motive power individually or in combination from two distinct powerplants. A possible configuration would be an IC engine and an electric drive motor on the same drive shaft. The electric drive motor would provide motive power in the regimes where the IC engine is less efficient. That same drive motor would then serve as a generator to charge the battery while the IC engine is providing the motive power. This same drive motor also serves as the flywheel and starter motor. Figure 5 depicts a typical parallel hybrid schematic.

Parallel hybrid systems provide the most complete coupling of the propulsion and electrical systems. A control algorithm shifts the motive power from the IC engine to the electrical drive motor to situations where both are contributing. The control algorithm governs "IC engine off" states, controls the smooth restart, and creates a seamless system for motive power generation responsibility. Co-simulation is the only viable approach if true simultaneous solution is not possible.

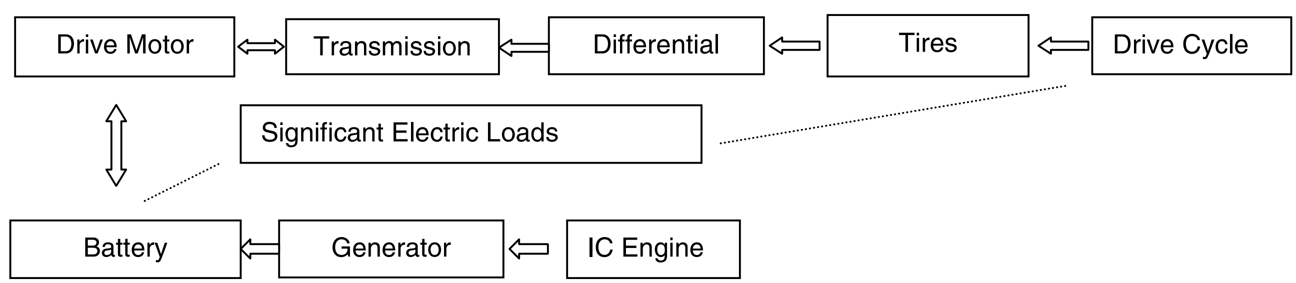

Figure 4: Series Hybrid Architecture

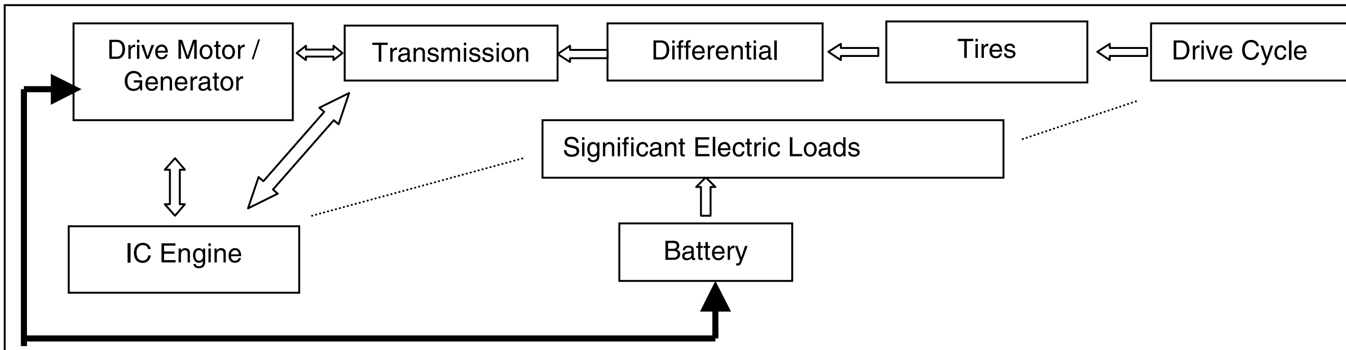

Figure 5: Parallel Hybrid Architecture

ALTERNATIVE VEHICLE ARCHITECTURES

Similar discussions could be written relative to electric vehicles, fuel cell / electric series hybrid vehicles, and the myriad of other nuances of hybrid concepts. The story will be the same for all. There is a deep coupling of the propulsion and electrical systems. Any attempt to analyze the efficiency of the entire vehicle relative to a drive cycle will require simultaneous solution of all the relevant equations. When simultaneous solution is not possible, co-simulation becomes a requirement.

CO-SIMULATION PLANS – ADVISOR AND SABER

The active contract "Modeling and Simulation Development for Advanced Energy Management and Propulsions Systems" will create the reality of co-simulation between ADVISOR and Saber. Through a template interface much like that presently utilized in ADVISOR, the future user will have the option to model the electrical system in Saber and co-simulate the propulsion system and the electrical system. This will make existing component models available in ADVISOR such as the ISET (Institut für Solare Energieversorgungstechnik) battery models available for improved representation of the electrical architecture. Moreover, for traditional vehicles, the future ADVISOR customer will be able to represent time varying electrical loads on the IC engine based upon electrical load switching and the interactions of the generator and battery. Templates will be provided for a user interface, and generic models will be provided much as the present ADVISOR has generic modules. Work on the contract began in June, 2000, and is scheduled to take two years for completion.

CONCLUSIONS

All analyses to determine vehicle energy efficiency over a drive cycle require careful analyses of the propulsion and electrical systems. The optimal situation is the simultaneous solution of the equations governing all the processes describing the creation, conversion, storage, and application of power. When the opportunity for simultaneous solution in a single solver becomes impractical, then co-simulation involving multiple distinct solvers becomes the option of choice. With sufficiently small time steps, the solution resulting from co-simulation should provide a very good approximation to the true "simultaneous solution" results.

Co-simulation of ADVISOR and Saber is becoming a reality for future versions of ADVISOR through a contract entitled "Modeling and Simulation Development for Advanced Energy Management and Propulsions Systems" between Delphi Automotive Systems and the National Renewable Energy Laboratory (Department of Energy funding).

CONTACT

John A. MacBain holds BS degrees in physics and mathematics from Case Institute of Technology (1971), an M.S. and Ph.D. in applied mathematics from Purdue University (1974), and an MSEE from the University of Dayton (1978). John served in the Air Force as an Associate Professor of Applied Mathematics at the Air Force Institute of Technology. Since that time, John has worked in industry spending eight years in advanced seismic and electromagnetic exploration development in the oil industry. The balance of the time has been with General Motors / Delphi Automotive with assignments ranging from the GM Research Laboratory to managing the Low Observable program at Allison Gas Turbines. John's current work assignment is in the Energenix Center where he has responsibilities for systems analysis. John can be reached at on the internet at john.a.macbain@delphiauto.com.

Comparison of fuel efficiencies and fuel flexibility of small automotive vehicles

Advisor Users Conference
Costa Mesa, California

August 24, 2000

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Key Points

- HEVs can reduce fuel use in two ways:
  - by improved fuel efficiency, and
  - by recharging from the electric utility grid.
- By reducing fuel use, HEVs reduce CO2 (global greenhouse gas)
- By reducing fuel use, HEVs also reduce NOx (key ozone precursor)
- HEVs can be a source of electricity for the grid (as well as recharging from the grid).
- Many HEV designs are likely to find profitable market niches

Table 1 - Vehicle Fuel Efficiency (mpg)[1,2]

Drive Cycle	CV 830 kg	FCV 1030 kg	SEV 1030 kg	PEV 930 kg	BEV 1030 kg
CYC_HWFET	52.5	84.7	39.3	55.9	139.6
CYC_FUDS	41.4	75.7	37.2	53.8	122.5
CYC_NEDC	40.9	81.1	38.9	50.9	129.2
CYC_1015	36.1	58.2	39.6	52.0	143.0

(1) See Appendix A for Advisor simulation parameters
(2) See Appendix B for NREL calculation of “gasoline equivalent fuel consumption” for FCV and BEV

Table 2 - Fuel Efficiency of FCV, SEV, PEV and BEV Compared to CV[1,2]

Drive Cycle	FCV/CV	SEV/CV	PEV/CV	BEV/CV
CYC_HWFE	1.6:1	0.8:1	1.1:1	2.7:1
CYC_FUDS	1.8:1	0.9:1	1.3:1	3.0:1
CYC_NEDC	2.0:1	1.0:1	1.2:1	3.2:1
CYC_1015	1.6:1	1.1:1	1.4:1	4.0:1

(1) See Appendix A for Advisor simulation parameters
(2) See Appendix B for NREL calculation of "gasoline equivalent fuel consumption" for FCV and BEV

Figure 1 - Comparison of Range and Refueling/Recharging Times for CVs, EVs and HEVs

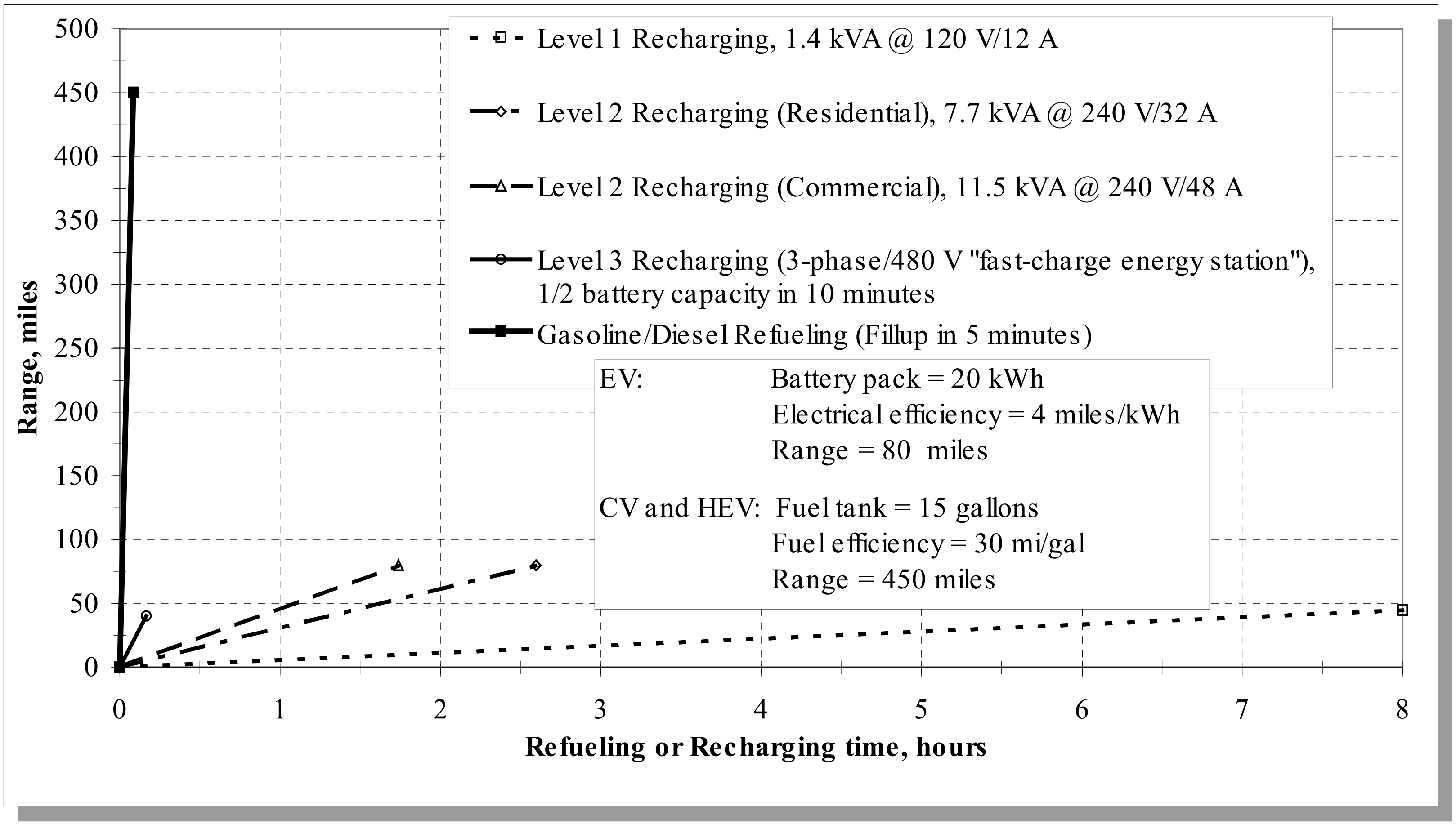


Figure 2 - Distribution of Personal Automobile Use

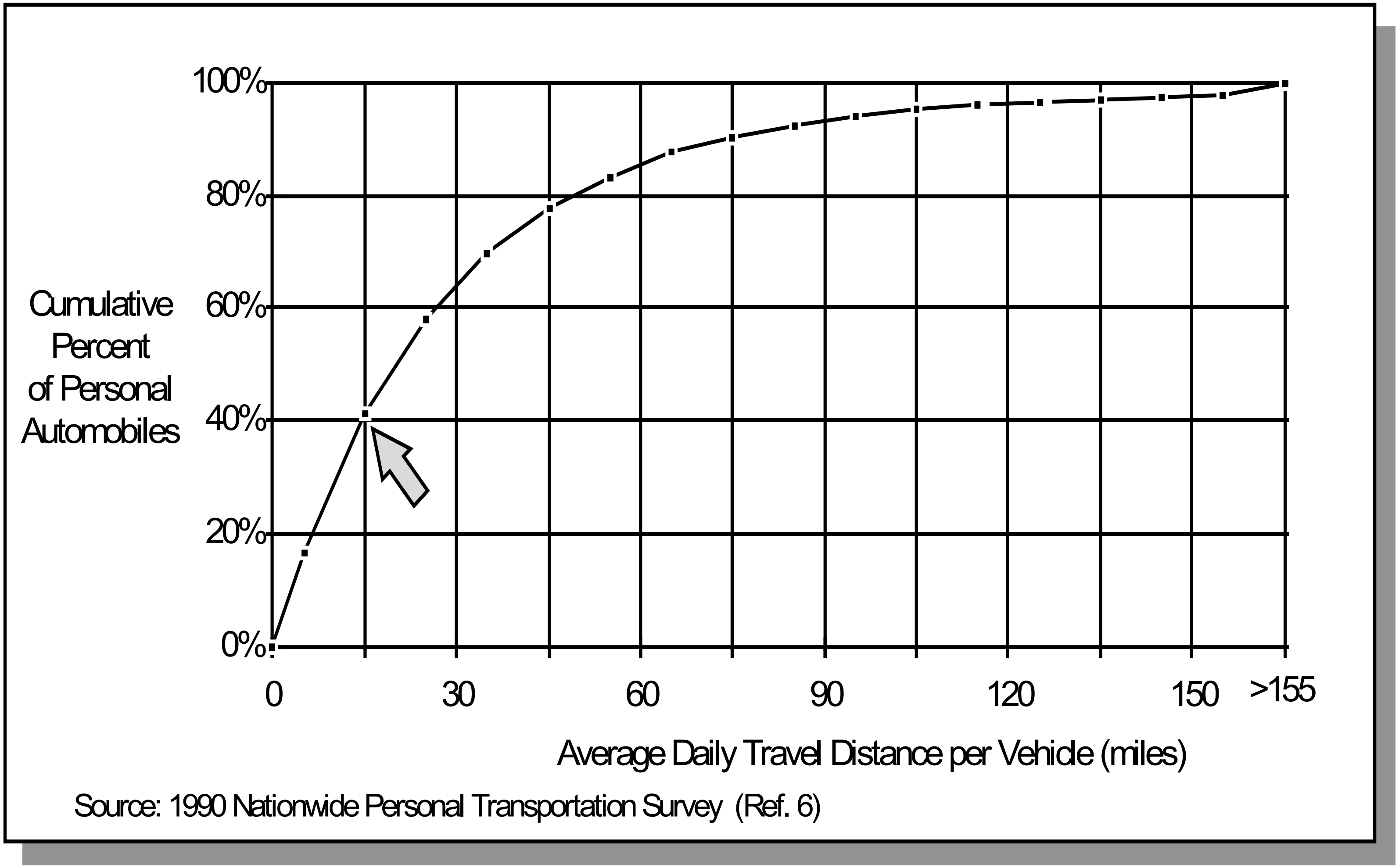
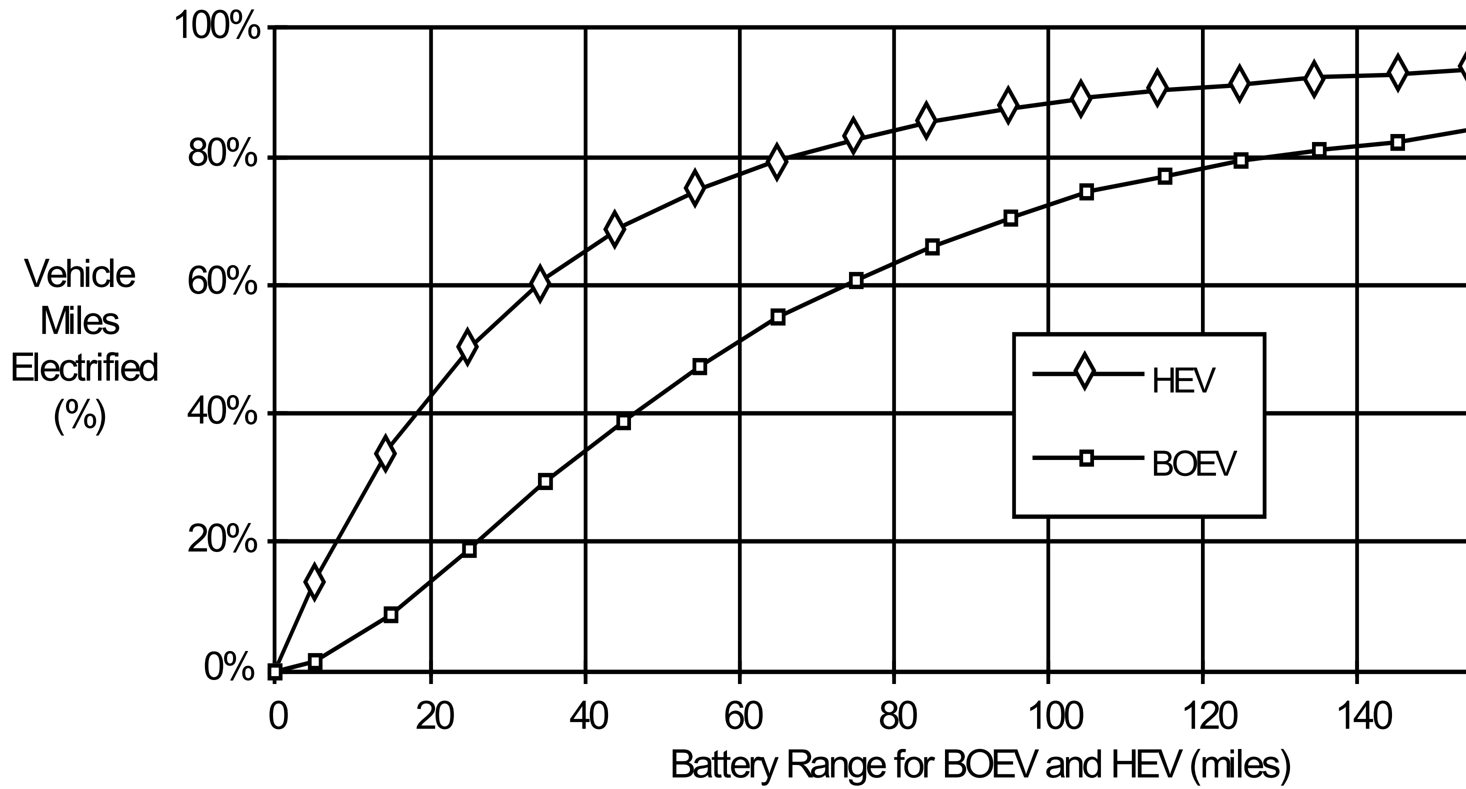


Figure 3 - Personal Automobile Miles Electrified

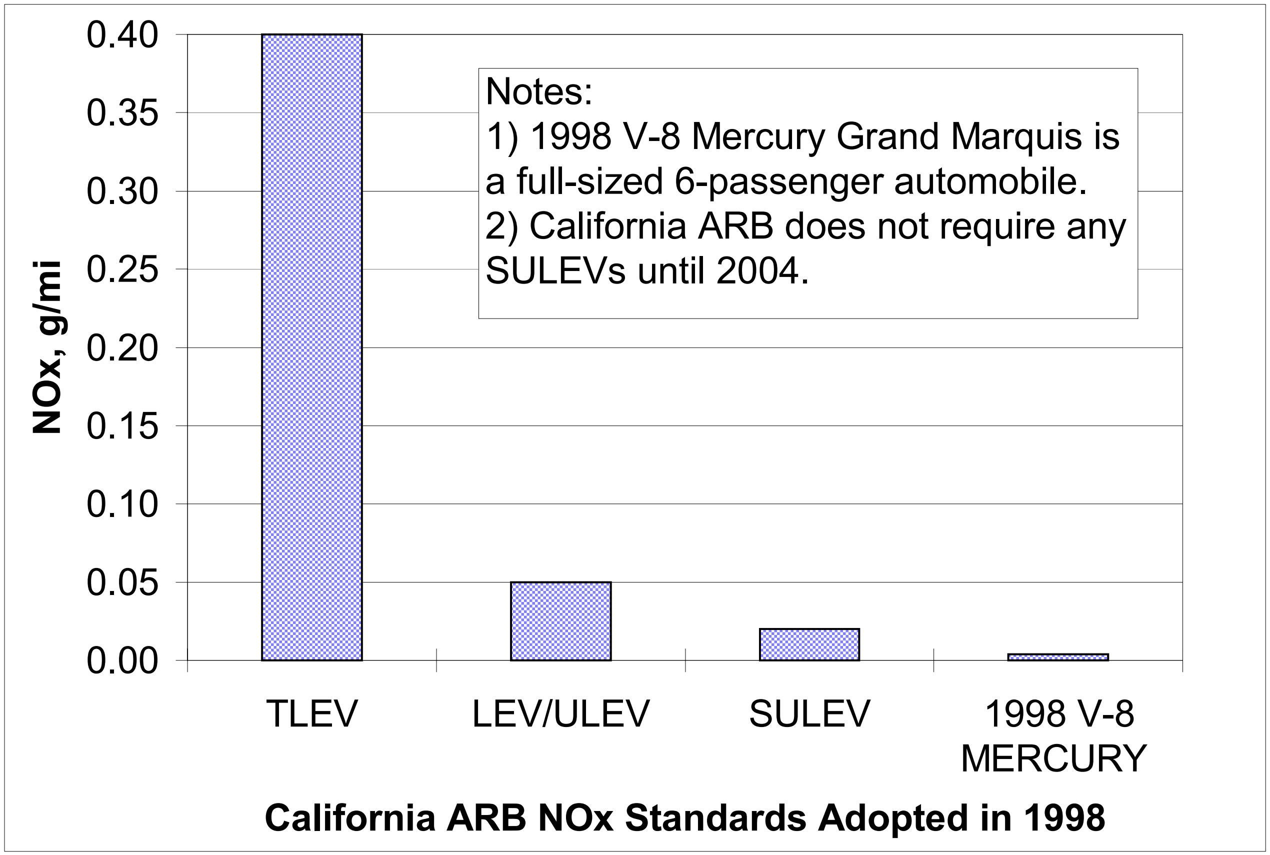


Source: 1990 Nationwide Personal Transportation Survey (Ref. 6) and NEVCOR.

Control of NOx emissions is central to the control of regional air pollution

- From Rethinking the Ozone Problem in Urban and Regional Air Pollution (1992 National Academy of Sciences):
- NOx is a major precursor to regional ozone and particulate matter.
- *"In the presence of anthropogenic NOx and under favorable meteorological conditions, background biogenic VOCs can contribute to summertime ozone concentrations exceeding the NAAQS concentrations of 120 ppb."*
- Hence, NOx control is necessary to achieve air quality standards.
- *"Except in California, NOx emissions reductions have not been a major component of most state implementation plans (SIP). Hence, efforts to achieve national air quality standards have largely failed."*
- Even in California, standards for NOx emissions from mobile sources have lagged actual accomplishments of the auto industry (next slide).

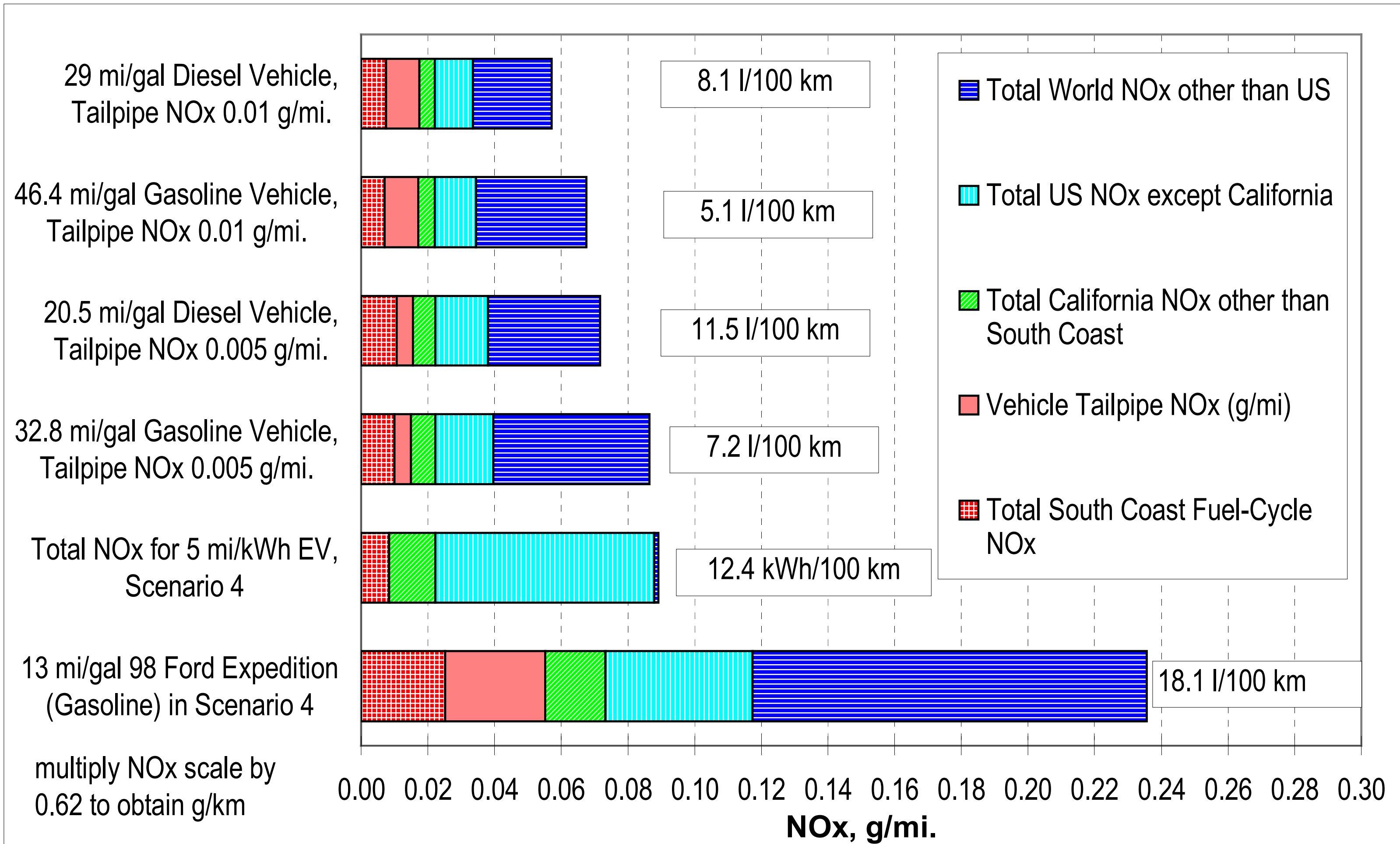
California NOx standards actually lag the accomplishments of the auto industry



ARB still considers the BEV to be the “Gold Standard”

- ARB considers the BEV to be the “Gold Standard” for two reasons:
  - 1) inherent emissions durability, and
  - 2) extremely low fuel-cycle emissions in California.
- However, the ARB admits that it is quite upbeat regarding emissions durability of catalysts; ARB observes that: *...with proper fuel tailoring adjustments, these latest technology palladium-rhodium designs lose virtually none of their emissions conversion capability over more than 100,000 miles of aging* (1998 LEV II amendments).
- Regarding low fuel-cycle emissions, the ARB is right; in fact, about 75% of all NOx emissions associated with electricity used by BEVs in the SoCAB will actually be generated outside California, and fuel-cycle emissions now dominate total emissions (next slide).

NO_x emissions of hypothetical hybrid SUVs that would match CA NO_x of a BEV in the SoCAB in 2010



Key Points

- HEVs can reduce fuel use in two ways:
  - by improved fuel efficiency, and
  - by recharging from the electric utility grid.
- By reducing fuel use, HEVs reduce CO_2 (global greenhouse gas)
- By reducing fuel use, HEVs also reduce NO_x (key ozone precursor)
- HEVs can be a source of electricity for the grid (as well as recharging from the grid).
- Many HEV designs are likely to find profitable market niches

Comparison of Fuel Efficiencies and Fuel Flexibility of Small Automotive Vehicles

John Reuyl and Robert Apter
NEVCOR, Inc.

ABSTRACT

ADVISOR is used to simulate hybrid-electric vehicles (HEV) that reduce fuel use through improved fuel economy or by recharging from the grid. “Flexible-fuel” HEVs are shown to “electrify” more miles than equivalent battery-electric vehicles (BEV), yet also travel long distances like a conventional vehicle (CV) but with improved fuel economy. The paper shows how HEVs can result directly in lower emissions of greenhouse gases and ozone precursors (e.g., NO_x). HEVs also could serve as a source of electricity for the grid. The paper concludes that no single HEV design will be best; instead, many designs could find profitable market niches.

INTRODUCTION

“Motor vehicles and the global environment are on a collision course. Motor vehicles are a major source of NO_x [nitrogen oxides], the key precursor emission to the formation of low-level ozone. As a result, most major metropolitan areas experience periods of unhealthy air quality each year. On a global basis, carbon dioxide (CO_2) levels increase each year, due in large measure to the increasing use of fossil fuels, and there is increasing consensus among researchers that climate change is occurring, in part, from these anthropocentric emissions of CO_2 and other “greenhouse” gases. There also is the knowledge that the increasing per capita consumption of fossil fuels in the face of an increasing global population is not sustainable.

“Yet the growth of modern economies has been dependent in part upon the expanding supply of energy. Of special need has been the secure supply of petroleum-based fuels for cars, trucks and buses.” (Ref.1)

This paper describes a variety of HEV technologies that can ameliorate these issues by reducing fuel use, reducing ozone-precursor NOx emissions and increasing the use of nighttime grid electricity.

In addition, while HEVs may become the next generation of mobility with “quantum leaps” in efficiency, they also could be used as a source of electricity for the grid.

DIVERSITY OF THE MOTOR VEHICLE MARKET AND THE OPPORTUNITIES FOR HEV TECHNOLOGIES

Hybrid-electric vehicles (HEV) can be configured in a variety of ways, and, as the HEV technology matures, each market sector (e.g., personal vehicles, buses, trucks) will have different configurations.

Even within a single sector, such as personal vehicles, different HEV configurations are likely to appeal to different buyers.

This diversity should not come as a surprise. For example, although today’s auto industry has been “maturing” for more than 100 years, the marketplace is filled with a variety of offerings, from economy transportation for less than USD 10,000 to custom vehicles costing more than USD 100,000.

Within this market segment for personal vehicles, there are very different technologies: minivans, vans, muscle cars, station wagons, sport utility vehicles (from 500 kg micro vehicles to 3,000 kg trucks), sedans of all kinds and sizes from economical 4-, 5-, and 6-passenger family sedans to luxury vehicles and limousines.

Even within any one very narrow niche of this market, remarkable diversity exists. Consider the choices within the category of SUV (or minivan, or sedan). Small, medium, large, 3-door, 4-door, 5-door; even within any one model (e.g., 4-door sedan), engines come in 4-cylinders, 6-cylinders, 8-cylinders; with or without supercharging; and the consumer choices continue for number of valves, cams, fuel systems, transmissions, etc.

This variety shows no signs of diminishing, and the HEV technologies open the doors to even more differentiation. As the HEV technologies mature, we can expect manufacturers to compete for market share with HEV features that are fine-tuned to individual buyers.

This paper will illustrate this diversity with small vehicles as an example.

HEVS CAN REDUCE FUEL USE AND CO_2

ADVISOR SIMULATIONS

Simulations with ADVISOR for fuel efficiency were completed for small vehicles, beginning with an 830-kg baseline conventional vehicle (CV). The competing vehicles were FCV (fuel cell), SEV (series-hybrid), PEV (parallel-hybrid) and BEV (battery electric). The key vehicle parameters are summarized in Appendix A. Each of the vehicles was similar except that the weights were adjusted to account for the different propulsion systems.

The results for fuel consumption are shown in Tables 1 and 2. NREL has provided a methodology whereby the "gasoline equivalent fuel consumption" of FCVs and BEVs can be compared to CVs (see appendix B).

Table 1 - Vehicle Fuel Efficiency (mpg)[1,2]

Drive Cycle	CV 830 kg	FCV 1030 kg	SEV 1030 kg	PEV 930 kg	BEV 1030 kg
CYC_HWFET	52.5	84.7	39.3	55.9	139.6
CYC_FUDS	41.4	75.7	37.2	53.8	122.5
CYC_NEDC	40.9	81.1	38.9	50.9	129.2
CYC_1015	36.1	58.2	39.6	52.0	143

(1) See Appendix A for simulation parameters

(2) See Appendix B for calculation of "gasoline equivalent fuel consumption" for FCV and BEV

Table 2 - Fuel Efficiency of FCV, SEV, PEV and BEV Compared to CV[1,2]

Drive Cycle	FCV/CV	SEV/CV	PEV/CV	BEV/CV
CYC_HWFET	1.6:1	0.8:1	1.1:1	2.7:1
CYC_FUDS	1.8:1	0.9:1	1.3:1	3.0:1
CYC_NEDC	2.0:1	1.0:1	1.2:1	3.2:1
CYC_1015	1.6:1	1.1:1	1.4:1	4.0:1

(1) See Appendix A for simulation parameters

(2) See Appendix B for calculation of "gasoline equivalent fuel consumption" for FCV and BEV

The drive cycles are standards in the motor vehicle industry and are well-known to vehicle designers. The US CYC_HWFET has the greatest fraction of highway travel, the US CYC_FUDS and European CYC_NEDC have a mix of urban and highway, and the Japanese CYC_1015 is an urban cycle.

Note that there are additional vehicle attributes that are not discussed in this paper, such as acceleration, braking, etc., that could differ from one vehicle type to another. The comparisons of efficiency are, however, of increasing importance and a major element of HEV design.

In Table 2 the fuel efficiency of the competing vehicles (FCV, SEV, PEV and BEV) are compared to the baseline CV.

In the sections that follow, the results in Tables 1 and 2 will be discussed and conclusions will be drawn.

HEVS CAN REDUCE FUEL USE THROUGH IMPROVED FUEL EFFICIENCY

The fuel cell HEV (FCV) that was modeled (see Table 1) offers much higher fuel efficiency than the equivalent CV. The superiority was the greatest in the European NEDC drive cycle wherein the FCV had double the fuel economy of the CV. (see Table 2).

Such improvements in fuel efficiency result directly in the reduction of 1) the use of petroleum fuels and 2) the associated generation of CO_2.

Such improvements in fuel economy will also be shown to reduce ozone-precursor emissions (e.g., NO_x).

However, FCVs face formidable technical and economic challenges, while HEVs using combustion engines are already in the market. These HEVs offer performance and utility that are comparable to conventional vehicles, and they, too, can offer substantial improvements in fuel efficiency.

In addition, technologies developed for HEVs (motors, controllers, energy storage technologies) will also be applicable for FCVs (and BEVs), thereby increasing their marketability.

The PEV has particular appeal because it offers substantially improved fuel efficiency when compared to a comparable conventional vehicle, especially in the urban drive cycle. Furthermore, the simulations summarized in Table 1 were done using the same conventional internal-combustion engine in the CV and the HEVs. As will be presented in a future paper (see Ref. 2), the engines for HEVs in the future will offer vastly more options than will be the case for CVs. Such optimization will permit further improvements in fuel economy for the HEVs.

The SEV that was simulated using the standard ADVISOR parameter selection shows an improvement over the CV only in the urban drive cycle. However, in proprietary work done at NEVCOR using ADVISOR, designs for small SEVs have been simulated that do provide much better fuel efficiency than the optimized CV baseline - typically more than 20% better for the NEDC drive cycle. The NEVCOR designs include improvements in a number of vehicle systems including energy storage technology, engine control strategy and vehicle optimization priorities.

In addition, it will be shown that so-called “grid-connected” SEVs can reduce fuel use by a surprisingly large amount.

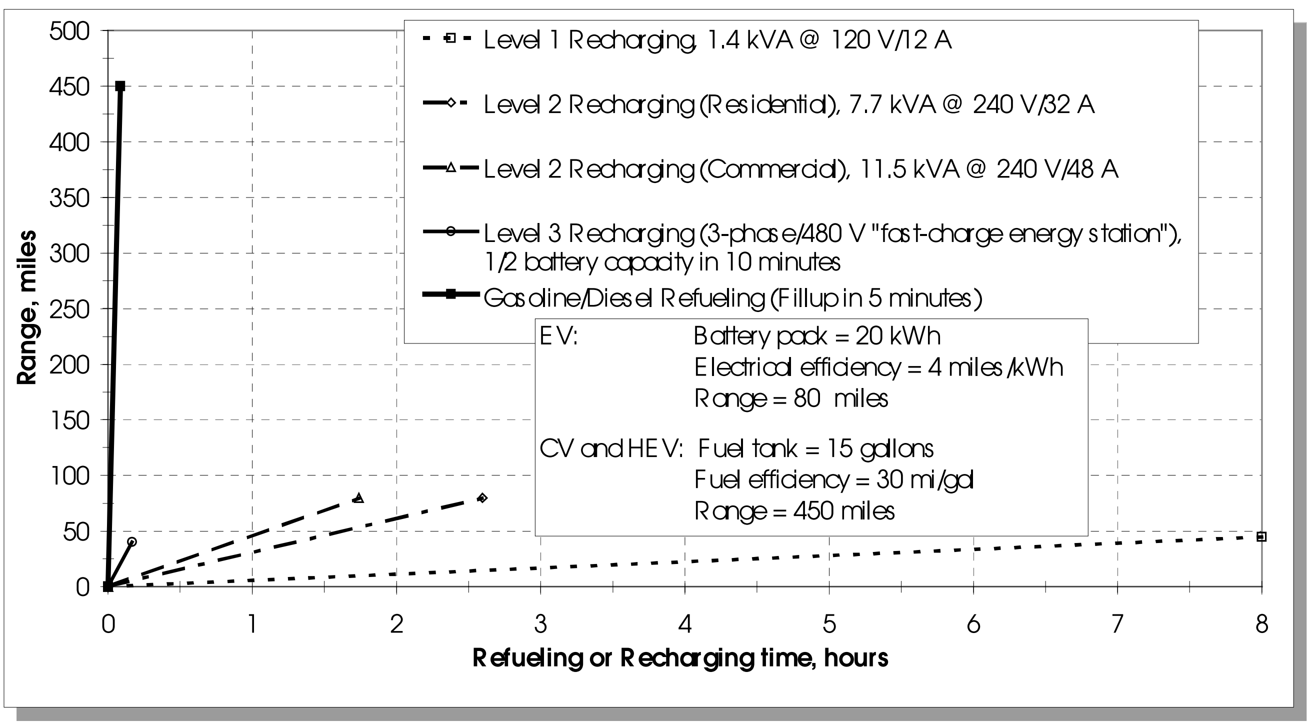
BEVS THAT RECHARGE FROM THE GRID REDUCE FUEL USE

BEVs provide mobility but use grid electricity instead of fuels. Since most electricity is generated from sources other than petroleum, BEVs actually displace fuel use by using grid electricity instead.

In addition, BEVs produce zero emissions at the vehicle, an attribute that gained political prominence in California in 1990 (see Ref. 3). During the past 10 years, since the mandate of zero-emissions vehicles (ZEV) by the California Air Resources Board (Ref. 3), BEV development has been pursued by virtually every major motor vehicle manufacturer.

However, BEVs have proved to be limited in their appeal because of their a) range limitation (typically 100-200 km), b) high cost (substantially more than an equivalent CV with no range limitation), and c) lengthy recharge time (see Figure 1).

Figure 1 - Comparison of Range and Refueling/Recharging Times for CVs, EVs and HEVs (from Ref. 10)



As a result, recent work has focused on a) longer range batteries (which are typically even more costly than the baseline Pb-acid technology), b) “rapid” recharge stations (which are not as rapid as refueling and provide much less range than a full tank of fuel, see Figure 1) and c) numerous studies to determine just how much range might be enough.

If these issues can be satisfactorily resolved and BEV costs can be acceptable for at least some consumers, then BEVs that be charged from the electricity grid offer an exceptional technology for improved “gasoline equivalent fuel efficiency” (see Tables 1 and 2). Potential applications in the near-term include post office fleets, parcel delivery, shuttle buses, and numerous specialty vehicle applications (e.g., lift trucks, aircraft tow vehicles, trash collection).

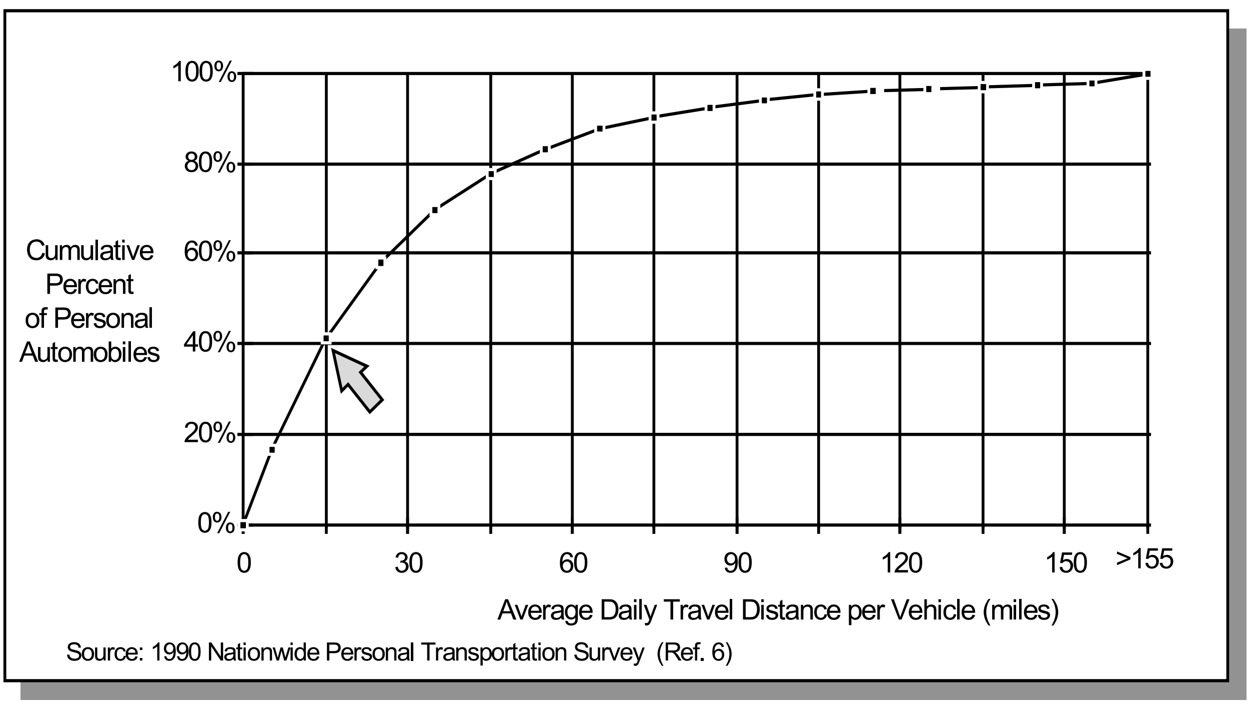
In the next section it will be shown that HEVs that can be recharged from the grid offer the same benefits

HEVS THAT RECHARGE FROM THE GRID ALSO REDUCE FUEL USE

Like BEVs, an HEV that can recharge overnight from the electric utility also reduces the use of petroleum. If such HEV technologies were commercialized, such vehicles could become a major new nighttime load on the grid, thereby displacing petroleum use, leveling loads, and improving utility profitability. This scenario is developed in more detail in this section.

An HEV with a relatively small (but high power) battery pack could travel all the short around-town trips and local commutes on electricity alone. In a conventional car (or in an HEV when using fuels), these short trips are the ones during which engines are cold, traffic is stop-and-go, mileage is poorest and emissions are greatest. In such a “grid-connected” HEV, the fueled-engine may not be needed at all for the shorter trips, serving instead as a supplementary source of energy for the longer trips.

Figure 2 - Distribution of Personal Automobile Use (from Ref. 4)



The number of vehicles that travel short distances each day is surprisingly large. Even in the US where average auto trips are the longest, Figure 2 (from Ref. 4) shows that more than 40% of all personal automobiles on the road on a typical day (roughly 40 million autos) actually travel that day 20 miles or less.

Such short distances are well within the feasibility of today's EV and HEV technology using relatively small, low-cost battery packs.

However, the majority of these same 40 million vehicles will also travel much longer distances on weekends, on vacation trips and on occasional side trips or emergencies during the work week.

The dilemma is that short-range BEVs cannot be used for these longer trips. Therefore, BEVs have been fitted with large, heavy (and expensive) battery packs in hopes of providing enough range to satisfy at least some potential users.

Yet HEVs can be optimally configured to meet both of these very disparate duty cycles; small, low-cost battery packs for the short trips and small engines that can provide the average power for unlimited long-range trips whenever necessary.

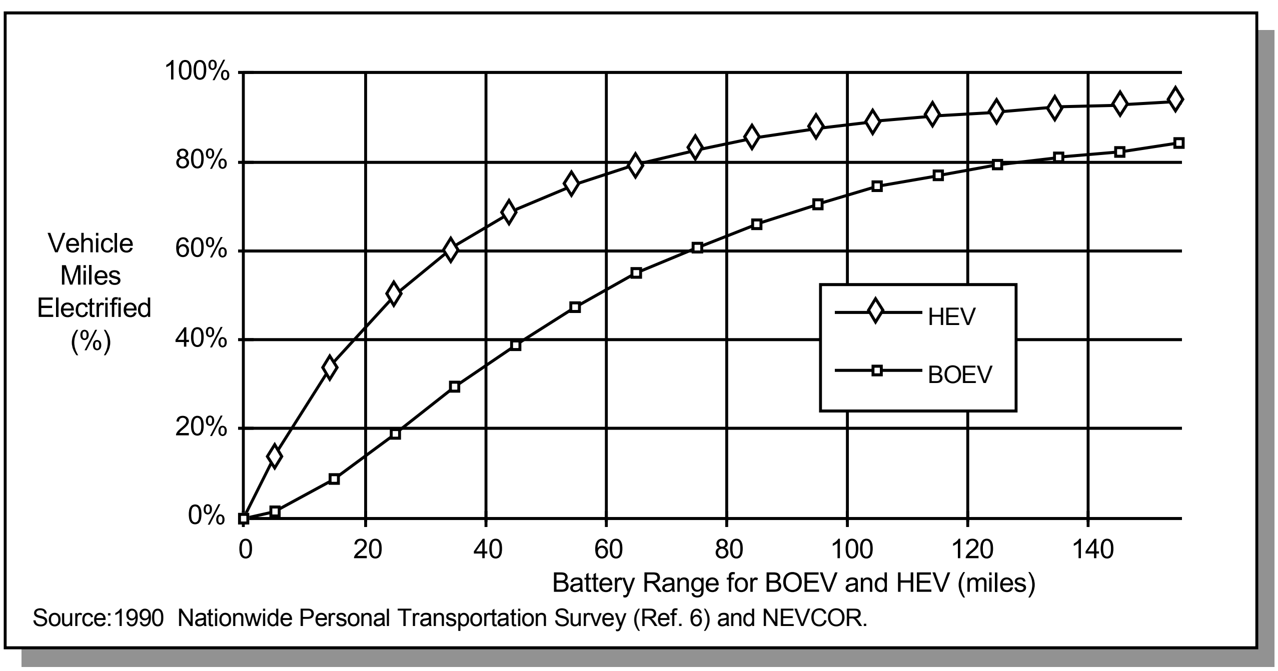
Figure 1 shows that recharging overnight for the short trips would be possible from any 110V receptacle, without the infrastructure expense for a) dedicated 220V circuits, b) high-power chargers or c) elaborate custom interconnect hardware and controls. Such overnight charging would help to level utility loads, thereby improving utilization factors and utility efficiency.

With its own on-board engine, such an HEV has no need for daytime recharging or an expensive daytime recharging infrastructure. For days and even weeks at a time, the engines in such HEVs may never be used, but they would always be available, providing the same "full-tank" feeling of security offered by the conventional vehicle.

Just as auto manufacturers offer a variety of engine/transmission options for today's buyer, such HEVs could be offered with a variety of battery and engine options to meet tomorrow's consumer choices. For example, the battery size and battery technology could be selected based on each buyer's likely average daily use. Buyers may choose engine size in much the same way as in a conventional vehicle; small engines for the economy-minded, larger engines for those expecting to haul trailers or do a lot of mountain driving.

According to the research in Ref. 4, even HEVs with very small battery packs could electrify a very large fraction of total vehicle miles. "For any given battery range, HEVs could electrify, on average, more miles than BOEVs [battery-only electric vehicles] …because HEVs can be driven on all trips, and the initial miles every day will be powered by utility electricity." (Ref. 4, pg. 12). Figure 3 (next page) is reproduced from Ref. 4; it shows that, compared to a fleet of conventional cars, a fleet of HEVs that plugged in every night and had only 30-mile battery packs could electrify roughly 50% of total vehicle miles traveled.

Figure 3 - Personal Automobile Miles Electrified (from Ref. 4)



Even if fuel efficiency when using fuels were unchanged in these “flexible-fuel” HEVs from today’s fleet average of 27.5 mi./gal, gasoline use would be reduced by about the same 50% as a fleet of HEVs with doubled fuel efficiency (to 55 mi./gal) but no ability to recharge from the grid. Obviously, were fuel efficiency to be improved in these HEVs (as is expected), fuel use would be further reduced.

The HEV also provides the same benefits of “gasoline equivalent fuel consumption” as the BEV when using grid electricity. Note from Table 1 that both the SEV and the BEV weigh the same 1030 kg. Thus, the SEV using grid electricity would have roughly the same “gasoline equivalent fuel efficiency” as the BEV when compared to a similar CV traveling the same route.

Note that the “grid-connected, flexible-fuel” HEV provides the user with mobility even when fuel shortages occur. While longer weekend trips may be curtailed, the essential daily work-related trips can be undertaken using grid electricity.

Such HEVs could vastly increase the market share for EVs beyond that for just the BEV. HEVs that can recharge at night from the grid could be the most practical way in the near-term of displacing transportation fuels with utility electricity.

HEVS CAN REDUCE OZONE-PRECURSOR EMISSIONS

THE IMPORTANCE OF NO_x CONTROL

In a major study of urban and regional air pollution, the National Research Council (NRC) concluded that “Of the six major air pollutants for which National Ambient Air Quality Standards (NAAQS) have been designated under the Clean Air Act, the most pervasive problem continues to be [tropospheric (i.e., near-ground)] ozone, the most prevalent photochemical oxidant and an important component of ‘smog’.” (NRC, Ref. 5)

Ozone forms when NO_x combines with VOCs (volatile organic compounds) in the presence of heat and sunlight. VOCs originate from a variety of sources both anthropogenic (e.g., paints, vehicle exhaust emissions) and biogenic (e.g., plants, trees). NO_x, on the other hand, occurs almost entirely from high-temperature combustion sources, and these sources are largely anthropogenic (e.g., vehicle engines, power plants).

The NRC determined that NO_x control would be key to ozone control. “NO_x control is necessary for effective reduction of ozone in many areas of the United States. ...in many urban cores and their environs, even if anthropogenic VOCs are totally eliminated, a high background concentration of reactive VOCs will remain.... In the presence of anthropogenic NO_x and under favorable meteorological conditions, these background biogenic VOCs can contribute to summertime ozone concentrations exceeding the NAAQS concentration of 120 ppb.” (Ref. 5)

The California Air Resources Board (CARB) also concluded that “...because ozone precursors, such as NO_x also react in the atmosphere to form particulate matter (PM), reductions in NO_x will be crucial to meet existing state and federal PM10 standards, as well as the new federal standards for fine particulate matter (PM2.5).” (CARB, Ref. 8)

However, “Except in California, NO_x emission reductions have not previously been a major component of most [State Implementation Plans] SIPs.” (Ref. 5) As a result, “Despite the major regulatory and pollution-control programs of the past 20 years, efforts to attain the National Ambient Air Quality Standard of ozone largely have failed.” (Ref. 5)

Based upon the conclusions of the NRC, the authors have focused their emissions work in the remainder of this paper on NO_x emissions.

VEHICLE NO_x EMISSIONS CAN BE REDUCED TO NEGLIGIBLE LEVELS

California’s standards for motor vehicle NO_x emissions, set by CARB, are actually lagging the auto industry’s capabilities. For example, one of GM’s largest passenger sedans in production, the 1998 V-8 Mercury Grand Marquis, achieves a NO_x level of 0.004 g/mi. as certified by the CARB (see Ref. 8). Yet CARB’s tightest NO_x standard is the 0.020 g/mi. SULEV (Super Ultra-low Emissions Vehicle) which is five (5) times more lax. Furthermore, the SULEV standard is not required until 2004 and then for only a small fraction of all vehicles.

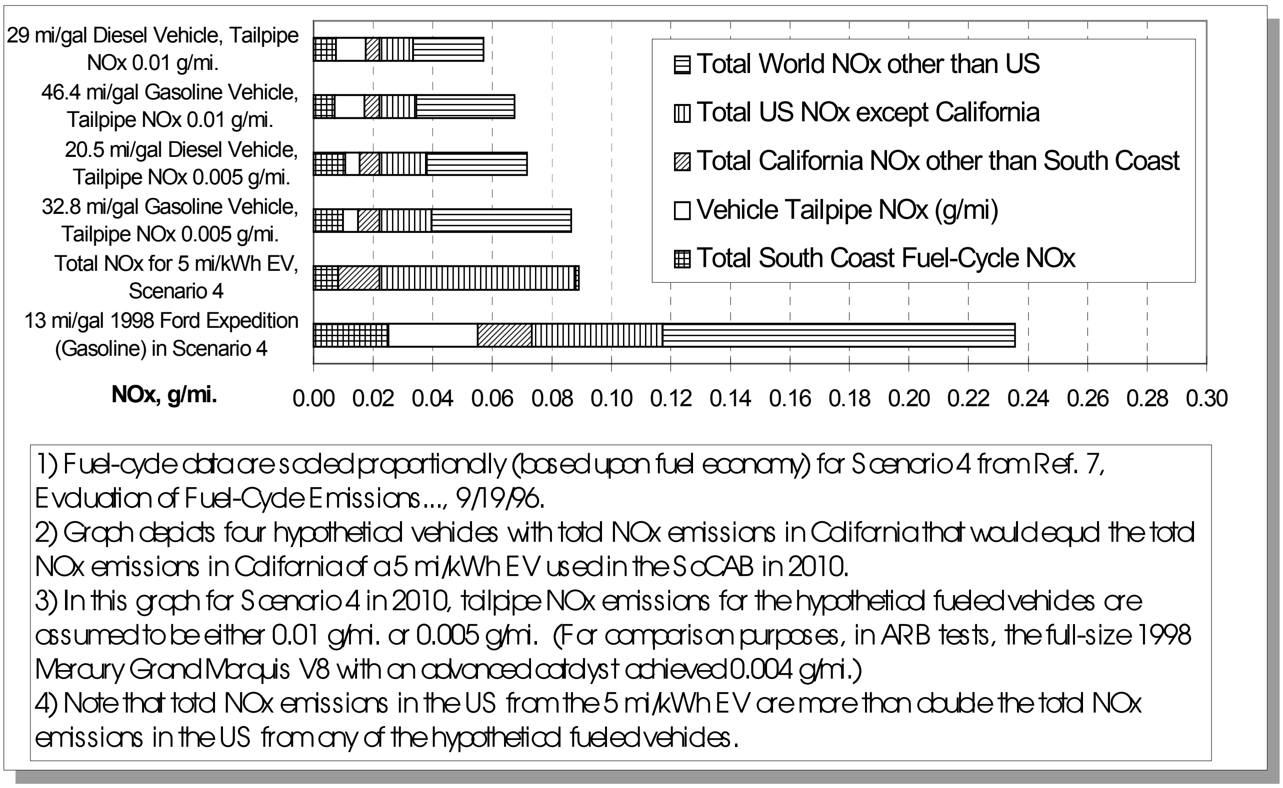
A biennial review of the ZEV Program is scheduled by the CARB for September 2000.

Vehicle NO_x emissions can now be reduced to such low levels that NO_x emissions from both electric- and fueled-vehicles would be dominated by the up-stream fuel-cycle emissions. Such emissions are directly proportional to the vehicle’s efficiency in using electricity and fuel and are discussed in the next section.

FUEL-CYCLE EMISSIONS DOMINATE TOTAL NO_x EMISSIONS

When exhaust emissions are at SULEV levels (0.02 g/mi.) and below, total emissions will be dominated by the emissions associated with the fuel cycle itself. Ref. 9 reports that, even for vehicles used in California, total NO_x emissions (vehicle plus fuel-cycle) for gasoline and diesel vehicles can be equal to, and even less than, total fuel-cycle NO_x emissions for electric vehicles. The data reported in Ref. 9 were developed and reported in Ref. 10 under a research contract for the National Renewable Energy Laboratory (NREL). Key results from this research are presented in Figure 4 and summarized in this section.

Figure 4 - Total NO_x emissions of a) 1998 Ford Expedition, b) 5 mi./kWh BEV, and c) four hypothetical HEVs that would have the same 0.022 g/mi. NO_x emissions in California as the BEV (all vehicles are operated in the SoCAB in 2010, Scenario 4) (from Ref. 10)



In order to determine the magnitude of fuel-cycle emissions, the CARB contracted with Acurex Corporation for an analysis specifically aimed at emissions associated with vehicles when they were operated in the Southern California Air Basin (SoCAB). The purpose of the study is quoted directly from Ref. 7, "This study investigated the emissions associated with the production and distribution of conventional and alternative fuels. Emissions from the production and distribution of fuels are known as fuel-cycle emissions and these can be significant in comparison to tailpipe emissions....The California Air Resources Board's (CARB's) zero-emission vehicle (ZEV) classification is based on zero emissions from electric vehicles; therefore, fuel-cycle emissions associated with incremental power generation might be compared with incremental fuel-cycle emissions from conventional fuels." (Ref. 7)

Although the Acurex study (Ref. 7) looked at both NO_x and VOCs, the research reported in this paper focuses upon NO_x emissions because of their importance as the primary anthropogenic contributor to ozone (as discussed in the sections above).

The Acurex study concludes that BEVs do offer a unique advantage in the SoCAB, due to regulations capping NO_x emissions for SoCAB power plants. "Power plants in the South Coast Air Basin are subject to the Regional Clean Air Initiatives Market (RECLAIM) regulation of the South Coast Air Quality Management District (SCAQMD), which provides a cap on power plant NO_x emissions for each utility. For larger usages of EVs in 2010, power generation will result in zero additional NO_x in the South Coast Air Basin due to RECLAIM limits." (Ref. 7)

However, Ref. 9 concludes that for the rest of California and for the US as a whole, gasoline and diesel-powered HEVs with even modest fuel efficiency may offer total NO_x emissions that are even less than the total NO_x emissions that are associated with the use of BEVs in the SoCAB.

Figure 4 (from Ref. 9, 10) shows total NO_x emissions for vehicles operated in the Southern California Air Basin (SoCAB) when using diesel, gasoline or electricity. In addition to the tailpipe NO_x levels (which are zero for an EV), the graph shows the fuel-cycle NO_x emissions associated with each fuel-type and whether those emissions occur a) in the SoCAB, b) elsewhere in California, c) elsewhere in the US or d) outside the US. (In Figure 4, Scenario 4 has been selected for presentation; Scenario 4 represents additional efficiency improvements over the Scenario 2 "standards applicable in 2010.")

The bottom bar of Figure 4 depicts the emissions of the 1998 Ford Expedition, a 3,000-kg sport utility vehicle (SUV). It's 0.03 g/mi. NO_x emissions at the tailpipe as determined by CARB testing are 0.01 g/mi. above the ARB's SULEV standard of 0.020 g/mi. (the tightest standard for fueled vehicles). However, because of its relatively low fuel efficiency (13 mi./gal), its total fuel-cycle NO_x emissions from Figure 4 are more than 0.23 g/mi., of which 0.073 g/mi. are in California. About half (0.118 g/mi.) occur outside the US (e.g., drilling, tankers at sea). The rest (0.044 g/mi.) occur inside the US but outside California.

The bar immediately above the Ford Expedition represents the fuel-cycle NO_x emissions of a 5-mi/kWh BEV. Such efficiency is deemed feasible for a variety of small 2-4 passenger BEV designs in 2010. Note that while such a BEV would have total NO_x fuel-cycle emissions of almost 0.09 g/mi., only 0.022 g/mi. occur in California.

In the next section, HEVs are described that could have the same low 0.022 g/mi. California NO_x emissions as the 5 mi./kWh BEV.

HEVS USING FUELS OR ELECTRICITY CAN MATCH THE CALIFORNIA FUEL-CYCLE NO_x EMISSIONS FROM BEVS

The CARB states that "ZEVs are the 'Gold Standard' based upon their extremely low fuel-cycle emissions in California and inherent emissions durability" (Ref. 8).

Emissions durability of fueled vehicles was an important issue during the early 1990s, and the "inherent durability" of the BEV ECS was an appealing image.

More recently, the CARB has been quite upbeat about the durability of the ECS (emissions control system) of fueled vehicles: "Discussions with catalyst suppliers indicate that with proper fuel tailoring adjustment, these latest technology palladium-rhodium designs lose virtually none of their emissions conversions capability over more than 100,000 miles of aging. The small increases in emissions of our two Expeditions without the benefit of proper fuel tailoring tends to verify this claim." (Ref. 8)

The CARB was quite correct that BEVs result in low fuel-cycle emissions in California (Ref. 8). In fact, in 2010 almost three-quarters of all NO_x emissions associated with the use of BEVs in the SoCAB (Southern California Air Basin) will actually be produced in other states (see Figure 4).

However, fueled vehicles could offer the same low NO_x emissions in California. For example, the top two bars of Figure 4 show a 29-mi/gal diesel vehicle and a 46 mi./gal gasoline vehicle that have NO_x tailpipe emissions of 0.010 g/mi.; both vehicles achieve the same California NO_x emissions (0.022 g/mi.) as the 5 mi./kWh EV.

Furthermore, total US NO_x emissions in the rest of the US from these fueled vehicles would be roughly 15% that of the BEVs (see Figure 4).

Such fuel efficiency for HEVs in 2010 seems quite feasible given the actual performance of current high-mileage diesel- and gasoline-powered prototypes.

The assumed NO_x tailpipe emissions of 0.010 g/mi. also seem quite feasible in 2010; according to CARB (Ref. 8), even the 1998, 6-passenger Mercury Grand Marquis with a large V-8 engine has already achieved 0.004 g/mi. NO_x tailpipe emissions.

The middle two bars in Figure 4 depict hypothetical vehicles that have only 0.005 g/mi. NO_x tailpipe emissions (this is still 25% more NO_x than the actual NO_x emissions of the 1998 Mercury Grand Marquis). If these hypothetical vehicles achieved only 20.5 mi/gal (diesel) or 30.8 mi/gal (gasoline), they, too, would produce the same California NO_x emissions as the 5 mi./kWh BEV.

These conclusions are especially important given the growing popularity of sport utility vehicles (SUV) with their low fuel economy and correspondingly high fuel-cycle emissions. The CARB (1998) LEV II amendments to the 1990 LEV Program subject these vehicles in 2004 and beyond to the same tailpipe standards as passenger cars, and their is every indication that HEV versions of SUVs could achieve SULEV standards for tailpipe NO_x emissions. Furthermore, HEV versions of SUVs also could achieve much better fuel economy and, therefore, much lower fuel-cycle NO_x emissions and CO_2 emissions.

HEVS CAN BE A SOURCE OF ELECTRICITY FOR THE GRID

HEVs may not be just the next generation of mobility. The concept of HEVs as a source of power to the grid was first patented in 1980 (Ref. 11). More recently, the participants in the Electric Technology Roadmap Initiative

(Ref. 12) have concluded that Distributed Generation (DG) will be a cornerstone of the 21st Century electricity-production system; as part of a DG system, the grid not only can deliver power to HEVs for recharging; the grid can receive power from the same HEV.

Already, stationary "co-generation" systems have been commercialized, and HEVs are often "stationary" for long periods of time. It is a relatively small step to envision that valuable assets like HEVs may provide more of a return-on-investment than just energy-efficient mobility.

CONCLUSIONS

HEVs can reduce fuel use (and therefore emissions of CO_2 and NO_x) by improving fuel economy and by displacing fuel use with utility electricity.

HEVS CAN REDUCE FUEL USE, NO_x AND CO_2 BY IMPROVING FUEL ECONOMY

"Of the six major air pollutants for which National Ambient Air Quality Standards (NAAQS) have been designated under the Clean Air Act, the most pervasive problem continues to be [tropospheric (i.e., near-ground)] ozone… (NRC, Ref. 5). The NRC determined that NO_x control was key to ozone control; "… even if anthropogenic VOCs are totally eliminated, a high background concentration of reactive VOCs will remain.... In the presence of anthropogenic NO_x and under favorable meteorological conditions, these background biogenic VOCs can contribute to summertime ozone concentrations exceeding the NAAQS concentration of 120 ppb." (Ref. 5)

Vehicle NO_x exhaust emissions can now be reduced to such low levels that NO_x emissions attributed to the fuel cycle dominate total vehicle NO_x emissions. By improving fuel economy, HEVs can reduce total NO_x emissions (exhaust plus fuel cycle) to levels comparable to the fuel-cycle NO_x emissions attributable to electric vehicles.

Improvements in fuel economy also reflect directly into a corresponding reduction in the production of CO_2, a principal greenhouse gas.

Fuelcell hybrid vehicles (FCV) offer much improved fuel economy when compared to conventional vehicles (CV). If technical and cost barriers can be overcome, FCVs would be effective in reducing fuel use, thereby reducing CO_2 and fuel cycle NO_x.

In the near-term, HEVs using combustion engines offer similar advantages. Such HEVs improve fuel economy by operating engines only in their most efficient domain, by capturing and storing braking energy, and by optimizing each vehicle subsystem and minimizing vehicle weight.

HEVS CAN DISPLACE FUEL USE WITH GRID ELECTRICITY

BEVs displace fuel use by using grid electricity. BEVs offer the greatest "gasoline equivalent fuel economy" as defined by NREL (see Appendix A), but their limited range, lengthy recharge time and high cost have limited their marketability to special niches.

HEVs that can be recharged overnight from the grid also displace fuel use; when using grid electricity for the local commutes and around-town trips, such HEVs can match the BEVs "gasoline equivalent fuel economy." Such HEVs also can travel unlimited long distances by using fuels.

In the longer term, as renewable energy technologies are commercialized, HEVs that can recharge from the grid may get their energy increasingly from renewable energy sources, thereby further reducing both carbon emissions and ozone precursor emissions (e.g., NO_x).

HEVS CAN BE A SOURCE OF POWER TO THE GRID

HEVs that can be recharged from the grid may also be a source of power to the grid. Analysis reported in Ref. 13 indicates that such HEVs represent a sustainable technology for the 21st century. These conclusions have been corroborated in Ref. 12, a major policy study from a broad coalition of participants led by the Electric Power Research Institute (EPRI).

MANY HEV DESIGNS ARE LIKELY TO FIND PROFITABLE MARKET NICHES

Toyota's Prius HEV offers the range, performance and comfort of a CV, and it has been a major success in the Japanese market. Toyota is now offering a version in the US that is optimized for the American market. Sales of the Prius have exceeded the combined sales of all BEVs from all manufacturers. Honda has entered the HEV market with the Insight. Although these entries are both hybrids, they differ significantly in their design and operation. Both are competitively priced.

In a new industry like HEV technologies and in the absence of a definitive vision of the future, there can be a tendency for engineering designers to grasp prematurely for "the best" HEV design. The authors argue, on the other hand, that many different HEV designs can emerge that could meet regulatory requirements and find profitable market niches. The future bodes well for those in the ADVISOR community who can develop these many diverse options for their marketing colleagues.

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DEFINITIONS, ACRONYMNS, ABBREVIATIONS

ACV	Advanced Conventional Vehicle
APU	Auxiliary Power Unit
ARB	(California) Air Resources Board
BOEV	Battery-only Electric Vehicle (BEV)
BEV	Battery-Electric Vehicle (BOEV)
CARB	California Air Resources Board
CNG	Compressed Natural Gas
CYC_1015	Japanese 10-15 mode driving cycle
CV	Conventional Vehicle
DG	Distributed Generation
DOE	Department of Energy
ECS	Emissions Control System
EPRI	Electric Power Research Institute
EV	Electric Vehicle (BEV, BOEV)
FCV	Fuel-cell Vehicle
FUDS	Federal Urban Driving Schedule
HEV	Hybrid-Electric Vehicle
HWFET	Highway Fuel Economy Test
kWh	kilowatt-hour
LDV	Light-duty Vehicle
LEV	Low-Emissions Vehicle
NAAQS	National Ambient Air Quality Stds
NEDC	New European Driving Cycle
NiMH	Nickel-Metal Hydride
NMOG	Non-Methane Organic Gas
NO_x	Nitrogen Oxides
NPTS	National Personal Transportation Study
NRC	National Research Council
NREL	National Renewable Energy Laboratory
PEV	Parallel Hybrid-electric Vehicle
PM	Particulate Matter
PNGV	Partnership for a New Generation of Vehicles
RECLAIM	Regional Clear Air Initiatives Market
SCAQMD	South Coast Air Quality Management District
SEV	Series Hybrid-electric Vehicle
SIP	State Implementation Plan
SoCAB	South Coast Air Basin
SULEV	Super ULEV
Super-EV	Super Electric Vehicle
Super-ZEV	Super Zero-Emissions Vehicle
SUV	Sport Utility Vehicle
ULEV	Ultra-Low-Emissions Vehicle
VOC	Volatile Organic Compounds
VMT	Vehicle Miles Traveled
ZEV	Zero-Emissions Vehicle

	<u>ADVISOR Simulation Parameters</u>
ACC_CONV	Accessories load, conventional vehicle
ACC_HYBRID	Accessories load, hybrid vehicle
Ahr	ampere-hour
CD	Aerodynamic Coefficient
CS	Control strategy
ESS_	Energy Storage System
EX_	Exhaust system catalytic converter
EX_SI	Conventional converter for an SI engine
EX_FUELCELL	Null catalyst for fuel cell
FA	Frontal Area
FC_SI41	Fuel Converter, 1- l engine, 41 kW
FC_ANL50H2	Fuel Cell, 50 kW net
GC_PM32	Unique Mobility SR180 motor/controller
MC_AC25	Solectria AC induction motor/controller
PTC	Powertrain control
PTC_CONV	5-speed conventional-drivetrain control
PTC_FUELCELL	Hybrid with thermostat CS
PTC_PAR	5-spd parallel electric-assist
PTC_SER	Series hybrid w/ pure thermostat CS
PTC_EV	for electric vehicle
TC_DUMMY	Torque coupler, lossless belt drive
TX_1SPD	Manual 1-spd, calling TX_VW for losses
TX_5SPD_SI	Manual 5-spd, calling TX_VW for losses
VEH_SMCAR	Road parameters for small car
WH_SMCAR	Wheel/axle for small car
Wt	Weight, kg

APPENDICES

A - SIMULATION PARAMETERS FOR EACH VEHICLE TYPE <NAME.M FILES>

Simulation Parameters	CV	FCV	SEV	PEV	BEV
FC_	SI41_EMIS	ANL5H2	SI41_EMIS	SI41_EMIS	-
EX_	SI	FUELCELL	SI	SI	-
TX_	5SPD_SI	1SPD	1SPD	5SPD_SI	1SPD
WH_	SMCAR	SMCAR	SMCAR	SMCAR	SMCAR
VEH_	SMCAR	SMCAR	SMCAR	SMCAR	SMCAR
PTC_	CONV	FUELCELL	SER	PAR	EV
ACC_	CONV: 0	HYBRID: 0	HYBRID: 0	HYBRID: 0	HYBRID: 0
Wt, kg	830	1030	1030	930	1030
CD	0.37	0.37	0.37	0.37	0.37
FA, m^2	2	2	2	2	2
Wheel rad., m	0.27	0.27	0.27	0.27	0.27
ESS_	-	Pb28	PB16_fund_Optima	PB16_fund_Optima	Pb28
MC_	-	AC25	AC25	AC25	AC25
TC_	-	-	-	DUMMY	-
GC_	-	-	PM32	-	-

ESS_PB16_FUND_OPTIMA.m: 12V, 16.5 Ahr, 6.68 kg module, 25-module pack

ESS_PB28.m: 12V, 28 Ahr 11.8 kg module, 25 module-pack

B - GASOLINE EQUIVALENT FUEL CONSUMPTION

From a communiqué from Tony Markel, NREL:

The gasoline equivalent fuel consumption for an electric vehicle is calculated as,

mpgge = (distance traveled, mi) / (energy used, J) * (lower heating value of gasoline, J/g) * (density of gasoline, g/l) / (3.785 l/gal)

where “energy used” equals the integral of (the power out of the energy system + discharge losses) / (coulombic efficiency over all discharge periods. The coulombic efficiency is accounted for here because you would encounter it in recharging your system back to its original state.

For a hydrogen fuel cell,

mpgge = (hydrogen fuel economy, mpg) / (density of hydrogen, g/l) / (lower heating value of hydrogen, J/g) * (lower heating value of gasoline, J/g) * (density of gasoline, g/l).

The density of hydrogen in our data file is that of compressed hydrogen stored at 24 Mpa (~3500 psi).

ADVISOR

Cosimulation: Partnering with the Software Industry I: Optimization and Thermal Modeling

Implementing Optimization in ADVISOR Using VisualDOC

Presentation

Paper

John Garcelon and Valdimir Balabanov,
Vanderplaats Research & Development, Inc.

Detailed Vehicle Thermal Systems Modeling in ADVISOR Through Integration with FLOWMASTER2

Presentation

Paper

Rory Lewis and Jason Burke, Flowmaster USA, Inc.

Implementing Optimization in ADVISOR

John Garcelon, Vladimir Balabanov

Vanderplaats Research and Development, Inc.

Leaders in Design Optimization Technology

Overview

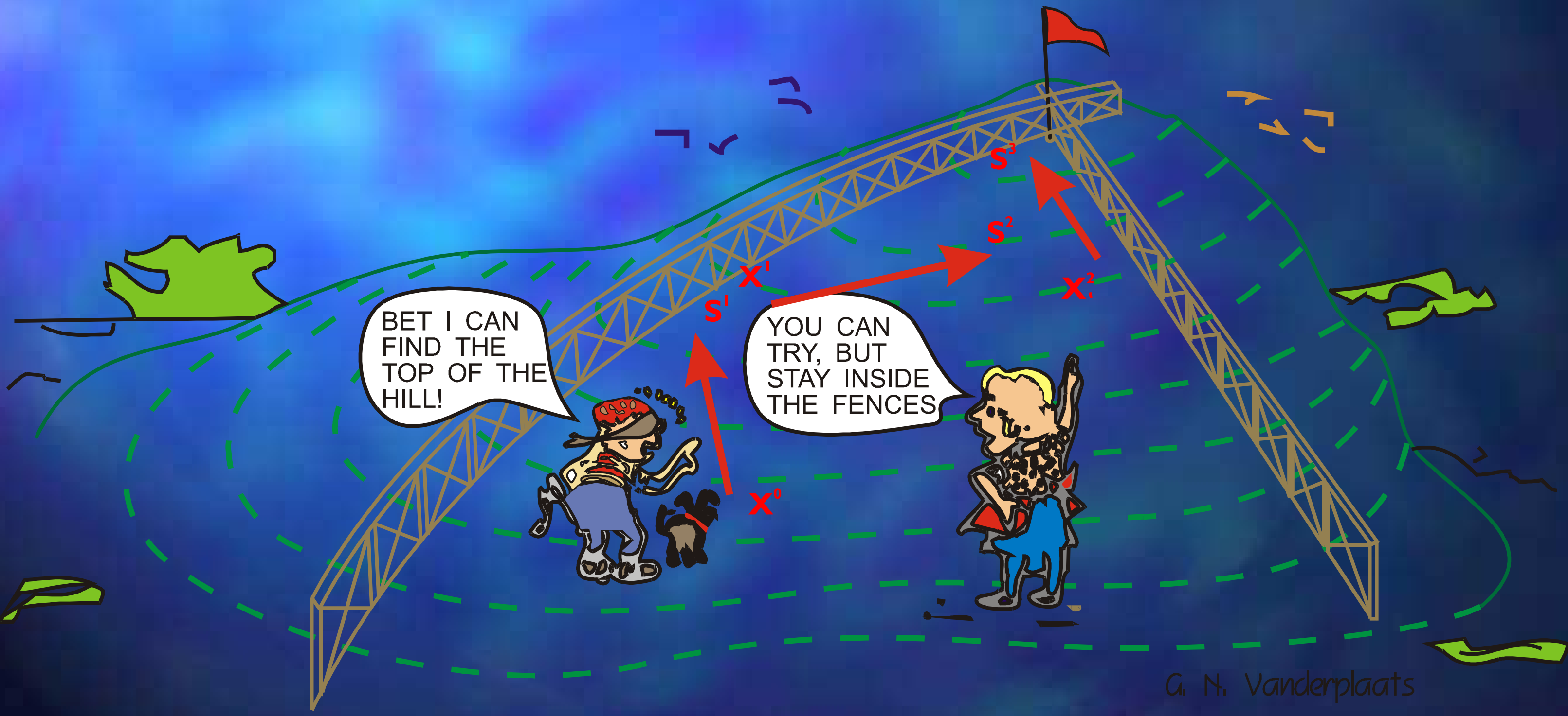
- Why optimize?
- How does optimization work?
- What is VisualDOC?
- Previous Efforts - Coupling ADVISOR and VisualDOC
- New VisualDOC Features
- VisualDOC API - Embedding VisualDOC in ADVISOR
- Summary

Why Optimize?

- Improve Performance
- Gain Insight into Difficult Design Problems
- Tool for designers

How Does Optimization Work?

THE PHYSICAL PROBLEM



How Does Optimization Work?

- Design Variables: {X}
  - parameters that may change, inputs
- System Responses
  - objectives, obj(X): minimize / maximize
  - constraints: $g_k(X) < 0$

Optimization Applications

- Structures
- Nonlinear Mechanics
- Computational Fluid Dynamics
- Simulation of Kinematics
- Chemical Processing
- Financial Planning

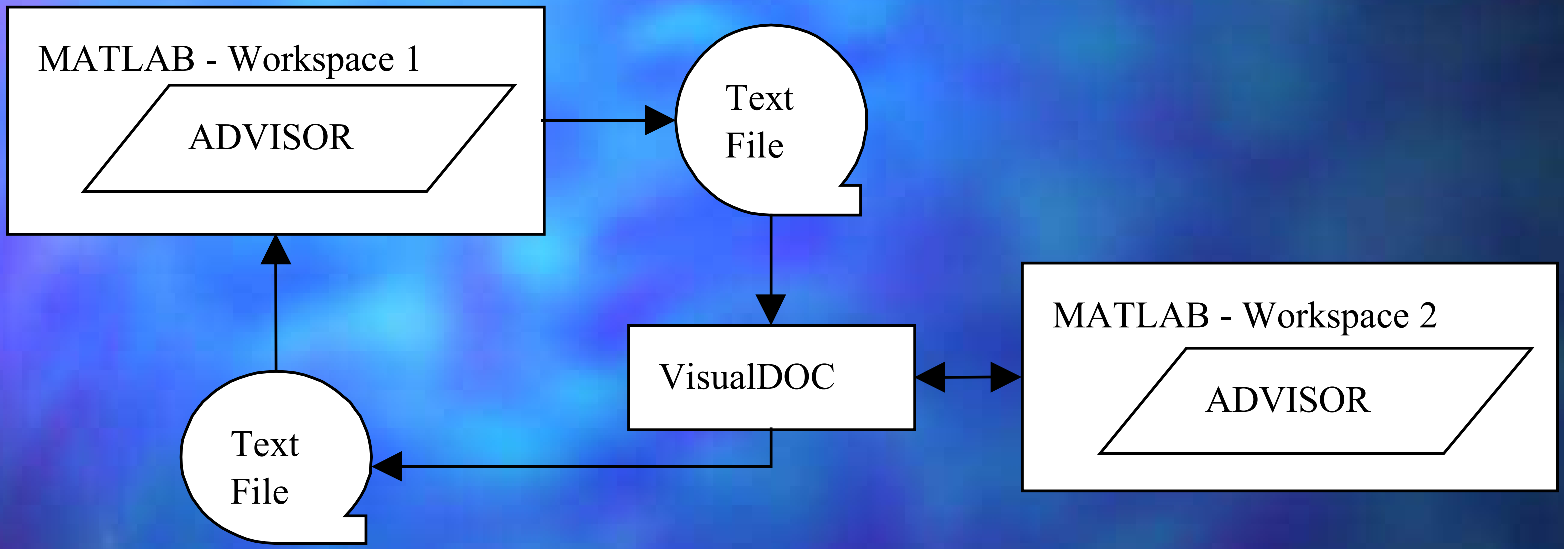
What is VisualDOC?

- General-Purpose Optimization System
  - Add optimization to almost any analysis
- Components
  - Algorithm Library
  - Response Program Interface
  - Graphical User Interface
  - Application Program Interface (API)
  - Design Database

VisualDOC Components

- Algorithms
  - Gradient-Based (MMFD, SLP, SQP)
  - Response Surface Approximate Optimization
  - Design of Experiments
- Response Program Interface
  - Couple VisualDOC to Analysis Programs
- Design Database
  - Leverage Design Studies
- API
  - Embedding Optimization

Previous Efforts: ADVISOR & VisualDOC



- Auto-size
- Parallel and Series Control Strategy Design

Control Strategy Design

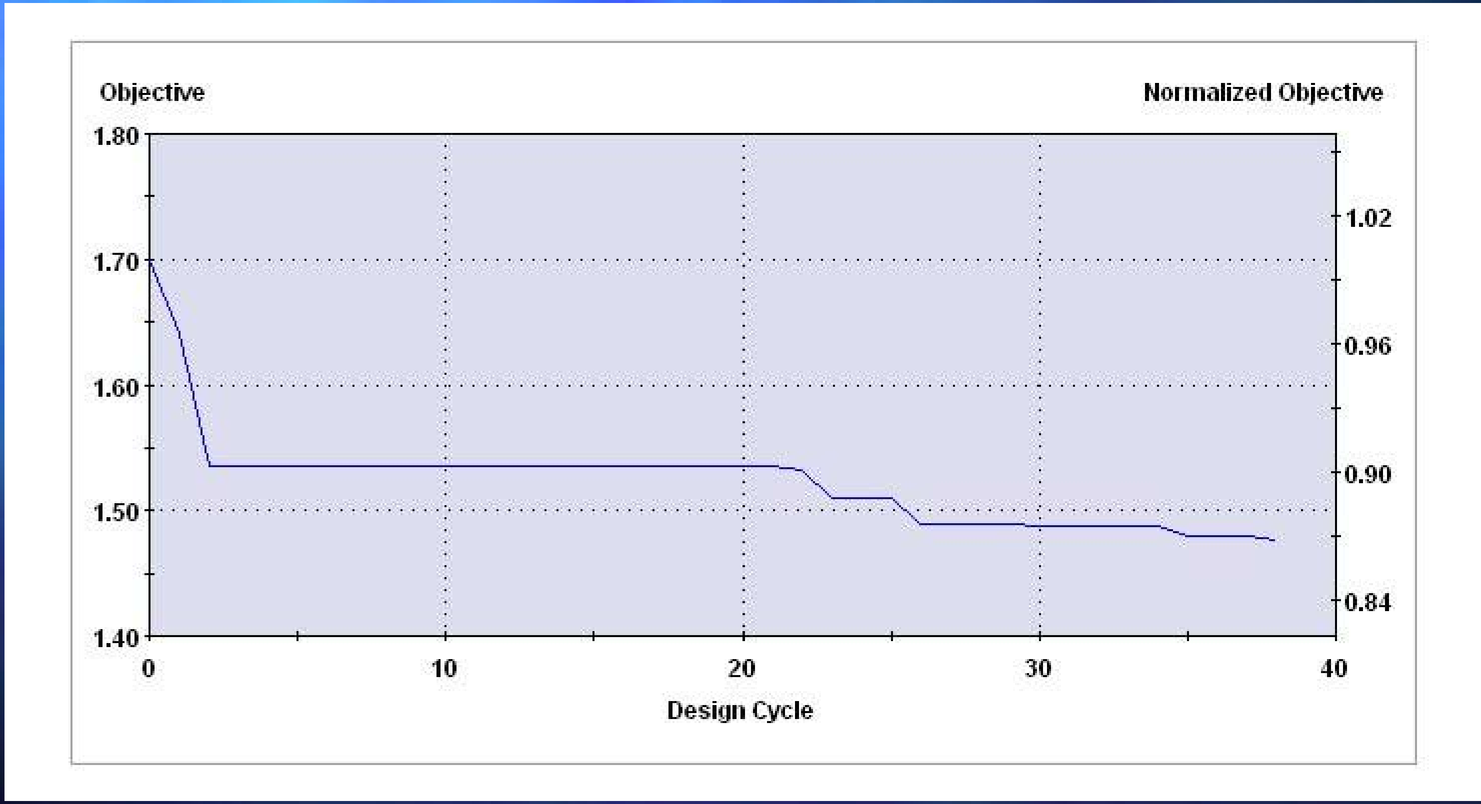
- Design Variables: Parallel Vehicles
  - high and low SOC
  - electric launch speed
  - charge torque
  - off torque and minimum torque fractions
- Design Variables: Series Vehicles
  - high and low SOC
  - minimum off time
  - charge power
  - maximum and minimum power
  - maximum power rise and fall rates

Control Strategy Design

- Responses
  - Any combination of…
    - fuel economy
    - gradeability
    - emissions (HC, PM, CO, and Nox)
    - acceleration performance (0-60, 0-85, 40-60)
  - As constraints and/or objectives
    - maximize, minimize, or meet a target

Previous Results

- Inverse of normalized fuel economy



Issues!

- Multiple MATLAB Workspaces
  - each with > 20 megabyte memory hit
- Difficult to alter existing problems and setup new problems
- Auto-size $\rightarrow$ Control Strategy
  - Ignores interdependent design variables
    - Eliminates design flexibility

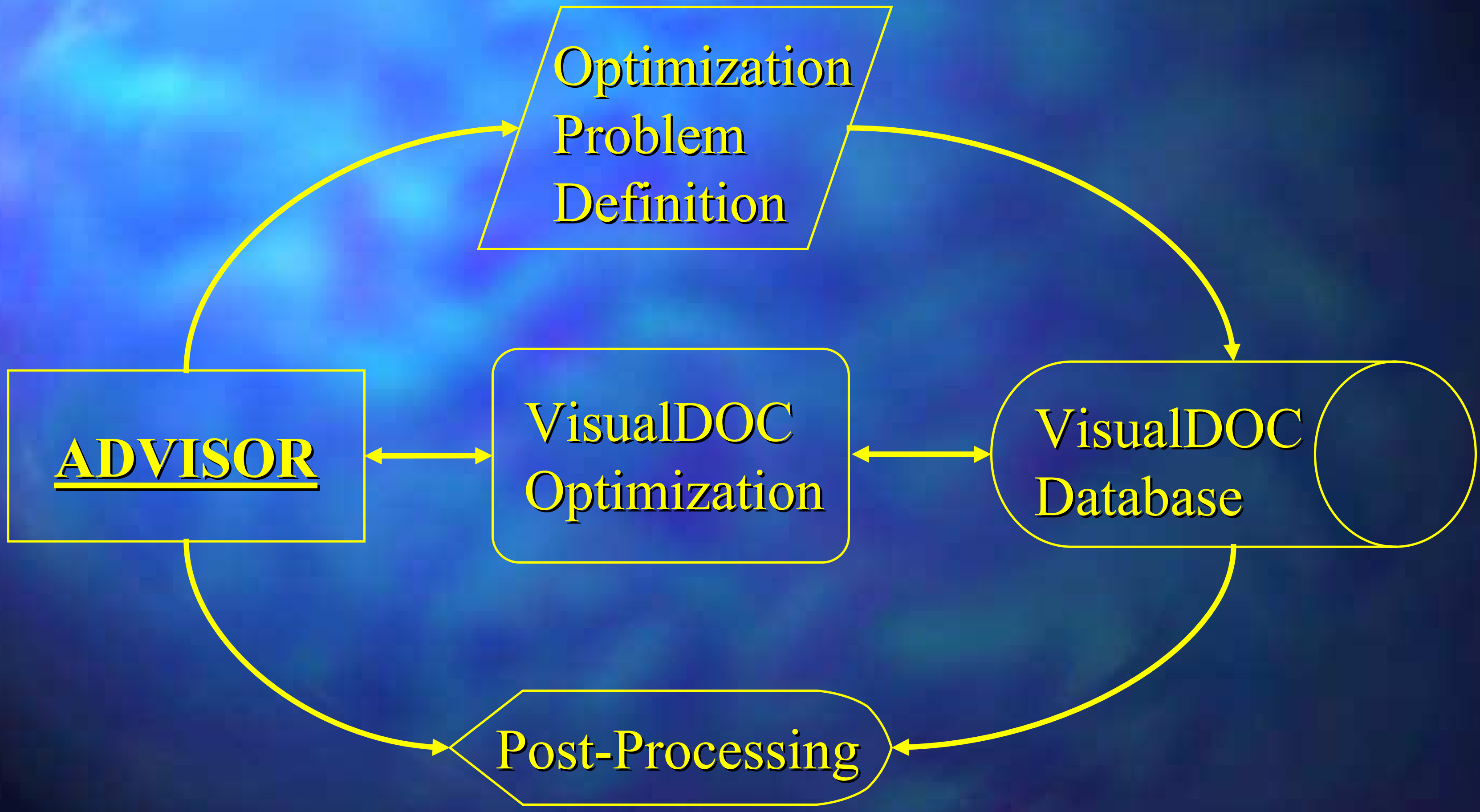
New VisualDOC Features

- Design Database
  - Improves problem definition flexibility
- Response Surface Approximations
  - Extended range of application
    - fewer analysis
- Design of Experiments
  - Generation of irregular design spaces
  - D-Optimal Design
  - Mixed forward regression models

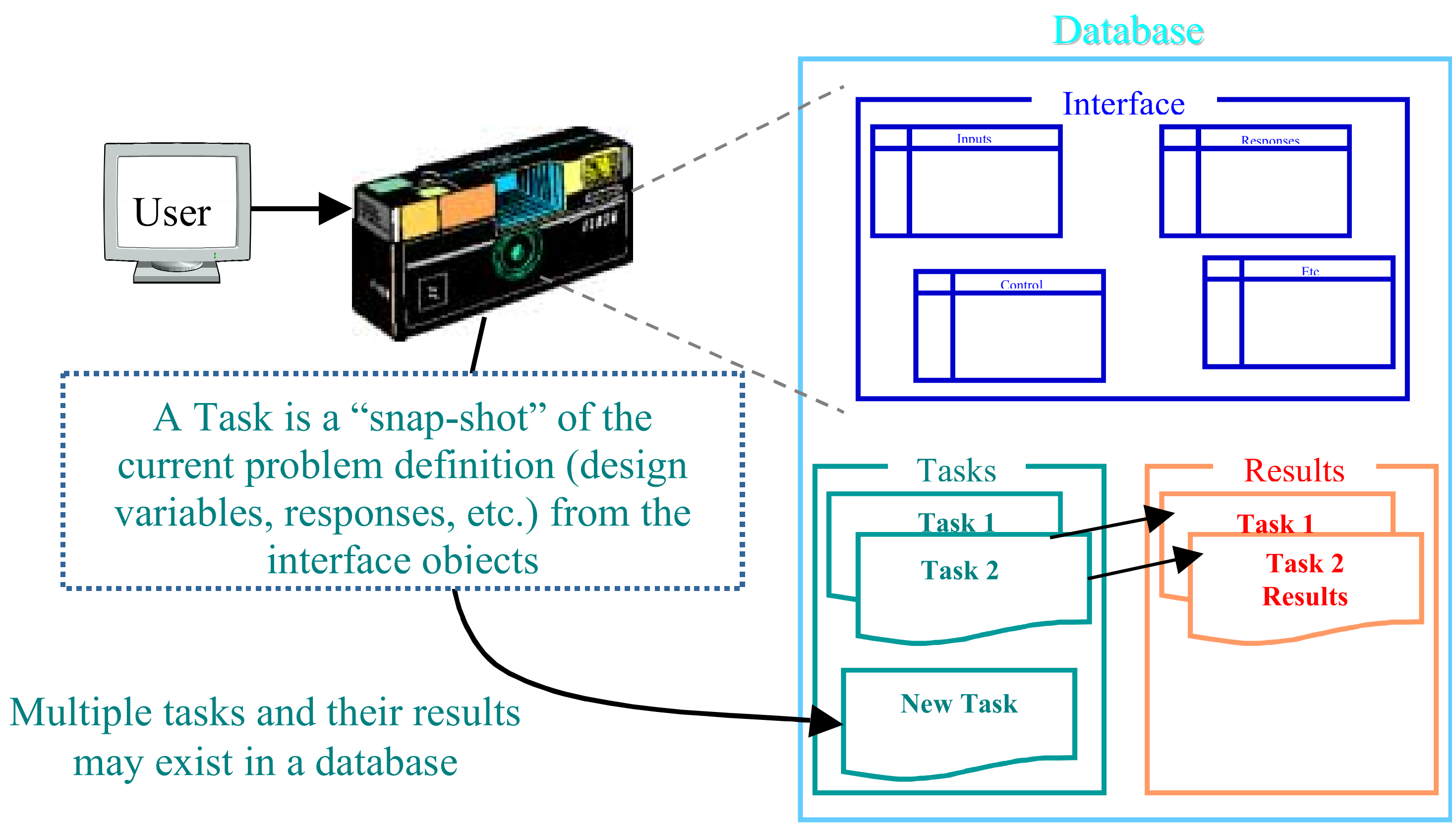
New VisualDOC Features

- Discrete Optimization
  - Leverages design points in the database
    - Faster with fewer analyses
- API
  - Embed VisualDOC into ADVISOR
    - MATLAB calling structure
    - Direct access to the design database
      - defining problems
      - retrieving results

Embedding VisualDOC in ADVISOR



Design Database Concepts



Design Database

- Object-Relational
- Multiple Runs and Tasks
  - DOE, Response Surface, Direct
- Problem (task) definition
  - Data, Algorithms
- Results
  - DOE, Response Surface, Direct
- VisualDOC API
  - Database Access Calls

Design Database Contents

- Interface Objects
  - Inputs, Responses, Auxiliary, Design Control
- Task Definition Objects
- Results Objects
  - Summary, Iteration, Design Point, Approximations, DOE, Residual

Embedding Tasks

- Optimization Problem Definition
- Calling Optimization Design Modules
- Post-Processing Optimization Results

Optimization Problem Definition

- How will users define design optimization problems?
  - ADVISOR GUI
  - MATLAB command window
  - VisualDOC GUI
- Goal: Allow users to design almost any ADVISOR variable using almost any ADVISOR response

Calling Design Modules

- VisualDOC design modules accessible as MATLAB function calls
  - Inherently iterative

```
state = INITIALIZE;
while state != DONE
    state = RSA( X, R );
    Modify_ADVISOR_Variables( X );
    R = Calculate_ADVISOR_Responses();
```

Post-Processing Results

- Database access functions
  - Allow real-time monitoring of progress
  - Complete response and design variable histories
  - Details about convergence, timing, errors

Implementation Schedule

- New ADVISOR release: August 2000
- VisualDOC 2 release: September 2000
- Prototype ADVISOR-VisualDOC API
  - fall 2000
    - comparison tests with previous coupling
    - generation and testing of new optimization problems using API
  - winter 2000/2001
    - complete integration

Summary

- New VisualDOC API
  - Easier, extendable optimization interface for ADVISOR
  - Native MATLAB function calls
  - New algorithms
  - Design Database
- Apply design optimization throughout ADVISOR

Implementing Optimization in ADVISOR Using VisualDOC

John Garcelon
Vanderplaats Research and Development

ABSTRACT

Parallel hybrid electric vehicles (HEVs) offer the potential, if properly designed, for significant fuel and emissions benefits as compared to conventional vehicles. This paper focuses on the application of optimization tools (i.e. VisualDOC) via a new Application Programming Interface (API) to the overall design of hybrid electric vehicles through multi-variable and multi-objective optimization using ADVISOR.

INTRODUCTION

Any vehicle design is a complex endeavor that involves multiple disciplines and multifaceted interacting systems (drive train, structures, aerodynamics, and auxiliary systems). HEVs offer additional technical challenges because they incorporate relatively new and emerging technologies. In most complex systems, it is difficult to qualify how variables in the subsystems interact and influence responses. Parametric studies can offer a great deal of insight; however, as the number of design variables increases, the interactions become less tractable. Design optimization offers a powerful set of tools that help engineers understand and improve design options.

Design optimization is the process of modifying specified parameters of a design in order to achieve specified goals. Typically, the parameters to be modified are called design variables and the goals are called design objectives. Most designs have some set of operating limitations; these are typically termed design constraints [1].

Design optimization is an iterative process in that numerous analyses must be performed as the design progresses from its nominal state to an optimum. The primary advantage to using optimization techniques is that the optimizer implicitly considers all interactions between design variables. Therefore, as the design becomes more complex (i.e., we consider more design variables), the optimization process automatically takes into account these interactions and how they influence performance.

VisualDOC [3] is a general purpose optimization system that provides the means to quickly couple numerical optimization to almost any analysis. Version 1.2 included a graphical user interface (GUI), an interface to MATLAB, a static object library, and a text file interface. Optimization techniques included gradient-based algorithms, response surface approximations, design of experiments (DOE), discrete/integer optimization, and multi-objective optimization.

Gradient-based algorithms such as Modified Method of Feasible Directions (MMFD), Sequential Linear Programming (SLP), and Sequential Quadratic Programming (SQP), all require gradients of the objective and constraints to find a maximum or minimum. Response surface approximate optimization creates numerical approximations of the true responses using a least square process. Response surface approximations can significantly reduce the number of analyses required to find an optimum and do not require gradients. Design of Experiments or statistical designs provide an arrangement of design points (i.e., sets of design variable values) that are useful in exploring the design space. A DOE may be viewed as a sensitivity study or as a rational starting strategy for response surface approximations.

This paper describes the next version of VisualDOC and how it relates to ADVISOR. An earlier version of VisualDOC was coupled with ADVISOR, and this paper addresses how the new version will impact ADVISOR users and developers.

PREVIOUS EFFORTS

Early in 1999, Vanderplaats Research and Development (VR&D) and the Systems Analysis Team at NREL, coupled ADVISOR v2.2 [2] and VisualDOC v1.0 [3]. This effort produced promising results and highlighted certain issues.

The most promising results from this effort were in the areas of "auto-sizing" and control strategy optimization. Both efforts were profitable with optimization identifying significant design improvements when applied to control strategy optimization. The optimizer worked well with control strategy problems (serial designs with 8 design variables and parallel designs with 6 design variables). Furthermore, combinations of ADVISOR responses could be considered as either objectives or constraints (i.e., fuel economy, gradeability, emissions, and acceleration times). Other design problems were also investigated, most notably, gear ratio and shift strategy optimization.

DESIGN STUDIES

One of the big advantages of using ADVISOR and VisualDOC was in the area of performing "design studies." The design studies performed chiefly examined the tradeoffs between fuel economy and emissions. In these studies, numerous optimization runs were made to investigate if a sacrifice in fuel economy could significantly reduce emissions to EPA Tier II levels using current test data as modeled in ADVISOR.

The following describes the general procedure taken in these design studies:

1. Choose Vehicle Type.
2. Auto-size the Vehicle.
3. Perform a 2nd Order Koshal DOE of the control strategy parameters.
4. Optimize the Control Strategy Using Response Surfaces with the DOE Design Points.

In performing these studies, we would modify the design objectives and emissions constraints to gain insight into the problem. Since a DOE run only requires responses (as opposed to objectives and constraints), a single DOE run could be leveraged and used in multiple optimization runs. Our DOE run required 28 ADVISOR analyses for a parallel problem and the optimum was typically found in less than 25 additional analyses. (NOTE: VisualDOC uses an adaptive, nonlinear update of the response surface approximations, which is why the responses surface approximate optimization requires analyses after the DOE run.) Performing these design studies required a formal coupling of ADVISOR and VisualDOC.

COUPLING ADVISOR AND VISUALDOC

The coupling of ADVISOR and VisualDOC was done in two ways. The distinction between them was in terms of which GUI you used (i.e., ADVISOR or VisualDOC). Because VisualDOC already supported a link with MATLAB, NREL developed a script to run ADVISOR without its GUI (i.e., no_gui_vrd.m). Because VisualDOC's GUI is a general-purpose optimization interface that most ADVISOR users would be unfamiliar with, the Systems analysis team provided integrated access to VisualDOC via the ADVISOR GUI for the solution of two specific design problems: auto-size and control strategy.

LIMITATIONS

The design studies illustrated some major limitations in our coupling of ADVISOR and VisualDOC. From a development standpoint, the primary limitations were ease of use and extensibility. To gain full advantage of reusing DOE runs in multiple optimizations and easily altering the design study parameters, engineers needed to use the VisualDOC GUI. Furthermore, it was very difficult to modify ADVISOR to consider even slightly different design optimization problems.

This lack of flexibility limited the potential of what design optimization may achieve in hybrid vehicle design. Considering powertrain control strategy optimization, the auto-size process determined a specific set of components based on the vehicle performance constraints. Since the sizes of these components are dependent on the current control strategy parameters, separating the design problem into two steps ignored interdependencies.

Process performance also suffered. Figure 1 shows how ADVISOR and VisualDOC worked when calling VisualDOC from ADVISOR. When ADVISOR called VisualDOC, a new copy of ADVISOR would start. The overhead required an additional 20 megabyte MATLAB workspace. Furthermore, all information was transferred via text files, which imposed significant constraints on the flexibility.

At this time, VR&D is developing the specifications for the next version of VisualDOC. NREL engineers and other clients needed more flexibility to embed VisualDOC into applications. Previous versions of VisualDOC and its predecessor DOC [4] were not designed for developers to embed its optimization capabilities into applications. Instead, users would "wrap" VisualDOC optimization around an analysis program like ADVISOR. Thus, one of the important new features of VisualDOC 2 would be an application programming interface (API).

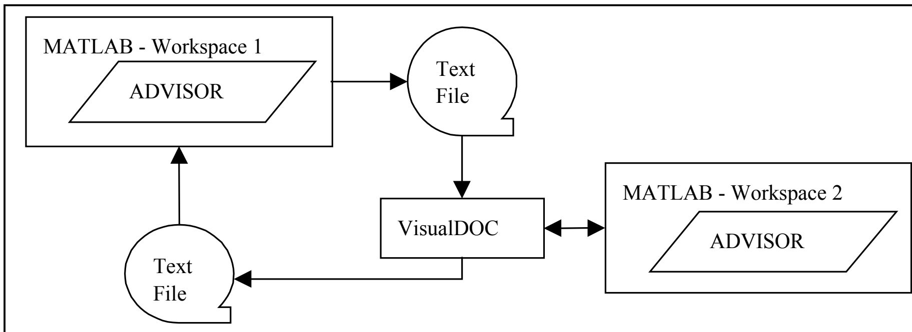


Figure 1: Calling VisualDOC from ADVISOR

NEW VISUALDOC FEATURES

VisualDOC v2 is a significant enhancement to previous versions. This section describes how these enhancements will influence ADVISOR.

INPUTS AND RESPONSES

VisualDOC 2 only exchanges inputs and responses with ADVISOR. Other optimization toolboxes require that one objective and perhaps constraints be computed from the responses as the design variables change. VisualDOC simply exchanges inputs and internally converts responses to objectives and constraints as required. This abstraction allows for any combination of inputs and responses in any problem without burdening ADVISOR with scaling of design variables, constraints determination, and/or handling multiple objectives.

DESIGN DATABASE

Underlying version 2 is an object-relational database that provides access to all VisualDOC results and problem parameters. ADVISOR no longer needs text files to transfer data with VisualDOC (see Figure 1). Instead, ADVISOR makes native MATLAB calls to the database to query, search, and sort design problem definitions and results. The VisualDOC database is a binary, multi-user, platform independent database. The database provides flexibility and facilitates reuse of design data. This paper discusses the database further in the section on the VisualDOC API.

RESPONSE SURFACE APPROXIMATIONS

Significant enhancements have been made in the response surface approximations. We have extended the approximations using a design point filtering and weighting approach. The least squares solver has also been enhanced to reduce the influence of numerical noise and poor conditioning. When performing optimization runs in ADVISOR, users can typically expect faster convergence and fewer analysis.

DESIGN OF EXPERIMENTS

The DOE module in VisualDOC has added features and several new statistical designs. These are summarized as follows:

- Enforced Design Variable Constraints
- D-Optimal Designs
- Mixed Forward Regression Models

Enforced Design Variable Constraints

Designers can easily create irregular design spaces by defining design variable constraints and enforcing them in DOE. All minimum variance designs implemented in VisualDOC place design points at the limits of design variables. As a result, most analysis programs including ADVISOR have difficulty analyzing some of these design points because they are at extremes. Furthermore, DOE can easily create invalid design points (i.e., design points that are physically impossible). For example in ADVISOR, you can provide a high and low state of charge as control strategy parameters. The limits of these variables can overlap; therefore, when DOE creates design points, it can easily create a point where the low state of charge is greater than the high state of charge. By creating a constraint between these variables such that the low state can never be equal or greater than the high state, the DOE can enforce this constraint when generating design points. The effect of this option is to reduce the total number of design points prior to creating approximations and performing analyses.

D-Optimal Designs

D-Optimal designs also reduce the number of design points prior to running the analyses and generating the approximations. The criterion that D-Optimal designs use is to maximize the D-efficiency for a given number of design points. Recall that D-efficiency is calculated as

$$D-efficiency = \frac{100}{n}\left|\mathbf{Z}^{\mathrm{T}}\mathbf{Z}\right|^{1/m}$$

where, **Z** is the model matrix (in least squares terminology), *n* is the number of design points, and *m* is the number of terms in the approximation model [5]. The set of design points that maximizes the D-efficiency is determined by an exchange algorithm [6].

Mixed Forward Regression Models

Mixed forward regression models can have a big impact in reducing overall runtime when approximations need only be generated once. Here, VisualDOC will create the best approximations up to a second order polynomial for a limited number of design points. This is important when one considers that a DOE and response surface approximations can become computationally expensive very quickly. In the case of a 5 design variable problem, to generate a full second order polynomial approximation requires 21 analyses; for a 10 design variable problem, 66 analyses are required; for a 15 design variable problem, 136 analyses are required. Moreover, some statistical designs are unsuited for generating second order approximations (e.g., two-level factorial designs).

The mixed forward regression model in VisualDOC 2 will generate mixed order approximations to minimize estimating error for a limited number of analyses. Thus, mixed second order approximations can be generated for a 10 variable problem with significantly less analyses than the 66 analyses required for a full second order approximation.

DISCRETE/INTEGER OPTIMIZATION

The branch and bound process [7] for discrete/integer optimization in VisualDOC has also been improved and takes advantage of the design database to eliminate reanalysis of previous design points. This significantly reduces the computational cost of discrete problems such as auto-size where the number of battery modules must be an integer.

The VisualDOC API is also a new feature in VisualDOC 2 and it is explained in the next section.

VISUALDOC API

The VisualDOC API is designed to allow application developers to incorporate VisualDOC into their applications. The VisualDOC API is a departure from the architecture of previous versions of VisualDOC where VisualDOC was designed to "wrap" around an analysis code. Although this wrapping was easy to implement, there were two significant drawbacks. First, users needed to invest time understanding optimization and the VisualDOC GUI. Second, the implementation was problem dependent; users could not easily develop a general optimization capability.

ADVISOR provides an intuitive, well-organized interface to hybrid vehicle powertrain analysis. Removing that interface and replacing it with a general purpose optimization interface made using VisualDOC with ADVISOR more difficult. Today, most applications include a GUI and the VisualDOC API allows developers to leverage their GUI and analysis capabilities with the optimization API from VisualDOC. Users can still easily wrap VisualDOC 2 around an application; however, the API provides even more flexibility to developers.

The foundation of the API like the VisualDOC system is the database. This means that to use the API, developers must use the VisualDOC database. This is not as constricting as it sounds since the database is very efficient. For example, an empty design database consists of two files, the data and index files, and is less than 15 kilobytes in size. Most average design runs (10 design variables and 30 responses) typically require a total database size of approximately 50 kilobytes. Furthermore, the database provides a convenient way to organize and store information that is already required.

The database organizes design data and provides fast access to VisualDOC parameters and results. The database is multi-user and platform independent. Therefore, simultaneous ADVISOR runs may access the same database, or the VisualDOC GUI could even be used to post-process design runs from ADVISOR.

The VisualDOC database has three sections, interface objects, design task objects, and results objects. Interface objects act like a white board for defining design problems. Design task objects are a snapshot of the interface objects that define a design optimization problem, and the results objects are the outcome from running a design task. Figure 2 depicts the database sections.

The process of taking a snapshot verifies that a task will run successfully. Multiple tasks in a single database collects all runs and their results in a single place, making the design study process more convenient and less prone to loosing information. The inverse operation of loading design task data and restarting is also available.

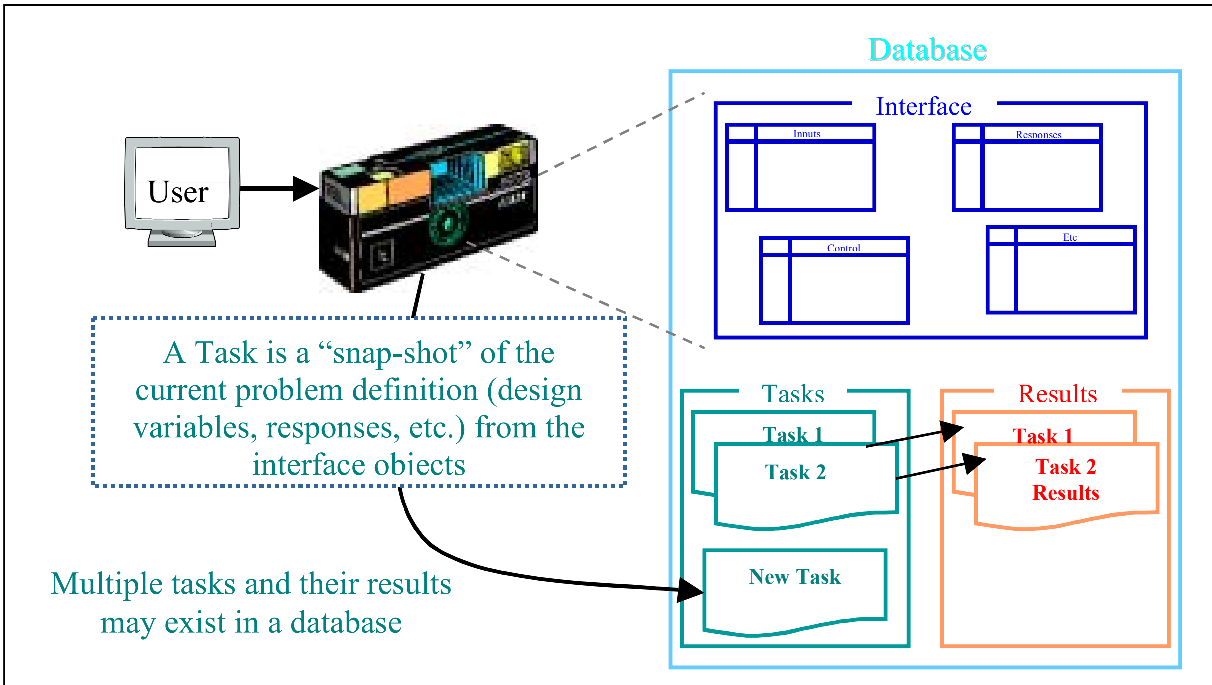


Figure 2: Database Sections

The API consists of four main parts as follows:

- Defining/Modifying Interface Objects.
- Functions That Invoke Design Modules.
- Retrieving Result Objects.
- Utility Functions.

INTERFACE OBJECTS

ADVISOR primarily works with interface objects in the database. Interface objects consist of the following object types:

- Inputs
- Responses
- Auxiliary
- Design Control

Input objects define what problem parameters may change, i.e., design variables. There are over 18 different attributes for an input object that define everything from the initial value and bounds on input to a name and description. The database provides default values for all attributes. Virtually any variable in ADVISOR may become an input object.

Responses are those values that ADVISOR calculates. Responses may have limits and thus be considered design constraints. VisualDOC also allows you to specify responses as design objects that you can minimize, maximize, or direct towards a target value. There are over 24 attributes for each response object and the database provides default values for all. These attributes define limits on the response when used as a constraint and how the response should be used as an objective if the user desires so.

Auxiliary objects are optional attributes that apply to input and response objects. They allow for linked and synthetic inputs and responses and define discrete set values for inputs.

The design control object defines optimization algorithms and algorithm parameters. There are over 70 attributes that define what algorithms to employ and their parameters. Everything from which statistical design to run for DOE to the finite difference step-size for calculating gradients is defined here. The database provides default values for all attributes.

A single API call, MakeTask, creates a design task from the currently defined interface objects. MakeTask first verifies that all interface objects are consistent and that the design task will run. For example, every design task requires one or more inputs and responses. MakeTask verifies that at least one input and one response have been defined. The types of data verification checks made are in the context of the design task to be run. Once the design task is created, ADVISOR may start running a design module.

DESIGN MODULES

Design modules operate with design task objects to create results. Design modules encapsulate the optimization algorithms. There are three primary design modules. These are Direct Gradient-Base Optimization (DGO), Response Surface Approximations (RSA), and Design of Experiments (DOE).

DGO supplies the MMFD, SLP, and SQP algorithms. Discrete optimization is integrated into this design module and is automatically applied when required.

RSA furnishes VR&D's latest response surface technology. RSA runs can use several of the statistical designs as a starting point or use a Taylor Series. Discrete optimization is also integrated into this design module. NOTE: Virtually any problem that RSA can run can also be run using DGO and vice-versa. The switch can be made by setting a simple flag in the design control interface object.

DOE gives users over 13 different statistical designs along with multiple derivatives of these designs. DOE can simply provide the design points or it can generate response approximations that can be used in subsequent optimization runs in lieu of calling ADVISOR.

RESULT OBJECTS

Each design module generates results while it runs. The following result objects may be created by the different design modules, depending on context:

- Results Summary
- Iteration
- Design Point
- DOE
- Approximation Models
- Residual

The results summary object is continuously updated by all design modules and provides a convenient means for ADVISOR to monitor the design run. There are over 35 different attributes that provide information about the design module run including the best current objective value and worst constraint values.

Iteration objects provide a history of the design progress. Each iteration object references a design point object.

Design point objects contain all design variable values and their corresponding response values. Design point objects may be leveraged from one design task to another. VisualDOC 2 also leverages the corresponding results. For example, ADVISOR may first make a DOE run to generate design points and then use those points in multiple design studies by running RSA. Each RSA run can use the design points (including responses) from the DOE run, thus reducing the computational requirements and total time to perform design studies.

DOE objects are created for every DOE run. DOE objects' attributes contain the statistical design efficiencies and other attributes consistent among all DOE design module runs.

The DOE design module also creates approximation models objects whenever the DOE module generates approximations. These attributes define the approximating polynomials.

The DOE design module also generates residual objects for all responses when it generates their approximations. The residual objects help measure the accuracy of the approximations. There are over 25 attributes for each residual object.

UTILITY FUNCTIONS

The utility functions of the API are used to open and create databases, check database integrity, and recover data from corrupted databases. Functions also exist to query the version and build numbers for each module including the database.

Because each language including MATLAB has different function calling structures, the VisualDOC API provides language specific calls. The API supports native MATLAB calls; therefore, ADVISOR can directly call the VisualDOC API from both m-files and the MATLAB command window.

COUPLING WITH ADVISOR

Coupling VisualDOC and ADVISOR using the API may be schematically described in Figure 3. Each of the three arrows connected to ADVISOR define interface points.

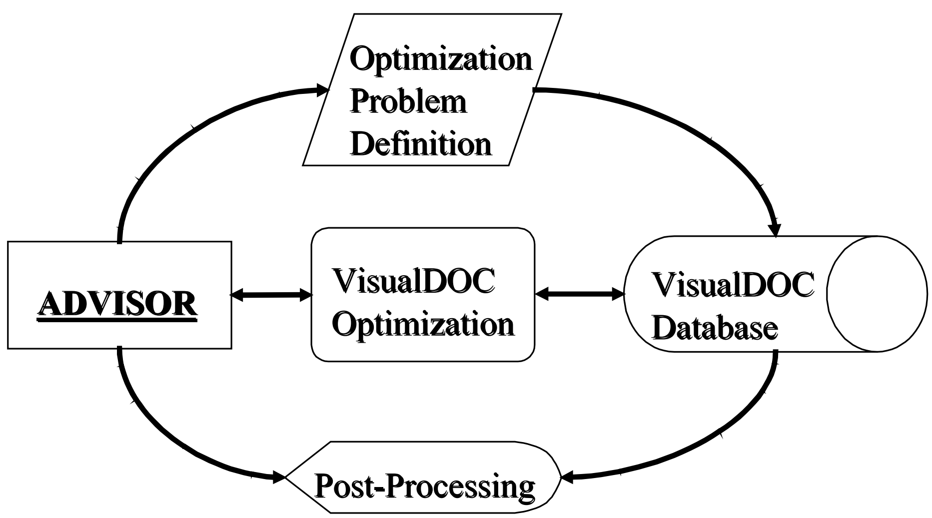


Figure 3: Coupling VisualDOC and ADVISOR

Before addressing the interface points, it is important to realize that using the VisualDOC API will eliminate the extra MATLAB workspace shown in Figure 1. Since ADVISOR directly calls the VisualDOC design modules, VisualDOC shares the ADVISOR workspace (Figure 4).

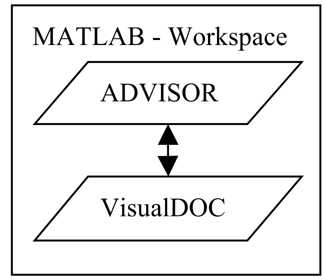


Figure 4: VisualDOC in the ADVISOR workspace

OPTIMIZATION PROBLEM DEFINITION

The question that needs to be answered here is how do we want to present general optimization problems to ADVISOR users? The goal is to do this in an intuitive manner that does not disrupt the continuity of the familiar ADVISOR GUI, but still easily allows for the definition of optimization problems in ADVISOR. There are a number of options here that we are considering since it will have impact on both development and use. Since the VisualDOC API allows us to define the problem either via the ADVISOR GUI (i.e., m-functions), the MATLAB command window, and even using the VisualDOC GUI, we have a great deal of flexibility when prototyping this interface.

VISUALDOC OPTIMIZATION

Once the VisualDOC database contains a design task, ADVISOR initiates the optimization run. Because VisualDOC's design modules are simply another MATLAB function call, the no_gui_vrd.m file no longer exists. The optimization iteration is directly coded within ADVISOR. For example, the RSA design module simply alters design variable values and requests that ADVISOR supply response values for these new design variables. The following pseudo-code shows the basic premise.

```
state = INITIALIZE;
while state != DONE
    state = RSA( X, R );
    Modify_ADVISOR_Variables( X );
    R = Calculate_ADVISOR_Responses();
```

Here, **X** and **R** are two MATLAB matrices. **X** represents the current design variable values and **R** represents the corresponding responses that ADVISOR provides. *Modify_ADVISOR_Variables* is a function that updates the ADVISOR workspace to reflect the new design variable values, and *Calculate_ADVISOR_Responses* computes the new responses according to the problem definition.

Because ADVISOR has many "dependent" variables (i.e., variables whose values dependent on other variables), *Modify_ADVISOR_Variables* is not a trivial function nor is *Calculate_ADVISOR_Responses*. However, we plan to use existing ADVISOR routines with only minor modifications to generate the necessary responses and to invoke the variable modifications for optimization.

POST-PROCESSING

The Post-Processing connection is relatively easy. The VisualDOC API provides functions for querying the database as to the run status and providing intermediate results for both inputs and responses. Real-time plotting capability is available.

IMPLEMENTATION SCHEDULE

At the time of this writing, the next version of ADVISOR is about to be released and VisualDOC 2 is in beta. The API will be in the next major release of ADVISOR. By early fall we expect to have a working prototype of the system described here and be conducting comparison tests with the old interface of ADVISOR and VisualDOC.

CONCLUSION

This paper describes current work being done to incorporate the latest design optimization technology into ADVISOR. Our goals in this work are to provide powerful and flexible optimization capabilities to users of ADVISOR such that they may optimize a wide variety of hybrid vehicle design problems using the analysis capabilities in ADVISOR.

ACKNOWLEDGMENTS

The author would like to acknowledge the assistance of the Systems analysis team in preparing this document and in performing the research described here. In particular, the author would like to acknowledge the efforts of Tony Markel.

CONTACT

The author may be contacted by email at jhg@vrand.com.

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FLOWMASTER 2

Detailed VTMS modeling in ADVISOR Through Integration with *FLOWMASTER2*

Rory Lewis and Jason Burke

Flowmaster USA, Inc.

What is ADVISOR?

- ADVISOR is a hybrid electric vehicle (HEV) simulation model written in a widely used software environment called MATLAB/Simulink. It tests the impact of changes in vehicle components, such as catalytic converters, climate control systems, alternative fuels or other modifications that might impact fuel economy or emissions.

FLOWMASTER

What is FLOWMASTER2?

- *FLOWMASTER2* is a thermal-fluid network simulation software package widely used by automotive industry for the analysis of vehicle thermal system performance.

FLOWMASTER

Why ADVISOR & FM2?

- *FLOWMASTER2* can easily model the details of a vehicles thermal system. This would be difficult to reproduce in ADVISOR.
- ADVISOR uses several factors, non thermal-fluid subsystems, which would be difficult to include in a *FLOWMASTER2* model to determine the boundary conditions in a vehicle thermal system analysis.

FLOWMASTER

Why ADVISOR & FM2?

- ADVISOR can provide *FLOWMASTER2* with better boundary conditions (e.g. engine heat rejection, speed etc…)
- *FLOWMASTER2* can provide ADVISOR with better system temperatures and heat rejections from the radiator and heater core.
- By integrating the two programs together, a more powerful and comprehensive analysis can be performed.

FLOWMASTER

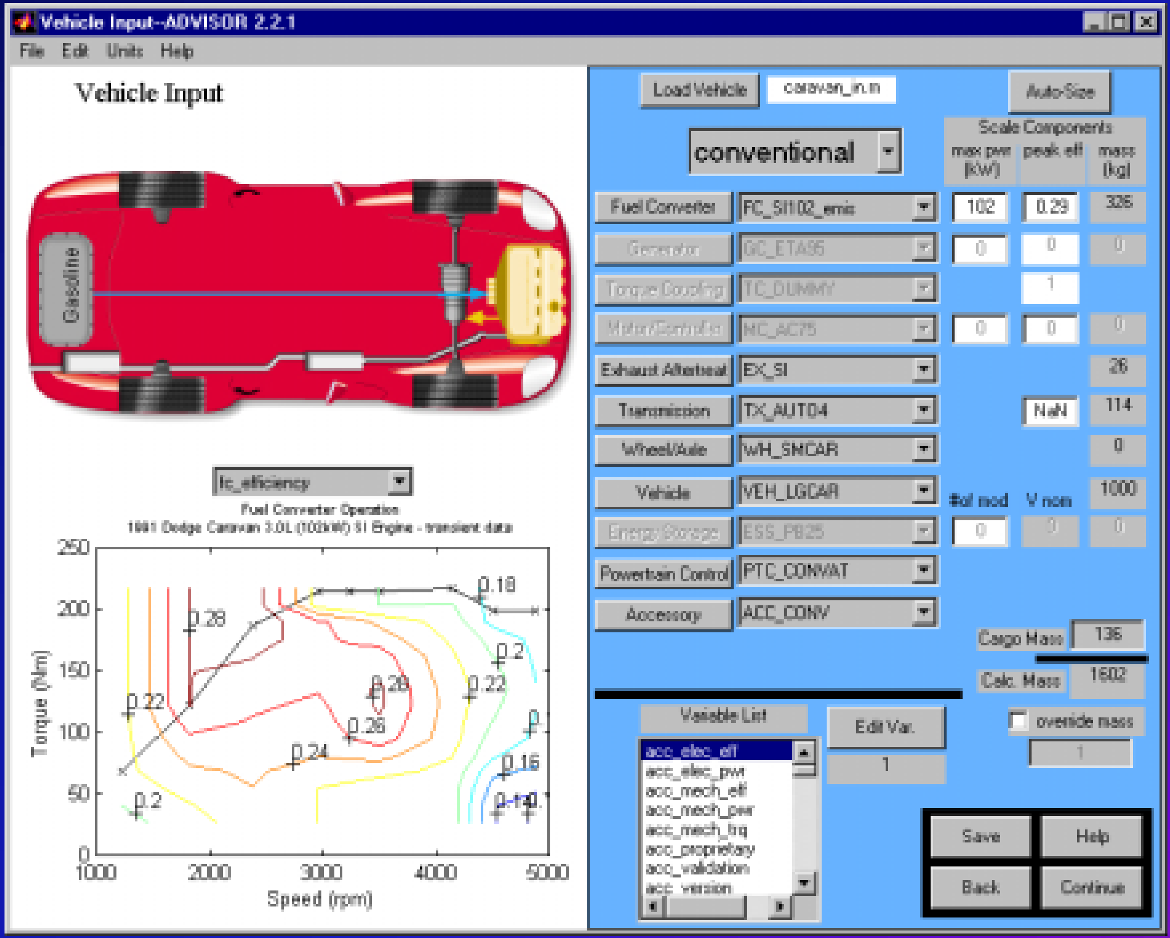
The ADVISOR model

The standard ADVISOR version 2.2.1 was used for a conventional vehicle with an automatic transmission:

- Conventional vehicle with FC_SI102_emis fuel converter, 1991 Dodge Caravan 3.0l;
- EX_SI exhaust aftertreatment;
- WH_SMCAR wheel/axle;
- VEH_LGCAR vehicle;
- ACC_CONV accessory.
- The data for vehicle mass, gear ratios, and wheel diameter were changed to represent the 1991 Dodge Caravan.

FLOWMASTER

The ADVISOR model

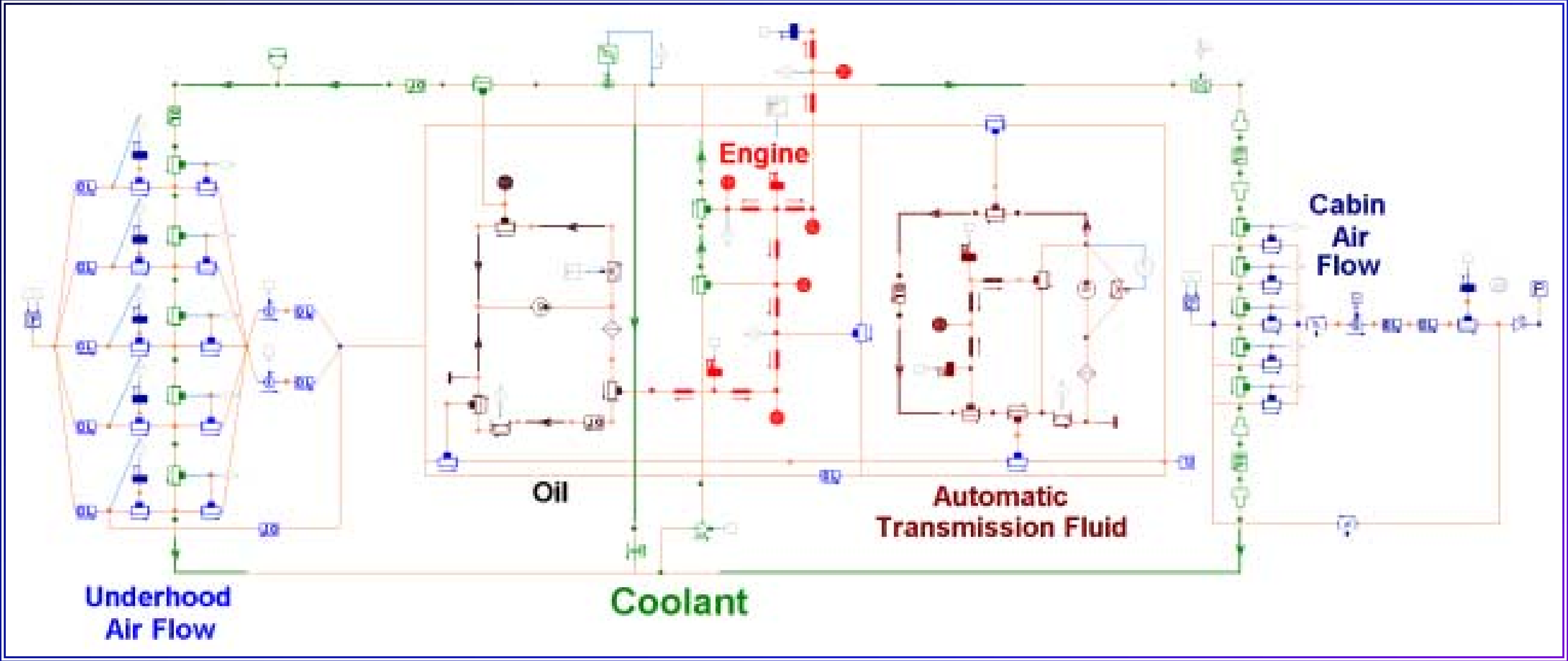


The FLOWMASTER2 model

- The *FLOWMASTER2* model used was developed from previous large car system data. The systems modeled include: engine coolant, engine oil, transmission fluid, underhood airflow and cabin airflow. These systems were modeled from a thermal hydraulic basis.

FLOWMASTER

The FLOWMASTER2 model



FLOWMASTER

The ADVISOR - FM2 link

- *ADVISOR controls the simulation*
- *FLOWMASTER2 runs in the background*
- *FLOWMASTER2 is called by a S-function in the fuel converter sub model, fc_tmp*, of the *main model bd_convat*
- *Microsoft COM/ActiveX capability in FLOWMASTER2 and Matlab/Simulink allow direct data exchange between the solvers*

FLOWMASTER

Data sent to FLOWMASTER2

Description	ADVISOR Variable	Notes
Engine heat rejection	*fc_th_pwr*	
Engine speed	*fc_spd_est*	
Vehicle speed	*mpha*	
Transmission loss (as heat)	*gb_loss_fm*	not a standard variable in ADVISOR
Torque converter loss (as heat)		(*htc_trq_in_a* * *htc_spd_in_a*) - (*htc_trq_out_a* * *htc_spd_out_a*)
Ambient temperature	*amb_tmp*	

FLOWMASTER

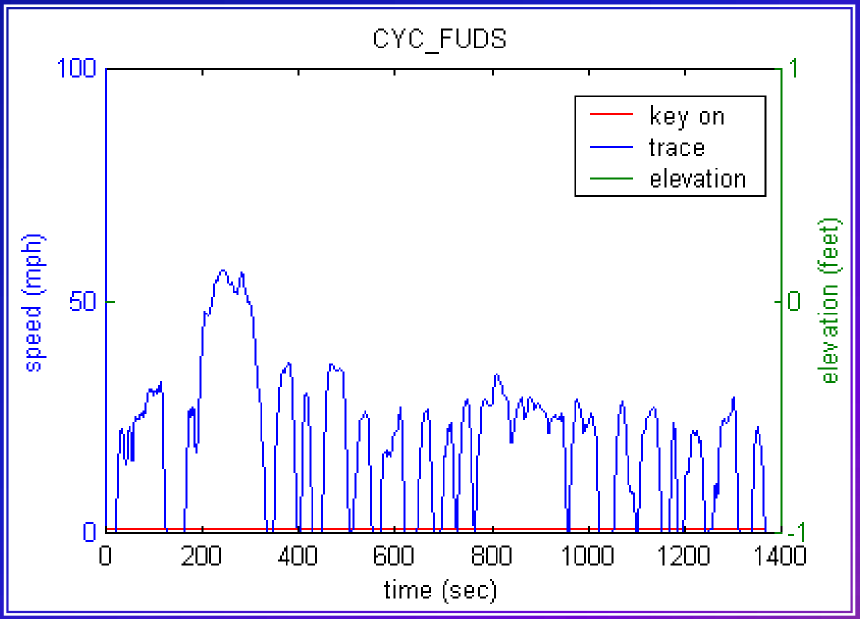
Data sent to ADVISOR

Description	ADVISOR Variable	Notes
Engine cylinder wall temperature	fc_tmp(1)	
Coolant temperature at engine exit	fc_clt_tmp & fc_tmp(2)	used for fuel economy and emissions calculations
Underhood air temperature	fc_tmp(3)	used in exhaust system heat transfer
Hood temperature	fc_tmp(4)	
Oil sump temperature	fc_oil_tmp	could be used for fuel economy and emissions calculations
ATF sump temperature	gb_atf_tmp	could be used in *htc* and *gb* loss prediction
Radiator heat rejection	fc_r_th_pwr	
Cabin heater heat rejection	fc_h_th_pwr	

FLOWMASTER

The co-simulation

- The combined model was then run over the Federal Urban Driving Schedule (FUDS) drive cycle. This drive cycle lasts 1372 seconds and is equivalent to the first two bags of FTP-75.

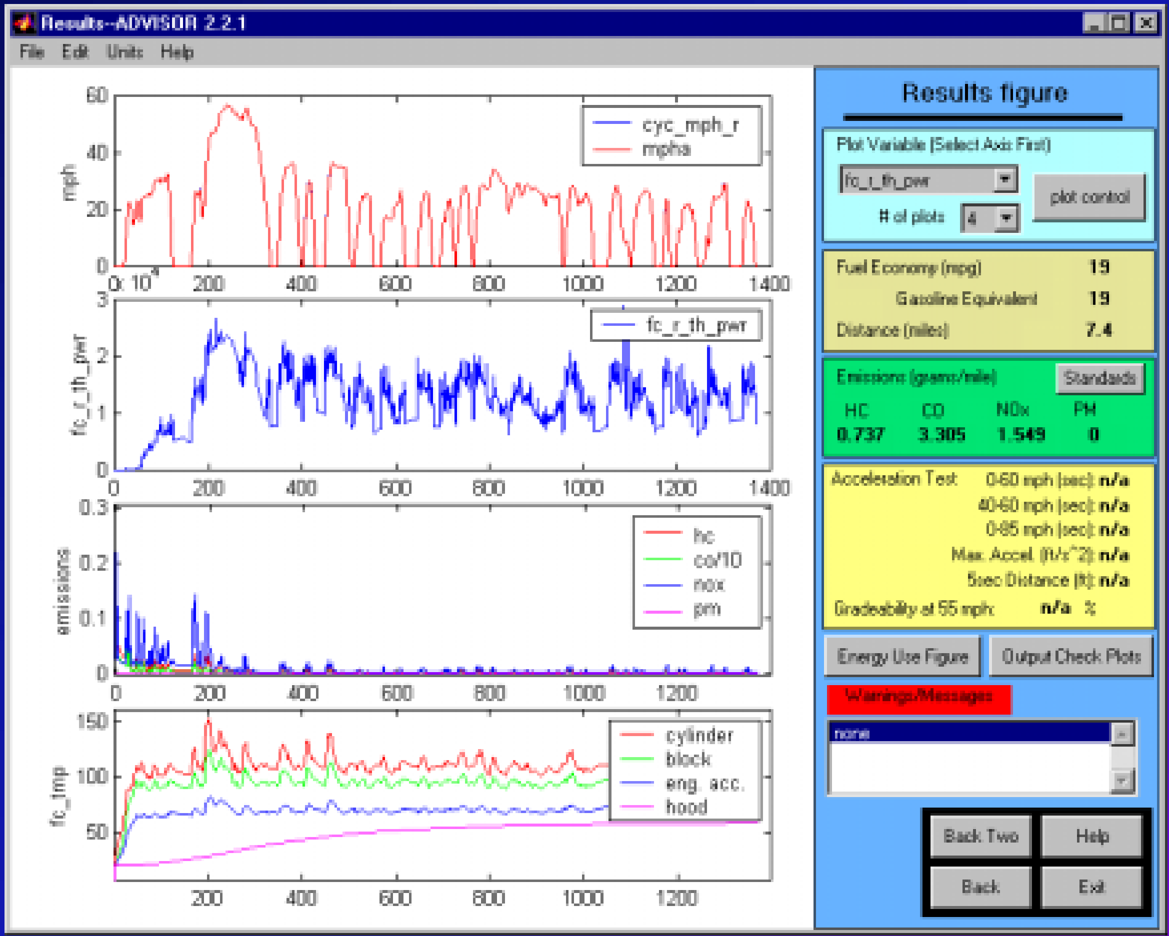


The Results

Exhaust Emissions (grams/mile)				
	Cold	Hot	Weighted Average	% Error
Advisor				
CO	12.63	0.728	5.846	244%
NOx	1.785	0.738	1.188	116%
HC	1.981	0.328	1.039	352%
***FLOWMASTER2* / ADVISOR Co-Simulation**				
CO	3.88	0.729	2.084	23%
NOx	1.63	0.738	1.122	104%
HC	0.807	0.329	0.535	133%
EPA Test				
CO			1.7	
NOx			0.55	
HC			0.23	

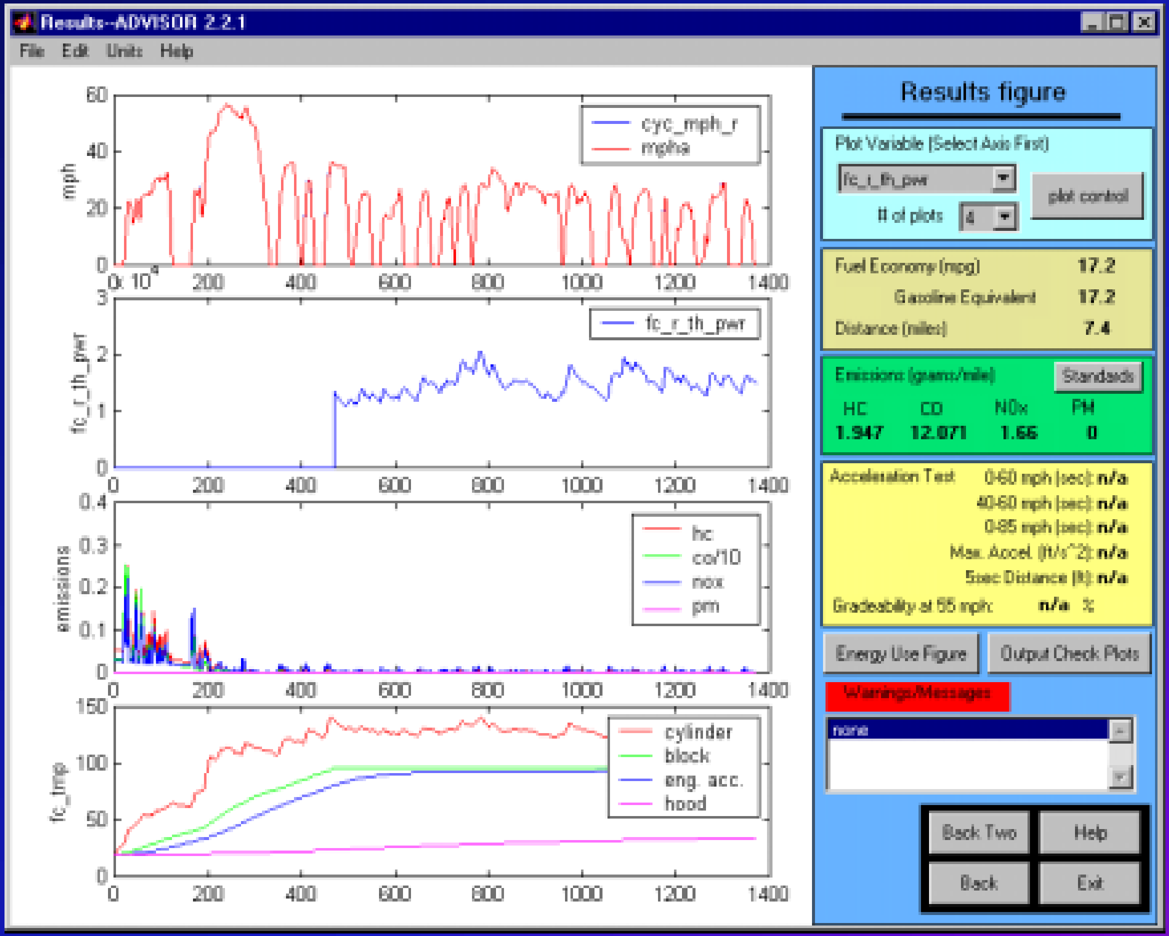
FLOWMASTER

Cold Start Results with Flowmaster2



FLOWMASTER

Cold Start Results without Flowmaster2



Conclusions

- *Vehicle warm-up time significantly effects emissions*
- *Accurately modeling the vehicle's thermal system is necessary to predict emissions*
- *An ADVISOR/FM2 co-simulation provides better results then independent simulations*

FLOWMASTER

Questions

FLOWMASTER

Detailed Vehicle Thermal Systems Modeling in ADVISOR Through Integration with *FLOWMASTER2*

Rory Lewis and Jason Burke
Flowmaster USA, Inc.

ABSTRACT

FLOWMASTER2 is a thermal-fluid network simulation software package widely used by automotive industry for the analysis of vehicle thermal system performance. The ability to integrate vehicle-specific thermal modeling with ADVISOR allows accurate prediction of the effects of thermal performance on the vehicle.

Every vehicle has different requirements for the control of powerplant and passenger compartment temperatures. System configuration and individual component performance has a significant effect on how the vehicle thermal system performs. Through the integration of ADVISOR's capability for complete vehicle and drive cycle modeling with *FLOWMASTER2*'s capability of accurately modeling a vehicle's entire thermal system, ADVISOR's ability to predict heat flows and temperatures throughout the vehicle will be improved. Thus, ADVISOR's ability to predict emissions, fuel economy, performance etc. will be improved as well.

This integration will also benefit current *FLOWMASTER2* users through improved boundary conditions for the vehicle thermal systems models. ADVISOR uses several factors, non thermal-fluid subsystems, which

to determine the boundary conditions in a vehicle thermal system analysis. Also, its built in ability to model several standard drive cycles enhances the integration between the two programs. These two factors combined make ADVISOR an easy and user friendly way to incorporate this functionality into *FLOWMASTER2*.

Each program complements the other in terms of capability, ease of use and functionality. By integrating the two programs together, a more powerful and comprehensive analysis can be performed.

INTRODUCTION

FLOWMASTER2 has been incorporated into ADVISOR for the modeling of the vehicle thermal system through co-simulation. This replaces the standard model of the vehicle thermal system in ADVISOR for the conventional vehicle model with an automatic transmission. The *FLOWMASTER2* model was constructed using the *FLOWMASTER2* graphical user interface and can be run and viewed directly through the GUI. The appropriate Simulink sub-model in ADVISOR was modified to include an S-function that calls the *FLOWMASTER2* model.

With this combined model, the detailed effects on vehicle performance, fuel economy and emissions by the thermal system can be examined. This combined model can also be used to simulate complex drive cycle boundary conditions on the vehicle thermal system. These simulations can predict how the system will perform prior to road testing.

PROGRAMS

FLOWMASTER2 is a One Dimensional internal fluid flow analysis program. It consists of a single program, which is used to set-up, run and review a simulation. The solver uses linearized partial differential equations in a matrix solution technique to solve for pressure, flow and temperature. *FLOWMASTER2* can deal with steady and transient flow, laminar and turbulent conditions and incompressible and compressible flow. Hydraulic power transfer systems can be easily simulated. Heat transfer can be modeled, including thermal inertia of the surrounding structure. The general purpose solver can solve linear, branching and looped networks. The Graphical User Interface is menu driven and has a common Microsoft Windows® look. Networks are drawn graphically on-screen and data entry, graph drawing, results manipulation, results export and import, run comparisons, custom reports and data security functions are all supported.[1]

ADVISOR is a hybrid electric vehicle (HEV) simulation model written in a widely used software environment called MATLAB/Simulink. This tool tests the impact of changes in vehicle components, such as catalytic converters, climate control systems, alternative fuels or other modifications that might impact fuel economy or emissions. The user can alter simulation results by selecting vehicle component types, sizes and parameters.[2] ADVISOR is developed and distributed by the National Renewable Energy Lab (NREL).

Simulink® is an interactive tool for modeling, simulating, and analyzing dynamic systems. Commonly used in control system design, DSP design, communication system design, and other simulation applications, Simulink enables you to build graphical block diagrams, simulate dynamic systems, evaluate system performance, and refine your designs. Built on top of MATLAB® Simulink offers immediate access to an extensive range of analysis and design tools.[3] MATLAB and Simulink are developed and by The Mathworks.

MODEL

The standard ADVISOR version 2.2.1 was used with the following vehicle input: Conventional vehicle with FC_SI102_emis fuel converter, 1991 Dodge Caravan 3.0l; EX_SI exhaust aftertreatment; TX_AUTO4 transmission; WH_SMCAR wheel/axle; VEH_LGCAR vehicle; PTC_CONVAT powertrain control; ACC_CONV accessory. The data for vehicle mass, gear ratios, and wheel diameter were changed to represent the 1991 Dodge Caravan. The standard ADVISOR vehicle input screen with the data set as used can be seen in figure 1.

The *FLOWMASTER2* model used was developed from previous large car system data. The systems modeled include: engine coolant, engine oil, transmission fluid, underhood airflow and cabin airflow. These systems were modeled from a thermal hydraulic basis. The ADVISOR model provides system boundary conditions, operating conditions and thermal loading.

The *FLOWMASTER2* network models the flow of the fluids through the system and the transfer of heat to the fluids from the powertrain and between the fluids. Hydraulically independent fluids paths including loops and branches are used for the different fluids involved in the vehicle thermal system. Fluid inertia and thermal capacitance are modeled in each fluid stream. The heat flow through and thermal inertia of the systems solid components are also modeled. Energy, as heat, is added to the system from the engine to the coolant and engine oil, and from the torque converter and transmission to the transmission fluid. System components are modeled by either an individual *FLOWMASTER2* component or, for greater detail, by a group of components. Each component is based on a physical model with both geometric and performance parameters as inputs. The *FLOWMASTER2* schematic for the network used is shown in figure 2. Each of the different fluid systems is shown in a different color, with the solid thermal model of the engine shown in red.

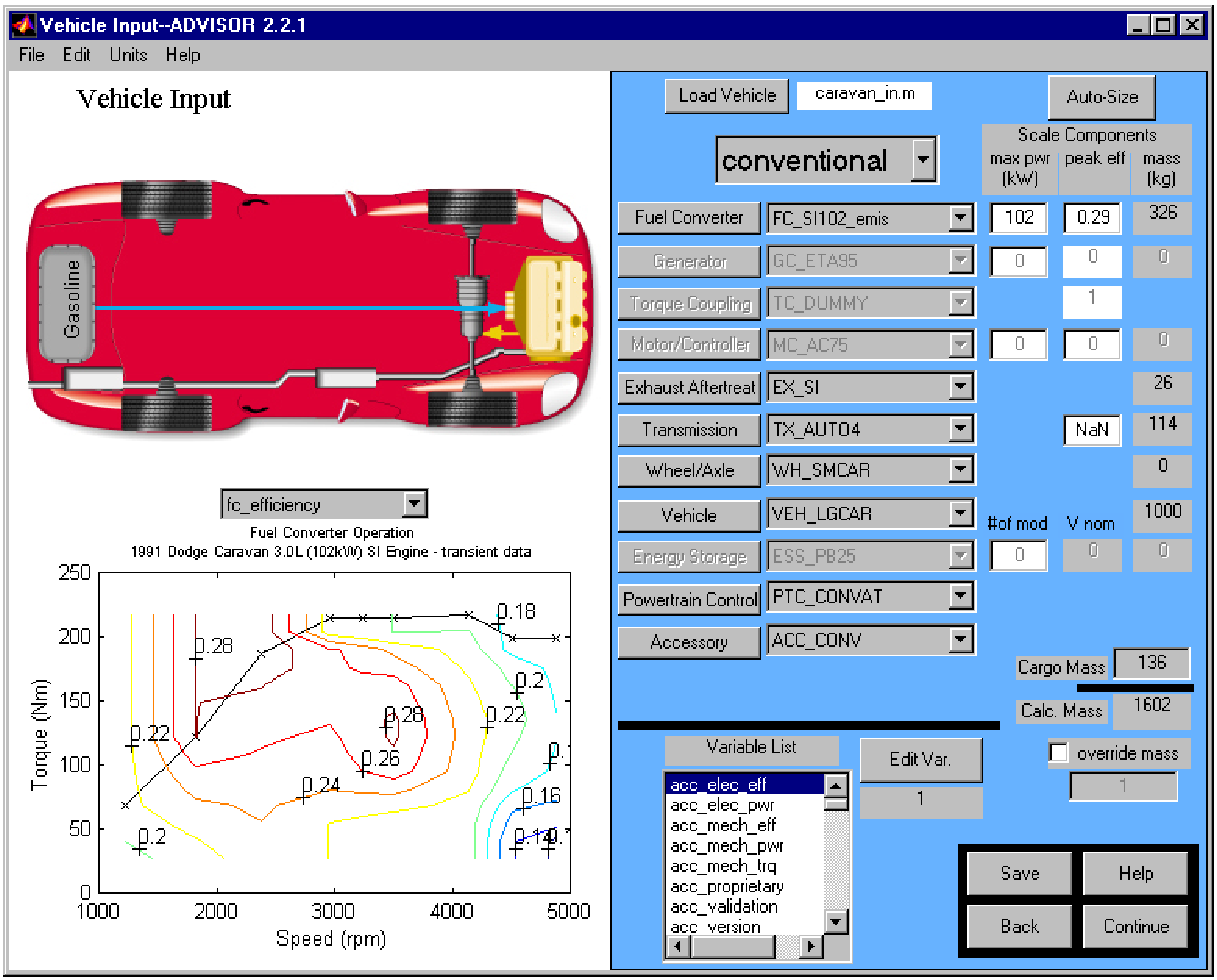


Figure 1: ADVISOR Vehicle Setup Screen

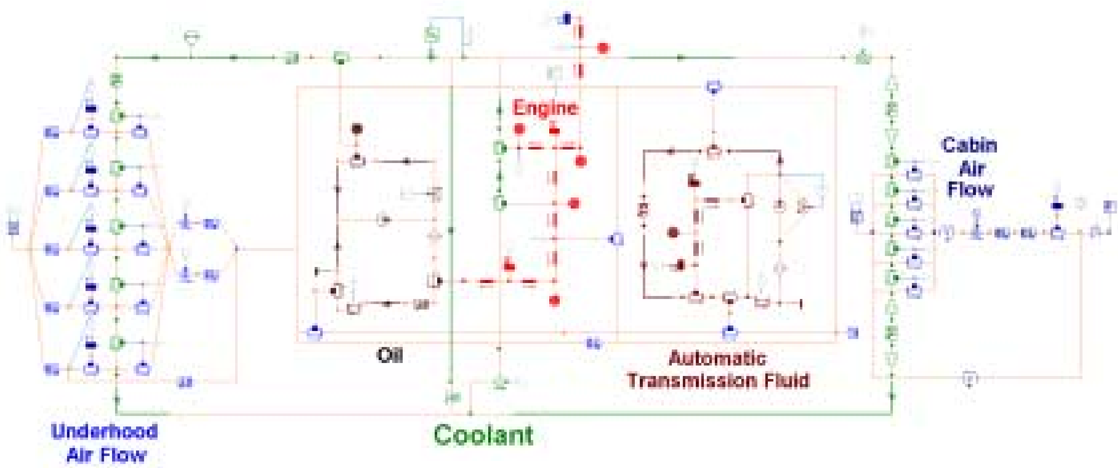


Figure 2: Flowmaster2 Vehicle Thermal Systems Model

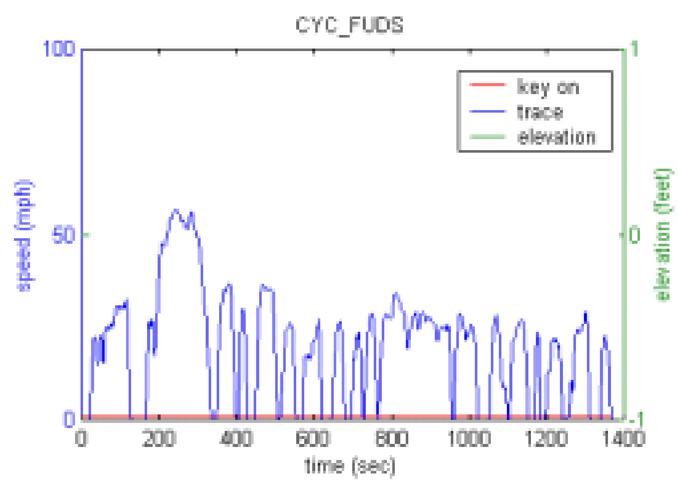
The following data is sent from ADVISOR to *FLOWMASTER2*:

Description	ADVISOR Variable	Notes
Engine heat rejection	*fc_th_pwr*	
Engine speed	*fc_spd_est*	
Vehicle speed	*mpha*	
Transmission loss (as heat)	*gb_loss_fm*	not a standard variable in ADVISOR
Torque converter loss (as heat)		(*htc_trq_in_a* * *htc_spd_in_a*) - (*htc_trq_out_a* * *htc_spd_out_a*)
Ambient temperature	*amb_tmp*	

The following data is sent from *FLOWMASTER2* to ADVISOR:

Description	ADVISOR Variable	Notes
Engine cylinder wall temperature	fc_tmp(1)	
Coolant temperature at engine exit	fc_clt_tmp & fc_tmp(2)	used for fuel economy and emissions calculations
Underhood air temperature	fc_tmp(3)	used in exhaust system heat transfer
Hood temperature	fc_tmp(4)	
Oil sump temperature	fc_oil_tmp	could be used for fuel economy and emissions calculations
ATF sump temperature	gb_atf_tmp	could be used in *htc* and *gb* loss prediction
Radiator heat rejection	fc_r_th_pwr	
Cabin heater heat rejection	fc_h_th_pwr	

The combined model was then run over the Federal Urban Driving Schedule (FUDS) drive cycle. This drive cycle lasts 1372 seconds and is equivalent to the first two bags of FTP-75.



METHOD

For the integration of the detailed *FLOWMASTER2* vehicle thermal systems model and the Simulink based ADVISOR vehicle systems model, *FLOWMASTER2* and Simulink were run together as a co-simulation. The ADVISOR GUI was used and Simulink controlled the simulation. *FLOWMASTER2* was called from an S-function in the Simulink model.

During the initialization of ADVISOR's conventional vehicle model, *FLOWMASTER2* is started and the appropriate model is loaded and initialized. *FLOWMASTER2* then continues to run in the background throughout the co-simulation. At each ADVISOR time step, updated values of the co-simulation variables are sent to *FLOWMASTER2*. The *FLOWMASTER2* simulation then runs until it is at the same time as ADVISOR. The variables are then read from *FLOWMASTER2* into ADVISOR. ADVISOR runs with a fixed one second timestep. The *FLOWMASTER2* model was run at a 0.25 second timestep, but can be run at any timestep.

The Simulink model behind ADVISOR, *bd_convat,* was modified to call *FLOWMASTER2*. The *bd_convat/fuel converter <fc>/fuel use and EO emis/fc_tmp* sub system contains the *FLOWMASTER2* link S-Function. All variables which are not standard inputs to this sub system are made available with Goto functions and read in with From functions. All of the outputs are standard outputs for this sub system.

No changes have been made to the ADVISOR GUI, therefore certain parameters must be set up in the S-function prior to running the model, namely *FLOWMASTER2* database and project directories, along with project and network names.

RESULTS

Results were generated with the ADVISOR-*FLOWMASTER2* co-simulation and with ADVISOR alone, using the same inputs. The results that were examined are for radiator heat rejection, emissions, engine temperatures, and fuel economy. For the co-simulation case, the radiator heat rejection and engine temperatures are calculated in *FLOWMASTER2* and then sent to ADVISOR. Emissions and fuel economy are calculated in ADVISOR, but are dependent on the results from *FLOWMASTER2*. The simulations were run for both hot and cold start cases. Figures 4 and 5 show the results for the ADVISOR and co-simulation runs, from a cold start.

The results were also compared to the emissions certification information for the 1991 Dodge Caravan from the EPA. The emissions results for the hot and cold start cases were combined according to the weighted average used by the EPA in 1991, 43% of cold start results and 57% of hot start results.

A comparison of the coolant temperature and heat rejection at the radiator for the four cases are shown in figures 6 and 7.

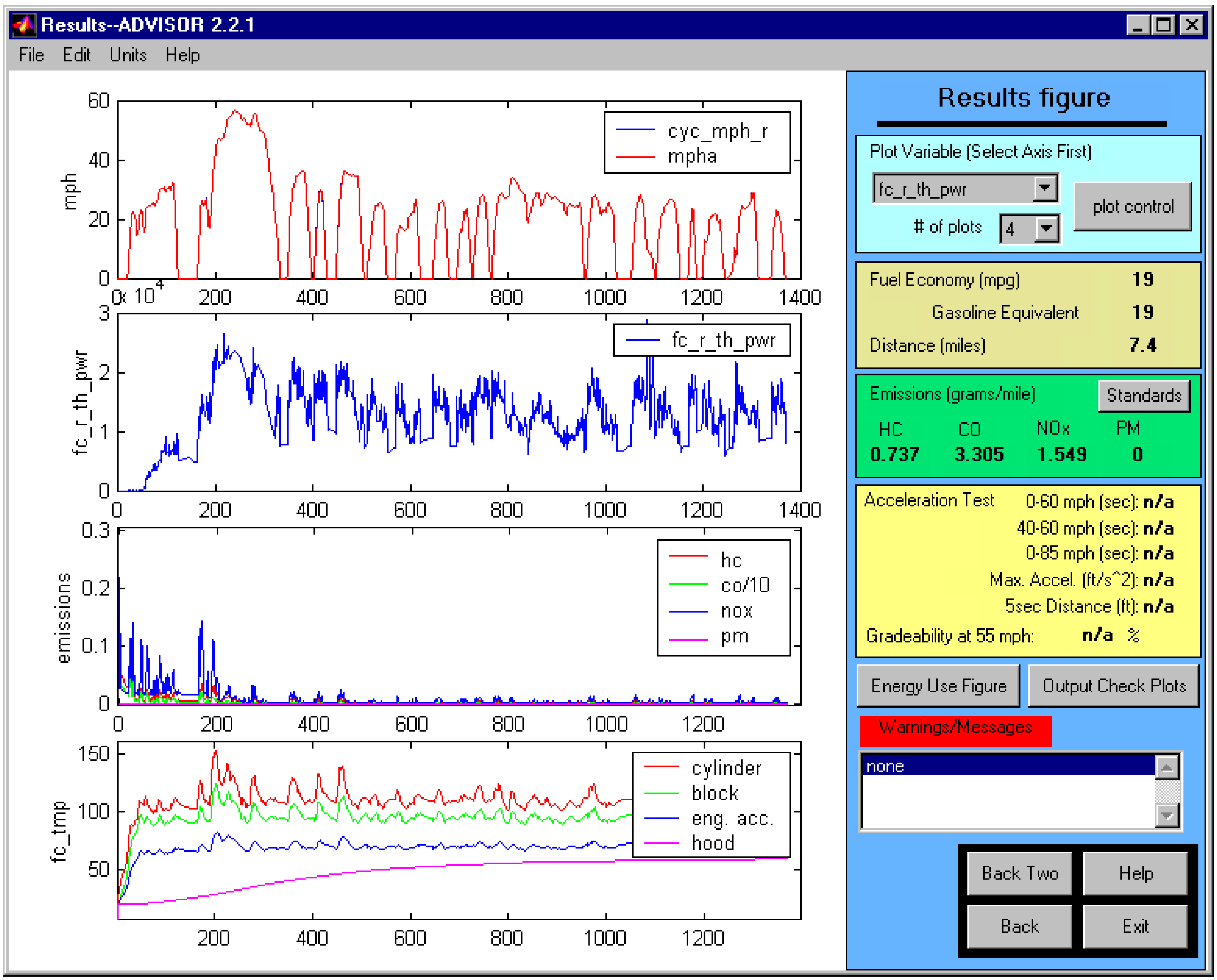


Figure 4: Co-Simulation Results (Cold Start)

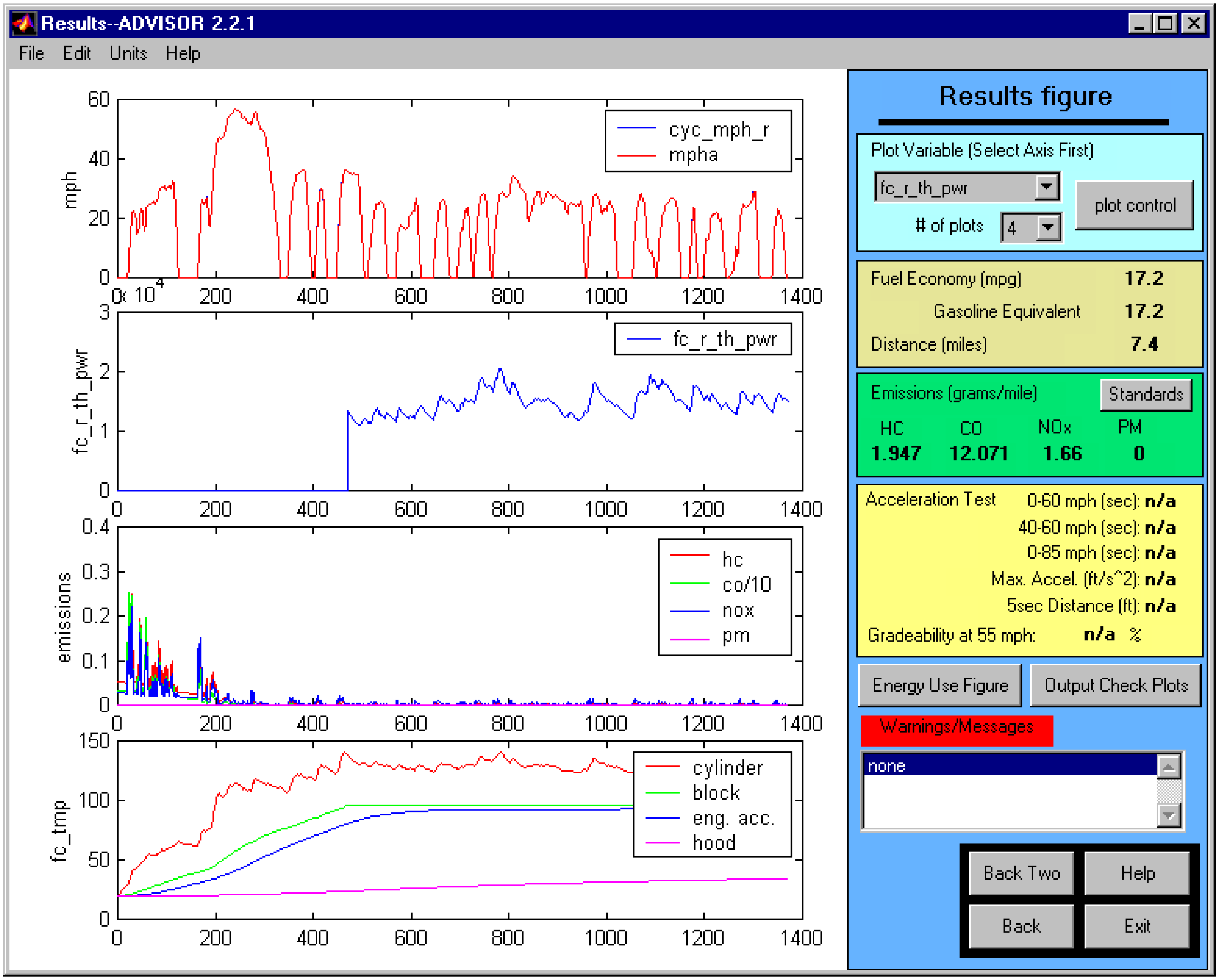


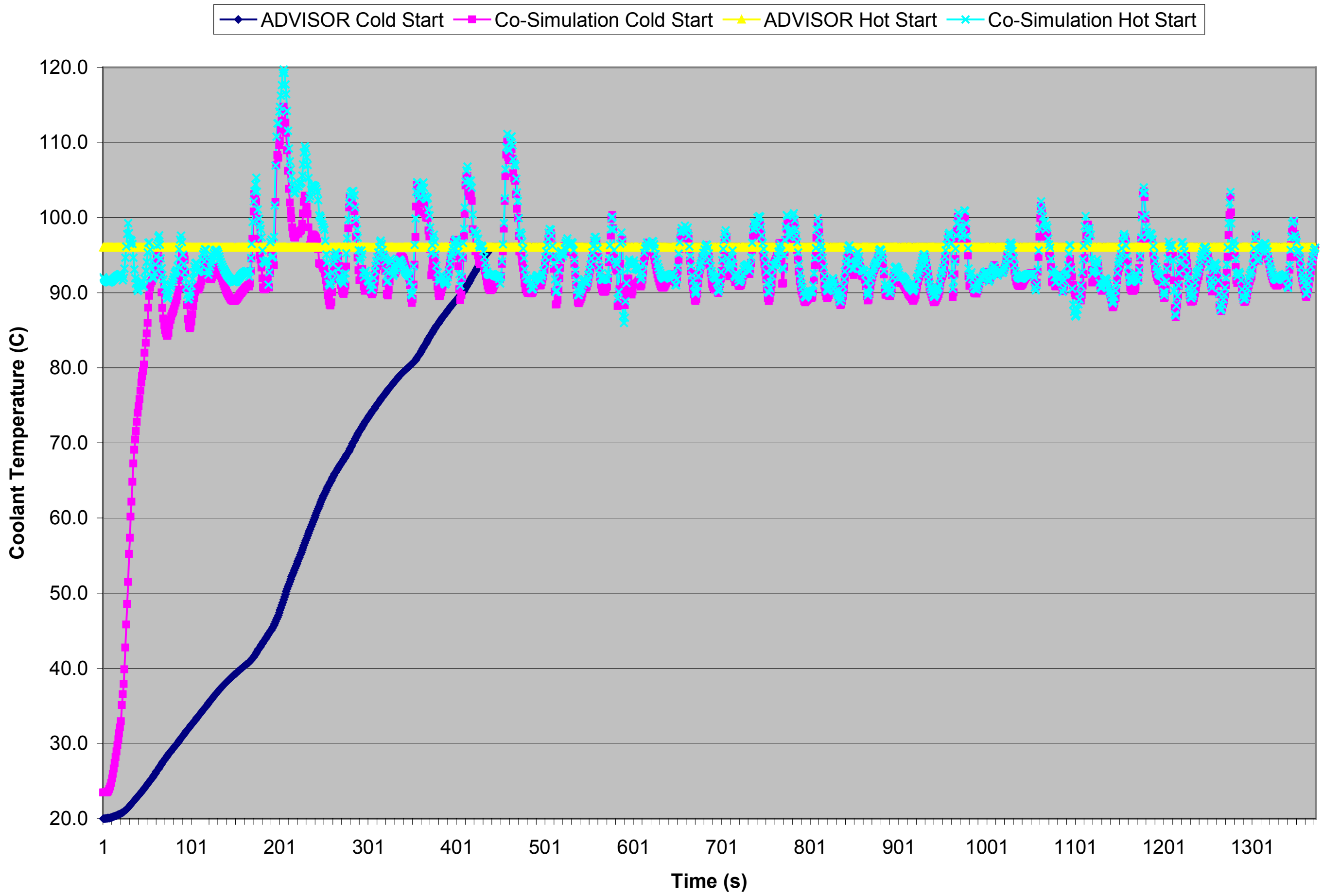
Figure 5: Advisor Simulation Results (Cold Start)

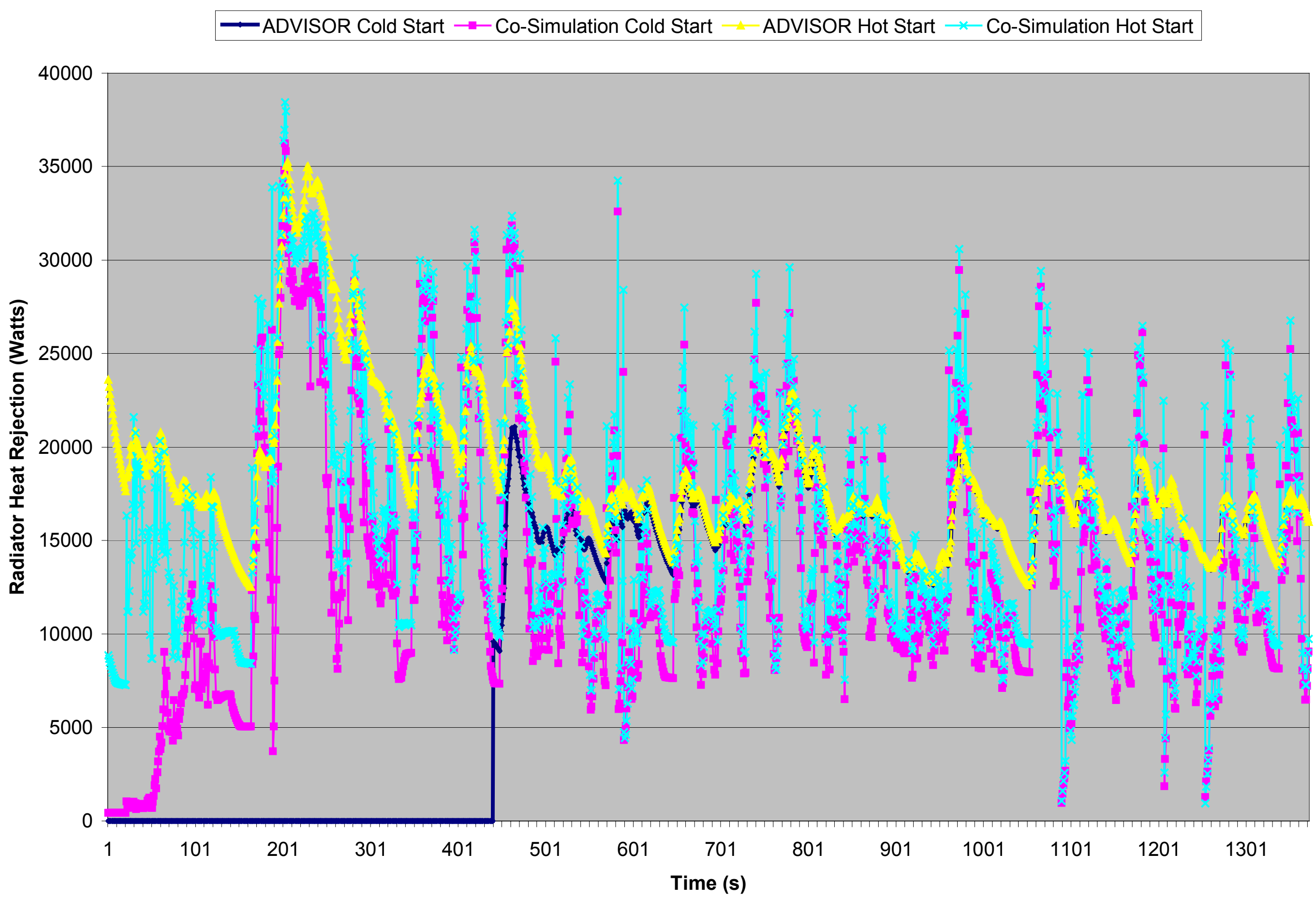
Exhaust Emissions (grams/mile)				
	Cold	Hot	Weighted Average	% Error
Advisor				
CO	12.63	0.728	5.846	244%
NOx	1.785	0.738	1.188	116%
HC	1.981	0.328	1.039	352%
FLOWMASTER2 / ADVISOR Co-Simulation				
CO	3.88	0.729	2.084	23%
NOx	1.63	0.738	1.122	104%
HC	0.807	0.329	0.535	133%
EPA Test				
CO			1.7	
NOx			0.55	
HC			0.23	

CONCLUSION

Differences in the vehicle thermal models can be seen to have an effect on the fuel economy and emissions of the vehicle. The significant difference in the warm-up time for the engine is the major reason for this. This is understood to be highly dependent on the thermal inertia of the thermal system, especially the volume of coolant and the mass of the solids directly heated by the cooling system. Design and operation of the thermostat will also effect the performance of the thermal system.

For the hot start simulations, the emissions are seen to be almost identical between the two cases. This is as expected, because as long as the thermal system can maintain a steady operating temperature, the emissions of a known powertrain will not be effected by its design. Small fluctuations in the coolant temperature, due to the lower system thermal inertia and detailed modeling of heat rejection, do not appear to have a noticeable impact of the modeling of emissions. This detailed modeling is valuable in that the simulation shows temperatures above normal design maximums for cooling systems.





Figures 6 & 7: Comparison between ADVISOR and *FLOWMASTER2* co-simulation results

However the emissions predicted are significantly higher than those reported by the EPA for the vehicle. This difference must be due to the input data used in the simulation for the engines emissions.

The effect on vehicle fuel economy and emissions due to the thermal system has been shown to be significant. The use of simulation in the design of a vehicle that includes accurate thermal system modeling will allow for optimization of the thermal system for fuel economy and emissions, not only to meet cooling and heating requirements.

The ability to add a detailed *FLOWMASTER2* vehicle thermal systems model to ADVISOR increases the flexibilty and accuracy of the complete vehicle and drive cycle simulation.

ACKNOWLEDGMENTS

We would like to thank Brian McKay of Ricardo Inc. for his work on the Simulink S-Function.

CONTACT

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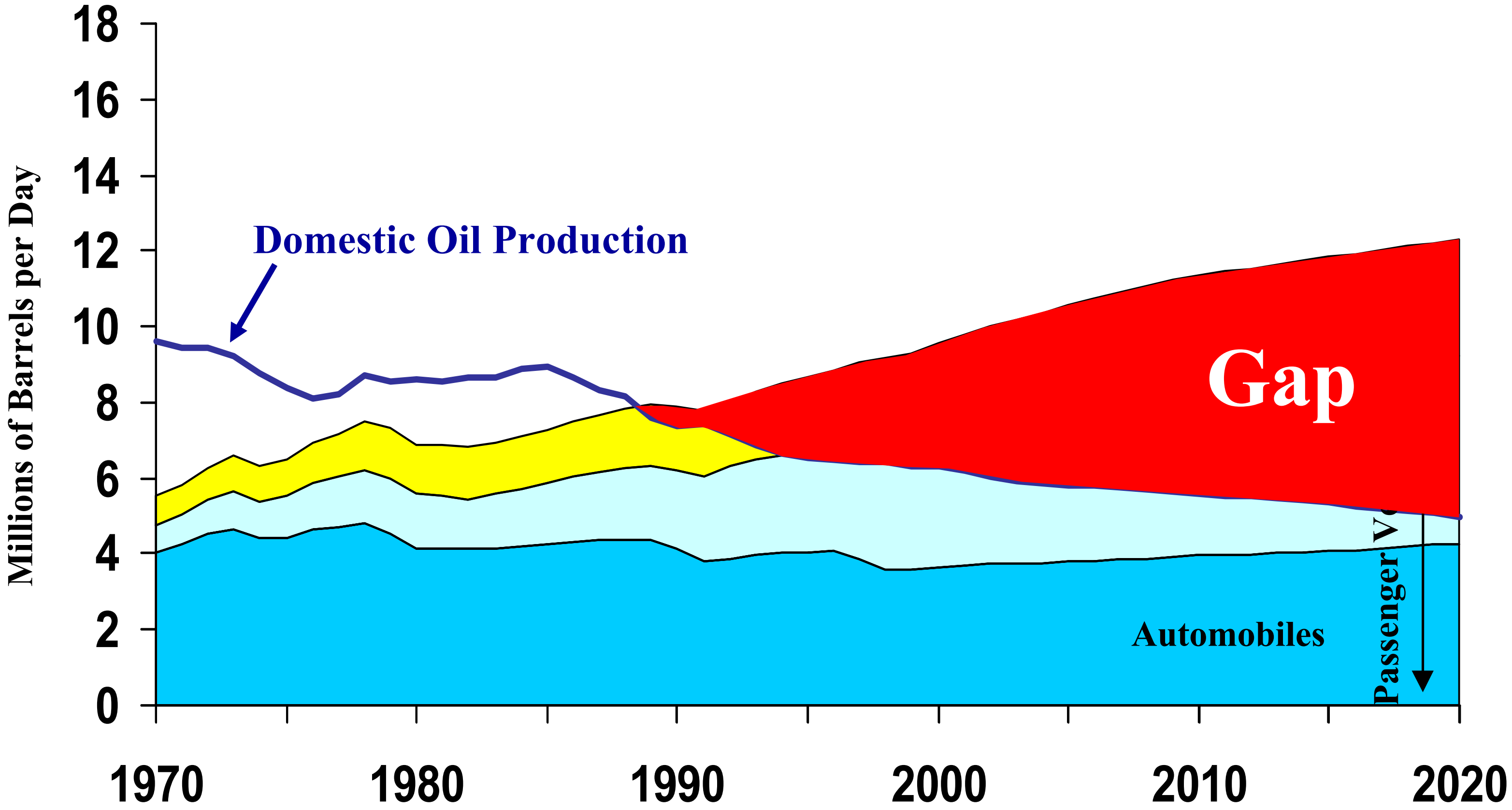
[1] Interfacing of 1D and 3D Fluid Dynamics Programs for the Simulation of a Diesel Engine Cooling System, Keith Austin, Development Manager, Flowmaster International Ltd
[2] www.ctts.nrel.gov/analysis/advisor.html
[3] www.mathworks.com/products/simulink

ADVISOR Users Conference

Bob Kost
Vehicle Systems Team Leader
Office of Advanced Automotive Technologies
Office of Transportation Technologies
U. S. Department of Energy

Double Tree Hotel
Costa Mesa, California
August 24 - 25, 2000

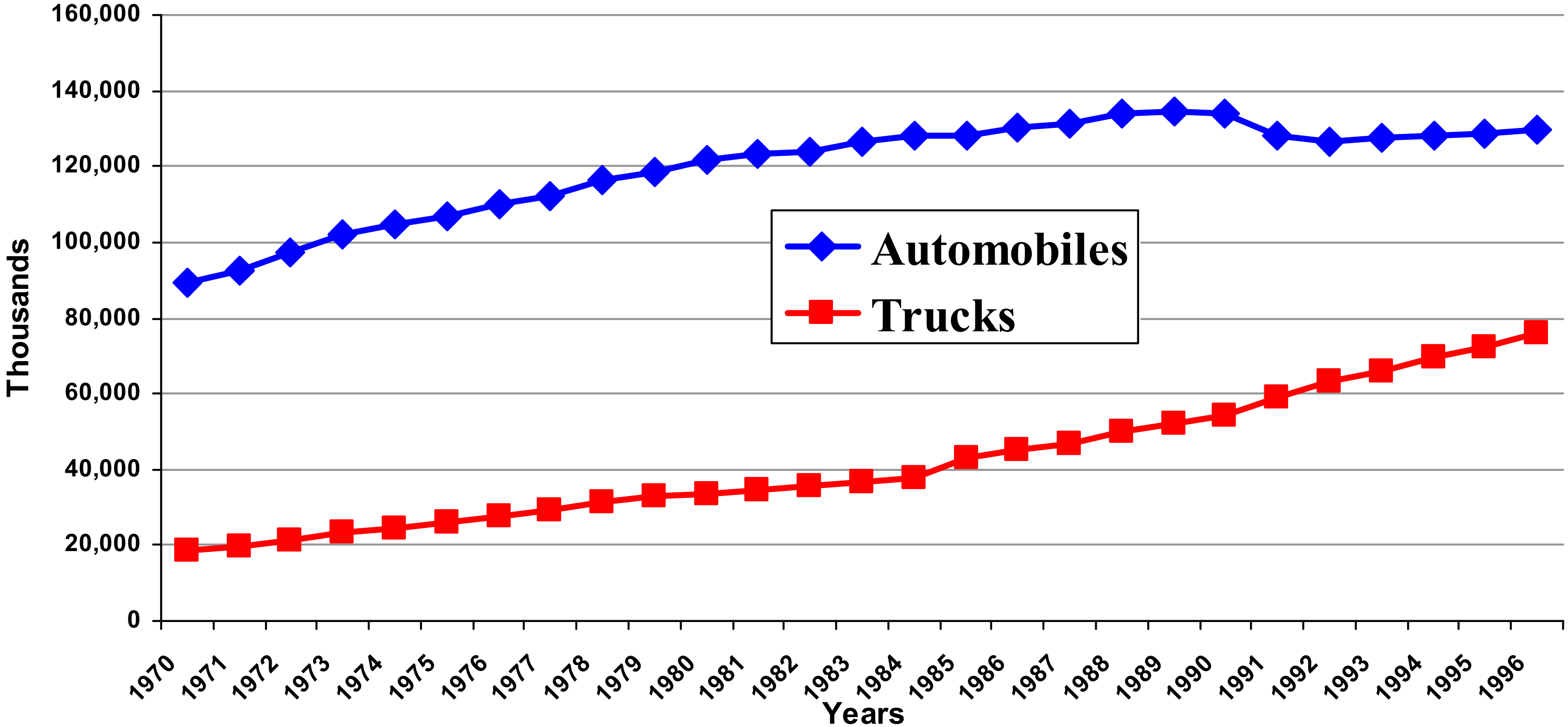
U.S. Highway Transportation Now Uses More Oil Than Is Produced Domestically



Source: Transportation Energy Data Book: Edition 18, DOE/ORNL-6941, September 1998, and EIA Annual Energy Outlook 1999, DOE/EIA-0383(99), December 1998

Dramatic Increases in the use of Trucks in the U.S.

Vehicle Systems

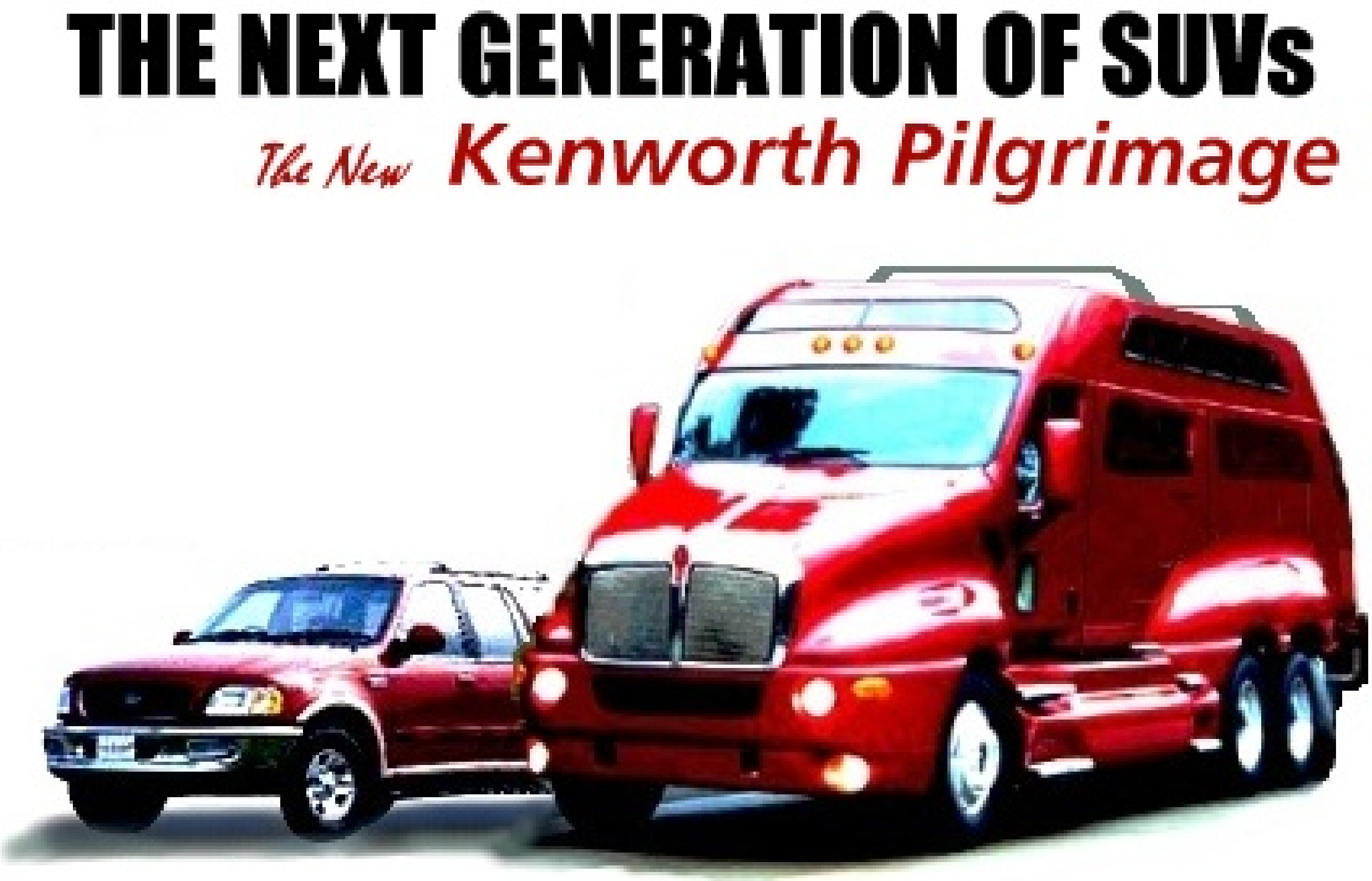


Source: Stacy C. Davis, Transportation Energy Data Book, Edition 18, Sept. 1998, ORNL-6941

Note: FHWA data were used. Starting in 1993, some minivans and sport utility vehicles that were previously included with automobiles were included with trucks.

Future SUV?

Vehicle Systems

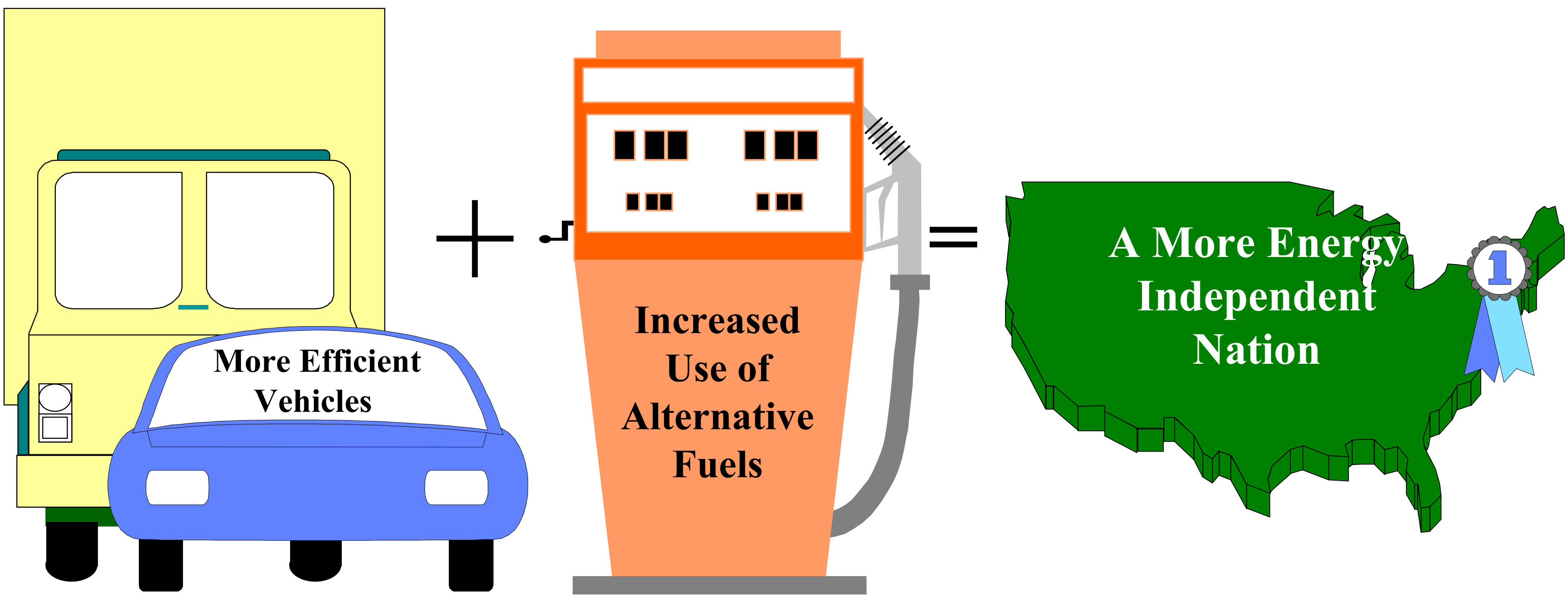


Source: MH Designs, “The Future SUV”, The New SUV Standard, <http://www.poseur.4x4.org/futuresuv.html>, (May 10, 1999)

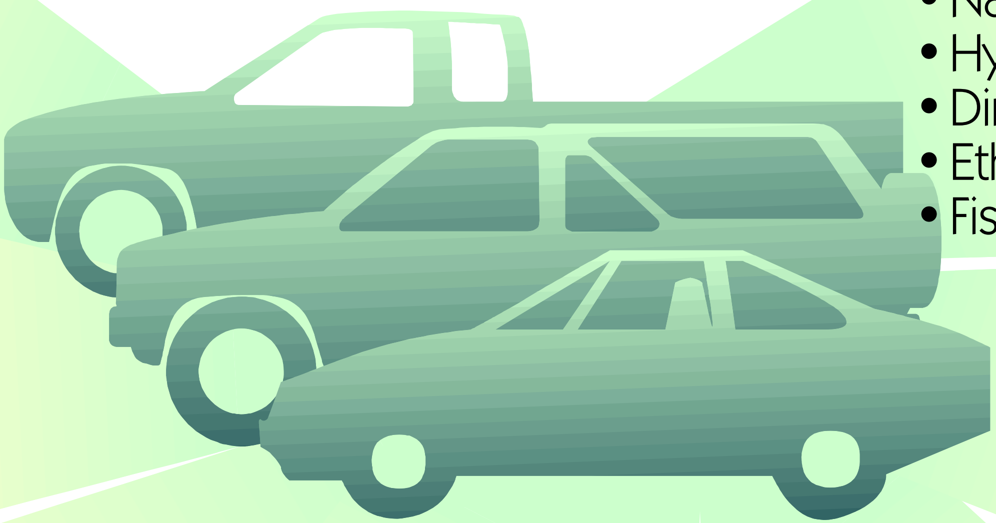
Office of Transportation Technology Objective

Vehicle Systems

- Improve fuel efficiency
  - Autos
  - Light trucks & SUVs



OTT/OAAT Is Pursuing Broad Range of Advanced Technologies



Energy Conversion

- CIDI
- Fuel Cell
- SIDI
- VCR

Fuels

- Gasoline/ Diesel
- Natural Gas
- Hydrogen
- Dimethyl Ether
- Ethanol
- Fischer-Tropsch Fuels

Energy Management

- Batteries
- Flywheels
- Ultracapacitors

Advanced Materials

- Metals
- Composites
- Ceramics

Power Electronics

- Inverters
- Motors
- Generators

Powertrain Configuration

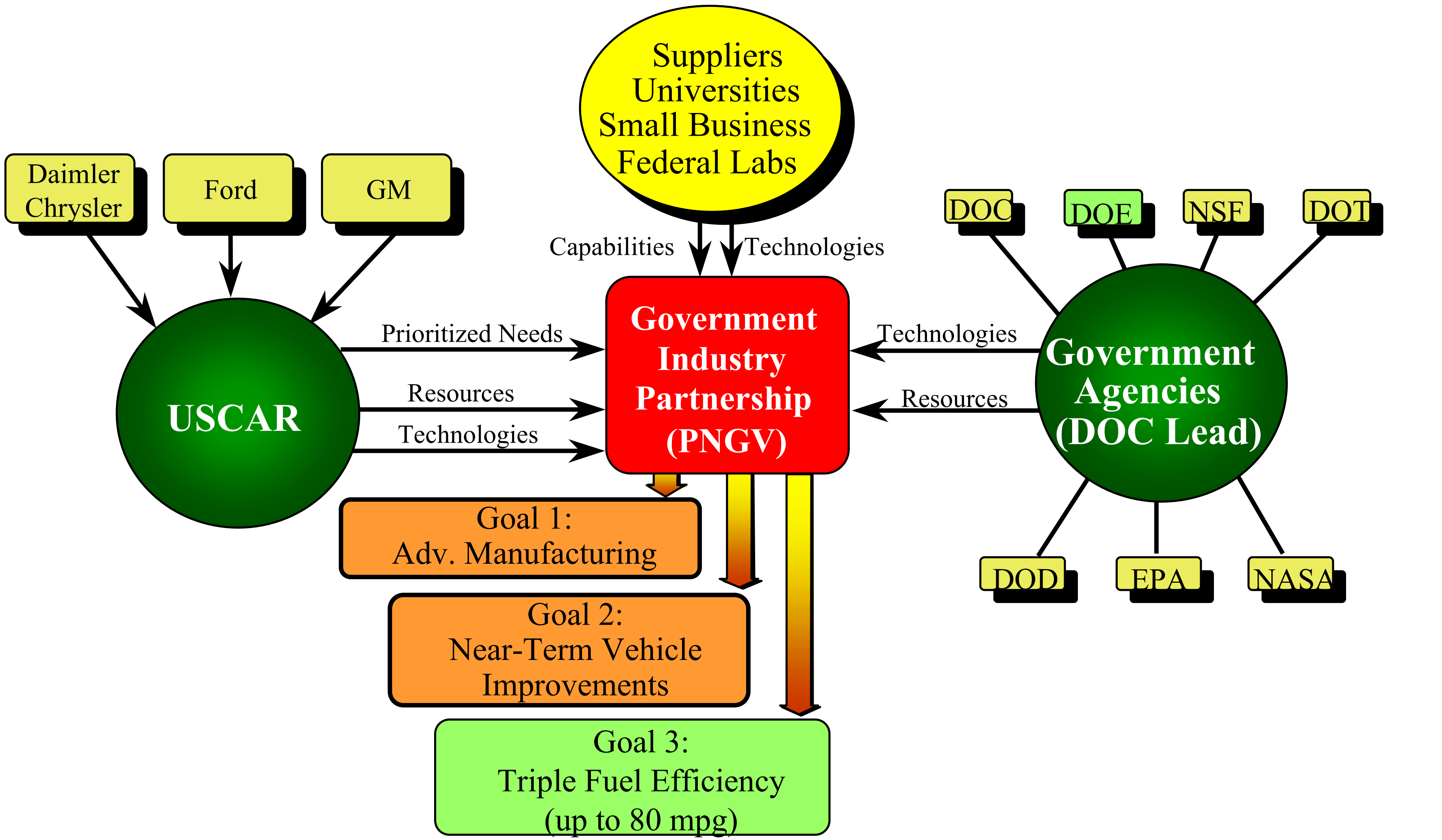
- Parallel Hybrid
- Series Hybrid
- Electric Vehicle
- Conventional

Other Attributes

- Accessory Loads

Government/Industry Working Together Under PNGV

Vehicle Systems



OAAT R&D Plan: Strategy
"Systems Driven - Barrier Focused"

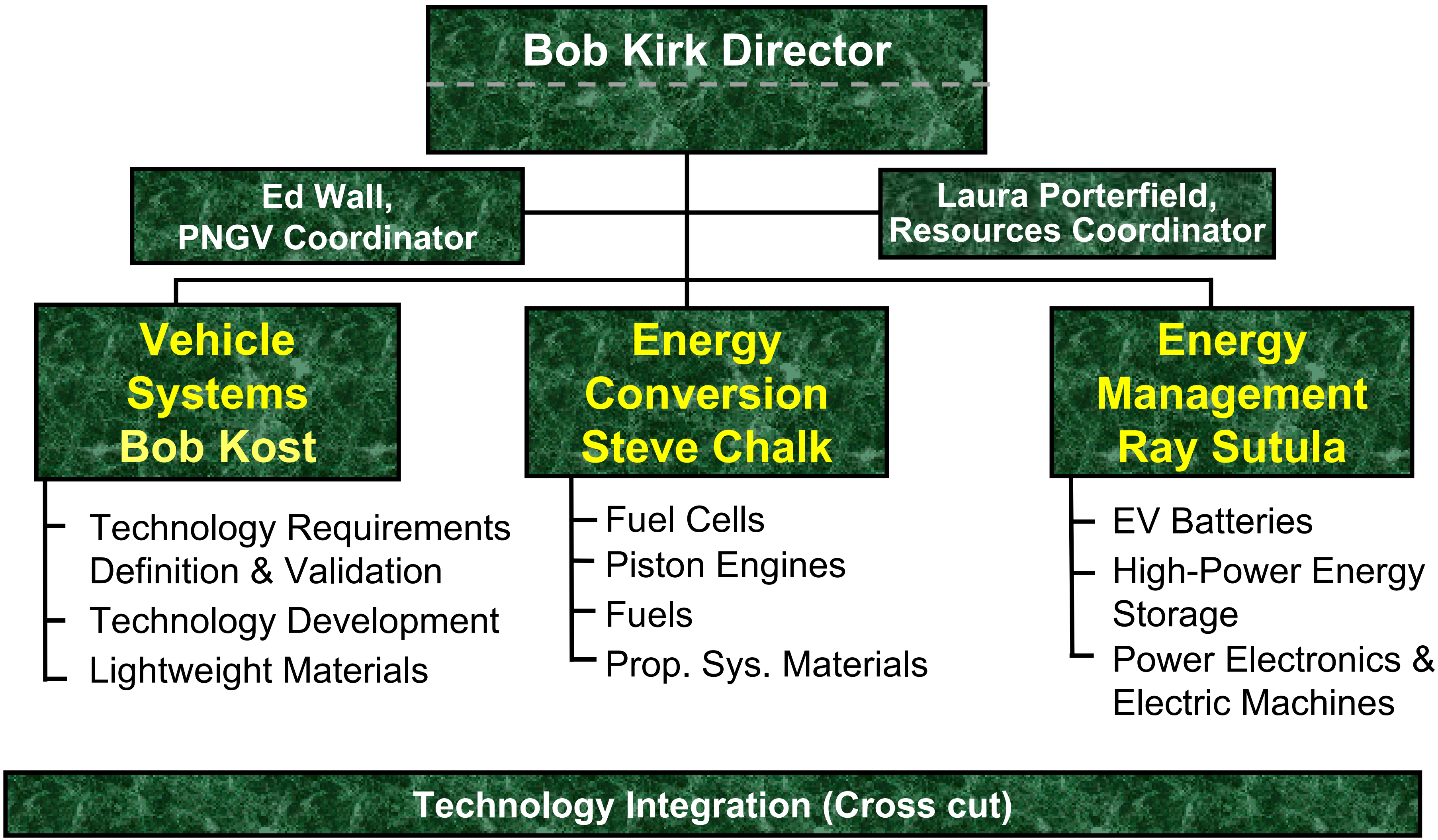
Vehicle Systems Driven*	❑ Derive all technical targets from a Common Vehicle System Perspective ❑ Culminate efforts with technology validation at the Vehicle System Level
Barrier-Focused	❑ Concentrate available funding on the most critical technical barriers to successful technology development (*Most "Bang for The Buck"*)

***R&D Constraints**

- Emissions Control Regulations (projected to be in place when technology is available for the marketplace)
- Safety Standards
- Attributes of comparable, competitive vehicles (including cost)

Office of Advanced Automotive Technologies

Vehicle Systems



Vehicle Systems Technology Objectives

Vehicle Systems

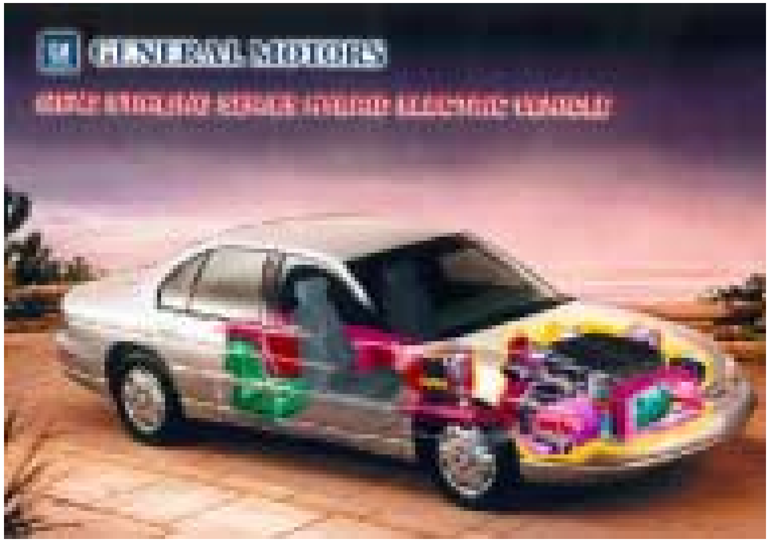
***Phase 1**:* By 1998, develop and validate production feasible propulsion subsystem technologies that will enable the achievement of 50 mpg in test-bed six passenger sedans that meet EPA Tier 2 emissions and retain all attributes and features of competitive automobiles

***Phase 2**:* By 2004, develop and validate propulsion subsystem technologies and validate OAAT developed technologies that will enable the achievement of 80 mpg in six passenger sedans etc.

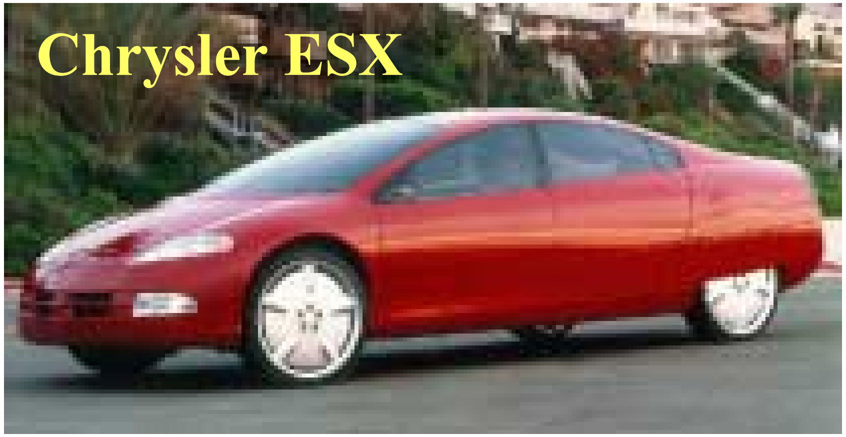
***Phase 3**:* By 2011, develop and validate production feasible vehicle system technologies that will enable achievement of 100 mpg in six-passenger sedans emphasizing non-petroleum fuels and zero emissions

Phase 1: *Serious Investment by Government & Industry*

$116M*



$151M*



$52.6M*

* 50/50 cost share

Methodology for Managing Vehicle Systems Consists of Three Integrated Activities

Systems Modeling & Analysis

- Guide/Prioritize Future R&D
- Sets Requirements & Targets
- Predicts Performance (F.E. Emissions, Transient, etc.)
- Control Strategy Development
- Component & Subsystem Model Development
- Test Procedure Development
- Vehicle Models (SUV, Lt Truck, HD, Auto)
- Optimization Techniques
- Evaluate new Concepts
- Parametric Studies
- Cost/Benefit Analysis

Digital Vehicle

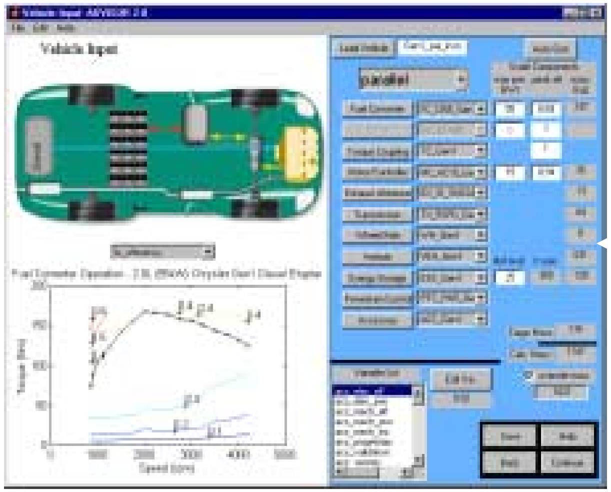
- Allows rapid layout to view problems and opportunities
- Helps OEM suppliers to become better prepared for system level designs
- Fewer design iterations & faster convergence on solution
- Ties together many different component projects in systems context for minimum energy and emissions
- Gives 1st Order Vehicle Designs & "packageable" products

Hybrid Test Facility

- Model Validation
- Validation of Component & Subsystem Technologies
- Benchmark technologies & vehicles worldwide
- Component, Engine & Vehicle Characterizations
- Hardware-in-the-loop
- Controls Strategy Development for improved efficiency & lower emissions
- Integration Tech. Development
- Test Procedure Development

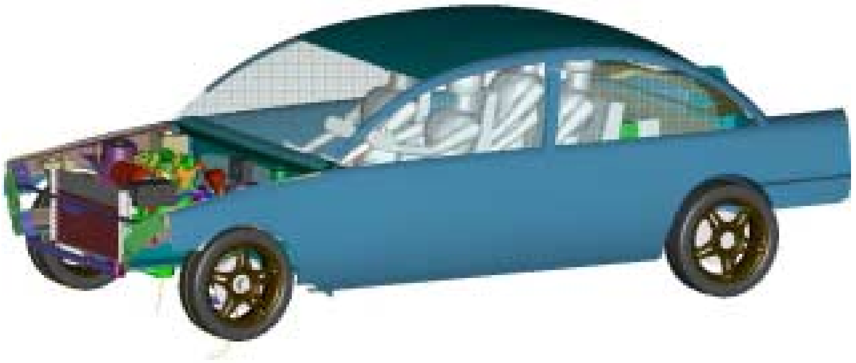
Advisor & Digital Functional Vehicle Linkage

ADVISOR



Vehicle Performance
Optimization
Cycle Analysis
Fuel Economy
Emissions

Digital Functional Vehicle

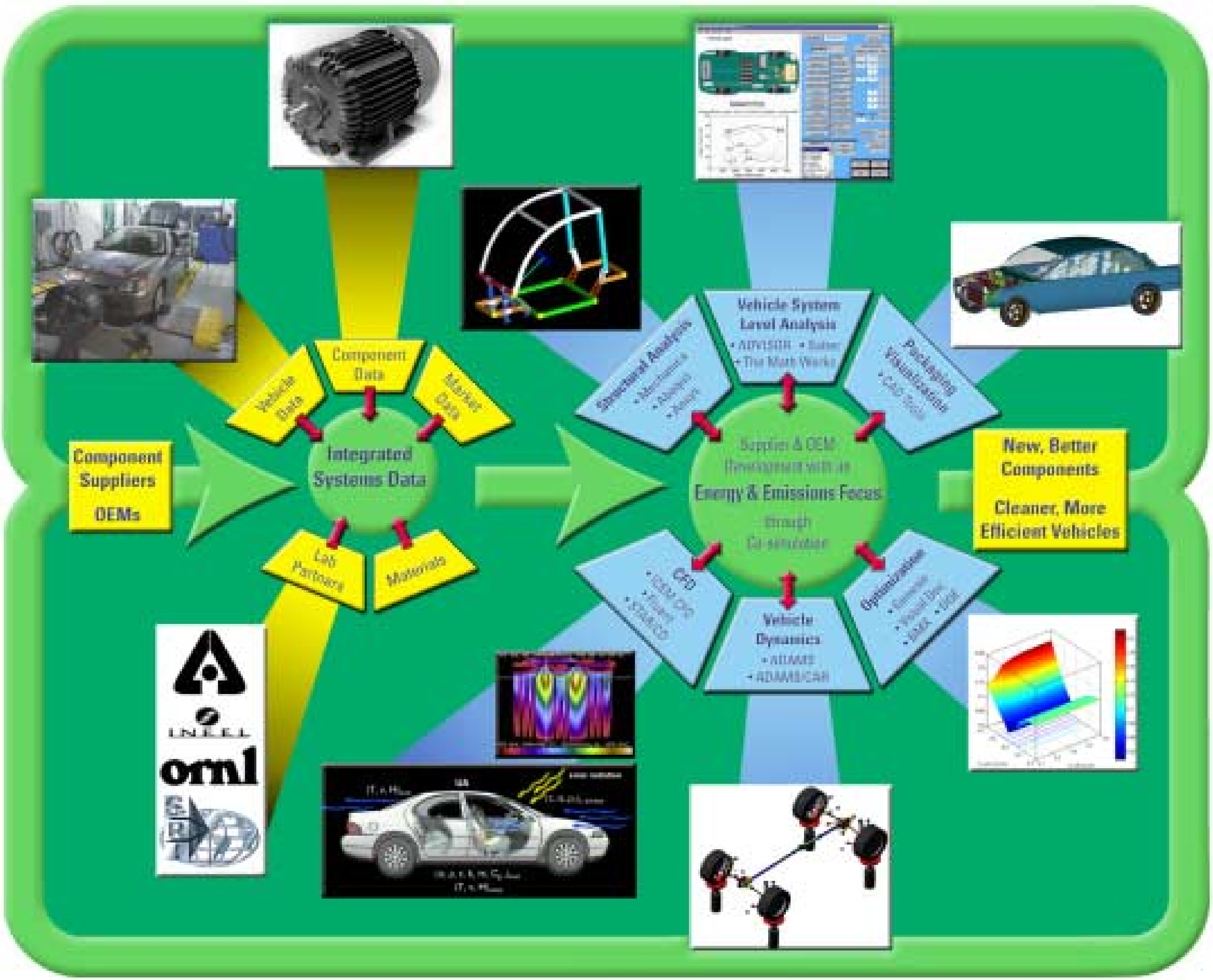


- Integrates Data from Many Different Analysis/Design Software
- Allows Thermal Effects Studies
- Passenger Comfort with min energy
- Makes Energy Optimization Integral to Vehicle Development
- Ties all phases of vehicle development to a common model/process

Migrating Toward Digital Functional Vehicle: Ultimate Goal

- Lower cost than building hardware -- more effective use of taxpayer money
- Allows trade-offs to be done earlier in design process
- Useful for setting future R&D directions
- Allows system level optimization with a focus on energy and emissions

Digital Functional Vehicle Process Highlights
Energy/Emissions Impacts



Results from DOE's Transportation R&D Are Displayed at International Auto Shows

Vehicle Systems

2000 Washington DC

Dodge ESX3
- Body system weighs 46% less*
- Efficient diesel engine, motor and battery achieve 72 mpg*
- Cost penalty halved to $7500

2000 Detroit Auto Show

Ford Prodigy Concept Vehicle
- Lightweight materials reduce vehicle weight 30% *
- Integrated starter/alternator *
- 33% reduction in aerodynamic drag
- Advanced diesel engine with 35% efficiency improvement *
- High power battery *

2000 Detroit Auto Show

GM Precept Concept Vehicle
- Vehicle mass reduced 45% *
- Eliminates need for power steering
- Lowest drag coefficient ever recorded for a 5-p sedan
- Fuel cell version achieved 108 mpg *

*DOE supported technologies

Future Challenges

- Continue to Develop Tools and Processes for Systems Integration and Optimization

- Provide Web Based Tools for Automotive Suppliers

- Develop Climate Control and Thermal Models

- Develop Engine Emission and After-treatment Control Models

- Develop System Cost Benefit Analysis Tools

ADVISOR

Forward-Looking Simulations Coupled With ADVISOR

Simulation and Validation of Hybrid Electric Vehicles using PSAT and PSAT-PRO

Presentation

Paper

Aymeric Rousseau and Maxime Pasquier, Argonne National Laboratory

The Reverse Engineering of a Diesel Engine: A Unified Systems Approach Using ADVISOR

Presentation

Paper

George Delagrammatikas and Dennis Assanis, University of Michigan

Using Forward Modeling of Hybrid Electric Vehicles with PSAT and PSAT-PRO

Maxime Pasquier (mpasquier@anl.gov),
Aymeric Rousseau (arousseau@anl.gov),

ADVISOR Conference, Costa Mesa, CA, August 24-25

DOE Supports Two Systems Models

ADVISOR

- Well-developed, powerful GUI, quick run-time
- Backward model

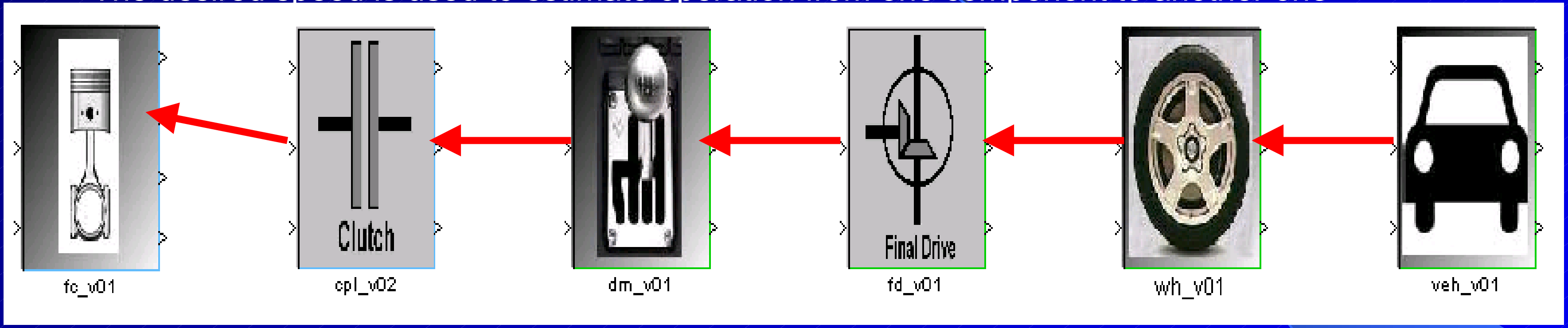
PSAT

- Control-oriented, transients, many configurations
- Forward model

Differences Between Backward-Looking and Forward-Looking Models

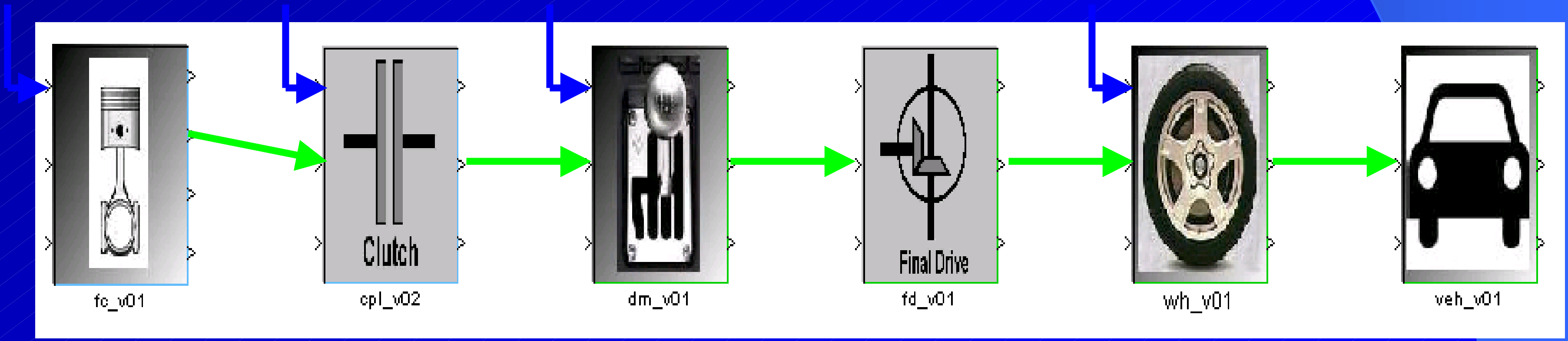
Backward looking model: Operation comes from cycle, components are not controlled

The desired speed is used to estimate operation from one component to another one



Forward looking model: Modeling with commands

Commands from a Powertrain Controller obtain the desired vehicle speed



Forward-Looking Model Capabilities

- Model and test:
  - Detailed powertrain component models,
  - Control strategies can be tested using real components and implemented in a vehicle micro-controller.
- Model the powertrain's transient phases (engine starting, shifting, clutch engagement / disengagement…)

⇒ Because the modeled components behave as in reality, we have
1) A higher precision of the simulation results
2) The possibility to test and validate the models on the test stand using prototyping

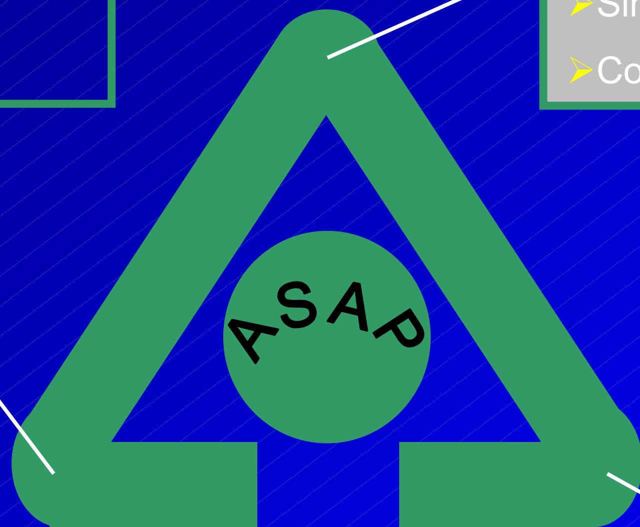
ANL's Systems Analysis Program

MODELING (PSAT):

- Choose the appropriate powertrain
- Choose component size
- Develop the best strategy

PROTOTYPING (PSAT-PRO):

- Integrate the strategy in a VCU
- Simulate in RT the test procedures
- Control the actual vehicle



TESTING (APTF):

- Perform the simulated tests
- Test and map components
- Test hybrid vehicles

What is PNGV System Analysis Toolkit (PSAT)?

A powerful modeling tool that allows the user to realistically simulate:

- Fuel consumption and exhaust emissions (eg. Federal Test Procedure, highway, all other cycles)
- Performance (eg. 0-30mph, 0-60 mph, 40-60 mph, distance in 5 sec., maximum launch grade, maximum continuous speed, 55mph at 6% grade)

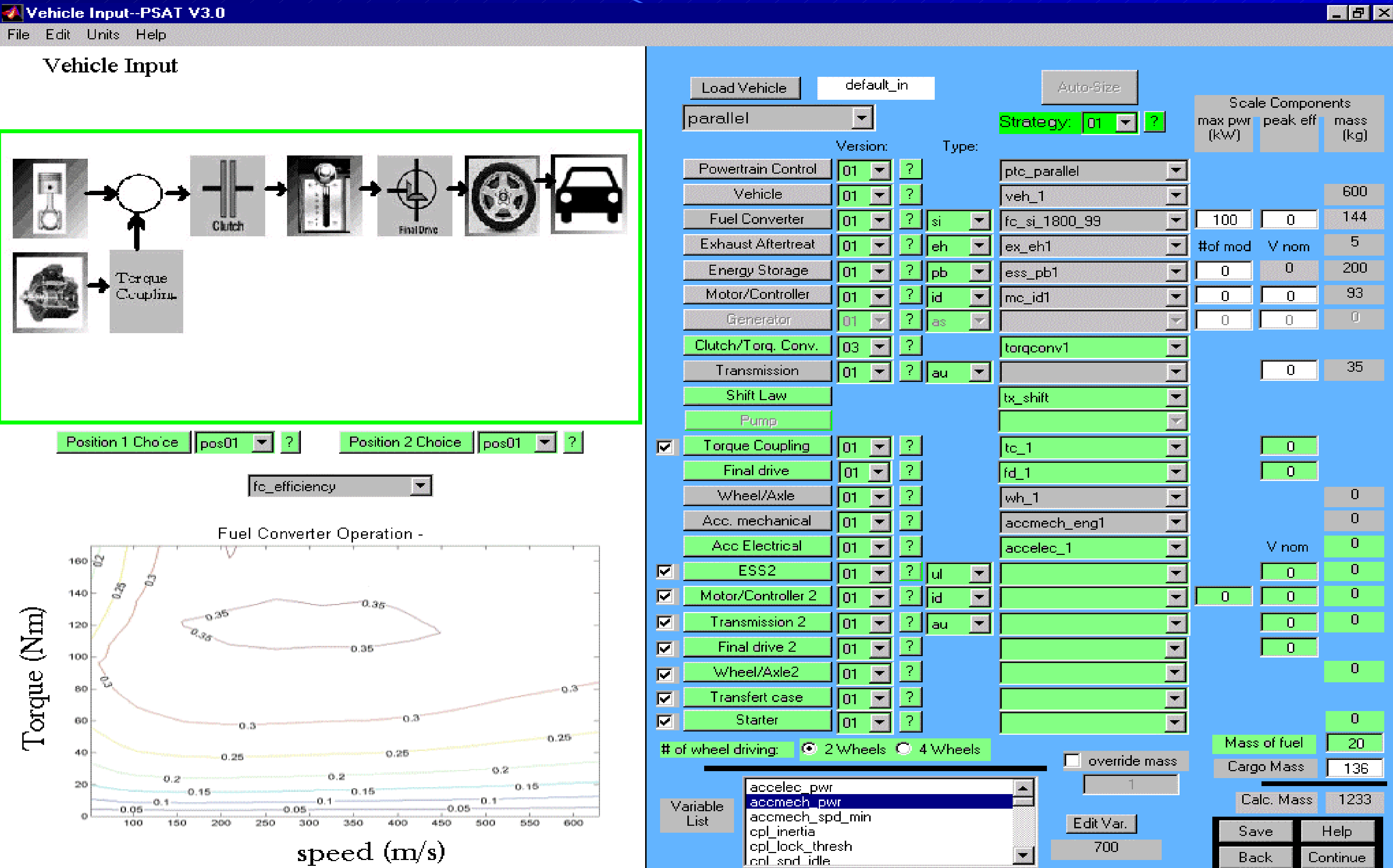
PSAT History

- First developed by Southwest Research Institute (SwRI) from 1995 to early 1999
- Program transferred to ANL in September 1999
- First funded by USCAR and now by DOE
- Developed under the direction and with the contributions of Ford, GM and DaimlerChrysler

Common GUI Development

- DOE's goal for PSAT and ADVISOR to share common GUI
- Since potential users are familiar with ADVISOR GUI, common GUI will operate like current ADVISOR GUI
- PSAT-specific functionality has been added to current ADVISOR GUI

Common GUI Integration



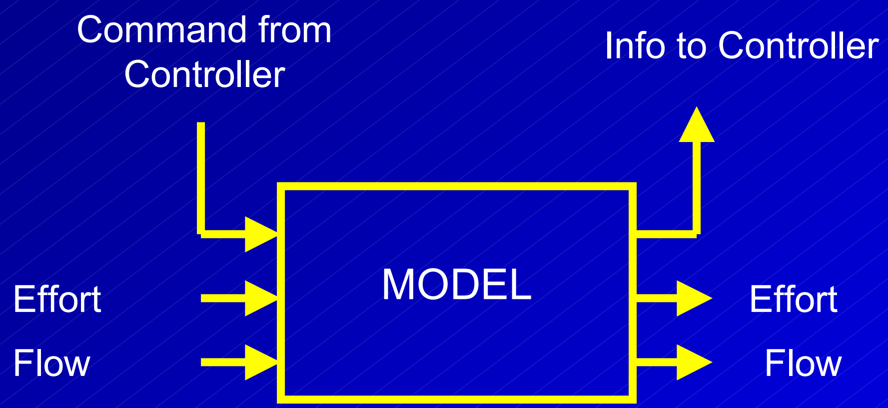
PSAT Currently Includes Many Configurations

- Large number of drivetrain configurations:
  - 3 conventional vehicles
  - 48 parallel hybrids
  - 24 series hybrids
  - 24 fuel cell hybrids
  - 1 power split hybrid (Prius-like)

➡ A wide variety of configurations is needed because we still don't know which one is the best for specific applications !!

PSAT V3.0 Has Modular Component Models

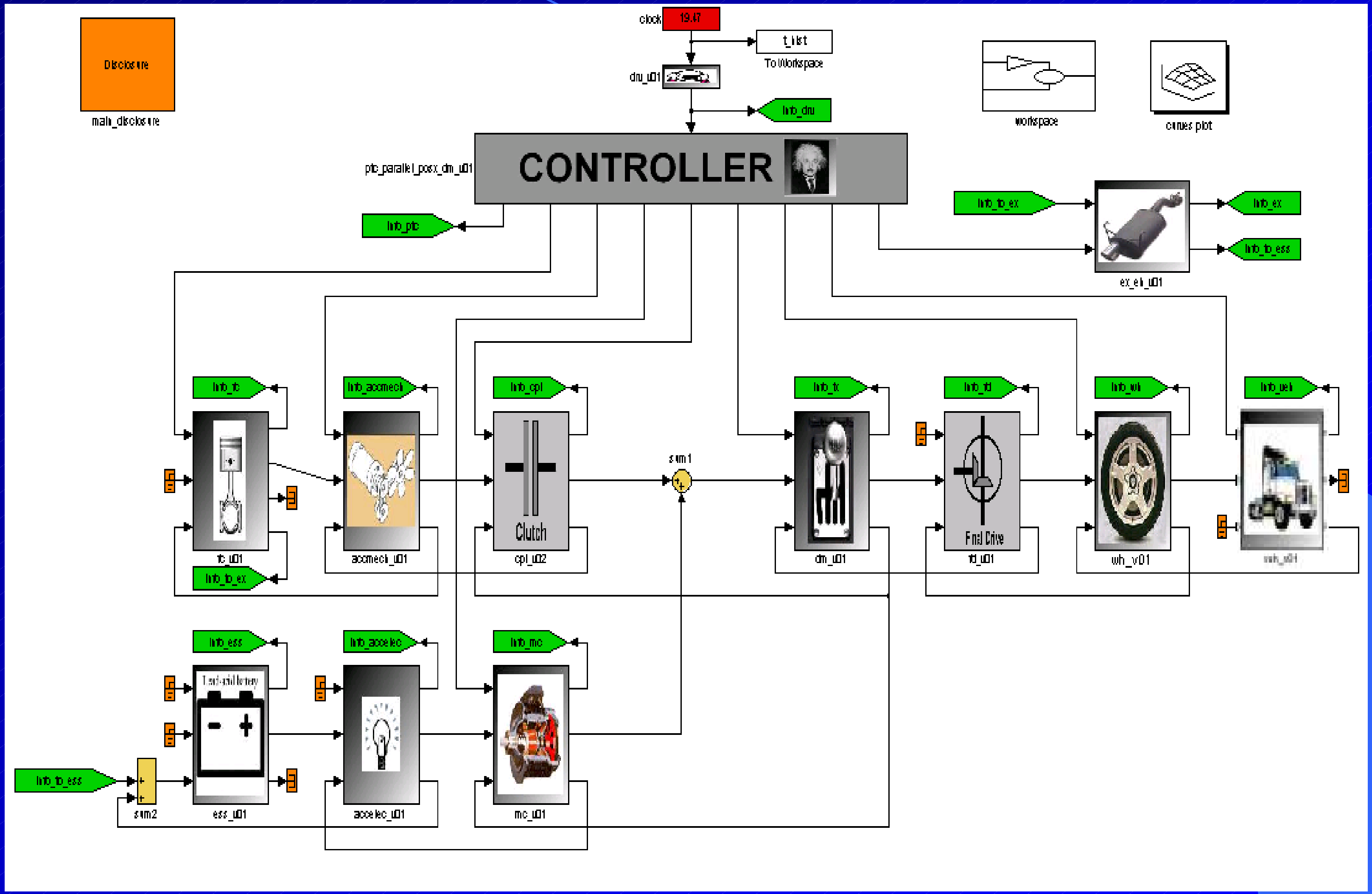
ANL - PSAT V3.0
nomenclature



Effort = Torque or Voltage
Flow = Speed or Current

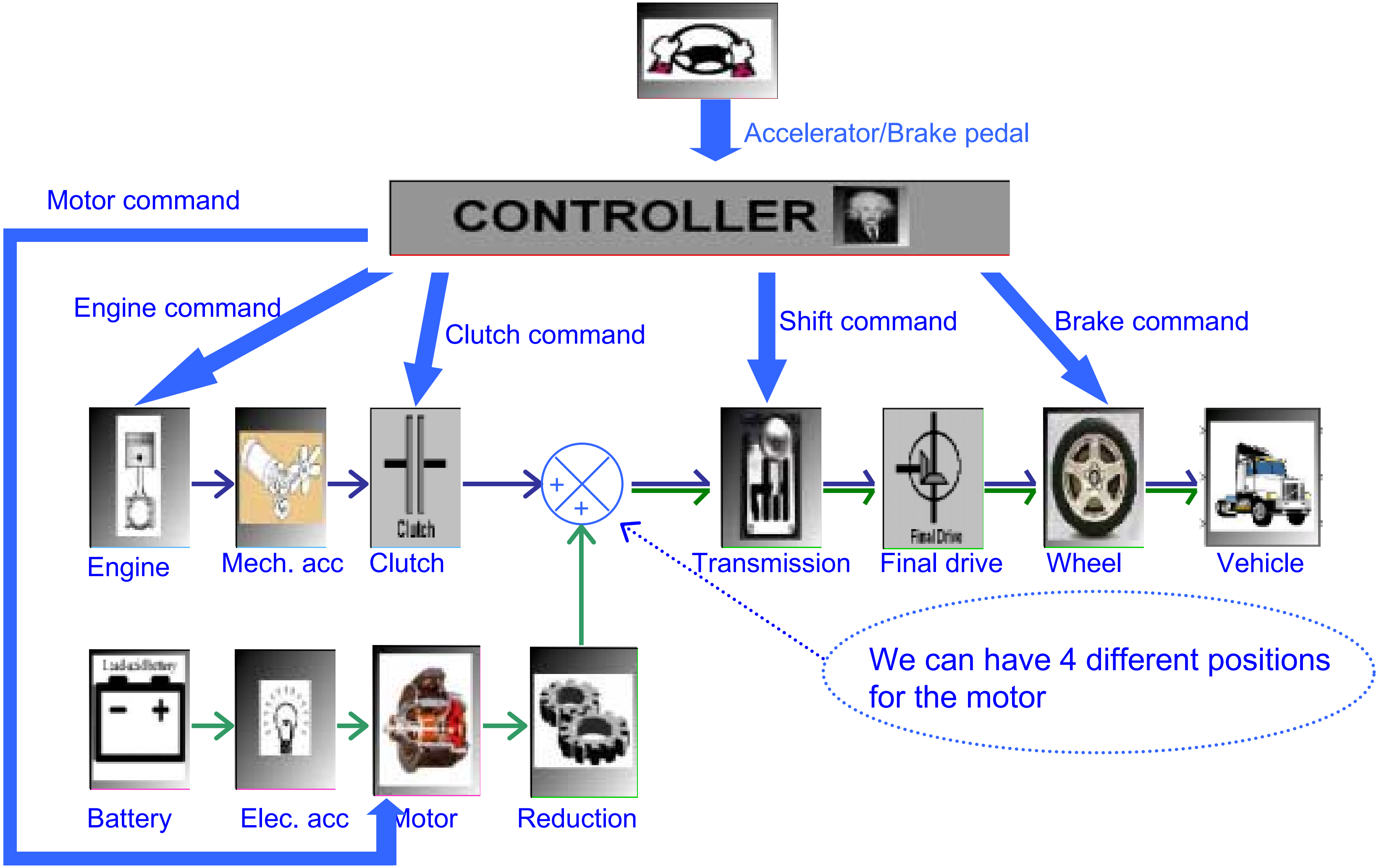
- All models follow Bond Graph principle
- All models have consistent input/output nomenclature
- Component models are plug-and-play
- Block diagram code representation for simple visualization

Parallel HEV SIMULINK Diagram in PSAT V3.0



Argonne National Laboratory
Transportation Technology R&D Center

PSAT V3.0 Flows Intuitively



PSAT Main Capabilities Summary

- Due to forward-looking philosophy:
  - Model reality with real commands,
  - Test advanced component models and control strategies,
  - Take into account transient phases.
- Due to ANL's work:
  - Each drivetrain is built according to the user choices
  - Large number of drivetrain configurations,
  - Easy integration of new models, data or control strategies,
  - Better organization allowing us to facilitate the link with the Prototyping phase.

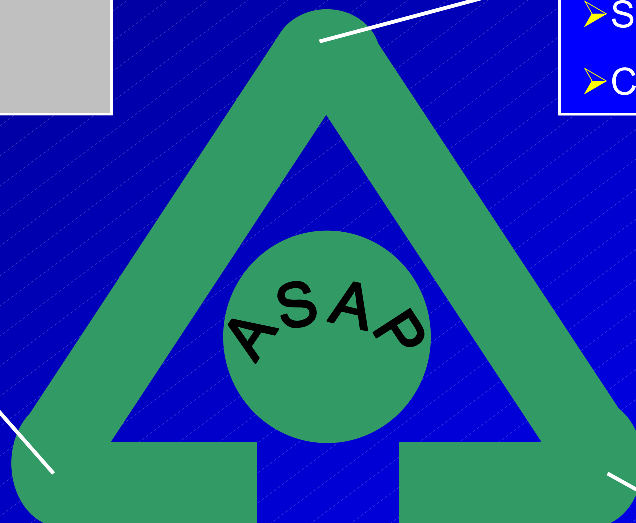
ANL's Systems Analysis Program

MODELING (PSAT):

- Choose the appropriate powertrain
- Choose component size
- Develop the best strategy

PROTOTYPING (PSAT-PRO):

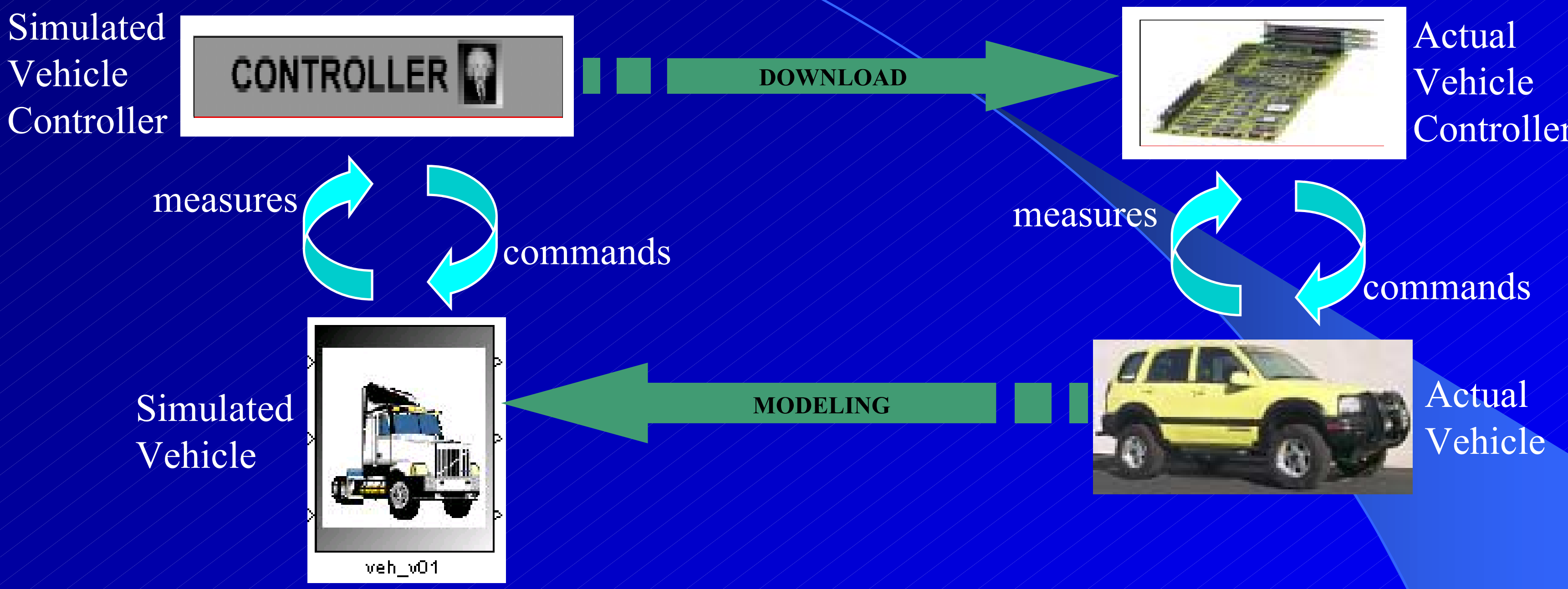
- Integrate the strategy in a VCU
- Simulate in RT the test procedures
- Control the actual vehicle



TESTING (APTF):

- Perform the simulated tests
- Test and map components
- Test hybrid vehicles

Prototyping → Definition



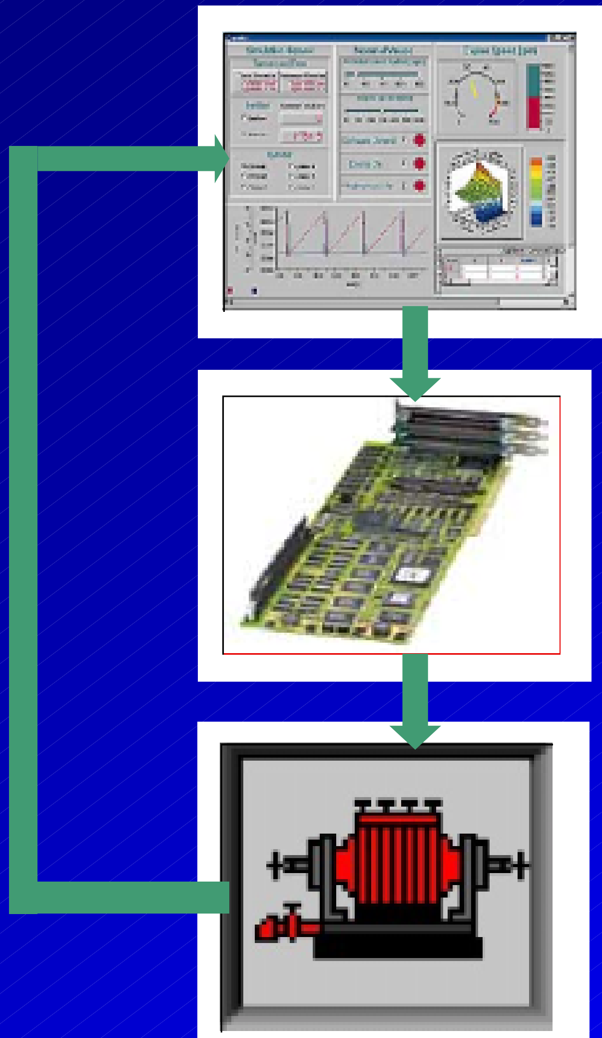
- To integrate a controller in an actual vehicle, extensions to PSAT are needed for prototyping: Argonne created PSAT-PRO

PSAT-PRO → Features

Purpose: **Users can go from PSAT modeling to prototyping using PSAT-PRO for any kind of vehicle or configuration**

- Generic and reusable
- Linked to PSAT
- Three steps used to control a powertrain
- Provides model validation

PSAT-PRO Is Generic and Reusable

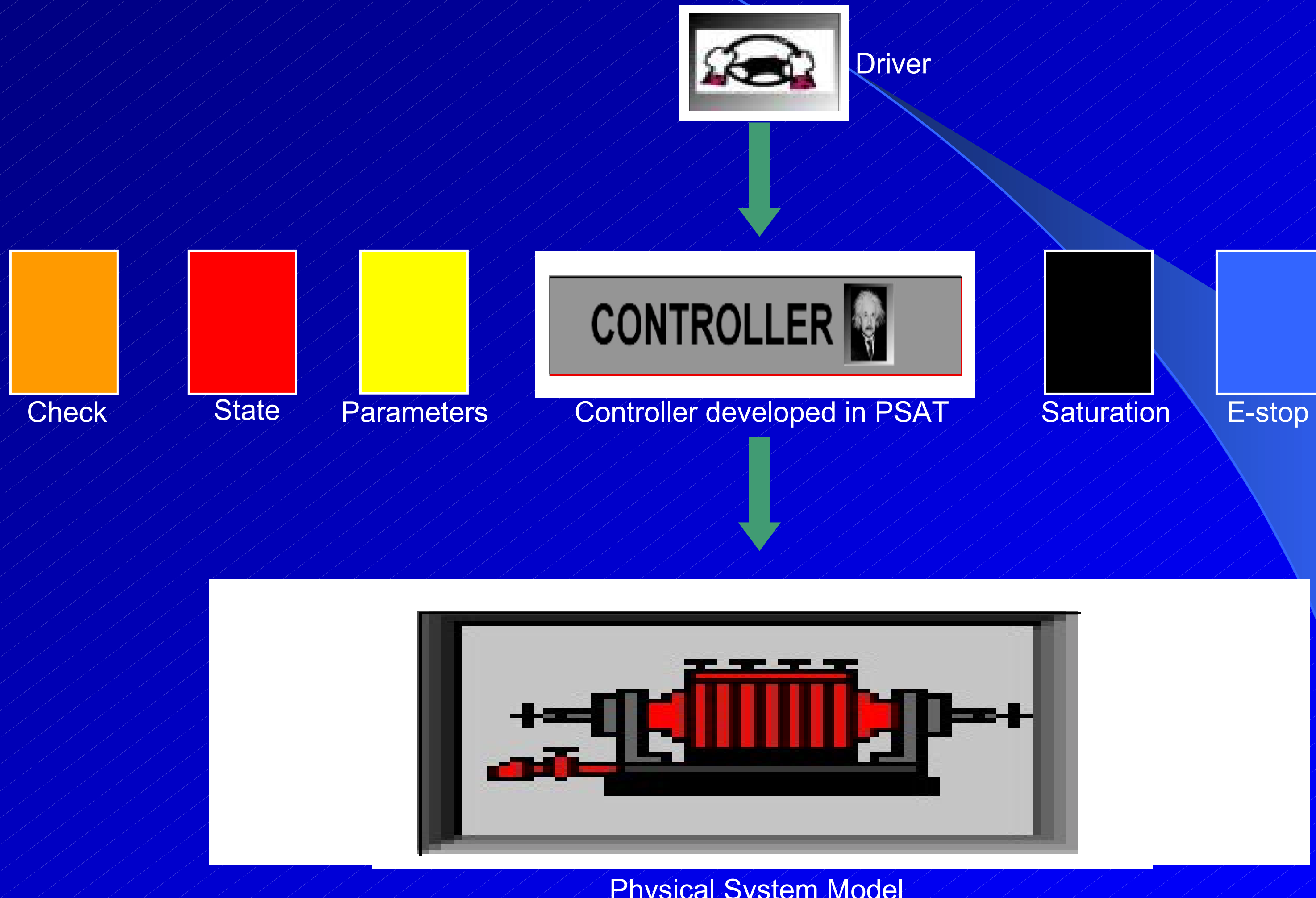


Test Procedure: We send the commands to follow the desired test procedure.

Control Command System: We command each component to follow the test procedure in accordance with the control strategy and with the components constraints.

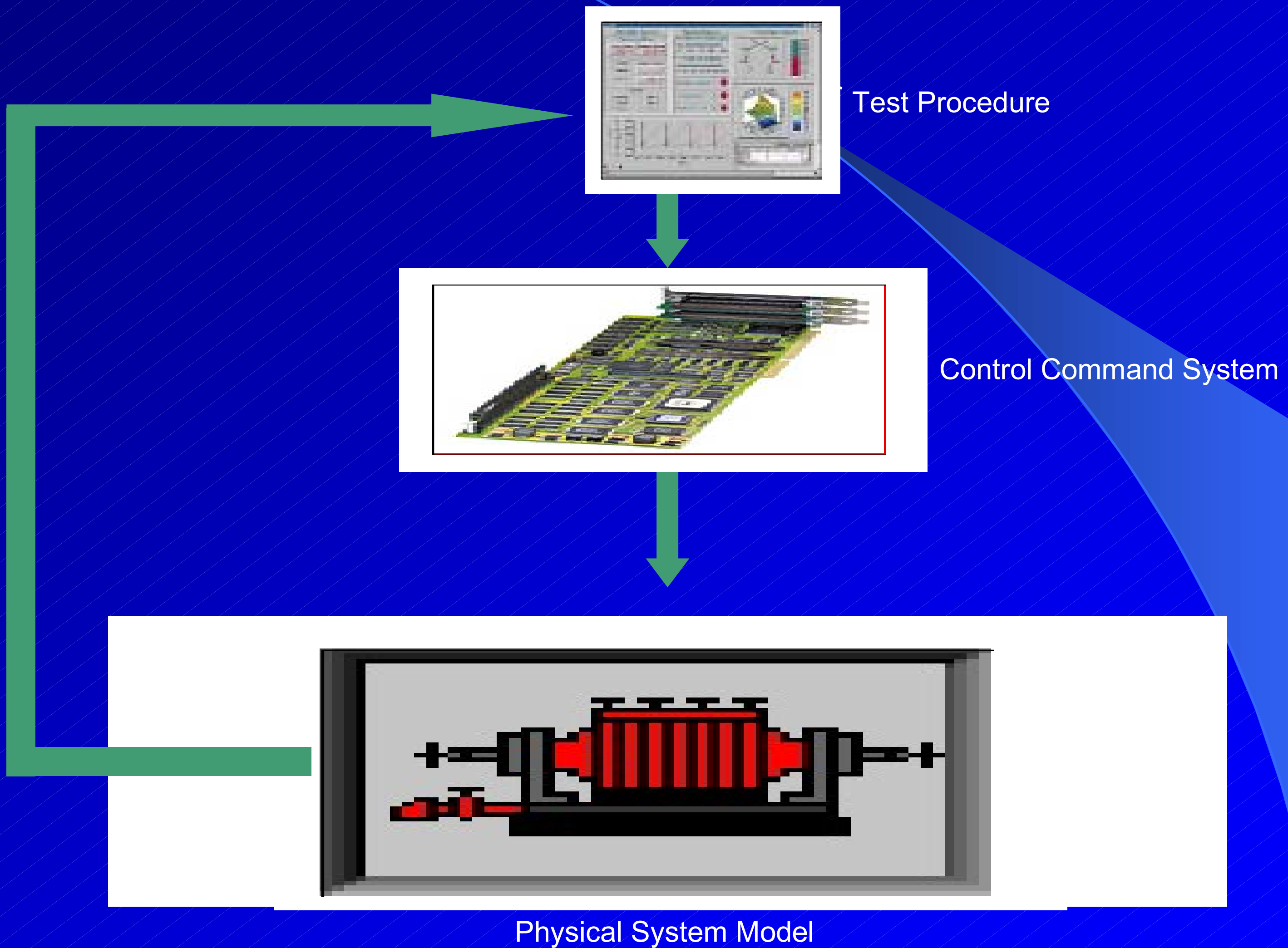
Physical System Model: The test stand or vehicle model should react exactly like the real system.

PSAT-PRO → Is linked to PSAT

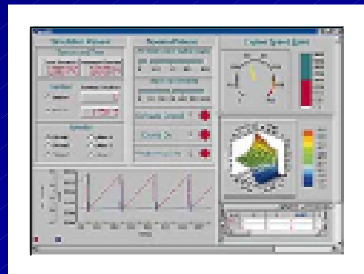


PSAT-PRO

Is linked to PSAT

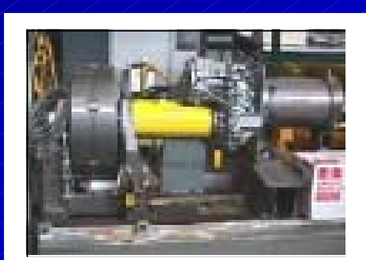


PSAT-PRO → 3 Steps Are Used To Control a Powertrain

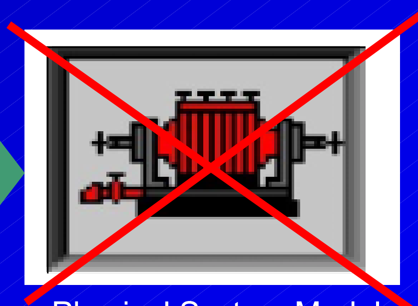


Test Procedure

Control Command System



Physical System



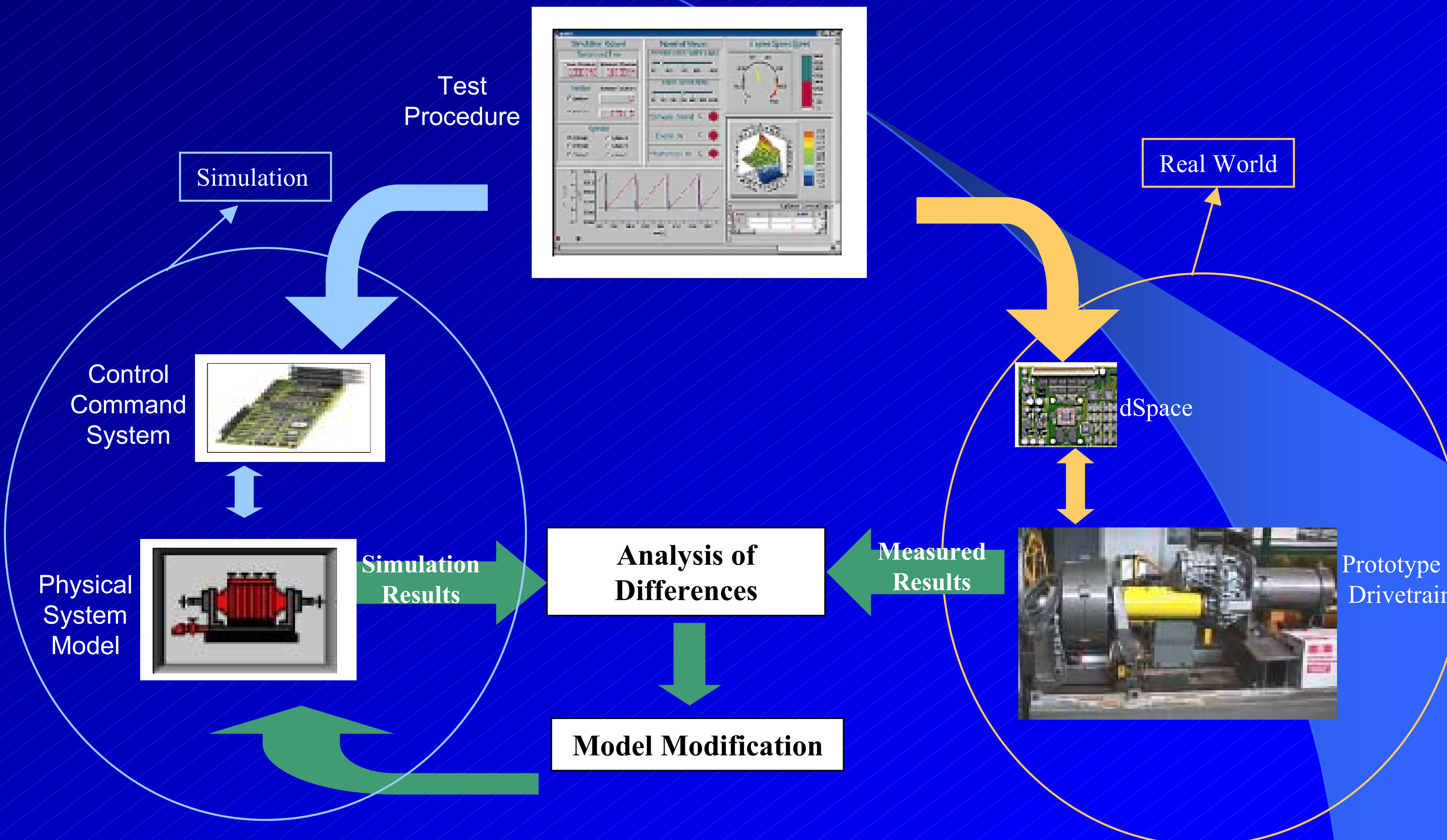
Physical System Model

1-Simulation :
We simulate the test procedure with the Physical System Model composed by the components library in order to check the model.

2-Simulation real-time (HIL):
We simulate the test procedure in real-time with the Physical System in order to check the control command system.

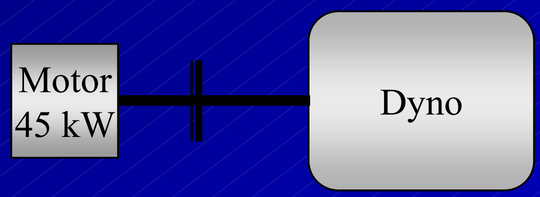
3-Control real-time (Rapid Prototyping):
We command the components to follow the test procedure and we control the Dynamometer to represent the vehicle behavior.

PSAT-PRO — Test Methodology Provides A Validated Toolkit

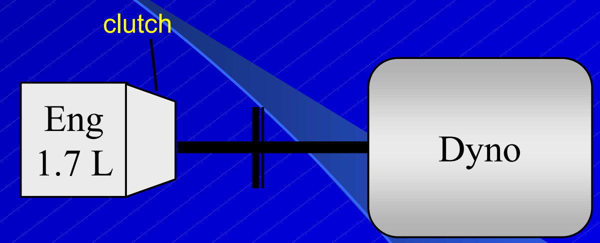


PSAT-PRO ANL Multi-step Development / Validation Plan:

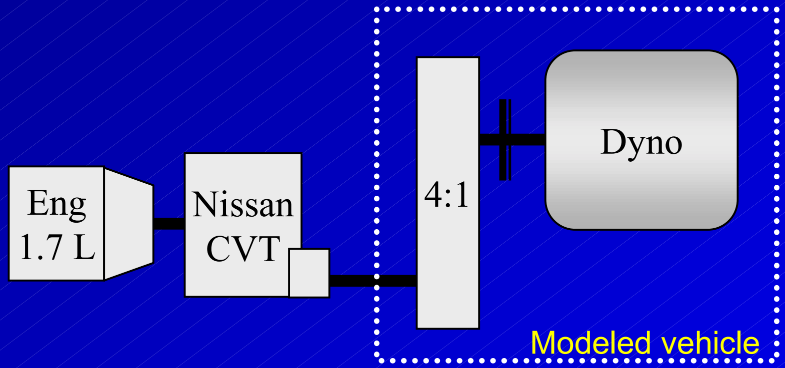
Phase 1 : Motor



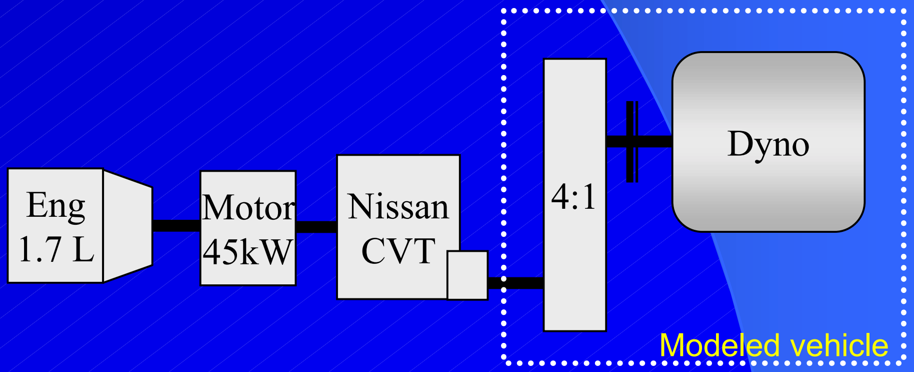
Phase 2 : Engine (with clutch and starter)



Phase 3 : Conventional Vehicle with CVT



Phase 4 : Post-Trans Parallel HEV with CVT



PSAT-PRO → Main Capabilities Summary

- High link between PSAT and PSAT-PRO
- As PSAT, PSAT-PRO is generic and reusable
- Any drivetrain configurations can be tested
- Easy integration of control strategies developed in PSAT
- PSAT can be validated as we use the same component models
- Possibility to simulate in real time to analyze the differences between simulation results and measures
- Post-processing tools facilitate the comparison simulation/test.

PSAT and ADVISOR → Conclusion

- ANL and NREL are working together to provide tools for industry and academia for HEV systems analysis
- PSAT now has, ADVISOR will soon utilize common variable naming convention
- Common GUI for both models will soon be available
- Test data from ANL is used for both models

ANL would like to work with you if you:

- are interested in developing controls or wish to use modeling for prototyping,
- have detailed, forward-facing component models that you would like to incorporate in PSAT,
- want to optimize a control strategy and test it in a vehicle

Simulation and Validation of Hybrid Electric Vehicles using PSAT and PSAT-PRO

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Argonne National Laboratory, 9700 South Cass Avenue, Argonne, IL 60439-4815

ABSTRACT

ADVISOR is a user-friendly, publicly available model useful in making fuel economy, performance, and emissions prediction in vehicles. ANL and NREL are working together to make a suite of HEV technology simulation tools the developer can use to help design HEV technology in a systems context. ADVISOR is an easy to use vehicle simulation tool that has a wide user base. ANL is continuing the development of the PNGV Systems Analysis Toolkit (PSAT) software model. A version consisting of non-proprietary component models is now available to component and systems researchers and developers. Both PSAT and ADVISOR have been modified to better exchange component data by sharing many of their variable names. The NREL-developed Graphical User Interface (GUI) familiar to ADVISOR users can now be used for PSAT after being modified. The GUI makes it easy to do component sizing, test execution, optimization, and visualization. PSAT, a forward-looking model, is well suited for development of control strategies and writing accurate dynamic component models because code can directly be imported and tested on a bench or in a vehicle. This paper will describe the ways vehicle the simulation models can be used to develop control systems by creating a seamless bridge between simulation and testing. This method is called the “Mechatronic Approach,” a powerful approach to rapid design and validation. ANL uses a Hardware-In-the-Loop (HIL) control unit based on the dSpace real-time computer control system to link individual components or full powertrain systems to the PSAT code. These HIL tests allow validation of control laws and physical system response. The results of the HIL tests help refine the models, which in turn allow for more accurate simulation studies. The HIL system can also be implemented in controlling an entire powertrain in a mule test vehicle for chassis dynamometer validation. The possible configurations and test objectives are outlined with examples and figures from Argonne’s powertrain test laboratory.

INTRODUCTION

Growing environmental and economic concerns have led the U.S. government to impose new emissions control regulations and consider new requirements for fuel efficiency by car manufacturers.

The Partnership for a New Generation of Vehicles (PNGV) is an historic public/private partnership between the U.S. federal government. The PNGV, which is led by the Technology Administration at the Department of Commerce (including 7 agencies and 19 federal laboratories) and DaimlerChrysler, Ford, and General Motors, aims to strengthen America’s competitiveness by developing technologies for a new generation of vehicles. The PNGV’s long-term goal, dubbed the “Supercar” goal, is to develop an environmentally friendly car with up to triple the fuel efficiency of today’s midsize cars without sacrificing affordability, performance, or safety. The other two PNGV goals are to significantly improve national competitiveness in automotive manufacturing and to apply commercially viable innovations to conventional vehicles.

The most promising design to increase fuel efficiency and decrease emissions seems to be Hybrid Electric Vehicles (HEVs). HEVs are vehicles that have both electric and fuel-consuming power sources [Combes and Cottard, 1992].

In a world of growing competitiveness, the role of simulation in vehicle development is constantly increasing. Because of the number of possible hybrid architectures, the development of this new generation of vehicles will require accurate, flexible simulation tools. Such a simulation program is necessary to quickly narrow the technology focus of the PNGV to those configurations and components that are best suited for achieving these goals. Therefore, the simulation should be flexible enough to encompass the wide variety of components and drivetrain configurations. Finally, it must be able to assist vehicle designers in developing specific strategies and implement them on prototypes.

In order to respond to the needs of industry, Argonne National Laboratory (ANL) undertook a collaborative effort to further develop the PNGV System Analysis Toolkit (PSAT) under the direction and contributions of Ford, GM, and Daimler-Chrysler. The model architecture is “forward-looking,” meaning that component interactions are “real world.” This method is computationally more intensive than “backward-looking” architecture; however, the result is a tool that will allow the advanced powertrain designer(s) to develop realistic control strategies and assess component behaviors in a system environment by using models closer to reality. These models were developed by using Matlab v5.3 and

Simulink v3. A nonproprietary version of this software is expected to be released in 2000.

To respond to these attempts (modeling and validation of HEVs using Hardware in the Loop), the mechatronic approach has been used [DeCharentenay et al., 1996]. Mechatronics represents a new generation of products that bring together elements of mechanical engineering and electrical and electronic technologies with information technology and software engineering.

This approach has been applied to the HEVs by using the bond graph methodology. Bond Graphs [Karnopp et al., 1990] are graphical descriptions of dynamics models based on power and informations flows. This technique offers the unique particularity to explicitly describe not only the energetic exchanges between the base elements of the physical structure of the system, but also the structure of its calculation. Moreover, the Bond Graph, as it uses a pictorial form of the physical structure and the calculated structure, appears as a link between the perception of the physical studied system, its models, their exploitation on a microcontroller, and the interpretation of the results.

In order to validate the models and their commands, we use the Hardware-In-the-Loop (HIL) method with a Dspace 1103 board. This approach allows us to test and validate the components and the whole drivetrain on the test bench.

The main objective of this paper is to present the possibilities and characteristics of PSAT. We begin with a description of the different drivetrain configurations that can be modeled. We then describe in more detail the organization and the capabilities of the software. Finally, using the description of the mechatronics approach, we explain the HIL methodology used to validate and improve our models.

PSAT PRESENTATION

To run a simulation, the user will have to first define some choices, such as the type of drivetrain or component. Then, PSAT gives the user the choice to create his/her own components (engine, motor, battery, transmission) by scaling existing data. Finally, for the parallel and series configurations, the user can chose if he/she wants to have a fixed ratio in between the motor and the principal power output shaft.

As PSAT is able to run both performance and consumption/emissions tests, the user should also choose what type of test should be done. In the case of an energy consumption test for hybrid configuration, a State-Of-Charge (SOC) equalization algorithm is also available so that the consumption results of different configurations or strategies can be compared with same SOC.

According to the user's choices, the software will build the appropriate model by using the right models, powertrain controller, and initialization files. The model will then be run automatically, and the results will be provided in the Matlab prompt command.

CONVENTIONAL CONFIGURATION

The main difference among conventional configurations is the choice of transmission: manual, automatic, or CVT. These drivetrains are used to validate PSAT's results with existing vehicles and serve as reference.

HYBRID CONFIGURATIONS

HEVs can be classified into two main architectures, as shown in Figure 1 (mechanical or electrical power

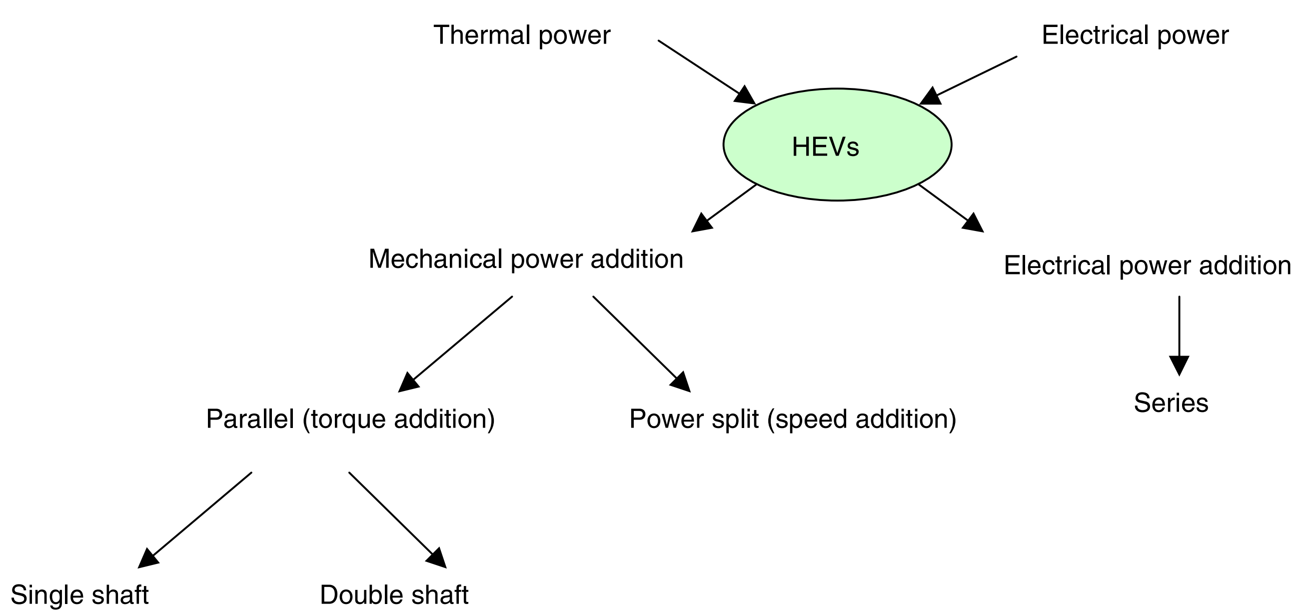

Figure 1: Classification of HEVs

addition). For a parallel or power split configuration (mechanical addition), the power is provided in a mechanical way (both the electrical and mechanical sources can be used directly at the wheel to propel the vehicle). In the series configuration (electrical addition), the power supplied is electric (electric motors provide all the energy used at the wheels).

<u>Series Configuration</u>

PSAT allows the user to choose, as the source of thermal power, between an engine and a fuel cell. More than 20 configurations are thus available:

- Three possible transmissions (manual, automatic, and CVT),
- Two different thermal sources, and
- Several different axle ratios (e.g., none, fixed gear).

<u>Parallel Configuration</u>

When we consider the parallel configuration, we can still divide it into two main architectures [Rimaux, et al., 1998]:

- Single shaft and
- Double shaft.

In the single-shaft configuration, the rotational speeds of the engine and the motor are linked by a fixed proportional ratio as follows:

$$W_{ICE} = k * W_{EM}$$

where k is a constant parameter.

In the double-shaft configuration, both of the speeds are independent (k is now a variable and not a fixed parameter anymore).

PSAT allows the simulation of more than 20 parallel configurations, including:

- Three possible transmissions,
- Four positions to add the torque of the motor, and
- The possibility to use a fixed ratio in between the motor and the main shaft.

The user can choose where to place the electrical motor. Four positions are proposed, as shown in Figure 2:

- Pos1: between the engine and the link element (clutch/torque converter),
- Pos2: between the link element and the trans-mission,
- Pos3: between the transmission and the final drive, and
- Pos4: between the final drive and the wheel.

Figure 3 shows an example of a parallel hybrid.

<u>Power Split Configuration</u>

A special case of the double-shaft hybrid configuration is the power split hybrid, which use a planetary gear, an engine, and two motors. One example of this configuration is the Toyota Prius, as shown in figure 4.

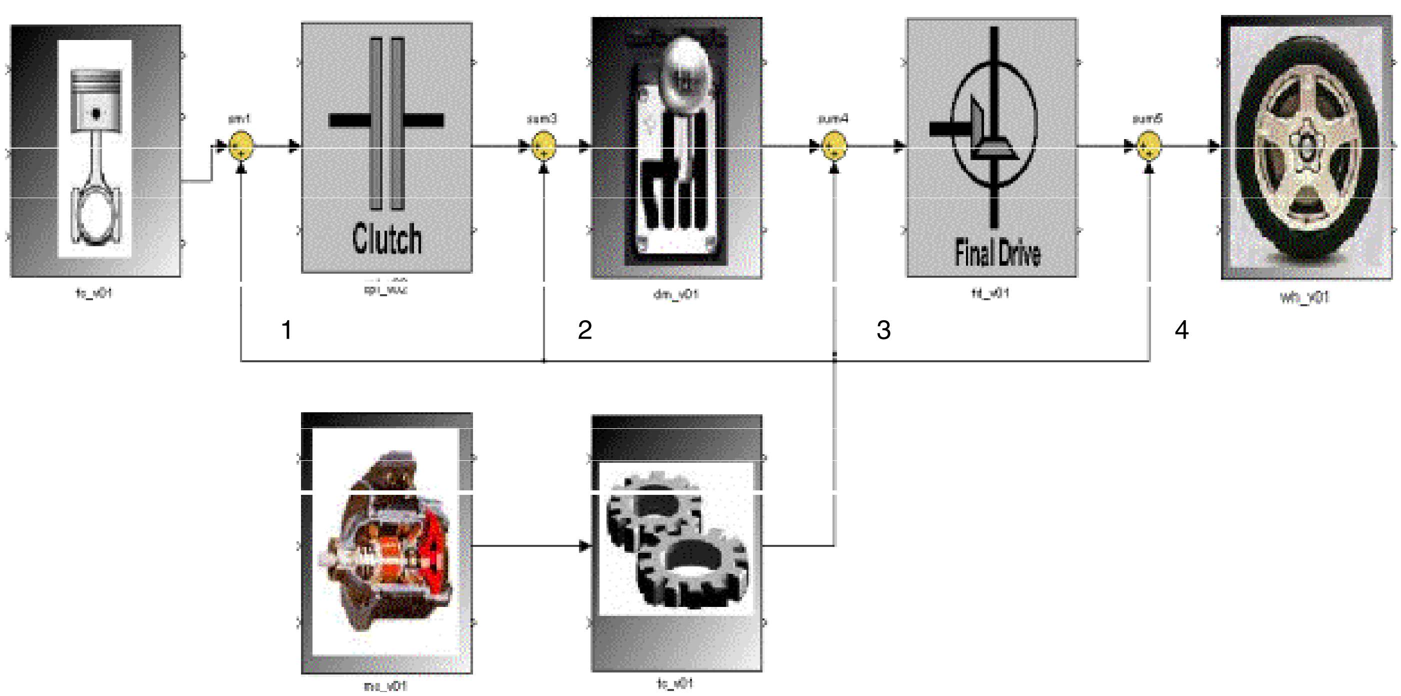

Figure 2: Four Positions of The Parallel Conficuration

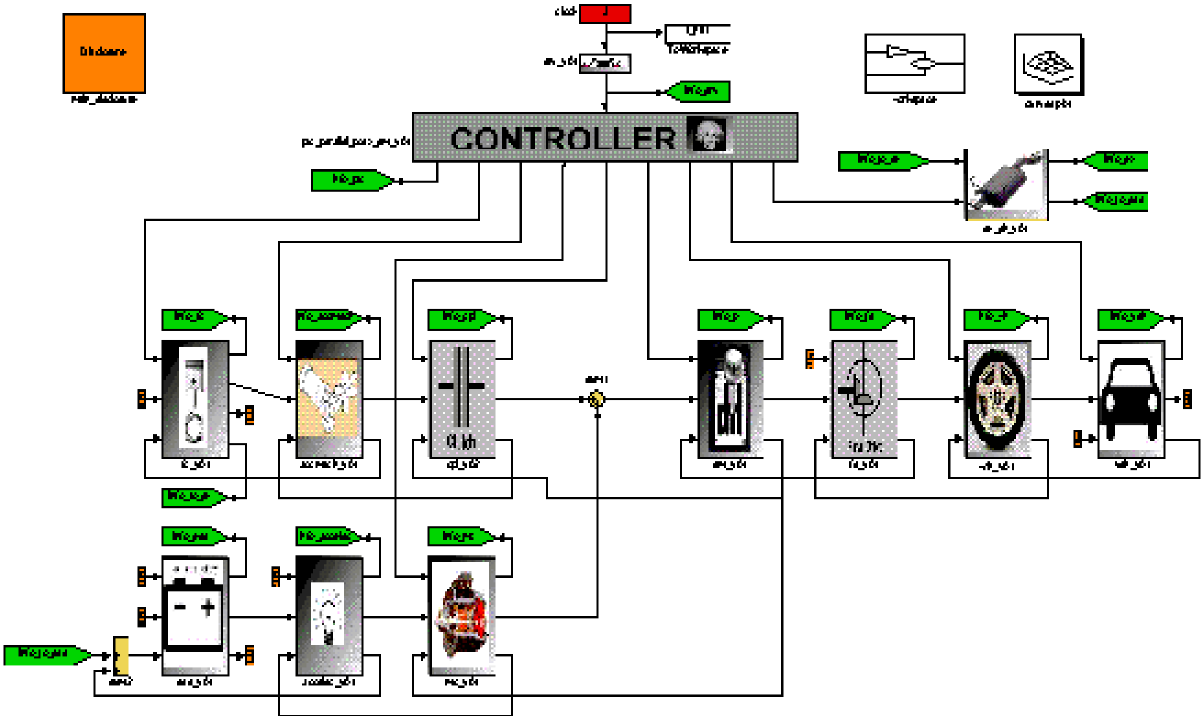

Figure 3: Example of a Parallel Hybrid Configuration in Position 2

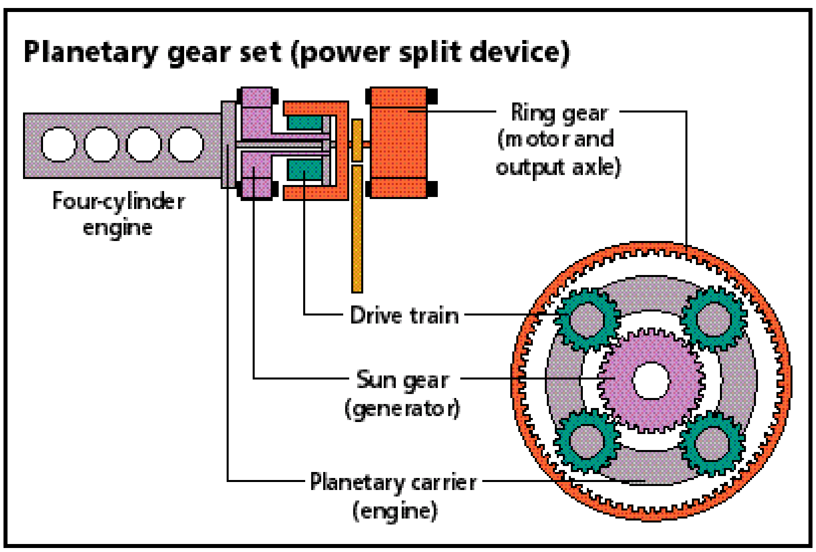

Figure 4: Schematic of Prius Planetary Gear Layout

PSAT ORGANIZATION AND CAPABILITIES

MODEL STRUCTURE

Organizational Format

In order to exchange easily the models and implement new ones, we use a common format between the input/output of the power ports by using the Bond Graph philosophy, as shown in Figure 5. The first ports are used for the information:

- Input: on/off engine, gear number, etc. and
- Output (sensors): torque, rotational speed, current, voltage, etc.

The output ports are used in the power controller (PTC) for post-treatment, plotting or information in the strategy. The second ports carry the effort (i.e., voltage, torque) and the last ones the flow (i.e., current, speed).

To have an optimal reusability of the models, each component has its own:

- Initialization file,
- Scaling file,
- Model,
- List of variables (output information), and
- Selector file.

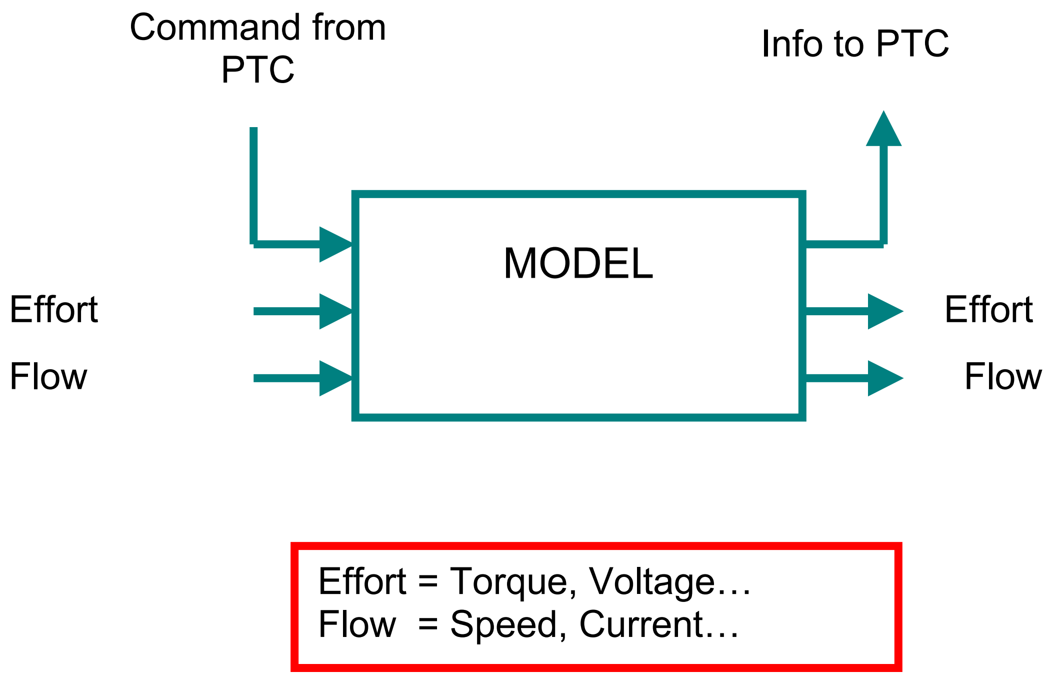

Figure 5: Global Formalism for the I/O of the Models Using Bond Graph

ORGANIZATIONAL STRUCTURE

Use of Library

To ensure that the models we are using are the last ones changed or are not modified, we decided to use a library in which all the models are saved. Libraries enable users to copy blocks into their models from external libraries and automatically update the copied blocs when the source blocks change.

Use of Masks

We masked the models in order to use the parameters as local instead of global variables. This approach allows us to use the same generic model twice with two different data sets. We use the "GOTO-FROM" method to carry the information in an array from the model block to the "workspace block" where they will be transformed into global variables and thus be used in post-treatment processing.

Figure 6 shows an example of a mask with an electrical motor.

Use of GOTO-FROM Format

To simplify the model, we decided to use the GOTO-FROM format as shown in Figure 7. As far as the models are concerned, all of the GOTO-FROM blocks are local and located at the upper level of the model (no blocks are located in the subsystems). Moreover, to facilitate the work for HIL (Control Desk access to the parameters and variables by using the Tags), the name of the Tags are defined as follows:

From_'variable name"
Goto_"variable name'

Use of Selectors

The Selector file allows us to parameterize the location of each variable in an array. Indeed, to carry sufficient information, three buses are used: one for the mechanical component, one for the transmission component, and the last one for the electrical side. Every bus consists of the output variables of each component. To find the place of each parameter in these buses, we use some parameterized value to establish its location. For instance, the variable "nb_fc_spd_hist" is located in the 4th position of the array "nb_thermic_variables" (which consists of the information coming from the engine, the clutch, and the exhaust).

Figure 8 shows an example of the use of selectors.

NOMENCLATURE OF VARIABLE NAMES

All the names of the software have been parameterized and follow some rules.

At the software level where the computations are made, everything is based on the name of the component (e.g., 'compo' = fc for fuel converter). In fact,

- The component model name is defined as 'compo'_cm (ex: fc_cm),

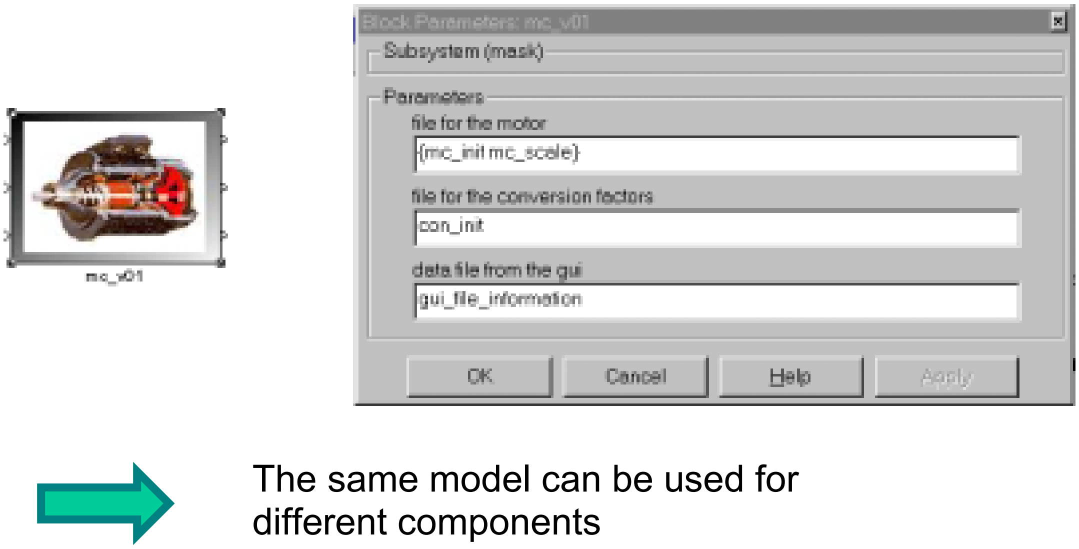

Figure 6: Example of Using a Mask

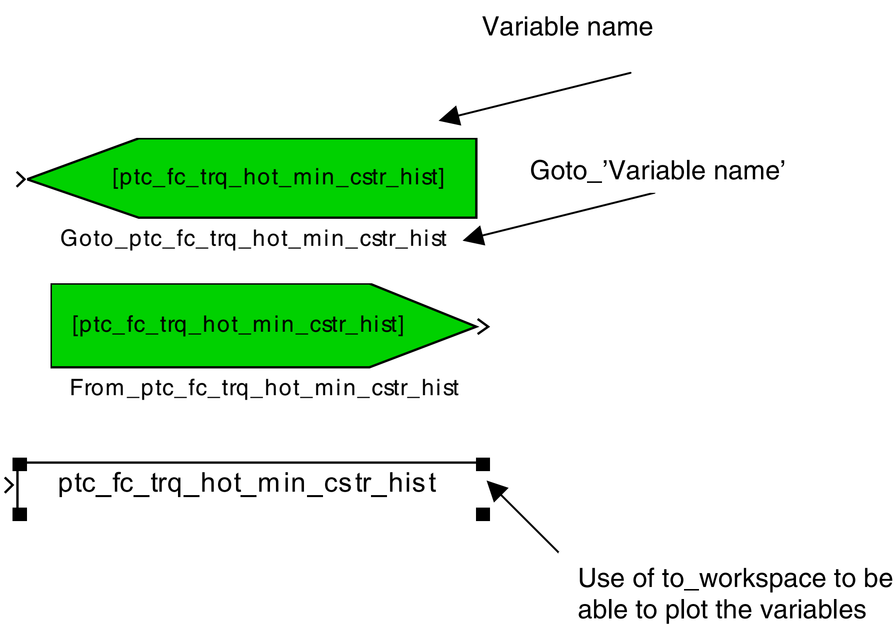

Figure 7: Example of Use of GOTO-FROM

- The initialization file is 'compo'_init,
- The scaling file is 'compo'_scale,
- The calculation file is 'compo'_calc,
- The parameter used to choose if we scale or not gui_scale_'compo',
- The parameters used to scale the component gui_'compo',
- The selector file associated with the model selectors_'compo'_cm, and
- The name of the main library of a component lib_'compo'.

At the component level, all of the variables and parameters also follow established rules and are named ccording to the component in which they are used and the type of data they represent.

POST-TREATMENT

At the end of a simulation, PSAT will display the results corresponding to user-defined preferences (performance or energy consumption and emissions). The user can also access the information of every model by using an easy and automatic way to plot the variables used for that run. For each component, we can plot and add as many variables as are located in the menu.

Figure 9 shows the choices available to the user after running a simulation with a parallel configuration in position 2 with a reduction block between the motor and the main shaft.

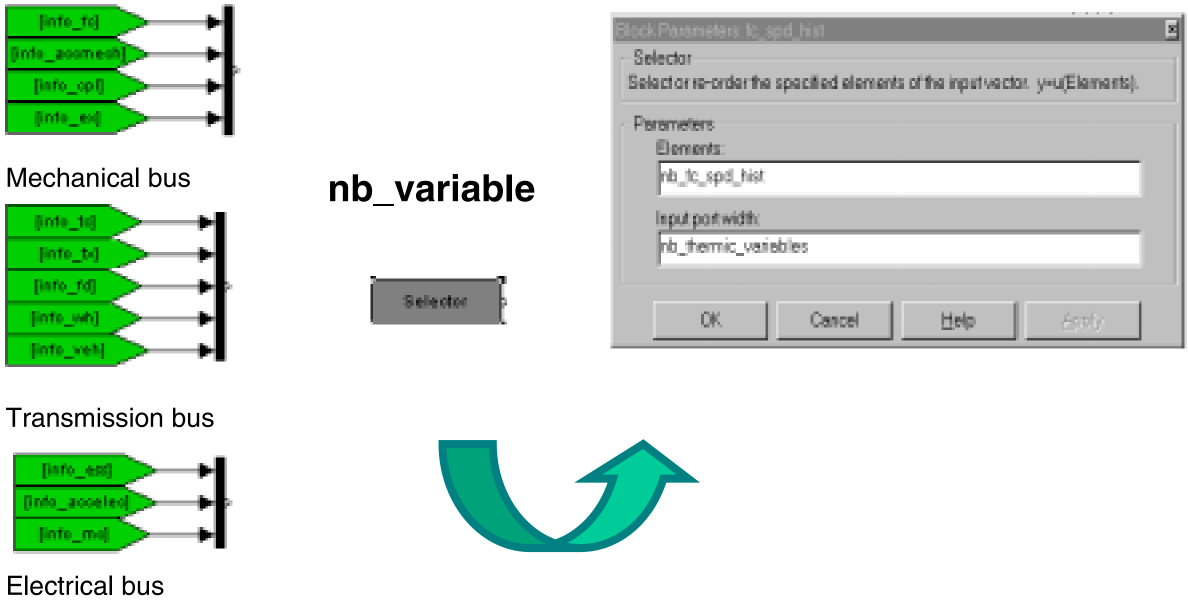

Figure 8: Example of Use of Selectors

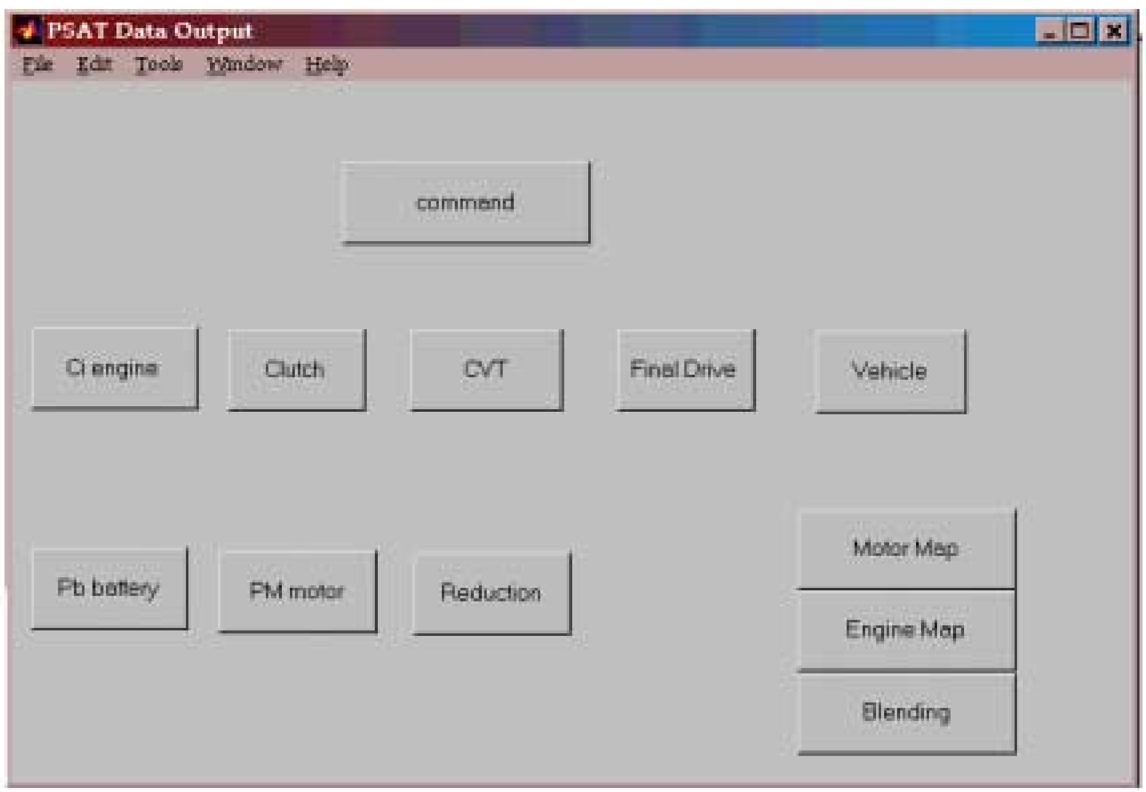

Figure 9: Choices of Plot for a Parallel Drivetrain with CVT

Figure 10 shows an example of the data plot for a battery.

NEW MODELS OR DATA IMPLEMENTATION

All of this structure has been developed for one goal: to facilitate the integration of new models and data into PSAT quickly and easily. For instance, the Bond Graph philosophy allows us to integrate any engine model into PSAT if the inputs and outputs are similar. Moreover, as far as the control strategy is concerned, the strategy demands that outputs are always the same for a specific configuration. For instance, in a parallel drivetrain using a manual transmission, the outputs will be:

- Engine on/off,
- Engine torque,
- Motor torque,
- Gear number, and
- Braking torque.

Another parameter that will facilitate the implementation of new components or control strategies is the choice of using only SI units.

PSAT VALIDATION USING HIL

MECHATRONIC APPROACH

The mechatronic approach can be represented as shown in Figure 11. It consists of defining, according to the customer's expectations (e.g., acceleration, maximum speed), the best HEV architecture and the size of the different components. Starting with a conceptual model (used essentially for consumption), we then improve it to a representational model (include such system parameters as stiffness). Using Dspace, we successively replace the simulated components by the real ones to finally control the whole prototype HEV powertrain. We then come back to the simulated models as soon as a problem is noticed on the test bench to correct it and improve the accuracy and robustness of the models.

PSAT VALIDATION

To validate PSAT, two different approaches will be used. To validate the models, we will use data gathered from some existing HEV vehicles and some PNGV prototypes. This method will allow us to compare a whole drivetrain configuration. The other way to compare the simulated results with the real data is to control a partial or whole specific drivetrain on the test bench. We have chosen a double-shaft post-transmission parallel hybrid with a CVT as our first test case. To verify each of our components, we decided to divide our tests into four phases:

- The first phase consists of validating one single component (motor).
- The second phase allows us to validate the engine starting and clutching.
- The third phase will be used to validate the CVT model and its ratio command.
- The last phase will lead to the validation of the whole drivetrain.

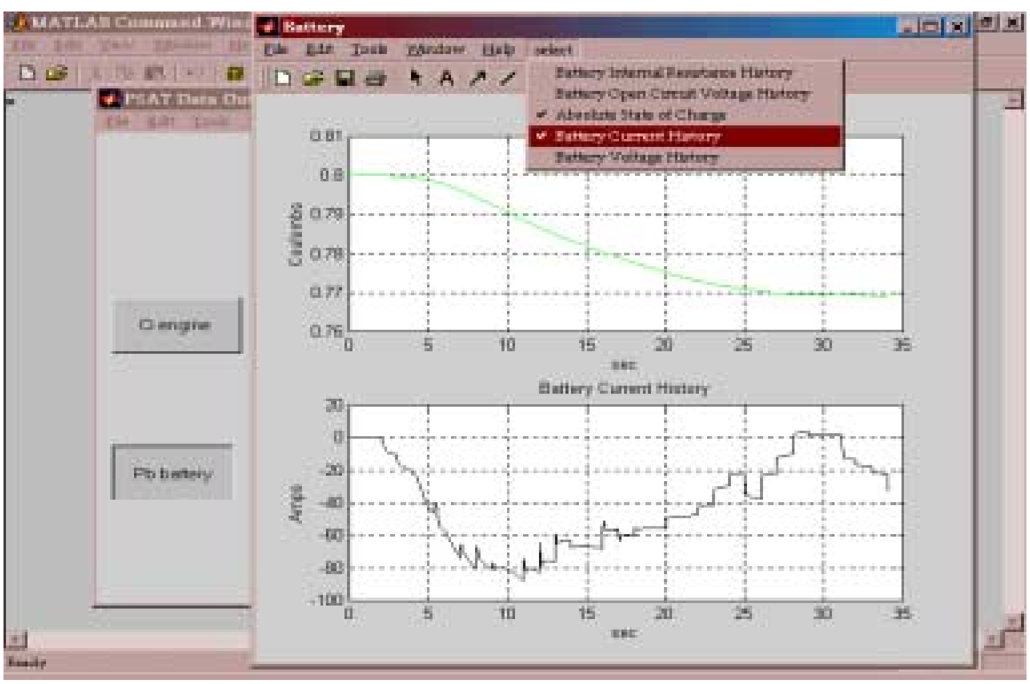

Figure 10: Example of Variable Implementation for the Battery

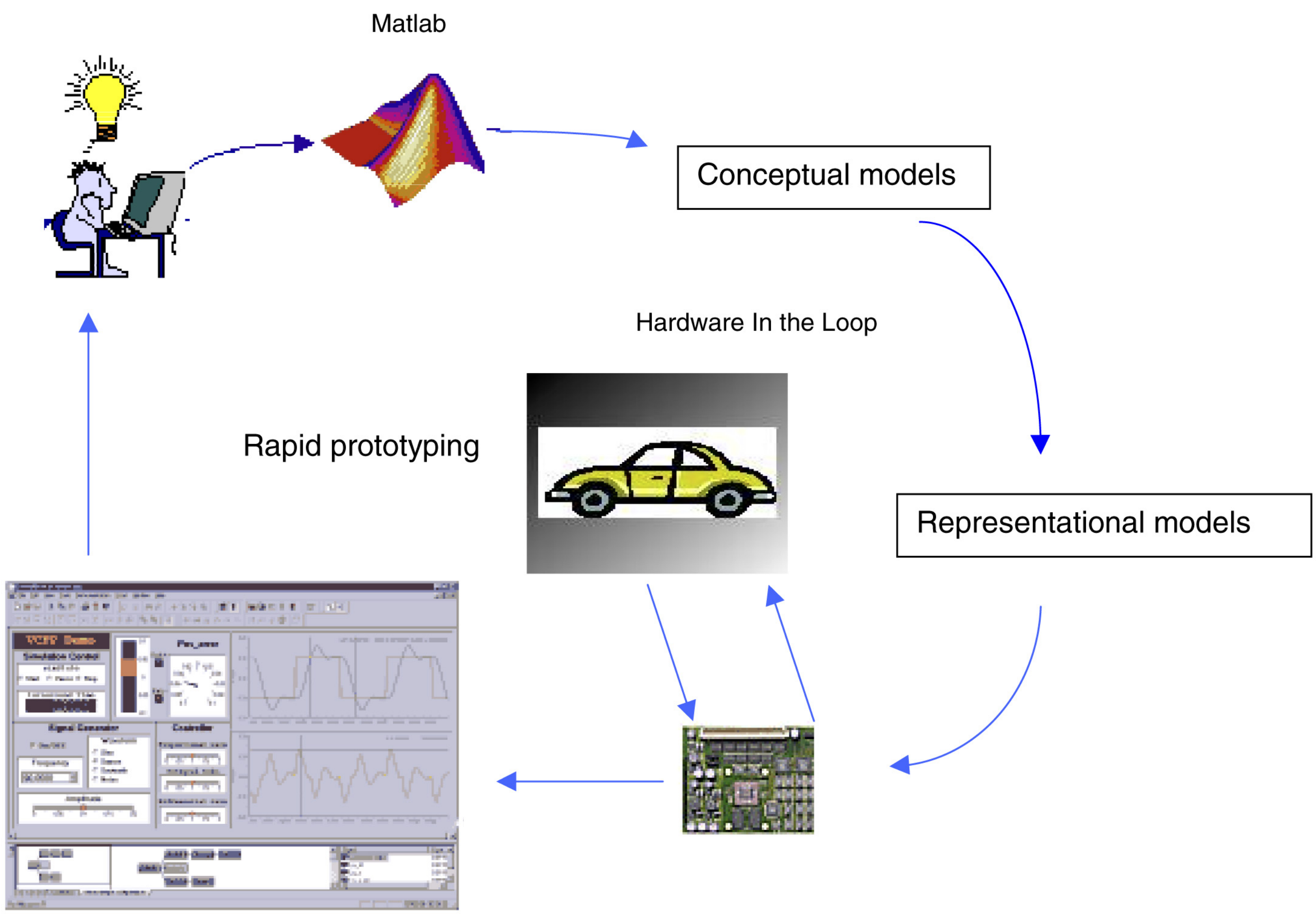

Figure 11: Mechatronic Approach

During each of the phases, we will use the measured data (e.g., torque, speed, current, voltage, transient

emission measurements) to come back to the simulated models to validate them.

Figure 12 shows the different steps of the HIL validation.

CONCLUSION

PSAT is a user-friendly simulation toolkit that allows the user to simulate a large number of different HEV configurations and implement the commands on prototypes by using an HIL technique. As the government-financed PSATs develop, our goal is to provide a nonproprietary version to a wide range of people later in 2000. Thus, by incorporating the data, models, and strategies of users, we can speed up PSAT's development for everyone's benefit and greatly strengthen this powerful simulation tool. In this world of increasing global competition, the value of a company is not based on what software it uses but on how the company uses it to accelerate the development of the next generation of fuel-efficient, environmentally friendly vehicles.

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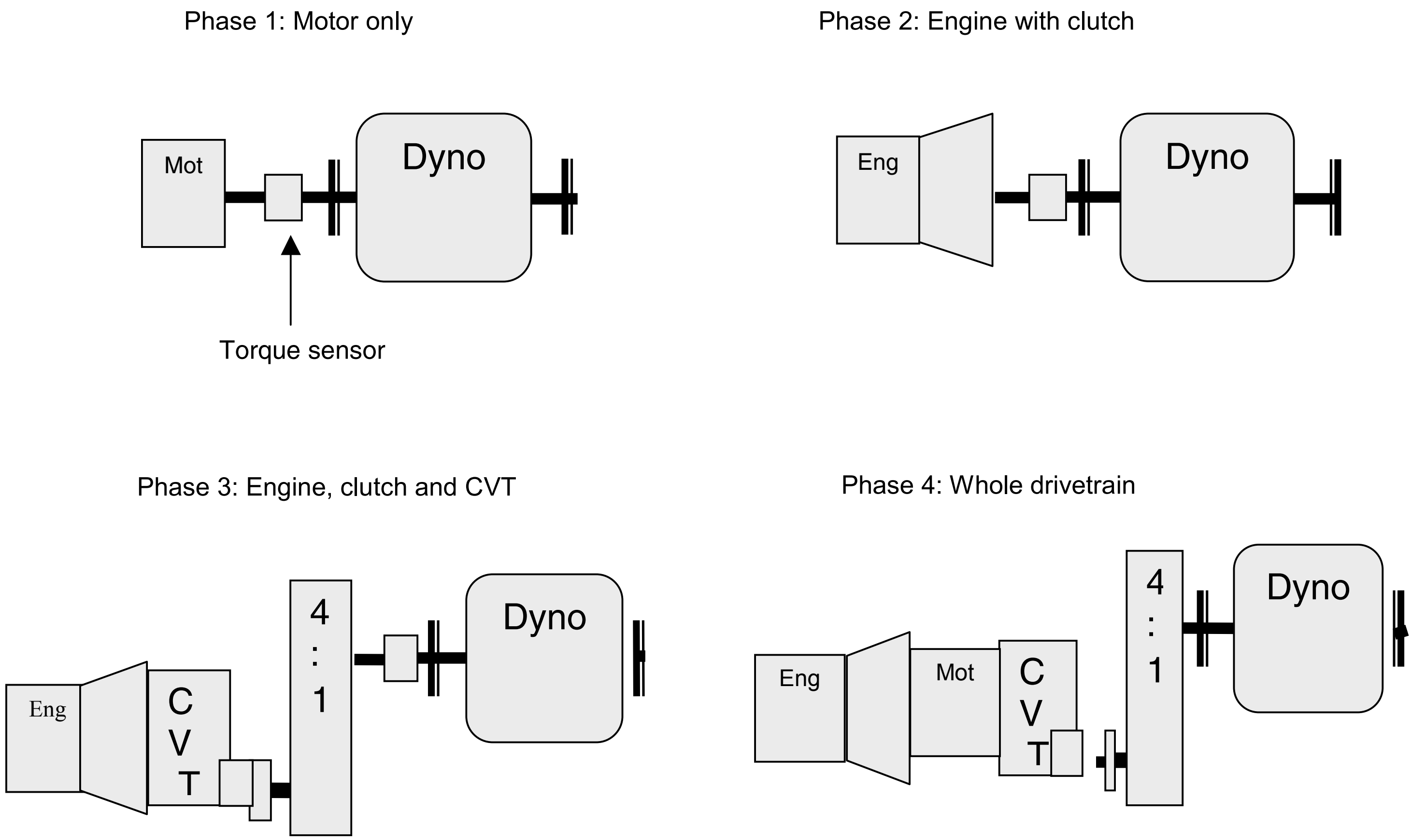


Figure 12: PSAT Validation Process Using HIL

The Reverse Engineering of a Diesel Engine: A Unified Systems Approach Using ADVISOR

George J. Delagrammatikas
and
Dennis N. Assanis

Automotive Research Center
The University of Michigan

ADVISOR Users' Conference - August 24 - 25, 2000

Outline

- **Motivation and Background**
  – Objectives
- **Traditional Methods of Engine Design**
  – ‘Library’ Approach
- **Engineering Tools Utilized**
  – ADVISOR and Turbo-Diesel Simulation
- **Application to ADVISOR**
  – Case Study Implementation
- **Conclusions and Future Work**
  – Lessons Learned and Direction of Research

Motivation

- Federal Regulations
  - Fuel economy (CAFE)
  - Emissions (NOx, smog, and other pollutants)
- Public Awareness
  - ‘Green’ movement
  - Global warming scare
- Decrease Dependence on Foreign Oil
  - Avoid another oil crisis - Energy security

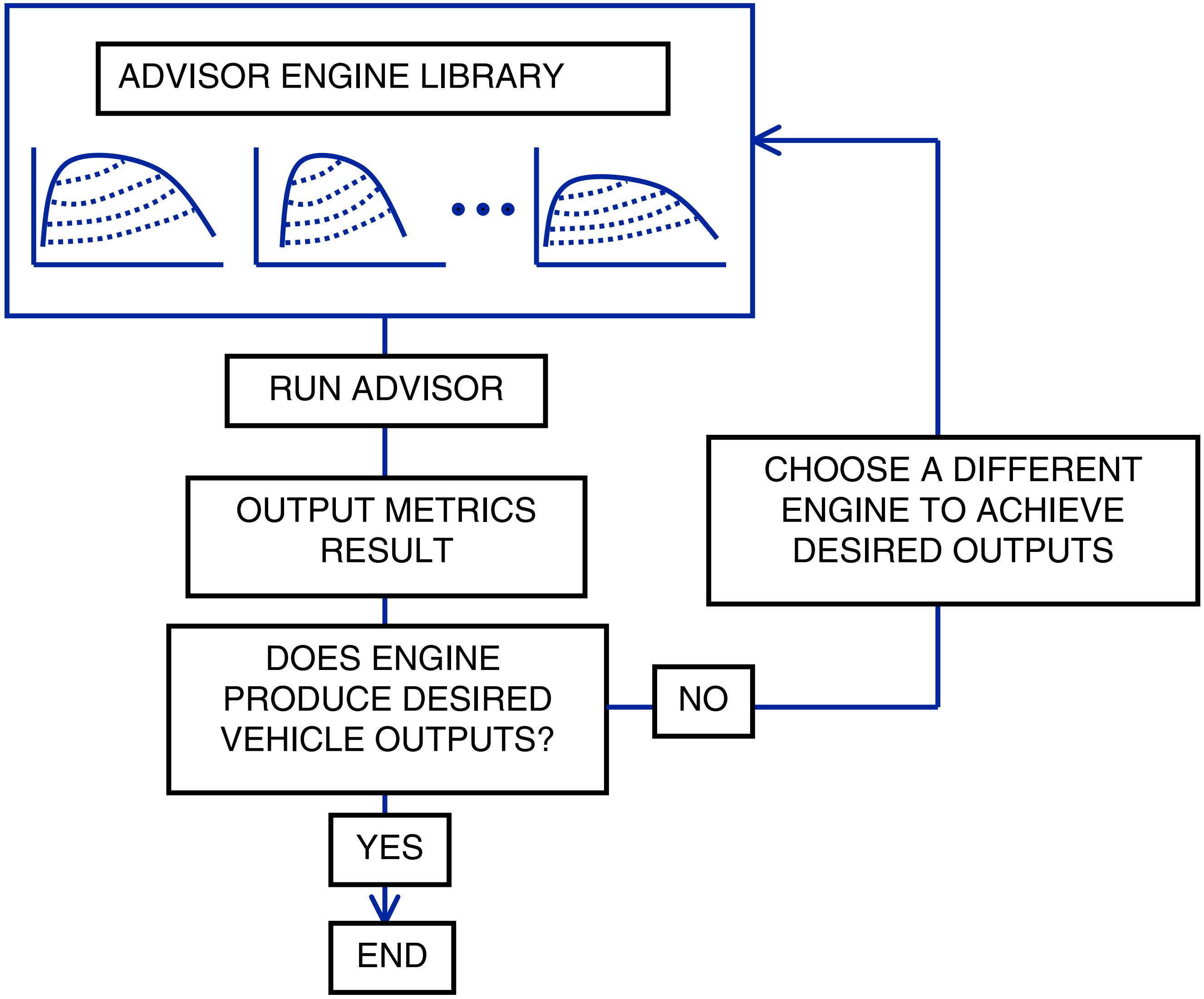
Objectives

- Design the optimal engine for a given vehicle
- Develop a framework to design this engine
  - Utilizing the proper simulation tools
  - Implementing the correct optimization scheme
- Perform a realistic case study to analyze trade-offs in design characteristics
- Extend methodology to different levels
  - More vehicle systems
  - Individual subsystems and components

Background

- Engineering tools used
  - ADVISOR
    - Conventional powertrain configuration selected (Wipke, Cuddy, et al 1997)
    - Feed-backward vehicle simulation
  - TDES
    - Turbocharged Diesel Engine Simulation (Assanis and Heywood, 1986)
    - Zero-dimensional, quasi-static and feed-forward
    - Enhanced to calculate an engine map for ADVISOR ‘on-the-fly’
  - MATLAB
    - SIMULINK - ADVISOR calculations
    - Optimization framework - Sequential Quadratic Programming (SQP)

'Library' Approach



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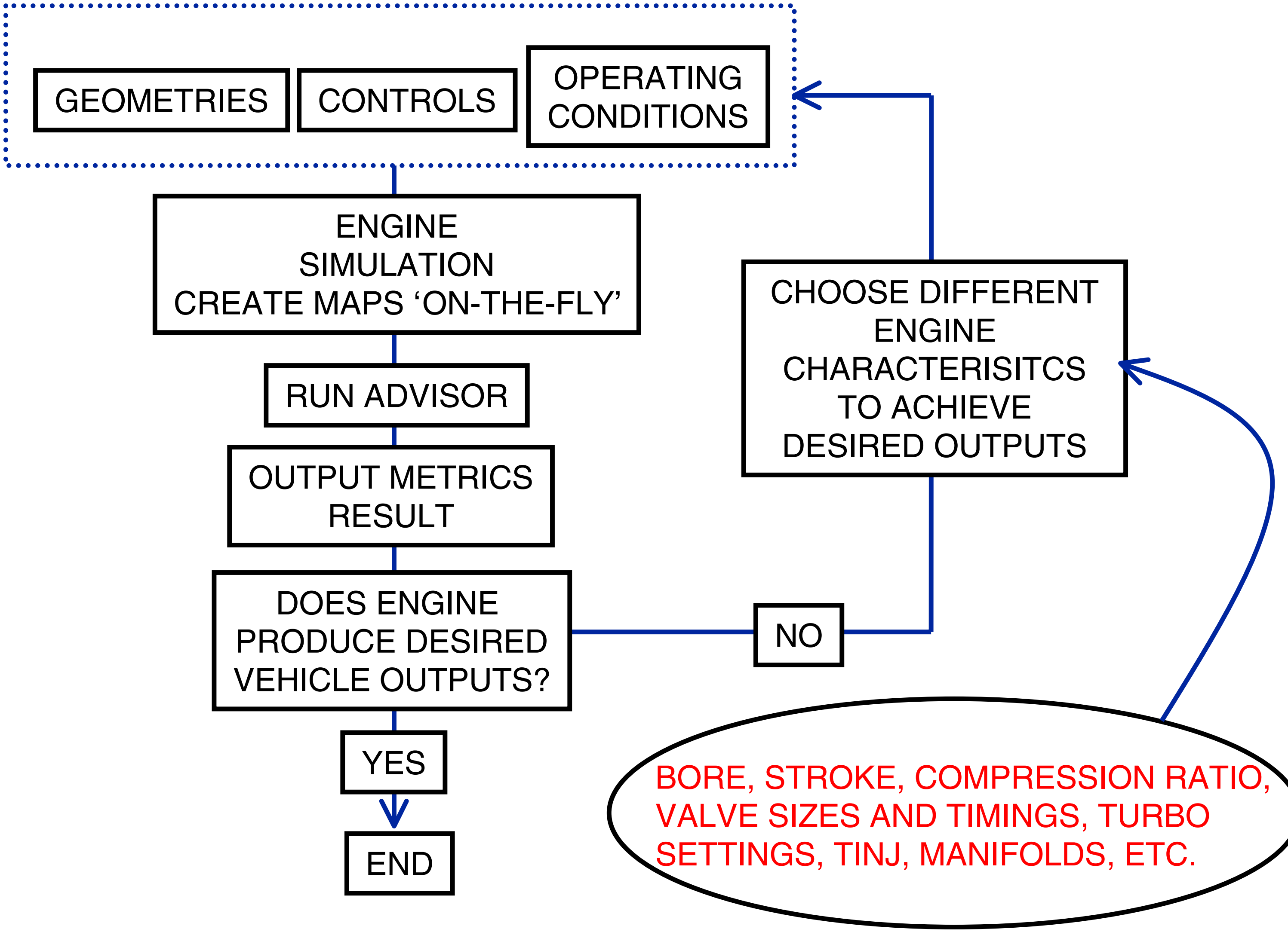
High-Fidelity ‘Library’ Approach



REVERSE ENGINEERING A DIESEL ENGINE

Issues with 'Library' Approaches

- Maps on file are for a given engine, under given operating conditions
  - Engine characteristics can vary dramatically
    - Different auxiliary devices used (turbo, supercharger, intercooler, etc.)
    - Different control strategies (VVT, VCR, VDE, etc.)
- Maps 'on-the-fly' can be made quite rapidly
  - Changing parameters within the engine cannot be detected by an optimizer
    - Must account for noise level of both simulations
  - 'Mix-and-match' techniques are time-consuming
    - Do not afford the user with great certainty that the final result is the true optimum

Model Decomposition

- Breaking up the large scale system into more manageable subsystems
  - Ensure conceptual simplicity of overall system
  - Decrease computational expense
  - Provide a methodical manner to perform trade-off analyses
- Modularity of base simulations used helps determine the decomposition method
  - 'Natural' break-up in this case (vehicle components)

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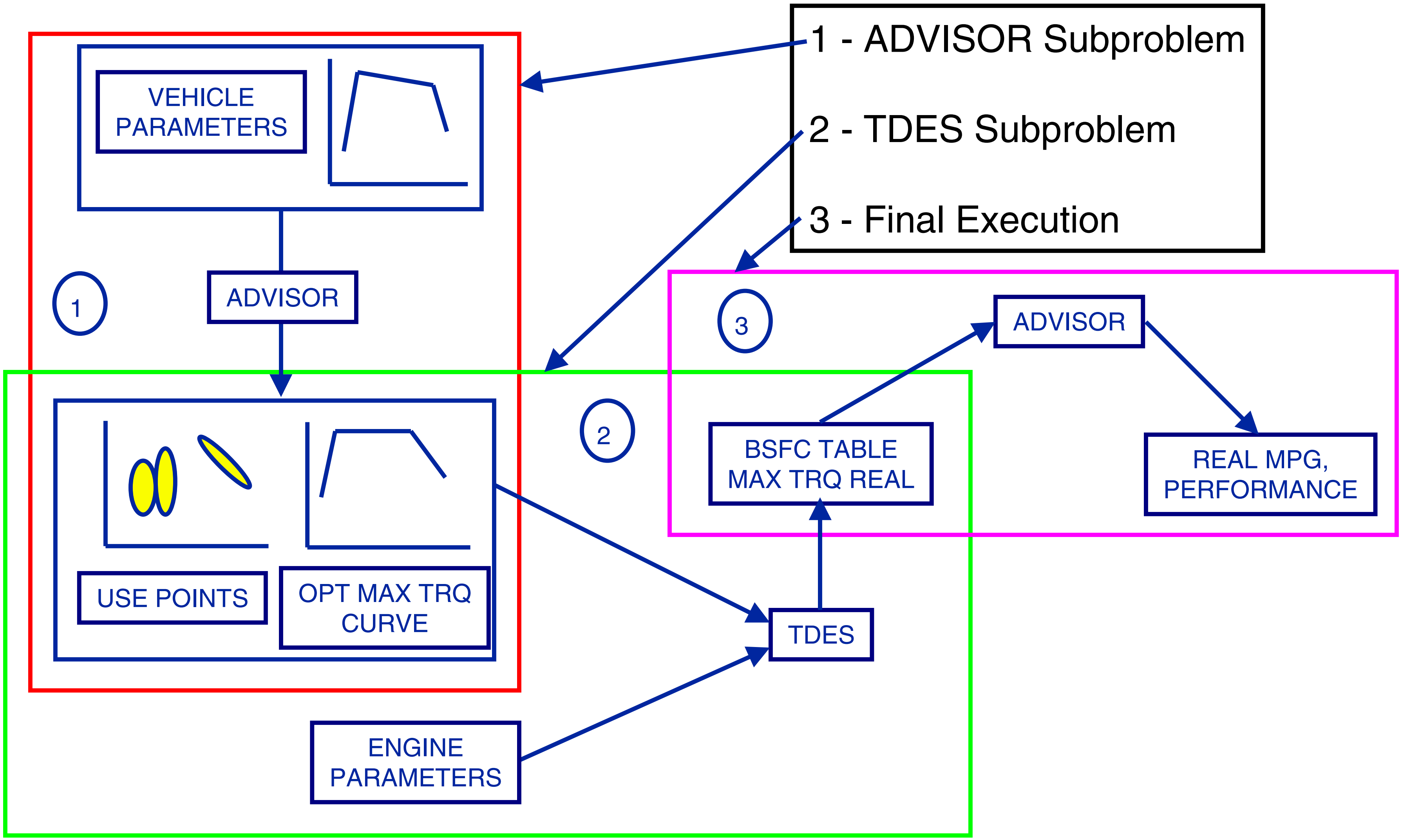
Decomposition and Coordination



REVERSE ENGINEERING A DIESEL ENGINE

Case Study Description

- **Pre-optimality**
  - Find out which parameters are important
  - Determine step sizes for optimization
  - Investigate different objectives to optimize
- **Optimization**
  - Execute the decomposed, coordinated subproblems and link their results
- **Post-optimality**
  - Perform trade-off studies to understand the impact of different parameters on the location of the optimum design

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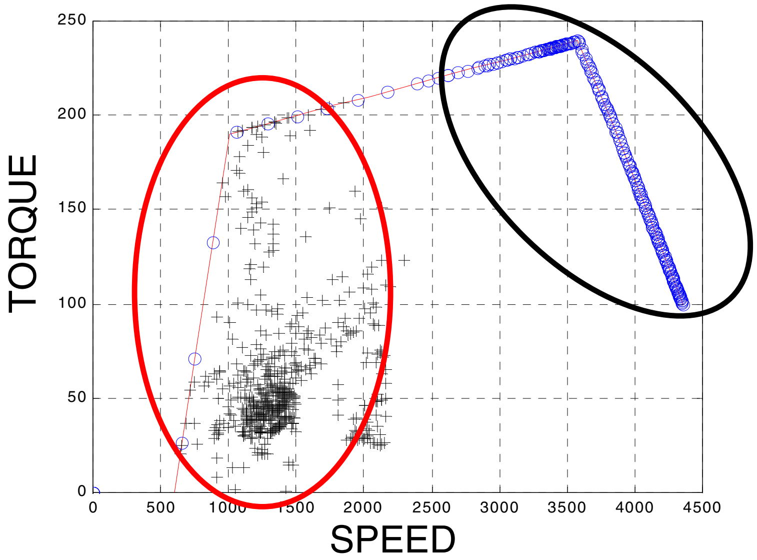
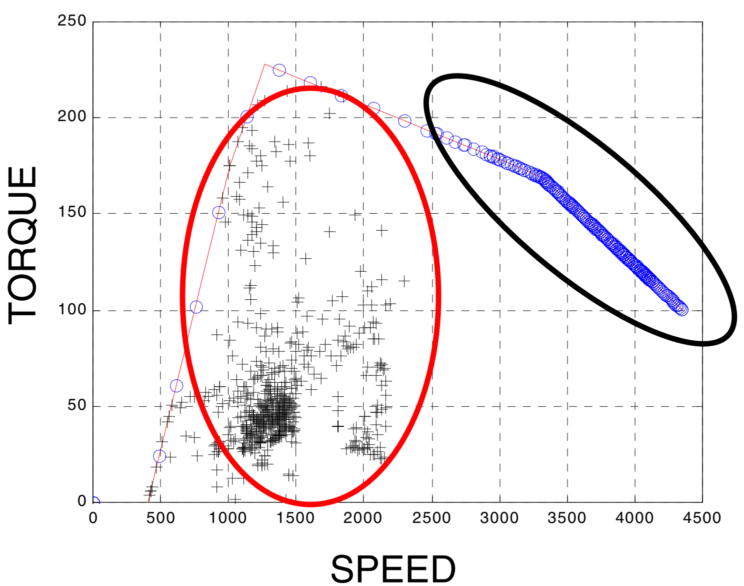
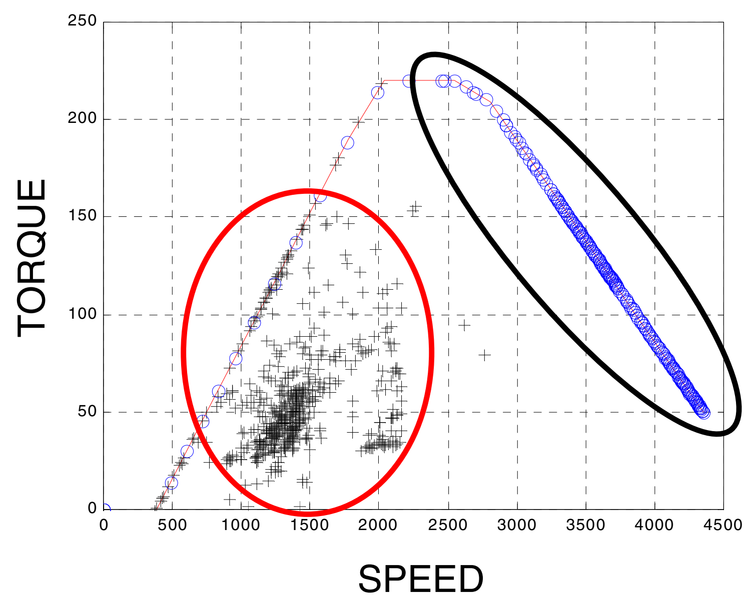
Parameterized Torque Curves



PERFORMANCE RUN

FUDS CYCLE





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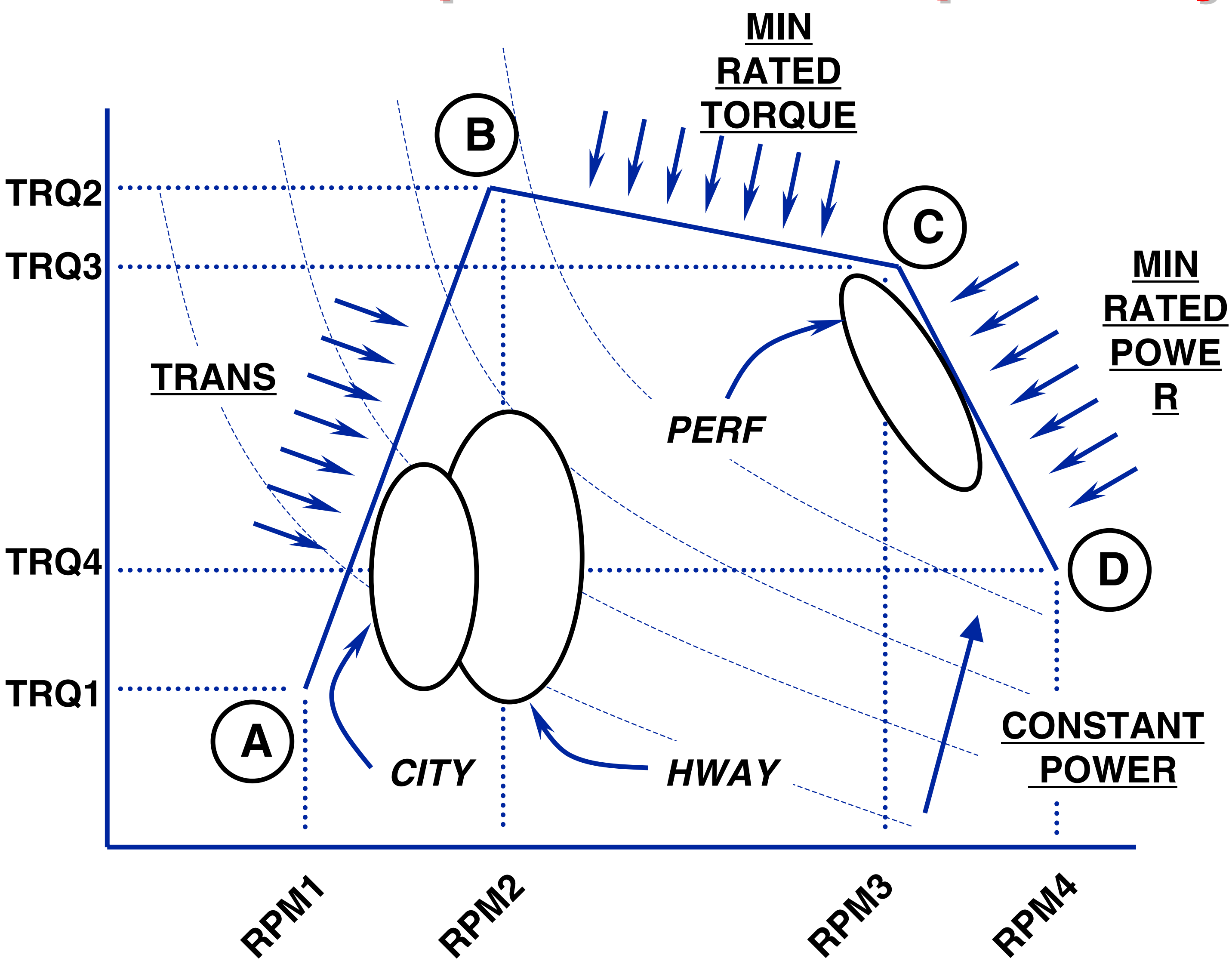
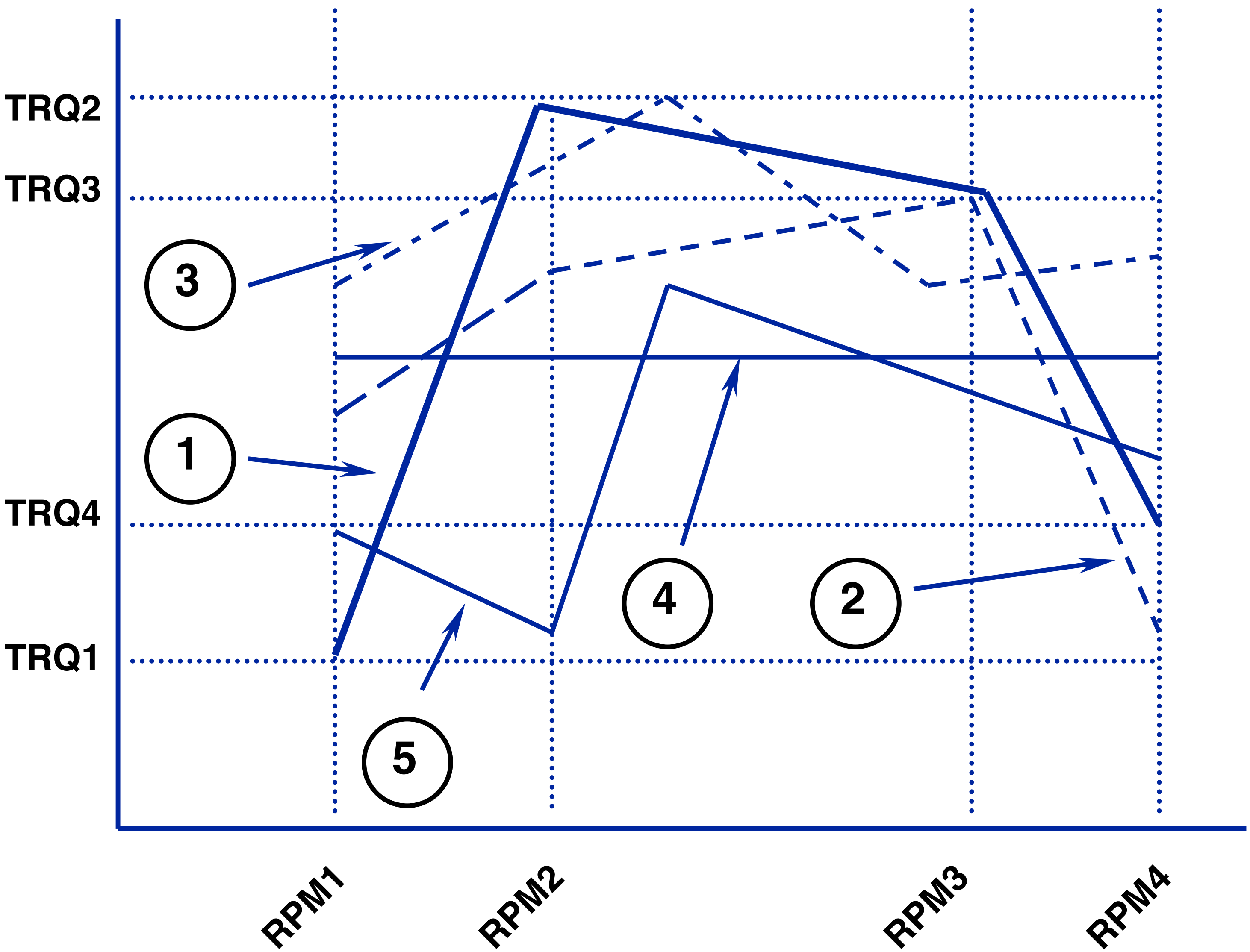
ADVISOR Subproblem: Preoptimality I

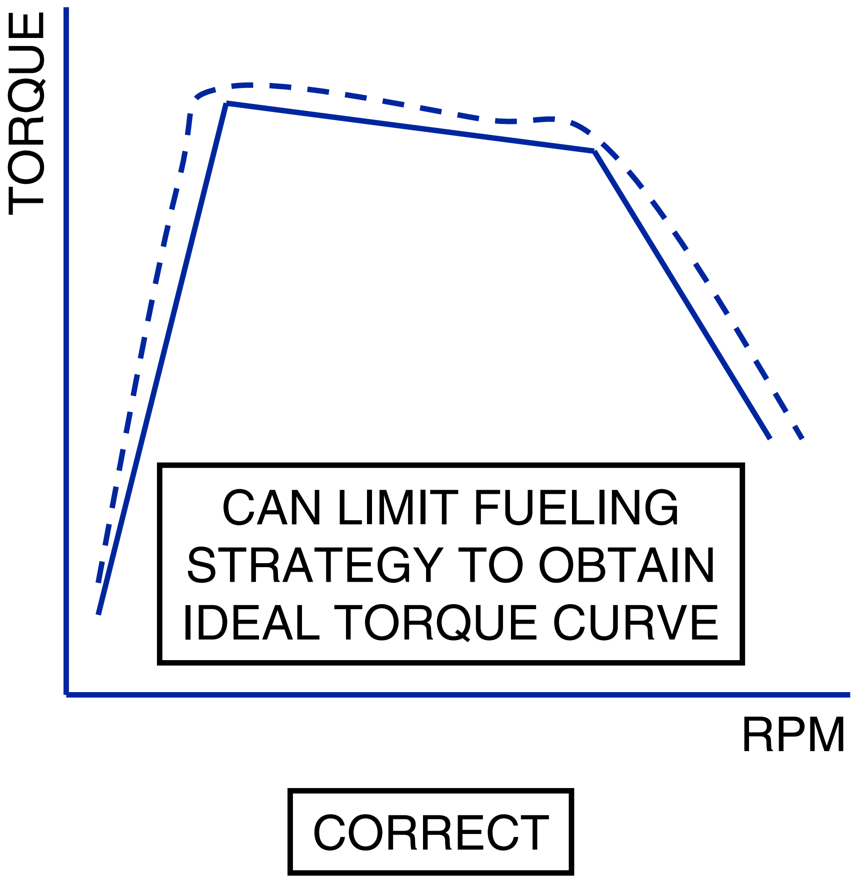


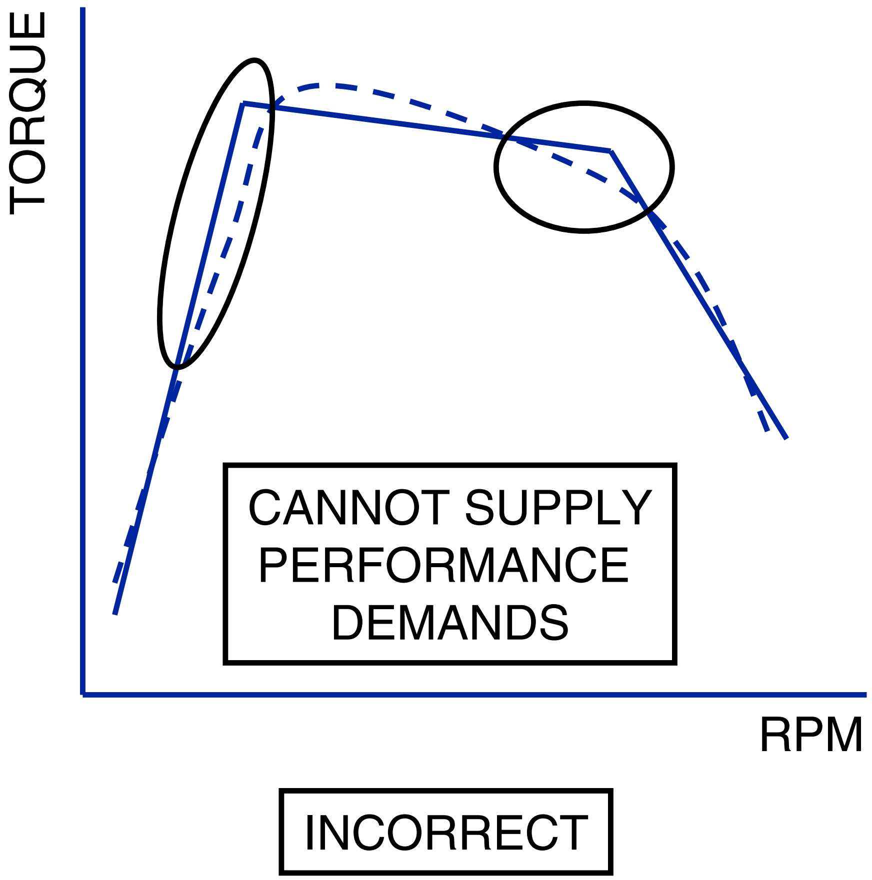
REVERSE ENGINEERING A DIESEL ENGINE

ADVISOR Subproblem: Preoptimality II

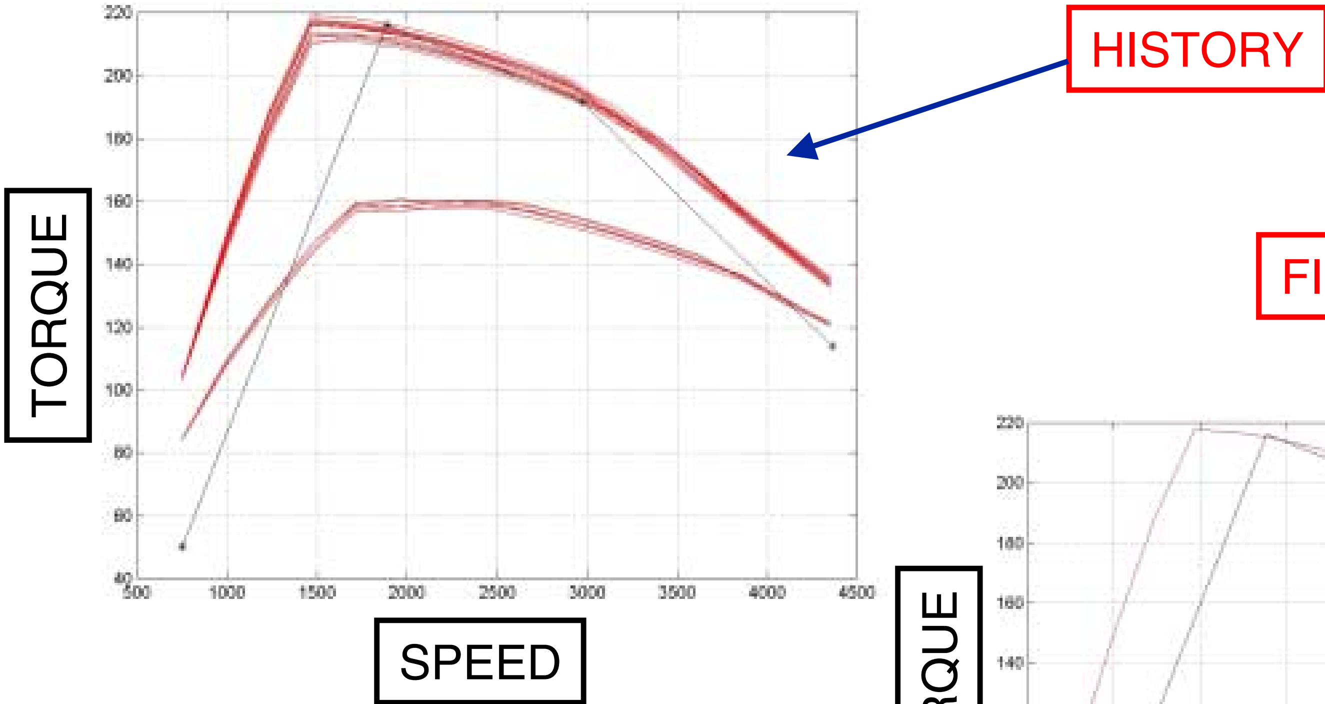


Engine Matching Scenarios





TDES Subproblem: Engine Matching



REVERSE ENGINEERING A DIESEL ENGINE

ADVISOR Subproblem: Problem Statement

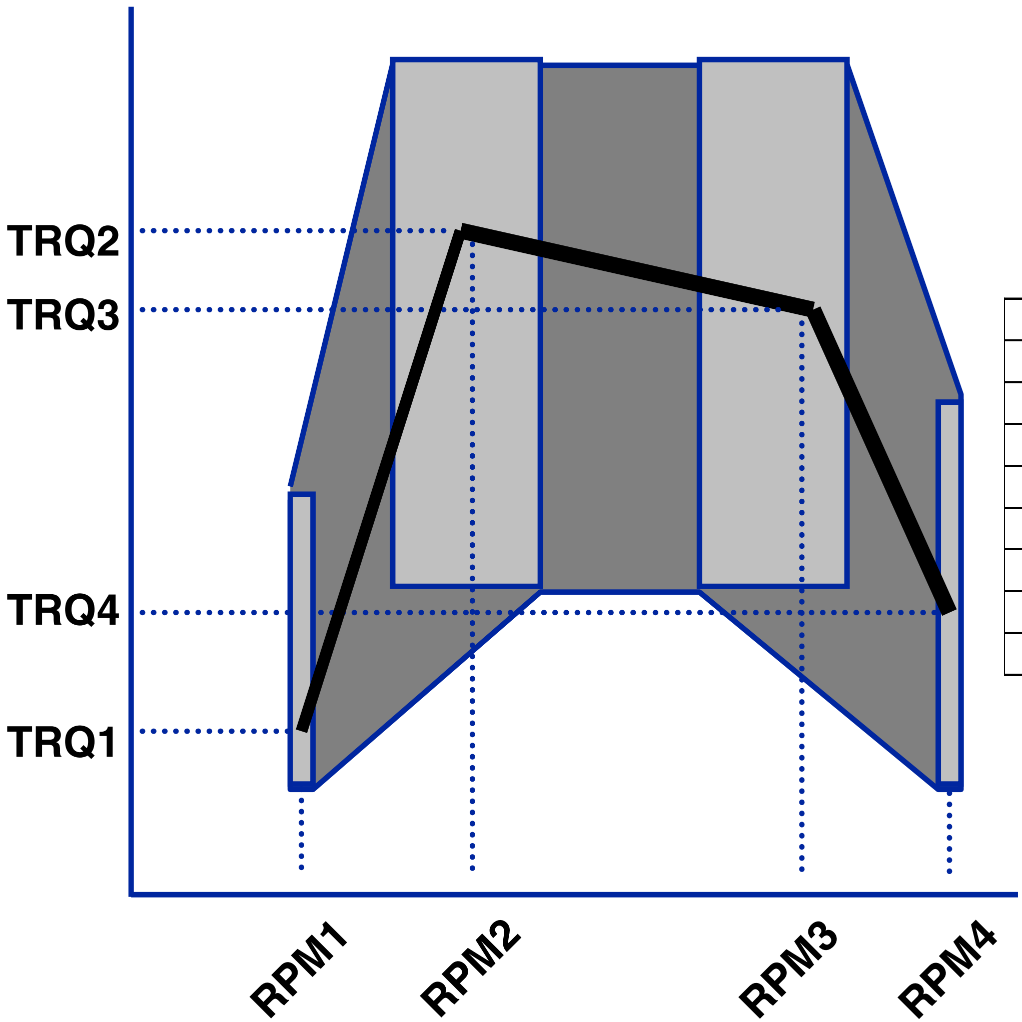
minimize (Rated Torque + Rated Power) =

f(RPM1, RPM2, RPM3, RPM4,
TRQ1, TRQ2, TRQ3, TRQ4)

subject to:

0 – 60 mph	□	12 sec.
40 – 60 mph	□	5.3 sec.
Maximum speed	□	100 mph
0 - 85 mph	□	24 sec.
5 sec. Distance	□	140 ft.
max acceleration	□	0.5 g's
cruising grade (55 mph)	□	6.5%
max launch grade	□	30%
max difference between vehicle and driving cycle speed traces	□	2 mph
number of gear shifts	□	180
TRQ3	□	TRQ2
TRQ4	□	0.7 (TRQ2)
TRQ1	□	0.5 (TRQ2)

ADVISOR Subproblem: Variable Ranges



VARIABLE	LOWER BOUND	UPPER BOUND
RPM1	750	850
RPM2	1800	2500
RPM3	2550	3000
RPM4	4350	4450
TRQ1	50	150
TRQ2	70	250
TRQ3	70	250
TRQ4	50	190

TDES Subproblem: Problem Statement

minimize f = engine displacement

subject to:

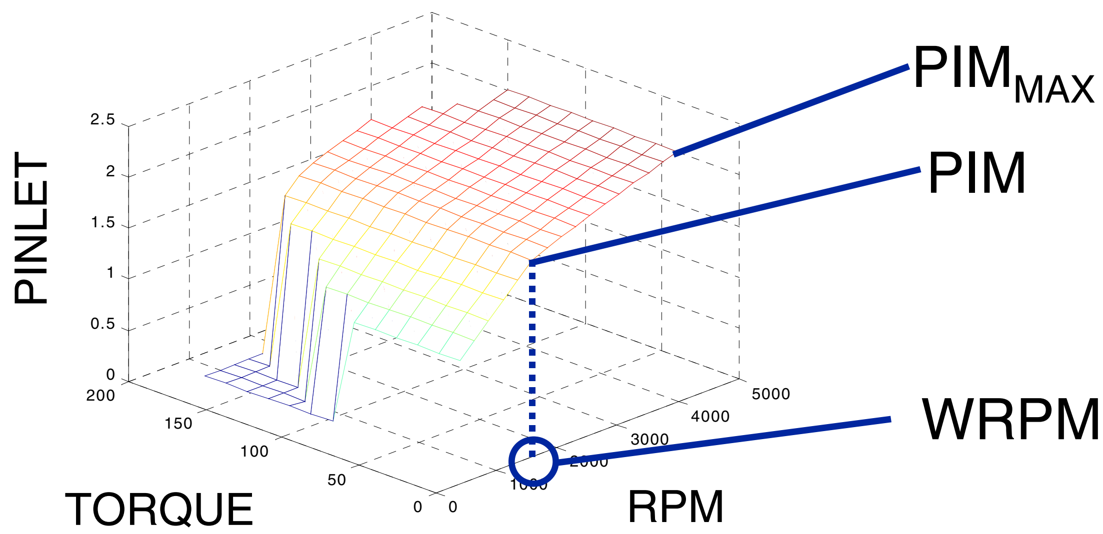
ADVISOR TRQ(i) □ TDES TRQ(i)

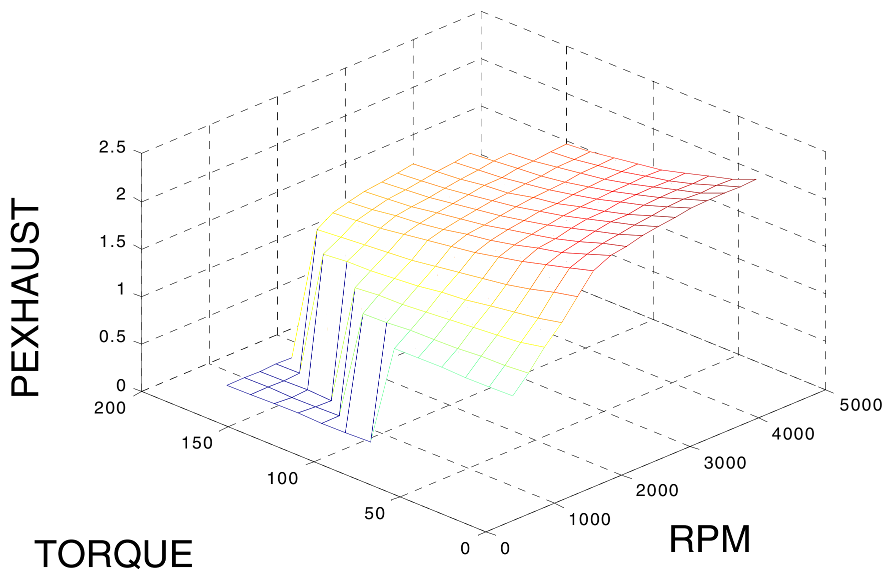
where i = 1 to 16

Variables:

DISP:	engine displacement
CMRTIO:	compression ratio
PIM:	inlet manifold pressure at wastegate activation point
WRPM:	wastegate activation point (RPM)
PIM_{MAX}:	maximum inlet manifold pressure

TDES Subproblem: Engine Variables





ENGINE DISPLACEMENT
COMPRESSION RATIO
WRPM
PIM
PIM$_{MAX}$

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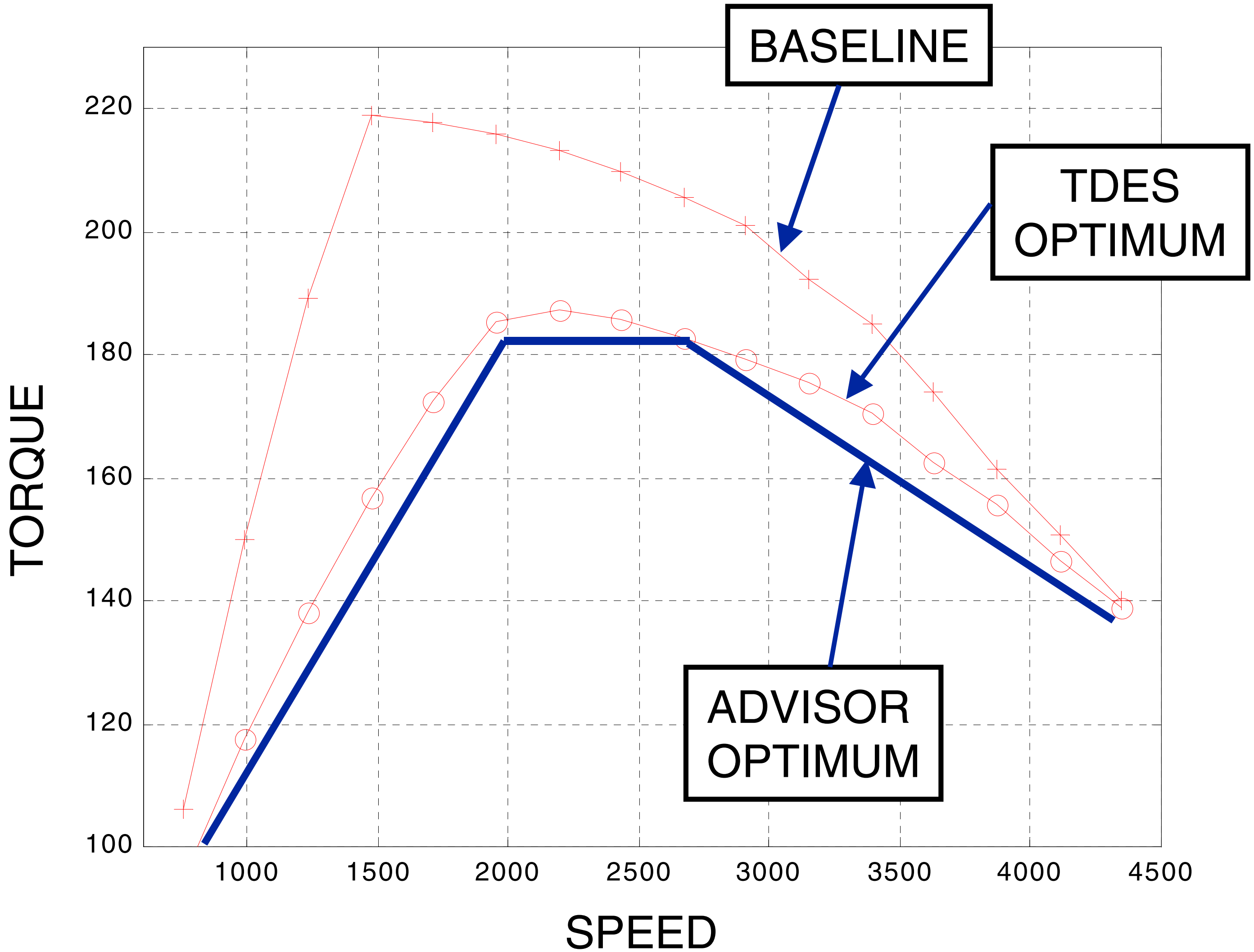
Final Maximum Torque Curve



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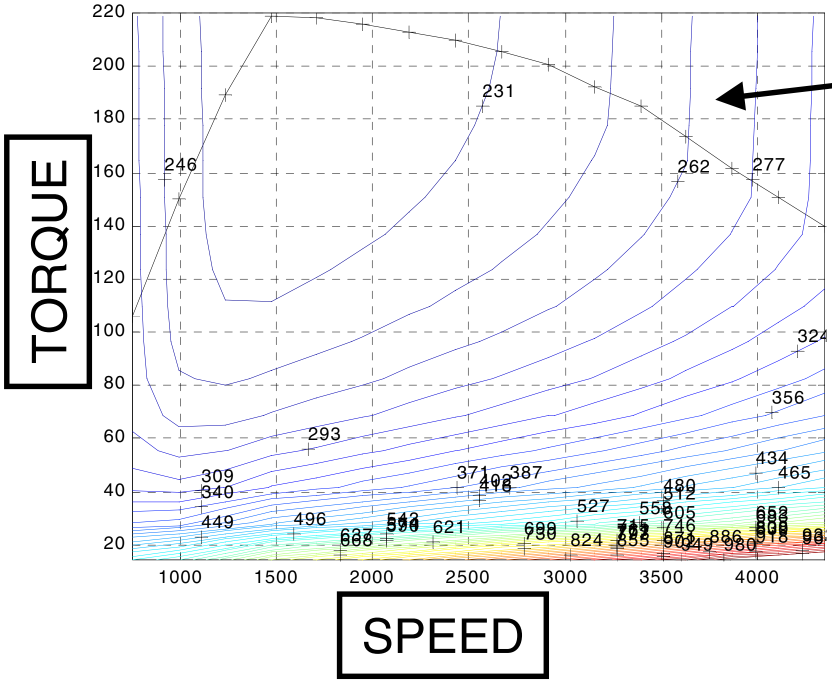
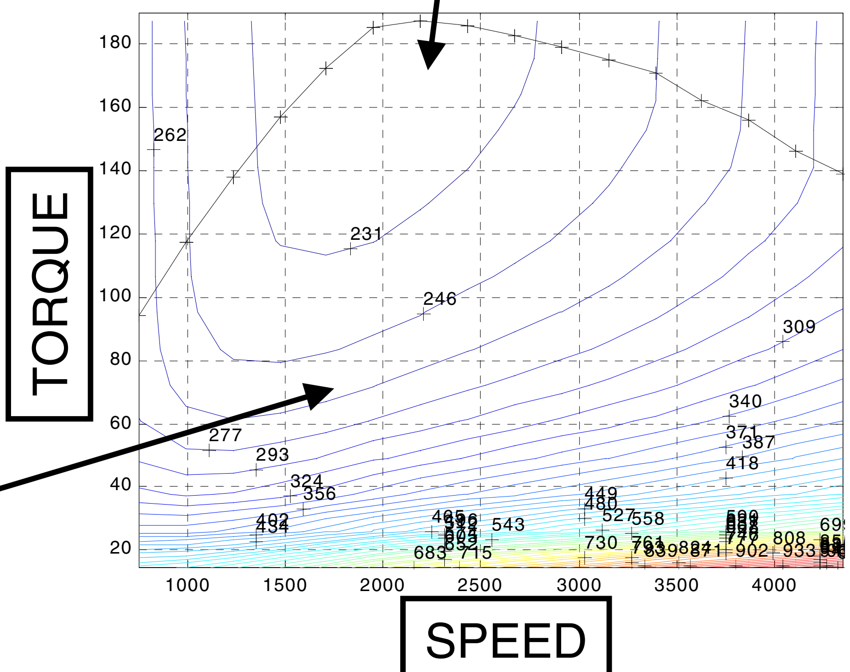
Baseline vs. Optimum Engine Map



BASELINE

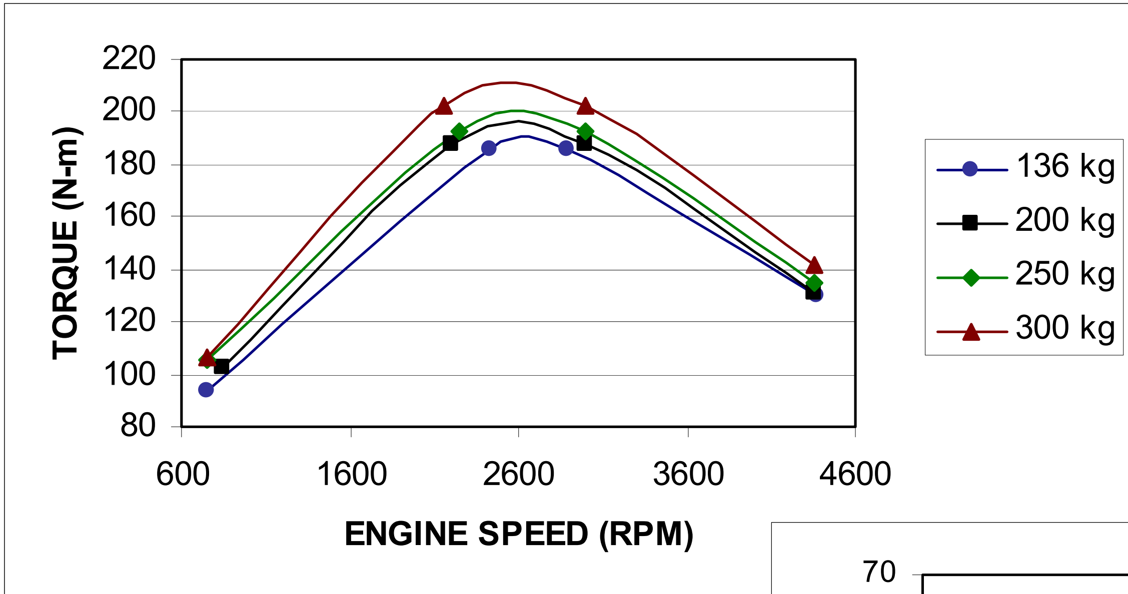
OPTIMUM

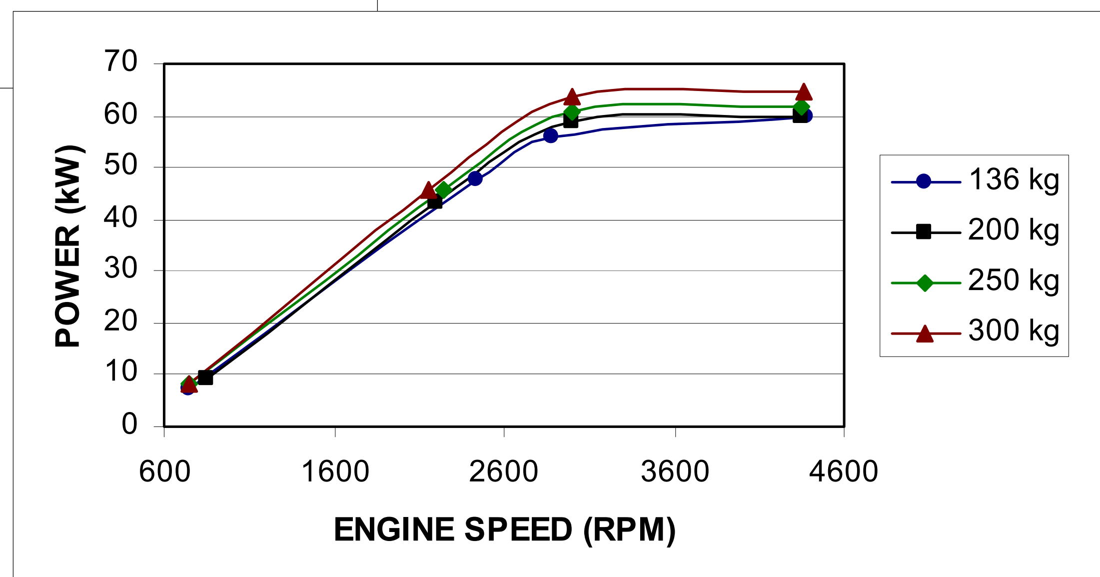


5.6% Better Fuel Economy in the FTP Cycle - almost identical performance to baseline

REVERSE ENGINEERING A DIESEL ENGINE

Post-Optimality: Cargo Mass Study



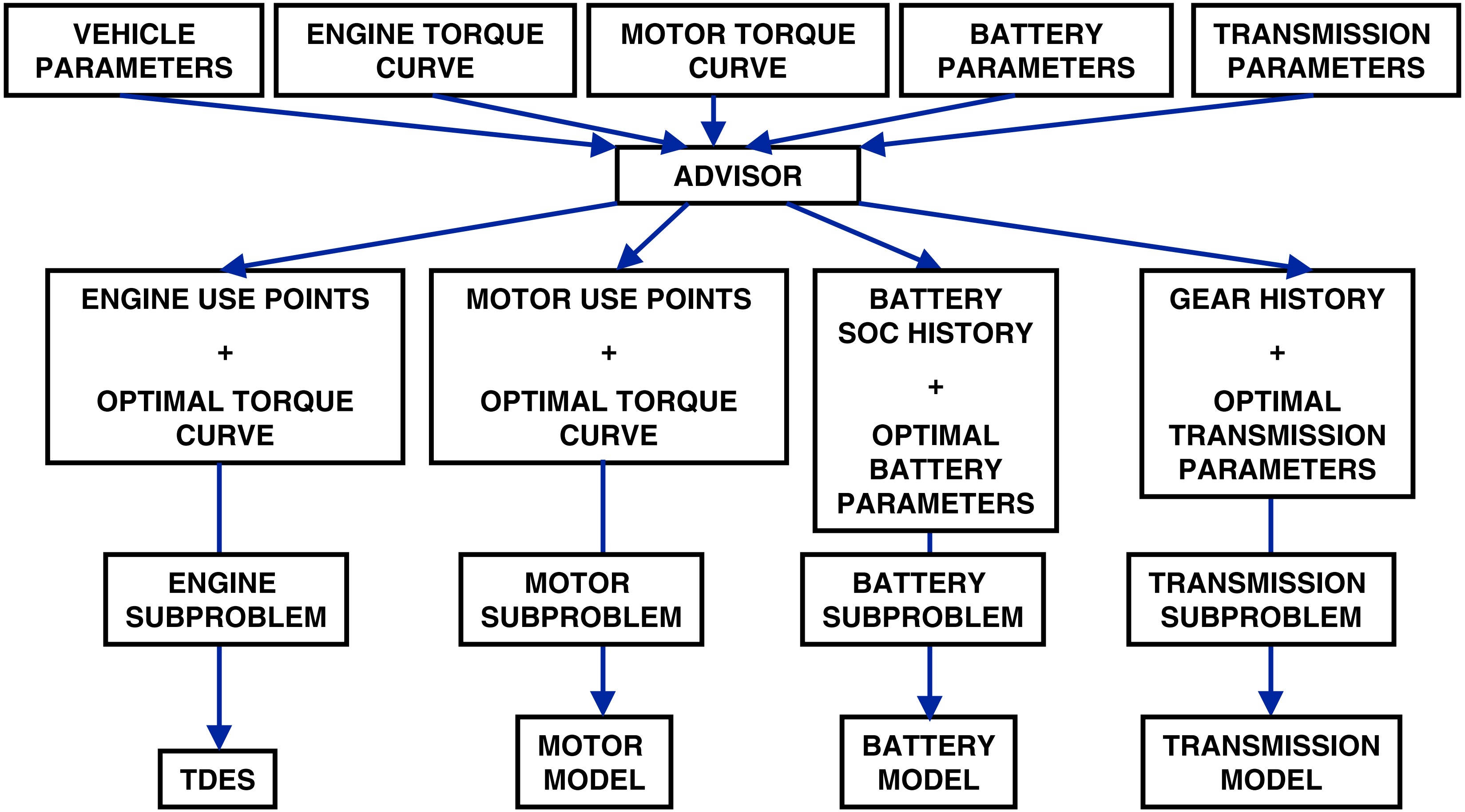


REVERSE ENGINEERING A DIESEL ENGINE

Research Direction

- **Emissions modelling**
  - Zero-, quasi - dimensional, and multi-zone models
- **Transmission parameters**
  - Gear ratios and upshift/downshift strategies
- **Trade-off analyses**
  - Vehicle mass, driving cycles, and product platform design
- **Methodology refinement**
  - Different parameterization techniques as well as coordination methods
- **HEV system applications**

Possible Decomposition of HEV System



The Reverse Engineering of a Diesel Engine: A Unified Systems Approach Using ADVISOR

George J. Delagrammatikas and Dennis N. Assanis
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Ann Arbor, MI

ABSTRACT

The need for a rigorous systems engineering approach to automotive powertrains has been addressed in this work from the perspective of the diesel engine. A high-fidelity engine simulation has been integrated with a total vehicle model for the purpose of reverse engineering the optimal powerplant for a given vehicle mission. Engine parameters have been coordinated between the simulations to develop a framework for total vehicle design. The design strategies discussed in this paper allow engine researchers to set targets for individual system components and to analyze the tradeoffs associated with different vehicle mission objectives. A detailed case study employing these techniques is presented for a conventional vehicle where the most fuel-efficient engine is found that simultaneously conforms to the desired performance criteria.

INTRODUCTION

The increasingly stringent requirements on fuel-efficient and environmentally-friendly automotive primemovers has encouraged the development of programs, both in industry and academia, to promote the research of alternative powerplants. The Partnership for the Next Generation of Vehicles (PNGV), a consortium of automobile companies, research laboratories, and universities, is involved in the discovery and development of new technologies intended to provide the motive force for vehicles of the future. More specifically, the advancement of alternative fuels and hybrid powertrain technologies is currently the primary PNGV goal.

In order to achieve this objective, the industrial, governmental, and institutional researchers have conducted field-testing and computational studies for the purpose of screening candidate technologies. Though simulation work is associated with great time and cost savings for the designer, the implemented models must be validated through prototype verification. Overall system simulation and design is an iterative process which rests heavily on the coordination of data between the modeler and the experimenter. Such overall system simulations exist for various vehicle configurations and range from proprietary automobile company codes to easily downloadable shareware. These simulations often contain simplified models of vehicle components that should be replaced or enhanced by a researcher on a need-driven basis.

In order to understand the effects of powertrain design on overall vehicle system behavior, we must first describe the vehicle analytically and perform meticulous studies on its feasible design domain. Therefore, validated simulations must be implemented within design frameworks to allow for more rigorous examinations of vehicle design. For this purpose, the ADvanced VehIcle SimulatOR (ADVISOR), a public domain software package, was developed by the National Renewable Energy Laboratory to aid in the analysis of Hybrid Electric Vehicles (HEV's), electric, and conventional (engine-only) systems.

The diesel engine is described within ADVISOR by an associated maximum torque curve, a brake specific fuel consumption (BSFC) table, and, if available, emissions maps. These graphs are available through steady-state tests on an experimental engine. Because the data for different engines are found within ADVISOR's library of components, the researcher's complete system designs are limited to the number of engines available in that library and by the operating control strategies employed by those engines during those tests. That is, for geometrically identical engines, the control strategies used in the steady-state tests unnecessarily constrain the candidate engine designs during simulation studies. A higher-fidelity and, therefore, more versatile engine simulation is needed in order to overcome these artificially-imposed limits on the design domain.

One approach for predictive engine design would be to model engine outputs as functions of bore, stroke, speed, load, and equivalence ratio within large scale vehicle systems. The correlations found in these functions are very helpful during the preliminary design process, but the engine, as a subsystem, must be modeled in a manner that would allow for component level design. For this reason, higher-fidelity simulations have been developed which implement first principles in their predictive capabilities. Though more time-consuming to validate and execute, these types of simulations allow the user to vary lower-level quantities, such as engine geometries and thermodynamic properties. In both these approaches, the lower- and higher-fidelity submodels can be integrated and executed simultaneously (as in ADVISOR). More specifically, the entire system model is a transfer function for all system inputs (regardless as to their effects on vehicle metrics) and outputs. Engine design using this ‘all-at-once’, or forward problem solving technique though, is iterative and computationally intensive for either engine modeling approach.

A more relevant and challenging exercise in the system design process is to identify the optimal engine for the vehicle’s mission. This process, which is the focus of this work, is termed ‘reverse engineering.’ Here, the system (vehicle) level objectives are converted into subsystem (engine) level targets which are then used to match a realistic subsystem to attain the vehicle’s mission. The design of the engine’s subsystems and components must be coupled to a vehicle model for overall system design and the data between different models must be coordinated in a systematic fashion. This process insures minimal computational expense and greater certainty that the final result is the true optimal design.

A procedure to allow the powertrain designer to quantify the tradeoffs associated with engine design at the component level is illustrated in this paper. The following work describes a methodology for powertrain optimization using enhanced versions of ADVISOR and a turbocharged diesel engine model. A technique has been developed to define the engine torque characteristics required to accomplish a specific vehicle mission. Then, an engine simulation has been implemented to find the most fuel-efficient engine that could deliver the performance requirements of that vehicle. In effect, this procedure solves the inverse problem – the vehicle determines the properties of the optimal powerplant it requires.

Implementation of a high-fidelity engine model with ADVISOR will be discussed along with the versatility in design achieved from their interaction. Then, the fundamental design issue posed in this research will be developed and extended to the simulations used. Finally, a representative case study to illustrate the flexibility of this design framework is presented and discussed.

ADVISOR: A BRIEF DESCRIPTION

ADVISOR is a MATLAB/SIMULINK-based, feed-backward simulation for HEV and conventional powertrains [Wipke and Cuddy 1997]. ADVISOR allows for analysis of the performance, emissions, and fuel economy of conventional, electric, and hybrid vehicles., and has been validated on numerous occasions in the open literature [Senger 1997]. The component models in ADVISOR are empirical, relying on input/output relations measured in the laboratory, and quasi-static, using data collected in steady state tests and correcting them for transient effects, such as the rotational inertia of drivetrain components. ADVISOR offers the designer great flexibility in changing many of the models found in it. These models act as placeholders that can be replaced by higher fidelity models when detailed studies regarding a particular subsystem are required.

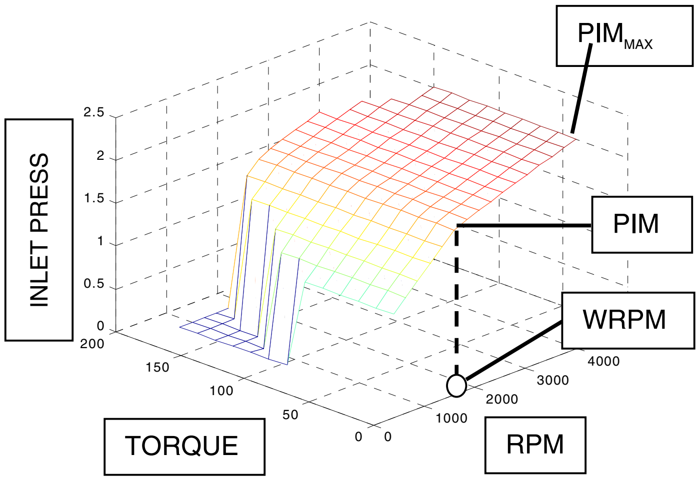
Each block represents a component of the calculation that determines vehicle fuel economy and performance metrics for a specified driving cycle. The block diagram starts on the far left with data regarding the actual cycle through which the vehicle is to be driven. Next, vehicle velocity is passed to a load-calculating block that finds the total load on the vehicle (including inertial, aerodynamic and rolling resistance). Then, the proceeding blocks calculate the loads and speeds that the engine and/or motor must output in order to accelerate the vehicle to the required vehicle speed.

The ADVISOR simulation style is called feed-backward since the flow of control begins with the torque required at the tire and ends at the fuel flow rate required by the engine. In real life, a vehicle operator has control of the fuel pedal and varies its position in order to get the required torque to achieve a desired speed. The first challenge in this research was to integrate ADVISOR with a high-fidelity engine simulation that is feed-forward in nature.

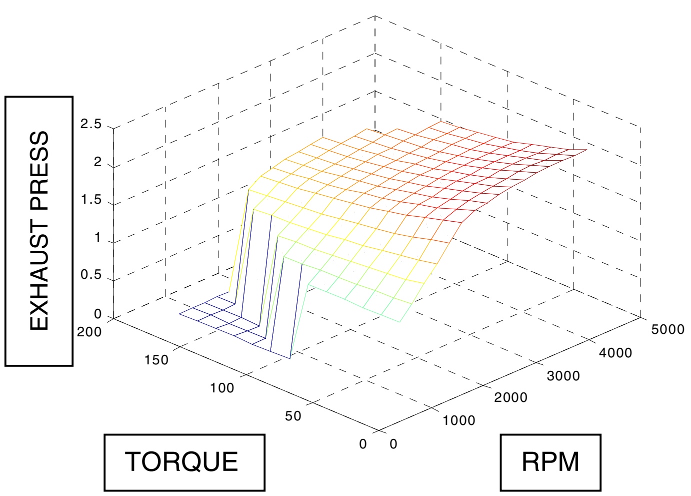
DIESEL ENGINE SIMULATION

The Turbocharged Diesel Engine Simulation (TDES) used in this work is a modified version of the parent code first developed by Assanis and Heywood [1986]. TDES is a zero-dimensional, quasi-static, feed-forward engine simulation which predicts engine outputs at a single operating point (engine speed and fueling rate combination). The diesel four-stroke cycle is treated as a sequence of continuous processes: intake, compression, combustion (including expansion), and exhaust. Quasi-steady, adiabatic, one-dimensional flow equations are used to predict mass flows past the intake and exhaust valves. Combustion is modeled as a uniformly distributed heat release process, using Watson’s correlation [Watson 1980]. Convective heat transfer in the combustion chamber is modeled using a Nusselt number correlation based on turbulent flow in pipes and the characteristic velocity concept [Assanis and Heywood 1986] for evaluating the turbulent Reynolds number in the cylinder. The characteristic velocity and length scales required by these correlations are obtained from an “energy cascade” zero-dimensional turbulence model [Tennekes 1972]. Radiative heat transfer is added during combustion [Heywood 1988]. The combustion chamber surface temperatures of the piston, cylinder head, and liner can be either specified or calculated from a specification of the wall structure. A friction sub-model based on the Millington’s and Hartles’ correlation [Millington and Hartles 1968] is used to predict the engine friction losses and convert indicated to brake quantities.

The calculations above are made for an individual cylinder only (termed the master cylinder) and are then imaged for the number of cylinders specified by the user. The interaction between the master cylinder model and the other components is accounted for in the manifolds modeled as separate control volumes. There is instantaneous mixing of all mass flows that enter the intake manifold with the gases in the manifold. To complete the system, a compressor is connected to the inlet side of the intake manifold and a turbine is connected to the outlet side of the exhaust manifold. The fundamental equations for turbocharger design can be found in [Watson and Janota 1982].



(a)



(b)

Figure 1: TDES parameterized inputs for inlet manifold pressures (a) and their associated, predicted exhaust manifold pressures (b).

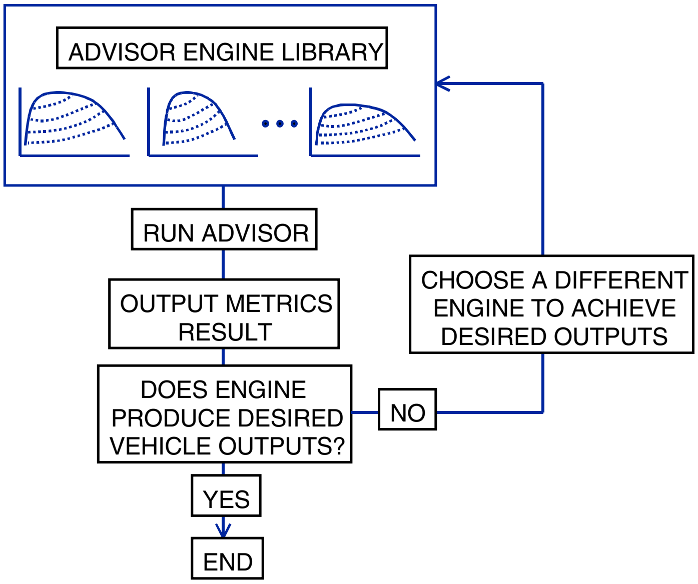
For this study, TDES was developed to emulate variable geometry turbocharging (VNT) with a wastegate. The parameters that describe the inlet manifold pressure (PIM), the maximum boost pressure (PIM_{MAX}), and the engine speed at which the wastegate becomes activated (WRPM) have been added to this simulation in order to simulate a realistic engine of this type. The turbine and compressor efficiencies were held constant throughout the engine speed and load range while exhaust backpressures were predicted. Example pressures are illustrated in Figure 1. By parameterizing the PIM and WRPM, TDES now enables the user to perform studies regarding novel inlet boost techniques including VNT, multi-stage turbochargers, and supercharger design. These investigations include the reverse engineering of auxiliary pressure boost designs in the same manner that the overall engine subsystem is designed in the work presented herein, and are currently being researched by the authors.

SOLVING THE FORWARD PROBLEM: USING DOCUMENTED ENGINE DATA

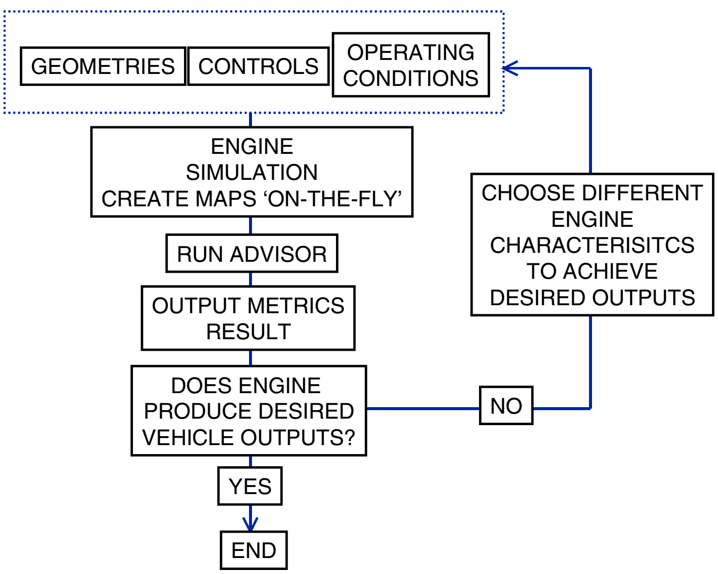
An ADVISOR user investigating the effects of engine parameters on overall vehicle metrics would typically select a suitable engine, transmission, and chassis for a particular application. Once ADVISOR is invoked, the performance metrics and fuel consumption criteria are calculated. At this point, the user would either vary the engine altogether or scale it linearly (using the associated torque and speed scale parameters). This procedure, illustrated in Figure 2 (a), is time-consuming and does not assure the user that the resulting engine configuration is optimal, or even realistic. To guarantee that the engine is a plausible design, we must introduce TDES as the engine model and link it, either directly or indirectly, with ADVISOR.

The motive behind linking TDES and ADVISOR was to separate all the engine-related variables and parameters from those that describe the rest of the overall vehicle. In so doing, more accurate studies regarding the engine subsystem could be performed because the overall system simulation's noise level would not adversely affect the TDES calculations. The flow of this process, illustrated in Figure 2 (b), is contrasted with the traditional approach mentioned earlier in Figure 2 (a). TDES outputs though, may still be masked by underlying vehicle simulation results if it were embedded within ADVISOR as in [Fellini et al 1999][Sasena et al 1999]. The following example illustrates this point.

Let us consider that the engine designer would like to understand the effects of varying bore size on the overall fuel economy of a vehicle driven through the Federal Urban Driving Schedule (FUDS). Before TDES and ADVISOR were coupled, this type of study was not possible. Now that the bore can be varied using TDES, an accurate prediction of engine characteristics can be produced for an engine by only varying the bore size. A new engine map could be produced 'on-the-fly' and sent directly to ADVISOR from TDES for system calculations.



(a)



(b)

Figure 2: Typical engine design method using ADVISOR currently (a). Technique implemented with an integrated engine model like TDES (b).

However, because the approximations present in ADVISOR's correlations bring with them inaccuracies to the final output, how is the designer to determine the true effect of a slight change in bore to the output MPG? Similarly, if these simulations were placed within a gradient-based optimization routine, how could the optimizer converge properly when the derivatives found at each design point were affected by the variable change and by an unknown noise or inaccuracy level in the simulation? There is now a need to separate these models while still keeping the information pertinent to their individual calculations consistent. The techniques illustrated in the following sections will address these issues.

SOLVING THE INVERSE PROBLEM: CREATING OPTIMAL ENGINE DATA

Among the various system outputs that are crucial in vehicle design are fuel economy, emissions, and performance; the federal regulations and PNGV constraints for which will be detailed shortly. Of the three, we will now assume that the principal factor behind the acceptance of a vehicle in a specific market is performance. Regardless as to how clean and efficient an engine is, it cannot be an admissible design for a vehicle if it does not supply the adequate power and torque levels required by the drivetrain and the consumer. Though extremely important design quantities, fuel efficiency and emissions characteristics under different speeds and loads must be optimized for the engine that already meets the performance criteria. To replicate the design process in the laboratory, we will shortly illustrate one powertrain design iteration through simulation and extend this procedure with an optimization framework.

Breaking down an overall system model into smaller submodels is performed in a methodical manner in order to decrease computational expense and to ensure conceptual simplicity. This procedure generally allows greater modularity among the many submodels involved, thus increasing the potential for their parallelization on different computers and/or optimization routines [Michelena et al 1999][Scheffer 1997]. Detailed descriptions of the basic groups of decomposition strategies can be found in the open literature [Papalambros et al 1997].

Depending on the modularity of the models found in the large-scale simulations being investigated, the user will find that one decomposition method may be more attractive to implement than others. In this study, the natural break-up of the subsystems, or object decomposition, was most suitable.

Figure 3 shows how ADVISOR and TDES were separated and what variables linked the two simulations. Since the programming styles of the two simulations (feed-backward and feed-forward, respectively) did not allow the two simulations to communicate, a modified Newton-Raphson techinque was developed to deliver an engine map automatically from TDES to ADVISOR in the required data format [ARC98-1][ARC98-2].

Block 1 and 2 represent the two decomposed optimization subproblems (ADVISOR and TDES, respectively). In Block 1, ADVISOR interprets the performance constraints placed on the vehicle as a maximum torque profile required by the engine. Upon finding the optimum curve to satisfy the vehicle mission, TDES matches the torque curve in Block 2. After finding the most fuel-efficient engine to do so, TDES then calculates the entire BSFC map and supplies Block 3 with the data. In the final block, ADVISOR simply calculates the true fuel consumption for the cycle using the data from TDES.

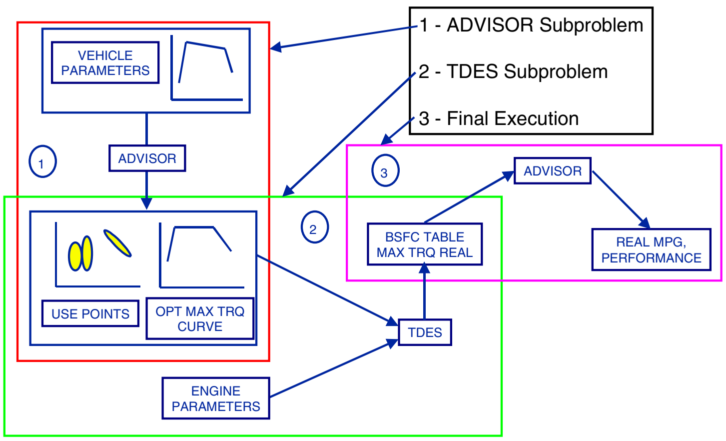


Figure 3: Schematic of decomposition procedure applied to ADVISOR and TDES.

Table 1: PNGV performance constraints used to define the engine's minimum required torque envelope.

0 – 60 mph	≤ 12 sec.
40 – 60 mph	≤ 5.3 sec.
Maximum speed	≥ 100 mph
0 - 85 mph	≤ 24 sec.
5 sec. Distance	≥ 140 ft.
max acceleration	≥ 0.5 g's
cruising grade (55 mph)	≥ 6.5 %
max launch grade	≥ 30%

Varying the Maximum Torque Curve – Because a real engine does not yet exist for our purposes and, realizing that the vehicle must have adequate acceleration to be acceptable, we parameterize the maximum torque curve of that engine. This curve then replaces the data for the engines previously used within ADVISOR and the associated BSFC and emissions calculations are suppressed. Thus, we can convert the parameters that define the engine's torque curve into the variables used in parametric studies or in an optimization routine.

The torque curve can be parameterized in a variety of methods that should be determined by the designer of the overall system. In this study, we have chosen to describe the maximum torque curve in a piecewise linear fashion. Three parameterized curves are shown in

Figure 4. Note that the (+) symbols are actual engine use locations during the FUDS cycle and the (o) symbols are for the performance run. Note that all of these curves are arbitrary and that developing a legitimate torque profile that is achievable by a real engine requires interaction with TDES.

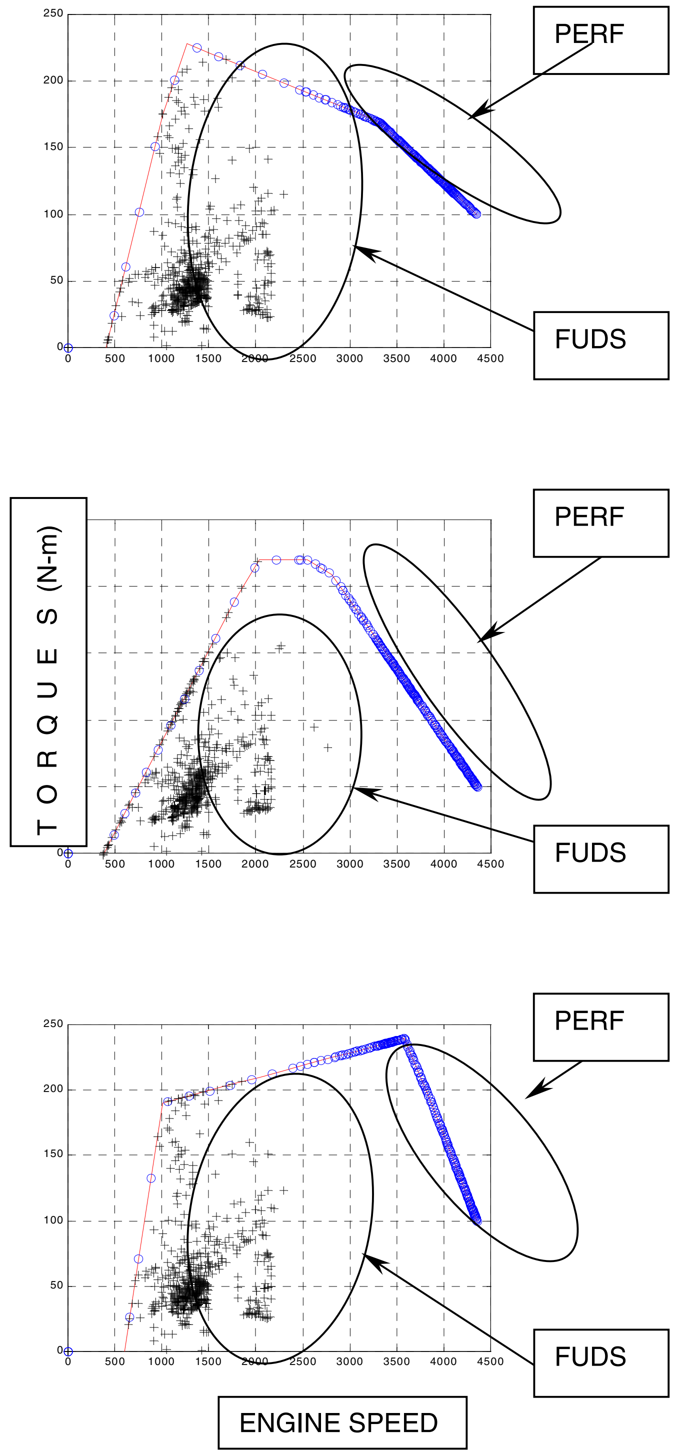


Figure 4: Three arbitrary, parameterized torque curves that were used in ADVISOR.

ENGINE MATCHING – The above subsections aimed at finding the profile of a maximum torque curve that would meet the vehicle's performance. The procedure described allows the designer to vary the location of the engine use points under the maximum torque curve.

How does one now reverse engineer the engine that will fit these torque demands while simultaneously meeting the ever-stringent fuel economy regulations? Also, how can the linking between the simulations be developed such that the transmission, torque profile, emissions, and BSFC characteristics of the powertrain are optimized at the system level?

TDES Torque Curve Matching Method – Because TDES was enhanced to automatically produce a complete maximum torque curve and BSFC map, it can now be wrapped within an optimization framework where it attempts to find a real engine which comes as close as possible to supplying the desired performance from ADVISOR, but can still remain as fuel-efficient as possible. The goal here is to guarantee that the real torque curve is always greater than or equal to the curve from the ADVISOR subproblem (not that the real torque curve is as close as possible to the required curve). Figure 5 explains this fact in more detail.

In Figure 5 (a), the ADVISOR and TDES curves were matched in a least squares sense. We see here that TDES cannot supply the required torque at certain levels (regions I and II specifically). In addition, the resulting engine has a displacement of 1.8 liters and is not highly boosted. Conversely, Figure 5 (b) shows a 1.7 liter that is highly boosted and has a high compression ratio.

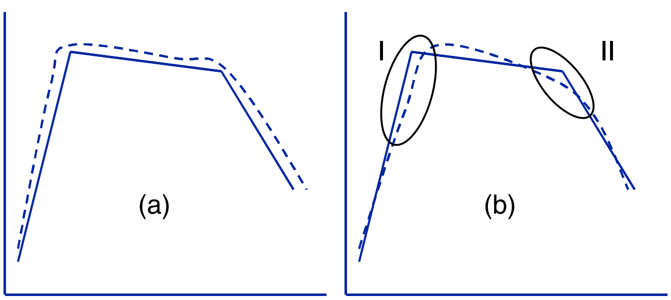


Figure 5: Different methods of matching ADVISOR and TDES maximum torque curves. (a) is correct, (b) does not afford the proper vehicle performance.

Once the BSFC tables were produced with TDES for both these engines and reimplemented within ADVISOR, the smaller engine yielded a higher MPG rating. Therefore, the 1.7-liter would be the more appropriate candidate design. Choosing the proper objective in the TDES subproblem is crucial in obtaining the most fuel-efficient engine; a fact that will be discussed shortly. The designer has the option of using either torque curve during the final ADVISOR MPG run. Though the engine is capable of achieving higher torques, it can be controlled electronically not to do so through a fuel-limiting strategy. The differences between the fuel economies in either case will be revisited shortly.

CASE STUDY OVERVIEW

Now that the simulations have been coordinated in the above manner and the required torque curve characteristics can be varied, we can formulate the problem which best describes the vehicle's mission.

A small passenger car's characteristics were chosen from the ADVISOR library of vehicle properties. The overall objective of this vehicle was to minimize fuel consumption during the Federal Test Procedure, which incorporates urban and highway driving patterns, as well as adhere to a number of minimum performance metrics. These performance requirements were listed in Table 1.

The design procedure that will be illustrated in the following section is composed of three distinct studies that allow the designer to perform a comprehensive assessment of the resulting engine. These studies are pre-optimality, optimization, and parametric investigations, listed in the order in which they should be performed. The discovery of optima through mathematical means can be found in [Papalambros and Wilde 1991].

Pre-optimality studies allow the user to determine the effects of potential variables in the system to the vehicle objective and the constraints placed on that system. Here, different vehicle parameters can be screened according to their effect on system outputs and their realistic variability within the actual system; candidate variables can then be studied in the subsequent optimization problem. Critical scaling factors and convergence criteria for the optimization run are also found in this step. These pre-optimality studies allow the user to also establish different objective functions that can be used in future trade-off analysis studies.

Upon determining the potential variables in the design, the user must formulate the problem which best describes the system being studied. During the optimization runs, the user may find that constraints have to be changed to more appropriately describe system boundaries. In addition, the objective function may be varied or scaled to ensure proper convergence. Because Sequential Quadratic Programming (SQP) was used in this case study, termination at local minima is expected, therefore, multiple runs at dramatically different starting points should be employed with this algorithm. This procedure is termed a 'multi-start' technique.

Finally, after these previous steps have been completed, parametric studies can be performed in order to better understand the effects of parameters on the location of the optimum in the feasible design space. The designer may find that the previously applied problem statement should also be modified. 'What if…?' type studies also fall under this design step. The following section will demonstrate these procedures.

ILLUSTRATIVE CASE STUDY

Pre-optimality studies were performed on the variables that describe the maximum torque curve while the transmission settings were held constant. Several important characteristics that vary the different sections of the curve were identified, along with percent changes of vehicle performance results with respect to these changes.

PRE-OPTIMALITY STUDIES - The goal of the pre-optimality study with ADVISOR was to minimize the rated torque and power of the engine while maintaining the required performance demands on acceleration and that there were no use points that would overspeed/load the engine. In effect, this maximum torque curve would represent the smallest possible engine that could be placed in this vehicle. General observations made from this study will now be discussed.

Figure 6 depicts a representative maximum torque curve that was used as an input to ADVISOR to extract vehicle performance metrics. Points A, B, C, and D are defined by an engine speed (RPM) and an associated torque (TRQ). After each execution, the engine visitation points (or use points) for the city, highway, and performance runs were plotted. The typical location and area covered by these use points are noted for each cycle.

In order to attain the required acceleration demands, line CD was constrained to be at most tangent to the constant power curve of approximately 70 kW (the vehicle that was selected needed only 66 kW to obtain the performance requirements). This line would be defined by the minimum rated engine power required by the performance run. The engine's required torque supply was defined by the height and length of line BC. Finally, line AB was varied until a minimum required distance was attained between it and the closest use point(s), that is, the points werer not allowed to exist above this line. For AB, the transmission parameters (denoted by TRANS) at the low speed range were the driving force behind this line's slope and height.

Note that many maximum torque curves were found that could satisfy performance mathematically. Figure 7 shows how widely these torque curves could vary and how unrealistic, from an engine perspective, several of these curves were. Lines 1 and 2 are both realistic curves that can be attained by the engine; we will see shortly which one is more desirable. Lines 3, 4, and 5 cannot be matched to an engine and are simply parameter combinations at local minima within the design space. In order to understand the typical shapes of real engine torque curves, TDES was then implemented in a series of pre-optimality studies.

The important observations from these runs will help in placing realistic constraints on the overall design problem. A torque curve may be able to minimize the rated power and torque of the engine, but how feasible is it to design? In addition, in order to make fair comparisons between engine designs, the same technologies were used in each. Therefore, if the fuel consumption ratings of a 1.9l and a 1.6l were to be compared, the optimum injection timing and realistic implementation of inlet boosting technologies should be compared. More specifically, a 1.6l engine with high boost and compression ratio should not be placed alongside a 1.9l naturally aspirated engine with low compression ratio.

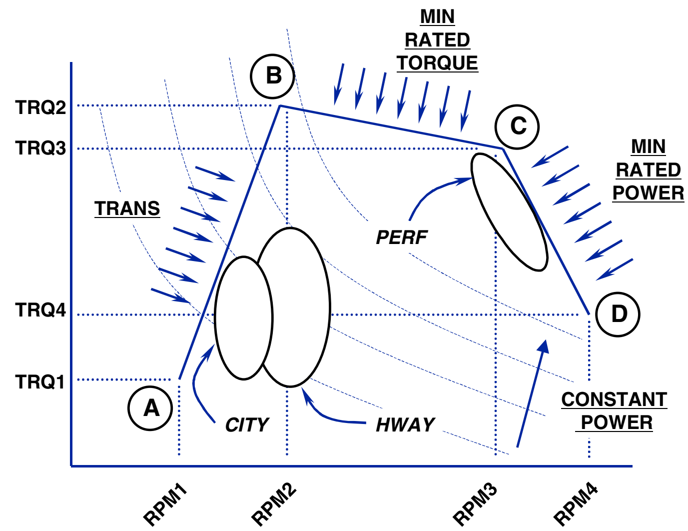


Figure 6: Representative maximum torque curve and the effects of different constraints on the heights and slopes of its three segments.

Based on the claim that for the same engine use points, a large engine would yield higher fuel consumption than a similar quality small engine, an optimization framework was developed to minimize both these quantities in a multiobjective function without any weight bias. Further studies concerning weights are left for future work.

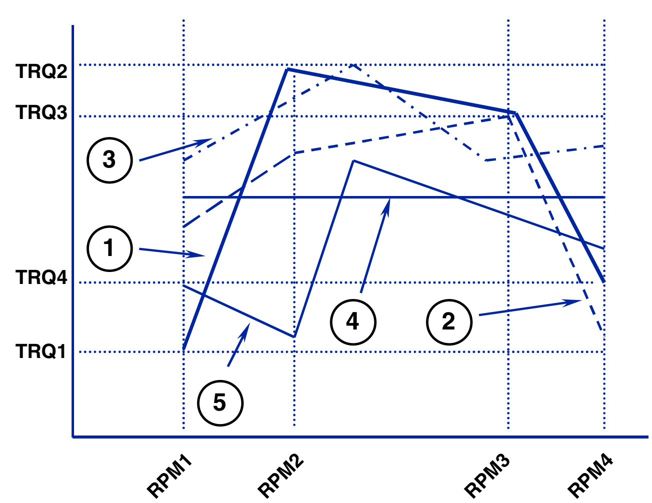


Figure 7: Examples of unrealistic torque curves that result from the ADVISOR subproblem pre-optimality study.

Each torque curve point in Figure 8 was allowed to move within its respective lighter region, which represents the domain of the variables within the optimization problem. The associated ranges for these variables are listed in Table 2. The darker region defines the feasible design space in the problem stated in Table 3. The optimization was performed at several starting points; a sampling of representative results, all of which meet or exceed the performance constraints, were shown in Figure 7. Note that there are dramatic variations between the plots, which indicate that the problem posed is not constrained properly and/or that the final result is very sensitive to the starting point.

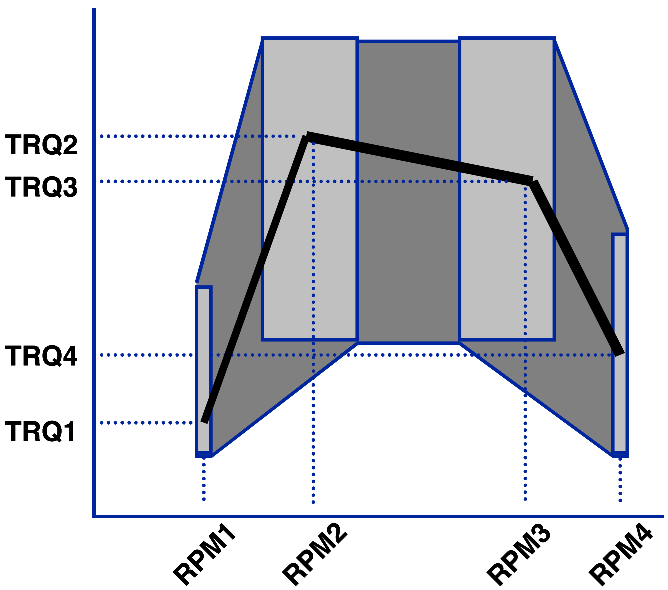


Figure 8: Range of the eight variables that defined the shape of the parameterized maximum torque curve in the ADVISOR subproblem.

The original constraints in Table 1 only reflected demands from the vehicle. Though a variety of engines could be matched to any one of these lines, we must first more thoroughly define the problem. Real-world drivability decisions were made in order to design the engines being used in vehicles today. Among them were achieving maximum torque at a low engine speed and not having to shift gears extensively throughout a particular driving schedule. For these reasons, TRQ2 must always be greater than or equal to TRQ3 (refer to Figure 6 or Figure 8 for terminology). ADVISOR was run with a baseline 1.9l engine, with data predicted by TDES, in order to find the baseline number of gearshifts.

Computational issues also arose during this process. Figure 7 illustrated several unrealistic maximum torque 'optima' which resulted during this study. Several obvious constraints are that TRQ2 must always be greater than or equal to TRQ3 and always greater than TRQ4 (unlike the conditions seen in lines 3, 4, and 5). These are mathematical constraints imposed on the engine, but there are also engine constraints that make the curve realistic. In addition, both lines 1 and 2 are valid, but the latter does not provide the drivability characteristics required by consumers. That is, maximum torque is generally preferred at the low-speed range for small vehicles. These bounds are found from pre-optimality studies using TDES.

Table 2: Range of variables for ADVISOR subproblem.

VARIABLE	LOWER BOUND	UPPER BOUND
RPM1	750	850
RPM2	1800	2500
RPM3	2550	3000
RPM4	4350	4450
TRQ1	50	150
TRQ2	70	250
TRQ3	70	250
TRQ4	50	190

The first of these realistic limits is that TRQ1 can never be greater than approximately 55% of TRQ2, attributable to the limits imposed by relatively low volumetric efficiency. Parametric studies on the entire range of engine sizes, boosting, compression, and injection timing prove this fact. By the same process, TRQ4 must be less than or equal to about 70% of TRQ2 mainly due to increased friction and decreased volumetric efficiency at high speeds. Note that these constraints only apply to the engines incorporating the technologies and engine qualitites noted previously. Finally, line AB in Figure 6 must be at least as high as the engine visitation points through the chosen driving cycle. After further pre-optimality studies, a complete optimization problem was formulated for the ADVISOR subproblem and is detailed in Table 3.

Table 3: ADVISOR subproblem definition.

minimize (Rated Torque + Rated Power) =

f(RPM1, RPM2, RPM3, RPM4, TRQ1, TRQ2, TRQ3, TRQ4)

subject to:

0 – 60 mph	≤ 12 sec.
40 – 60 mph	≤ 5.3 sec.
Maximum speed	≥ 100 mph
0 - 85 mph	≤ 24 sec.
5 sec. Distance	≥ 140 ft.
max acceleration	≥ 0.5 g's
cruising grade (55 mph)	≥ 6.5 %
max launch grade	≥ 30 %
max difference between vehicle and driving cycle speed traces	≤ 2 mph
number of gear shifts	≤ 180
TRQ3	≤ TRQ2
TRQ4	≤ 0.7 (TRQ2)
TRQ1	≤ 0.5 (TRQ2)

Upon finding a candidate torque curve using the ADVISOR routine, a real engine must be matched to the desired curve. For this reason, TDES receives the final torque curve from ADVISOR and begins to match it with a viable map. Note that the curve from ADVISOR is the minimum torque requirement for that vehicle, therefore, an engine from TDES does not necessarily have to match this curve exactly Figure 5 illustrates this point. Because the torque curve from TDES is produced at an overall fuel/air equivalence ratio of 0.7, the engine's electronic control unit (ECU) can limit the maximum fuel allowable at each engine speed such that the theoretical curve can be met for transmission purposes. In addition, once the engine is matched, TDES produces the BSFC map which is later inserted in ADVISOR to perform the necessary fuel economy calculation.

The TDES subproblem is set up in the following manner, shown in Table 4. Note that the different sets of curves reflect the history of the optimization run in Figure 9 (a), and (b) shows the final output. Let us now perform the optimization study in the next section.

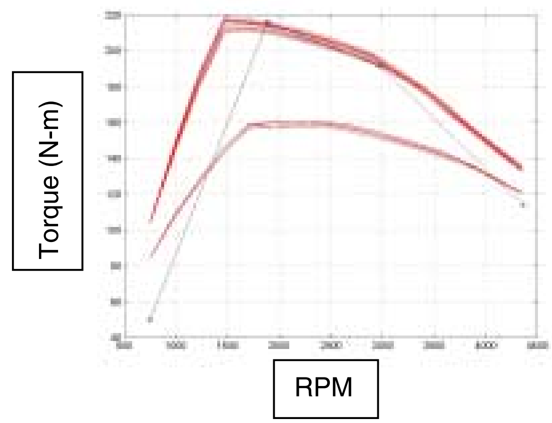
Table 4: TDES subproblem definition.

minimize f = engine displacement		
subject to:		
ADVISOR TRQ(i)	≤	TDES TRQ(i)
		where i = 1 to 16

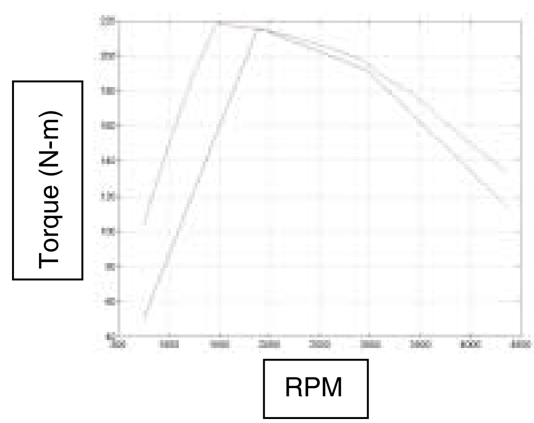
OPTIMIZATION STUDY – The problem statement with constraints and variables are listed in Table 3. Note that the ranges for the variables are the same as in Figure 10, but the feasible design space has now been properly defined. A mulststart routine was performed; the optimal maximum torque curve and BSFC table of which will be compared against a baseline engine in the following section. Note that the curve will be as flat as possible during the midrange of speeds and is constrained at the high speed range by the friction and volumetric efficiency limit of a real engine. The speed at which maximum torque occurs at the low speed range (line AB) is somewhat sensitive to starting position, but because the speed difference of all the resulting outputs is within the computational step size of that variable, the results are considered identical. This point will be revisited shortly and shown to be inconsequential to the final design of the engine.

At this point, the torque curve was supplied to TDES where the TDES subproblem was invoked. After a number of multistarts, the engine with the smallest displacement, which matched the ADVISOR torque curve, was found. The resulting torque curve and corresponding BSFC table will be contrasted with a baseline engine in the following section.

The next step in this process is to determine if this engine truly provides improved fuel economy at the required vehicle performance. The torque curve and fuel map are then sent back to ADVISOR where the fuel mileage is calculated. This calculation can be made in several ways. First, the required torque curve can be used in conjunction with the optimum TDES fuel map. Next, the TDES torque curve can be used with the TDES fuel map. This procedure would allow the user to determine whether the constant transmission settings can now be varied to maintain performance, but increase cycle fuel economy as well.



(a)

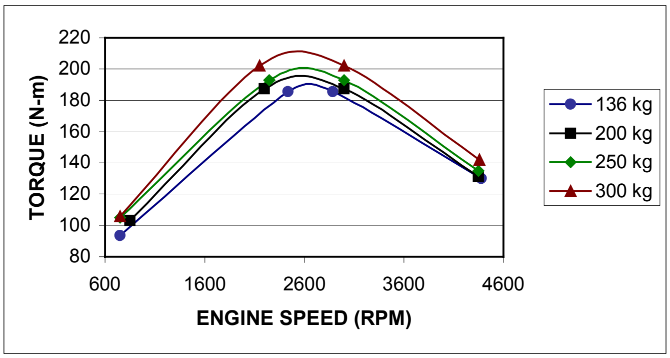


(b)

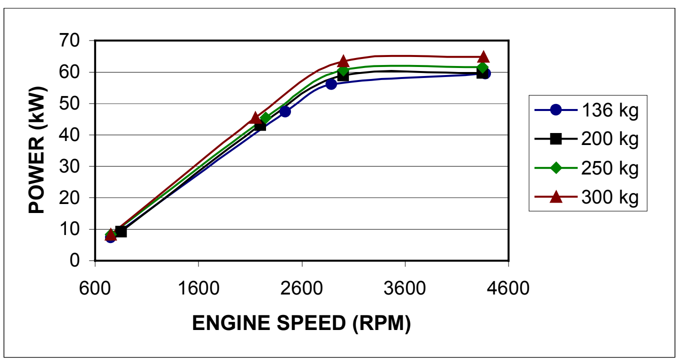
Figure 9: Sample TDES subproblem history (a) and final result (b).

POST-OPTIMALITY STUDIES – Potential "What if…?" type studies that can be performed in this part of the investigation may include a relaxation or a tightening of the original performance metric constraints, such as decreasing the 0-60 mph time of the vehicle or the allowable 5 second distance. As an example, the authors have decided to keep the problem statements for both submodels the same but vary the cargo mass of the overall vehicle. This study is especially of interest to the vehicle designer of small to mid-sized vehicles with ample passenger space or storage capacity.

The optimization steps were carried out in an identical manner with those performed earlier except that the cargo mass was varied for each case. The masses were ranged from 136 kg (for the baseline study) to 300 kg. The solutions to the ADVISOR subproblem are shown in Figure 10, where (a) contains the torque curves and (b) shows the associated power levels reached. Next, these curves were transferred to the TDES subproblem whereupon the engine geometries and boost controls were matched. As one would expect, the size of the desired engine would necessarily be greater and have moderate to high boost properties. The engine displacements for this range of engines and their associated cargo masses are listed in Table 5.



(a)



(b)

Figure 10: Results from post-optimality parametric study on cargo mass. (a) shows the maximum torque curves of the optimal engines and (b) depicts their corresponding power curves.

Table 5: Optimal engine displacements for the post-optimality parametric study.

CARGO MASS	LITERS
136	1.692
200	1.831
250	1.931
300	2.028

The user could now proceed to devise other similar studies that would aid in the engine decision-making process. In addition, various driving cycles and performance constraints could be placed on the vehicle that would alter the location of the optimum engine in the feasible design space. Let us now ascertain the validity of this methodology by comparing the resulting engine against a baseline that would have been chosen if the user implemented the traditional combinatorial technique described at the beginning of this paper.

COMPARISONS WITH BASELINE

The candidate baseline engine configuration, which was chosen as the reference for improvement, was a 1.894-liter (nominal 1.9-liter) diesel engine with VNT, variable injection timing, and high compression ratio. This engine resembles the VW 1.9l TDI engine which exists in the ADVISOR library and is a suitable choice for the selected chassis and transmission. Upon completion of the first design iteration, the resulting diesel engine was a 1.692 liter (nominal 1.7-liter) with similar inlet manifold boost pressure and injection timing capabilities. The maximum torque curves are shown in Figure **11** and the BSFC tables are depicted in Figure 12 (a and b). Upon linking these engine maps with the use points determined by the given transmission, a fuel economy improvement of approximately 5.6% was observed for the FTP cycle while maintaining almost identical performance metrics.

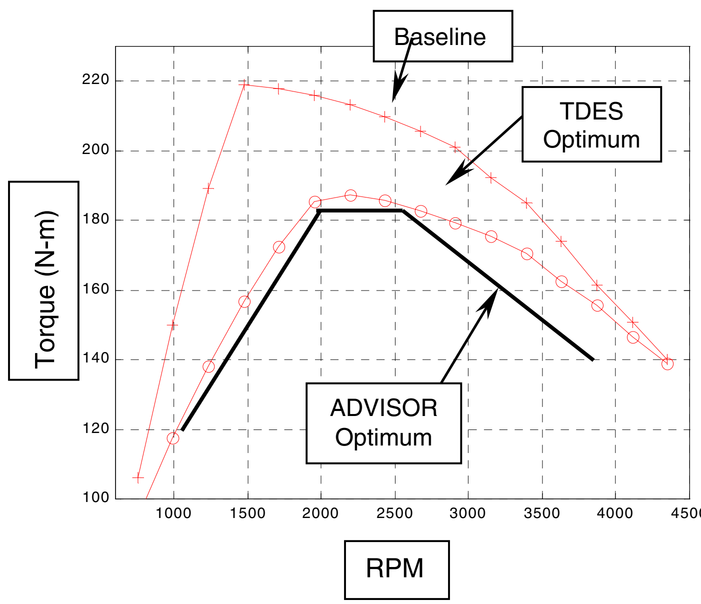


Figure 11: Comparison between baseline 1.9-liter and optimum 1.7-liter maximum torque curves.

At this point, the user has the opportunity to vary the transmission parameters for further improvements in fuel economy, as well as the various engine-specific geometries and controls that would serve the similar purpose. For instance, for the optimized engine case, the maximum torque curve from the ADVISOR subproblem can be used in conjunction with the associated BSFC table for that engine. Then, the actual maximum torque curve is used and ADVISOR is executed to find the new use points for that torque curve.

As was noted earlier, the user can now implement either the ADVISOR or the TDES curve with the output BSFC table. When ADVISOR is run now with these quantities, the location of the use points at the low end, defined by low speed range of the torque curve, do not change significantly and the resulting fuel consumption difference between approaches is negligible. One could now potentially investigate the fine tuning effects of the gear ratios and shifting strategies that would vary the MPG for the FTP cycle.

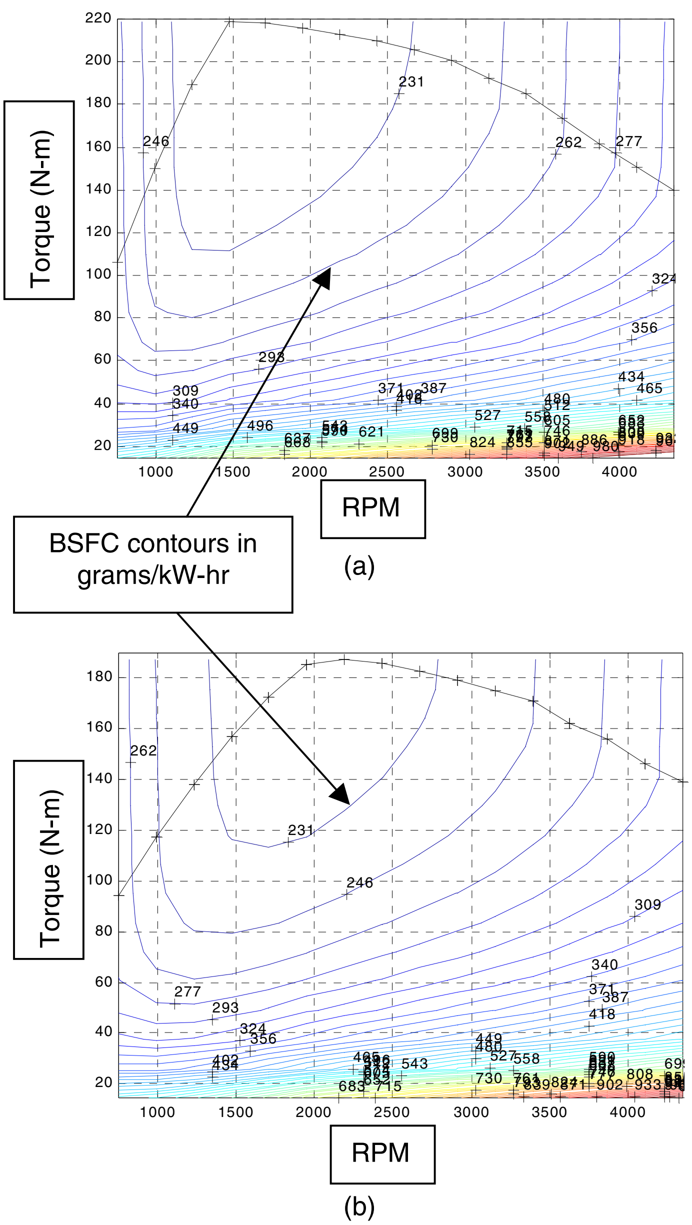


Figure 12: BSFC tables for baseline (a) and optimal (b). Note that the baseline engine does have the higher peak fuel efficiency, though this location is never used.

CONCLUSIONS

The methodology detailed in this paper is the first generation in the development of a framework for the preliminary design of a diesel engine within a vehicle. The reverse engineering practices present within this framework have allowed the authors to change the properties of an engine map through parametric and optimization studies in order to improve the fuel economy of a vehicle driven through the FTP driving schedule while maintaining minimum performance characteristics. The manner in which the system was decomposed and the problem statements posed for each subproblem are specific only to ADVISOR and TDES. Similar strategies can be applied to other simulations if the treatment of the maximum torque curve (in the system simulation) and engine parameters (in the engine model) resemble that shown here.

Realistic constraints on the diesel engine's design have been found through parametric studies and applied to an optimization problem within ADVISOR to find the minimum torque envelope for a given application. This torque limit was then applied to an engine matching problem within TDES in a sequential manner to find the smallest, and thereby, most fuel-efficient, engine that would supply the necessary power and torque requirements for the specified application.

Upon matching the smallest engine for the vehicle requirements, a number of variables could be changed in order to tune the engine and the transmission to further improve fuel economy. Among these are the engine's injection timing, manifold dimensions, and compressions ratio as well as the gear ratios and shifting parameters of the transmission. One must note that, if the fuel economy is improved after each decomposition step, the certainty that the final result is truly the optimal design for the system increases, but is not guaranteed.

The decomposed system that has been developed in this framework is an outline that can be implemented for other vehicles to design subsystems and components individually while adhering to the overall vehicle objectives. Among these systems are the various configurations of the diesel-based, hybrid electric vehicles as well as purely electric drivetrains which are the focus of on-going studies by the authors.

FUTURE WORK - Because this research is still in its infancy stage, there are many issues that have arisen which must be addressed in forthcoming studies. First, the target in the ADVISOR subproblem will be investigated from the perspective of a multiobjective function with varying weights for the rated power and rated torque. The height of the torque plateau and the slopes of line CD will be investigated from this viewpoint to determine their effects on performance parameters. Preliminary studies indicate that not only does the height of the curve increase, but its slopes at the low and high speed range are also affected drastically.

Then, post-optimality parametric studies must be performed to quantify the significance of different system values on the vehicle's mission. That is, vehicle cargo mass, vehicle chassis weight, rolling resistance, aerodynamics, and transmission parameters will vary the required engine size – but to what degree do they each affect fuel economy? Can we use knowledge gained from these studies to screen potential vehicle design changes and determine which ones should be targeted first for greatest fuel economy improvements? Different driving cycle selections must be investigated along with varying the performance constraints in the ADVISOR subproblem.

In addition, the methodology will be continued for one more fidelity step in order to determine the effects of even smaller changes within the engine subsystem to the performance of the overall system. In this context, efforts have already been made in the area of variable compression ratio, continuously variable transmission capabilities, as well as flexible valve timing capabilities.

The parameterization method for the maximum torque curve in ADVISOR will also be researched. The sensitivity of the objective function in this subproblem with respect to the ERPM points has raised several concerns. Fourth-order quadratic functions, which can afford rather flat plateaus and the necessary slopes in the low and high speed ranges, are potential candidates for this study. In addition, the PIM, PIM_{max}, and WRPM parameterization scheme for the TDES subproblem will also be modified to make the boost scenarios predictive (and more realistic) with turbocharger maps or perhaps neural networks.

Next, efforts will be made to incorporate an emissions modeling and optimization strategy to the overall design framework. Though preliminary NO_x and dry particulate matter models have already been implemented within TDES, they have not yet been validated and therefore not presented in this paper. Methods similar to those described earlier will be implemented for this puprose.

Finally, this work is the precursor to an optimization strategy for the parallel HEV which will require a greater degree of coordination between submodels. Transmission and motor design and control quantities are being screened for their potential incorporation within a scheme similar to the one presented above.

ACKNOWLEDGEMENTS

The authors would like to thank the generous contributions of the members of the Automotive Research Center at the University of Michigan. This research could not have been performed without the assistance of Panos Papalambros and his group in the area of design optimization techniques for large-scale systems. The works and advice of Nestor Michelena, Zoran Filipi, Michael Sasena, and Ryan Fellini were influential in our understanding of the issues relating to optimization methodologies as well as powertrain design. Finally, Keith Wipke, Mathew Cuddy, and Valerie Johnson, from the National Renewable Energy Laboratory, assisted us in developing the tools required for the application of this methodology within ADVISOR.

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New Concepts From Universities

A Hybrid-Propulsion Powertrain with Planetary Gear Set: Simulation Results and a Design Approach

Presentation

Paper

Marco Santoro, Dresden University of Technology
Leone Martellucci, University of Rome

Use of ADVISOR for simulation of a Hybrid Electric Vehicle with a Stirling Engine as the Auxiliary Power Unit

Presentation

Paper

Luis Figueroa and Owen R. Fauvel, University of Calgary
Graham T. Reader, University of Windsor

GWU Hybrid Electric Sport Utility Vehicle Design for FutureTruck 2000 Competition

Presentation

Paper

Mohd-Syaifuddin Mohd, Zeki Gokce, Vahid Motevalli, and Kartik Bulusu

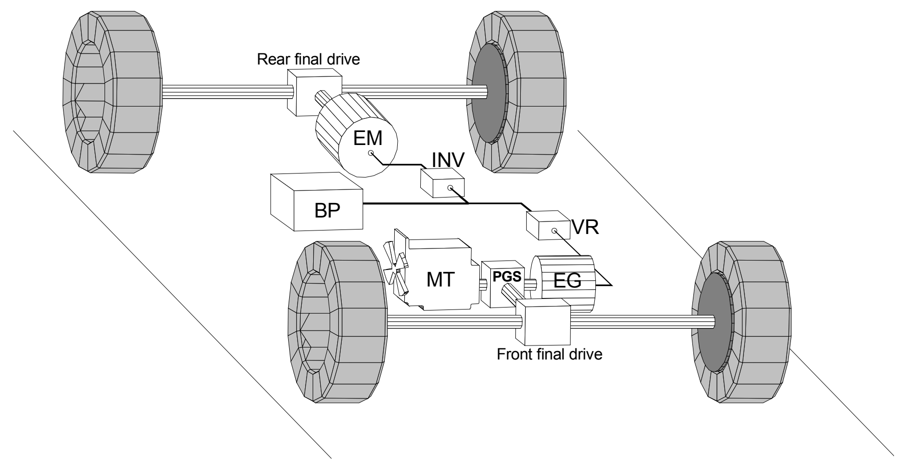
Leone Martellucci Marco Santoro

A Hybrid-Propulsion Powertrain with Planetary Gear Set: Simulation Results and a Design Approach

University of Rome I "La Sapienza" - Italy Dresden University of Technology - Germany

The SIPRE 3 drivetrain

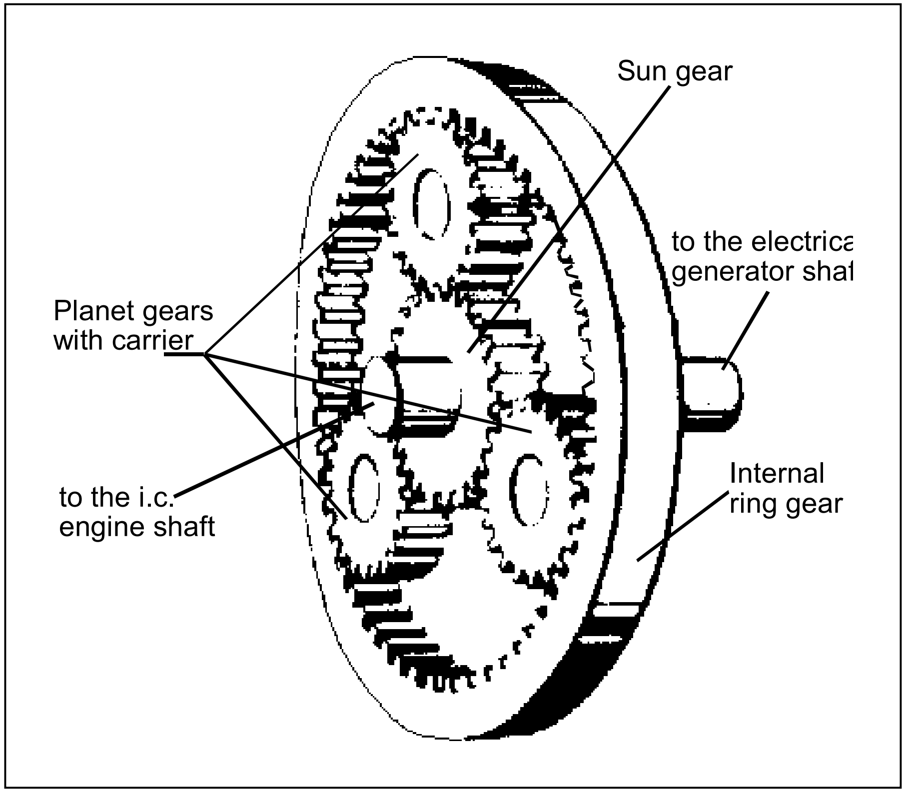
- Parallel Power-Split
- *Sluggish* dynamic behaviour of ICE
- Traction torque provided directly by the ICE and by the electrical drive at the same time
- 2 or 4-wheel-drive layouts available
- Pure electric operation into restricted zones



BP: battery pack; EM: electric motor; INV: inverter;
MT: internal combustion engine; PGS: planetary gear set;
EG: electrical generator; VR: voltage regulator

Planetary Gear Set links

- ICE to the Sun Gear
- Generator to the Planetary Carrier
- Driving Shaft to the Ring Gear

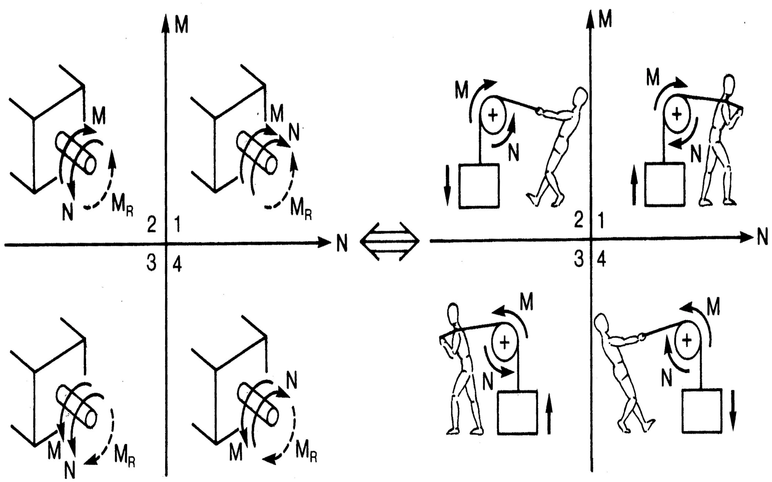


$$\omega_{engine} = \frac{1}{\tau} \cdot \omega_{driving\_shaft} + \frac{\tau - 1}{\tau} \cdot \omega_{generator}$$

$$\omega_{driving\_shaft} = \tau \cdot \omega_{engine} + (1 - \tau) \cdot \omega_{generator}$$

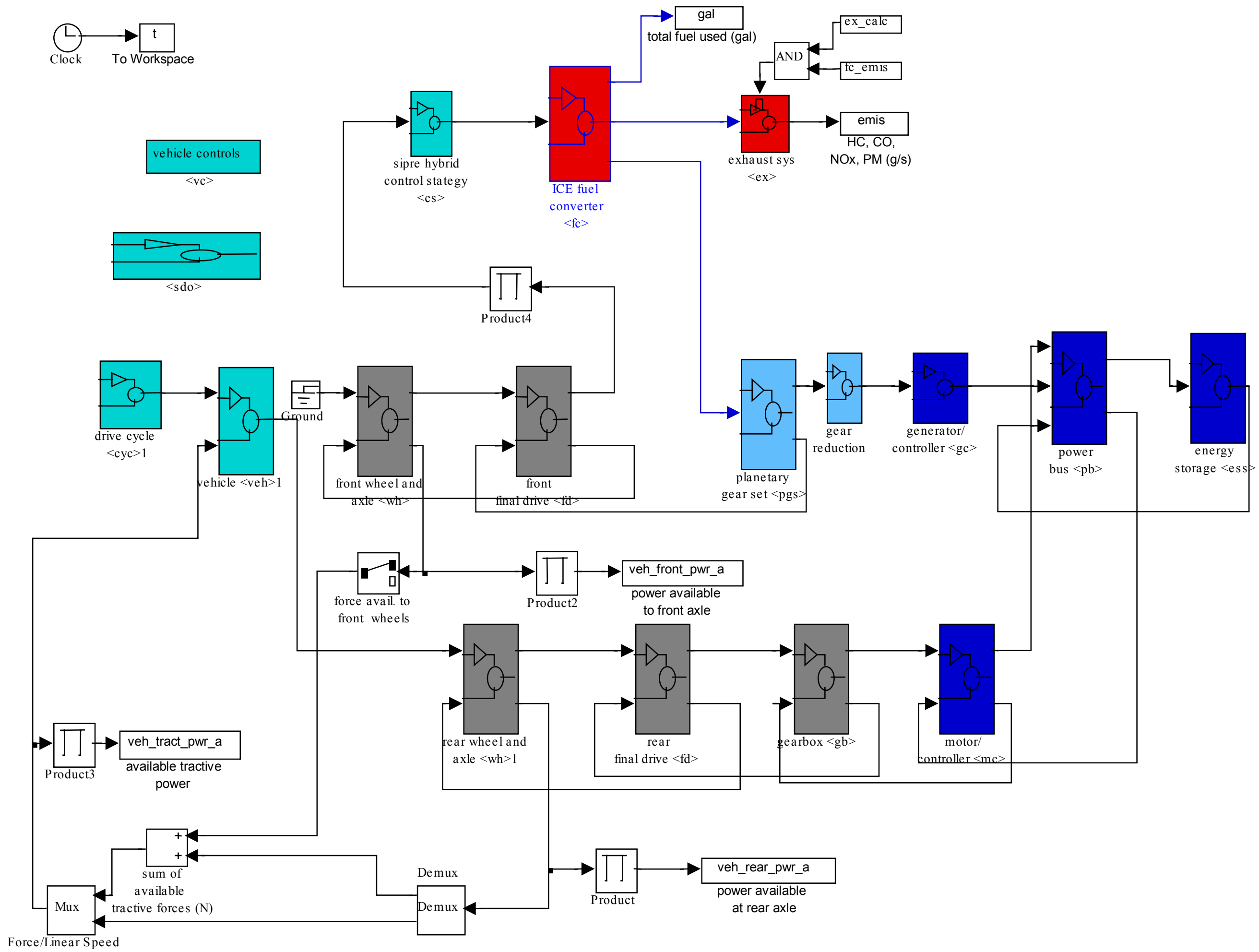
$$\omega_{generator} = \frac{\tau}{\tau - 1} \cdot \omega_{engine} - \frac{1}{\tau - 1} \cdot \omega_{driving\_shaft}$$

Operating conditions of electric machines

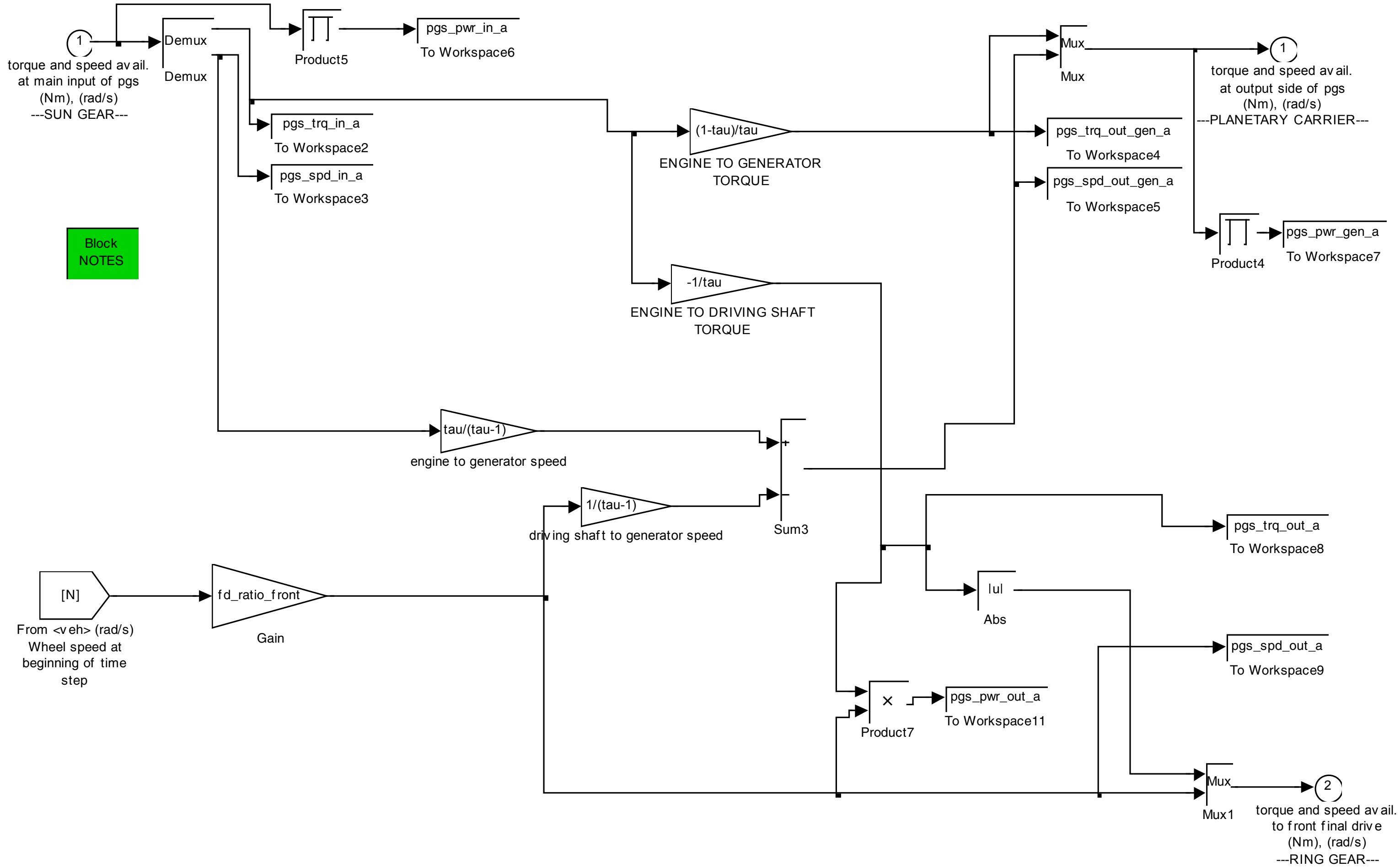


M: traction torque; M_R: resistance torque;
N: rotation speed

- The electric motor driving the rear wheels operates in the 1st (traction motor) or 4th (regenerative braking) quadrant
- The electrical generator connected to the PGS planetary carrier operates in the 1st/2nd or 3rd/4th quadrants, depending on the sign of the PGS conversion ratio τ

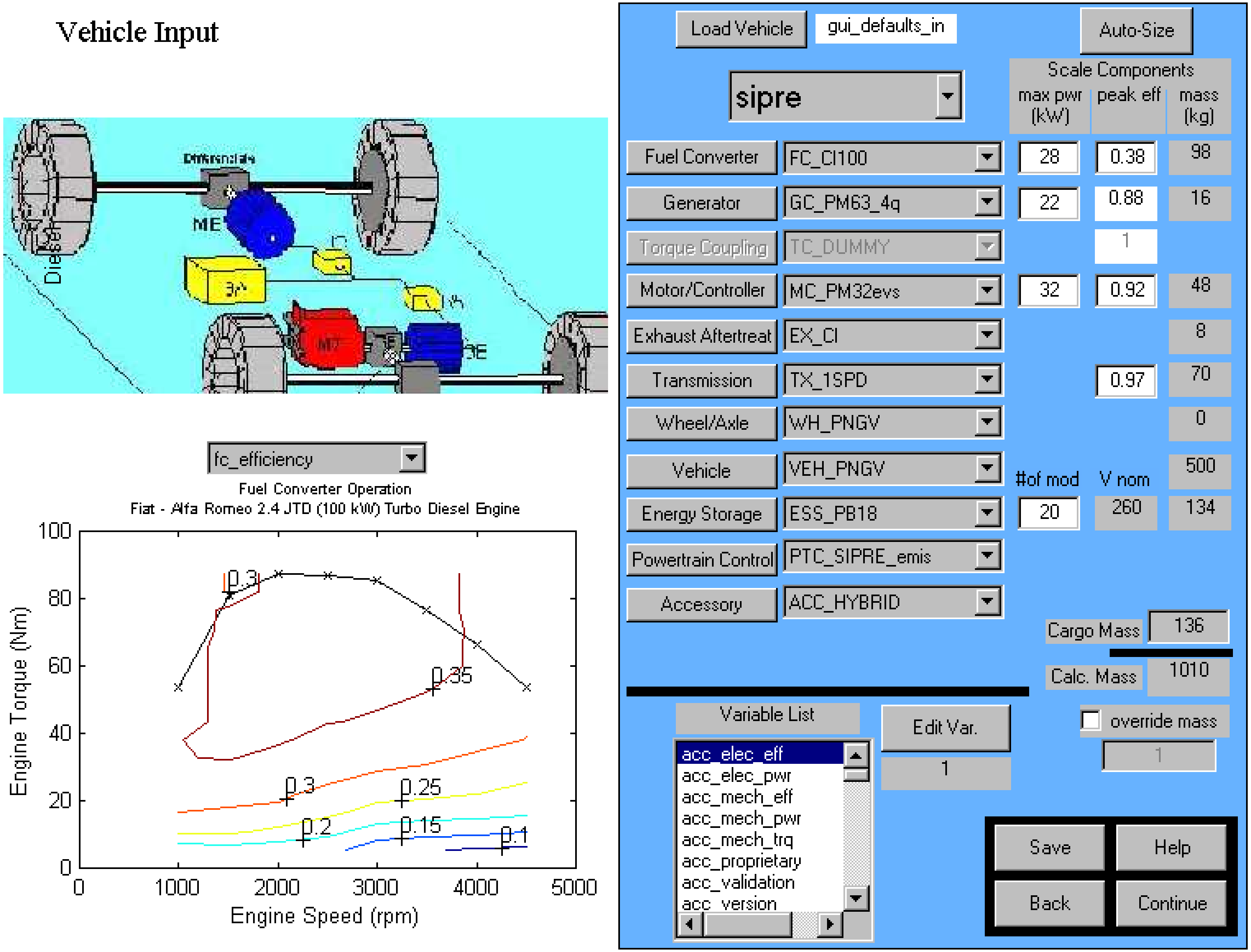


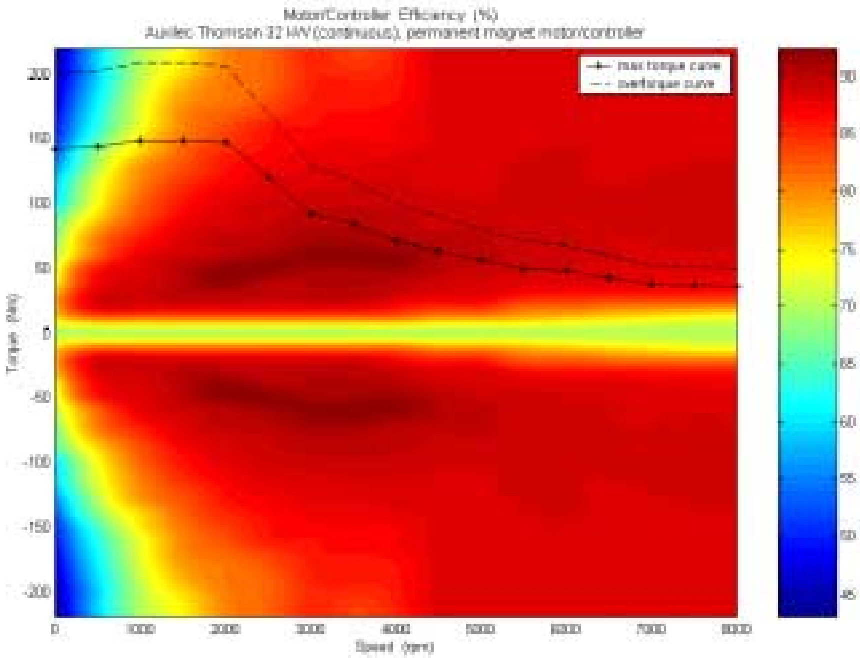
4WD SIPRE 3 Simulink model



Planetary-Gear-Set Simulink model

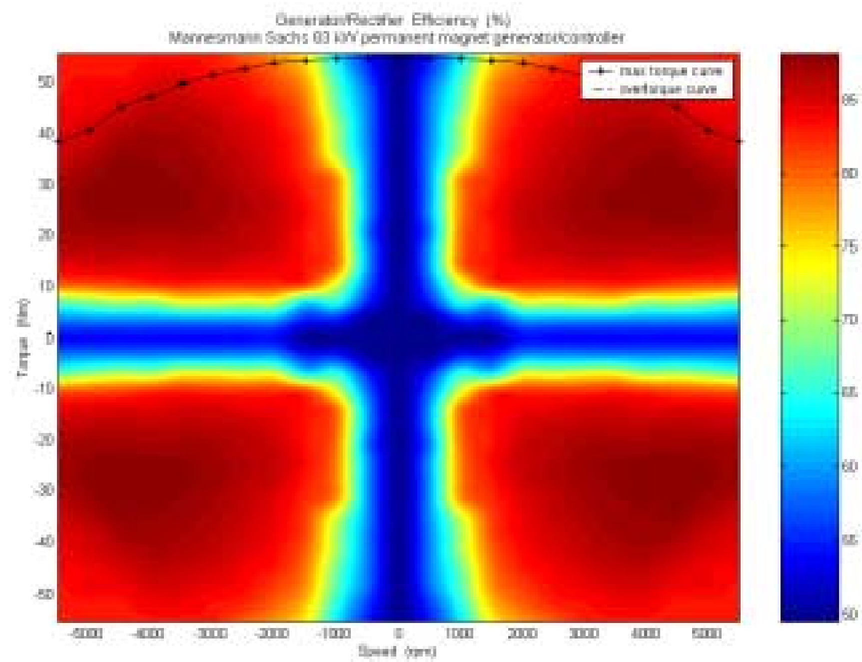
Vehicle Input



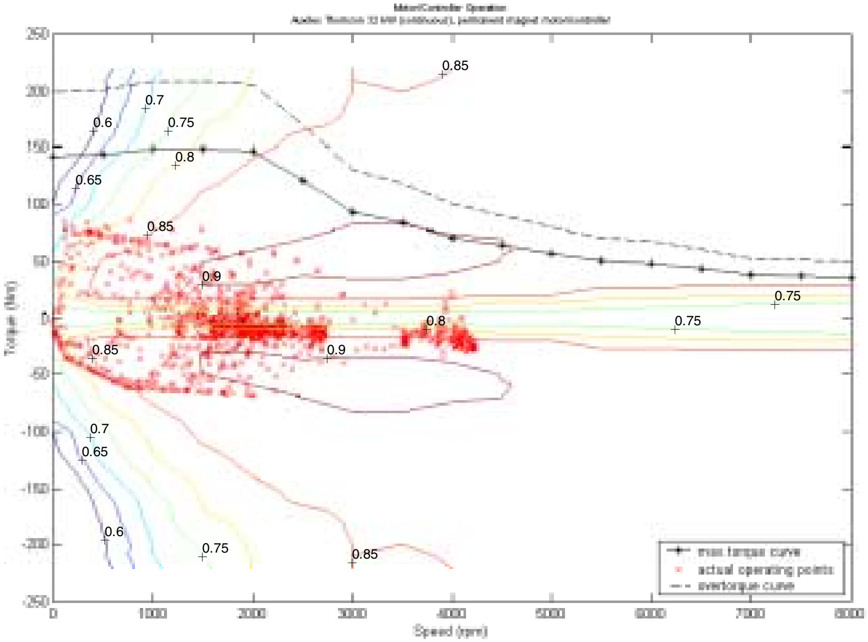


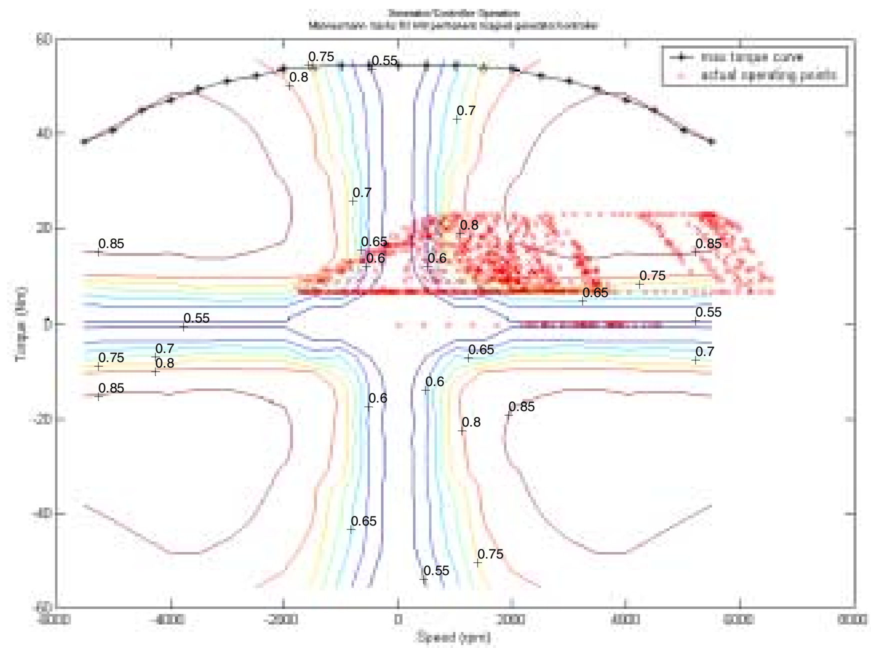
Auxilec Thomson 32 kW PM traction drive

22 kW generator/controller scaled from Mannesmann Sachs 63 kW PM generator/controller

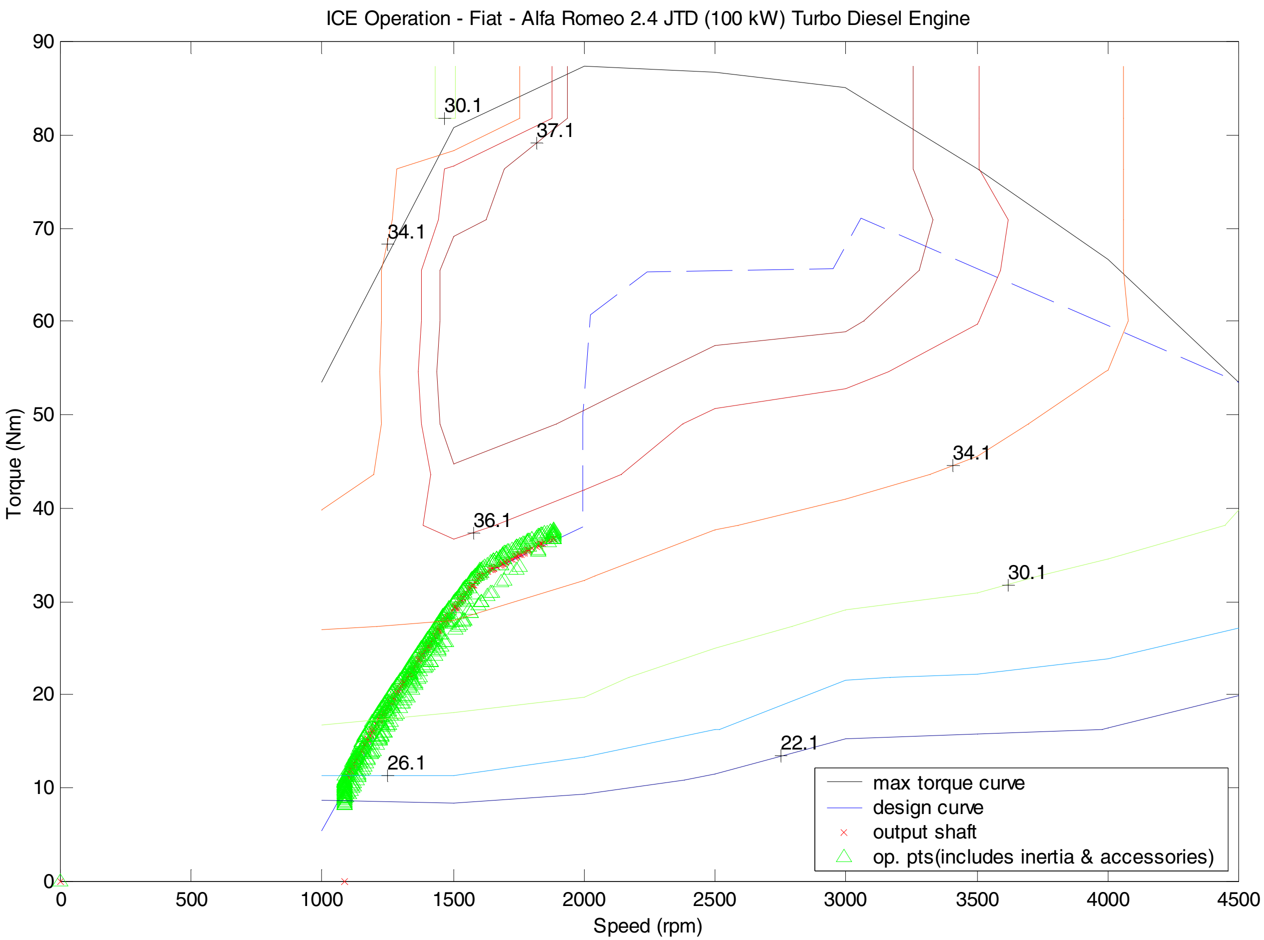


Electrical-machines efficiency maps

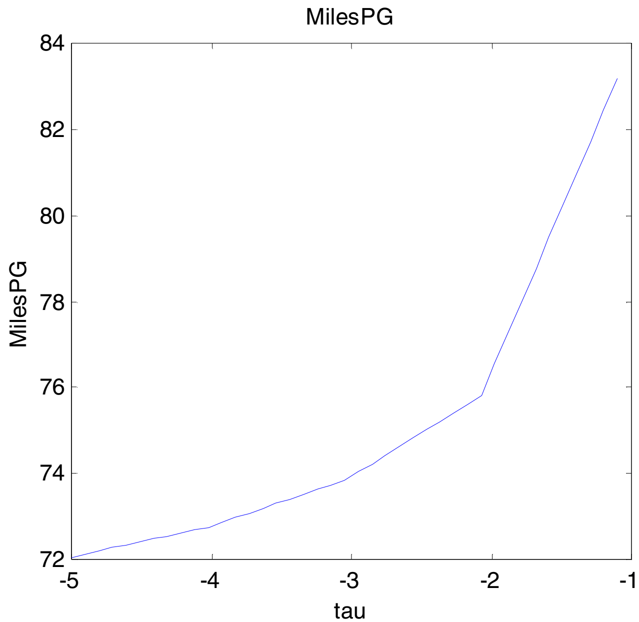


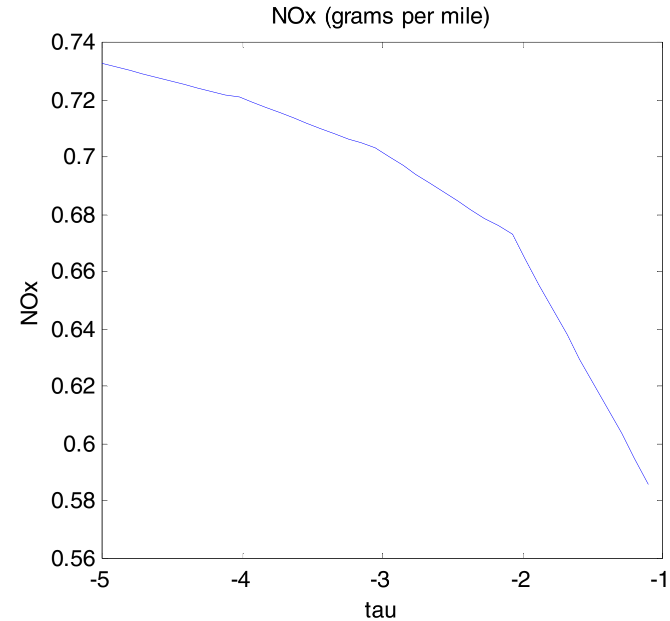


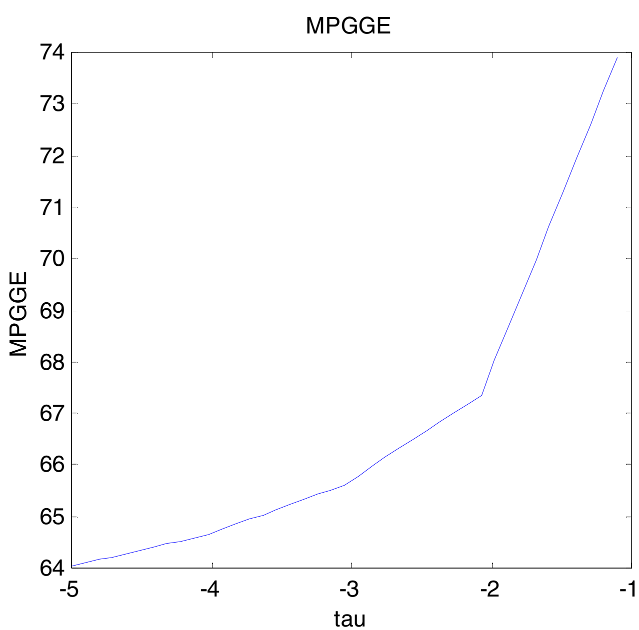
Electrical-machines operating points over the FTP cycle

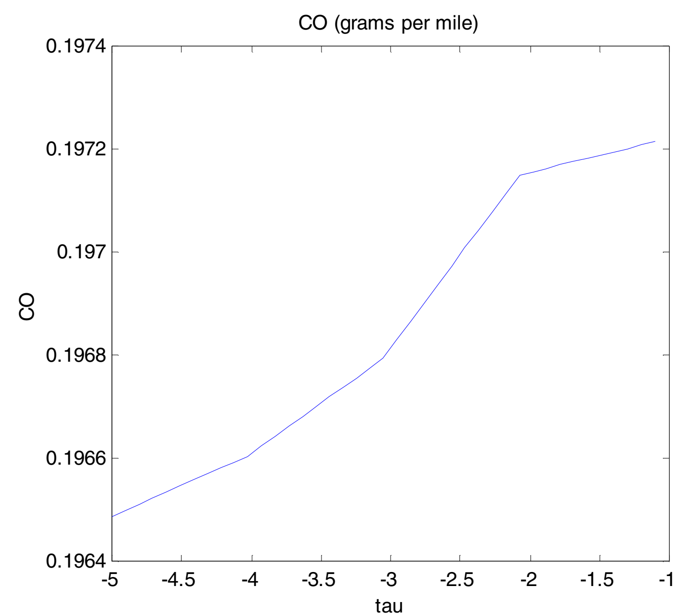


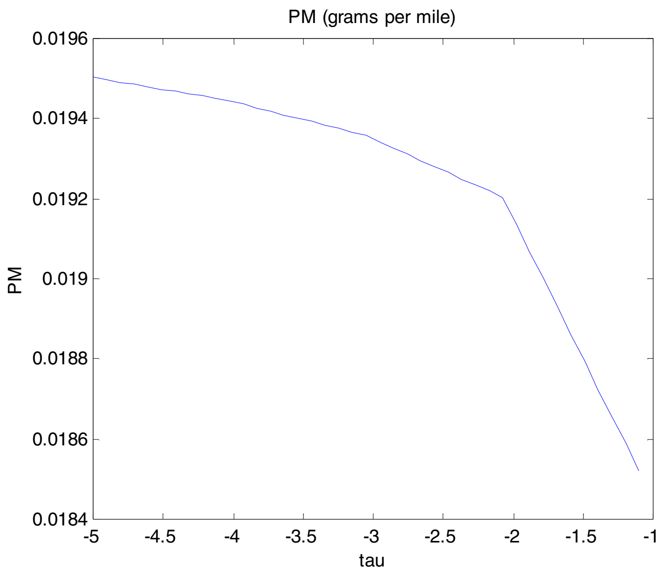
Engine operating points over the FTP cycle

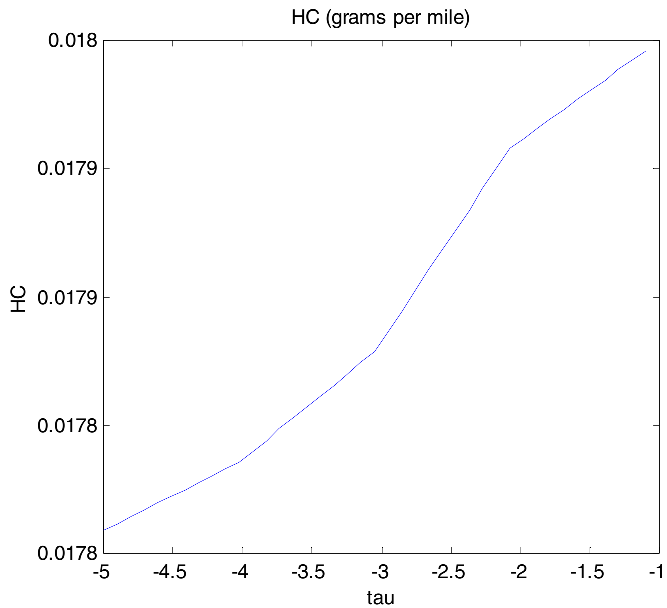

MilesPG
MilesPG
84
82
80
78
76
74
72
-5
-4
-3
-2
-1
tau

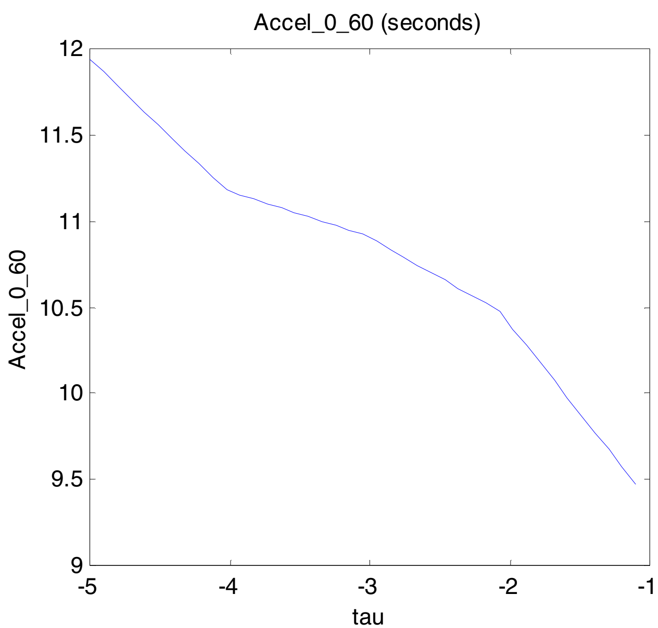

NOx (grams per mile)
NOx
0.74
0.72
0.7
0.68
0.66
0.64
0.62
0.6
0.58
0.56
-5
-4
-3
-2
-1
tau

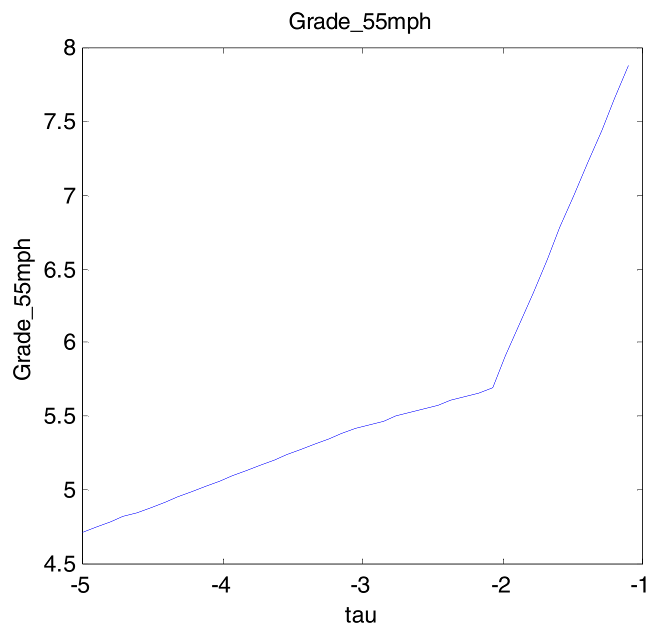

MPGGE
MPGGE
74
73
72
71
70
69
68
67
66
65
64
-5
-4
-3
-2
-1
tau


CO (grams per mile)
CO
0.1974
0.1972
0.197
0.1968
0.1966
0.1964
-5
-4.5
-4
-3.5
-3
-2.5
-2
-1.5
-1
tau


PM (grams per mile)
PM
0.0196
0.0194
0.0192
0.019
0.0188
0.0186
0.0184
-5
-4.5
-4
-3.5
-3
-2.5
-2
-1.5
-1
tau

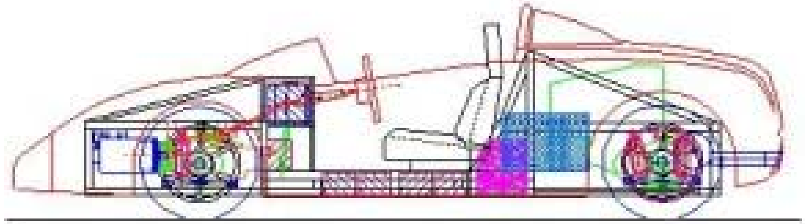

HC (grams per mile)
HC
0.018
0.0179
0.0179
0.0178
0.0178
-5
-4.5
-4
-3.5
-3
-2.5
-2
-1.5
-1
tau


Accel_0_60 (seconds)
Accel_0_60
12
11.5
11
10.5
10
9.5
9
-5
-4
-3
-2
-1
tau


Grade_55mph
Grade_55mph
8
7.5
7
6.5
6
5.5
5
4.5
-5
-4
-3
-2
-1
tau

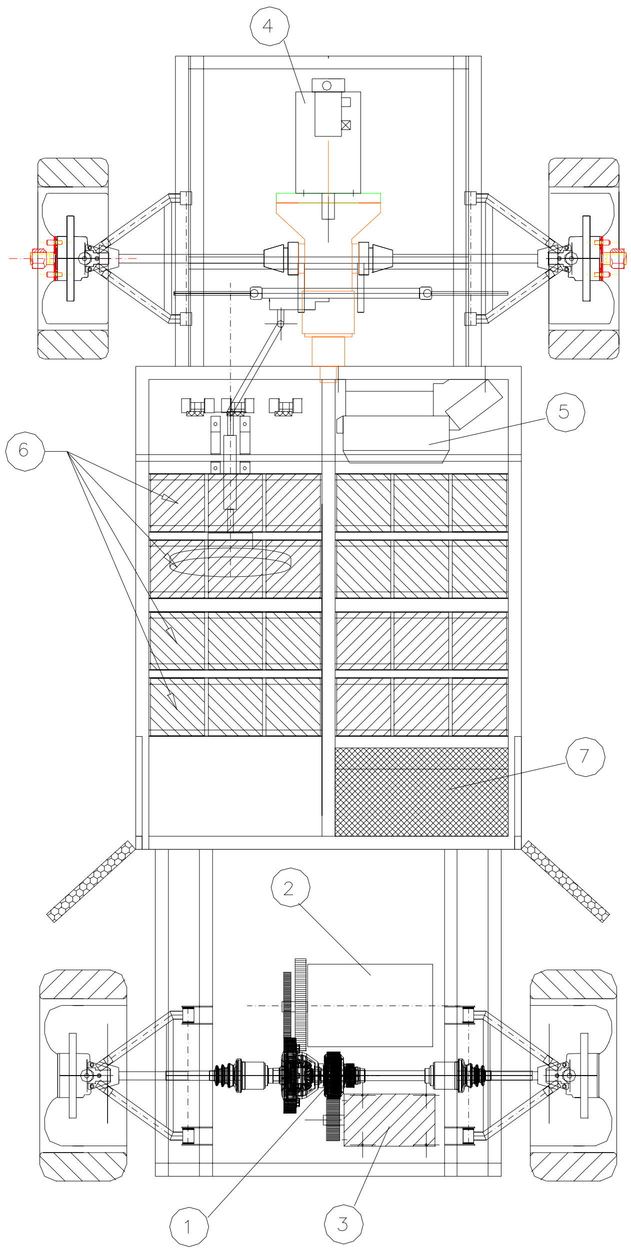
The parallel hybrid *Kjara*

- Two-seat roadster
- The engine drives the rear wheels

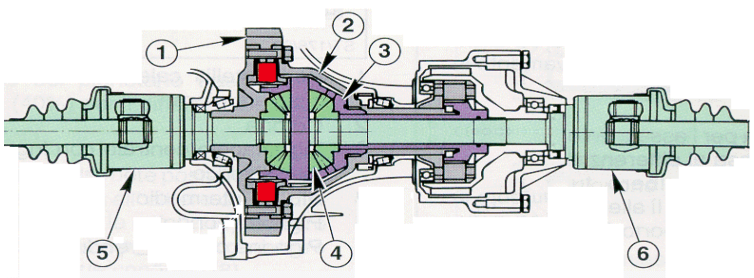


- The motor drives the front wheels

Kjara tested on Lombardore (Turin) track.



1, Planetary Gear Set with differential;
2, Diesel engine; 3, Electrical generator;
4, Electrical motor; 5, Electronics; 6, Battery pack; 7, Diesel fuel tank.



1, Sun gear carrier; 2, External case;
3, 4, final drive with differential; 5,6, axle shaft joints

Planetary Gear Set from 1992 4x4 FORD Escort, sold in the European market.

A Hybrid-Propulsion Powertrain with Planetary Gear Set: Simulation Results and a Design Approach

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Dresden University of Technology - Germany

Leone Martellucci
University of Rome I "La Sapienza" - Italy

ABSTRACT

A power-split hybrid powertrain adopting a planetary gear set is proposed in this work as alternative to the traditional hybrid-propulsion schemes.
The main advantages of this drivetrain are:

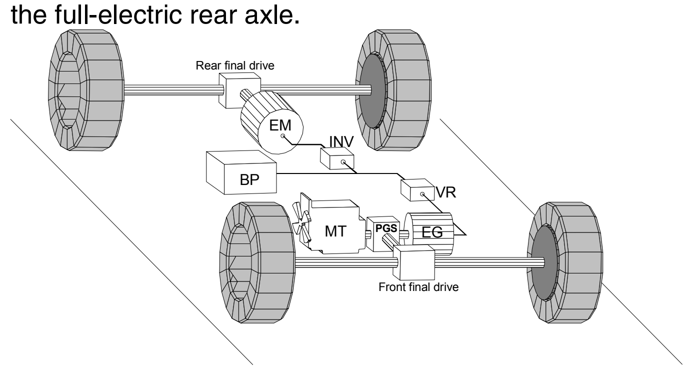
- *Sluggish* dynamic behaviour of the internal combustion engine, like in series powertrains;
- Traction torque provided directly by the Internal Combustion Engine (ICE) and by the electrical drive at the same time, like in parallel powertrains;
- 2 or 4-wheels-drive layout;
- Pure electric operation when driving into restricted zones.

The Simulink® model which allows ADVISOR© to generate energy flows and emissions of the vehicle is presented. Moreover, the paper explains the control strategy and proposes a design approach of a sports-car adopting this powertrain.

INTRODUCTION

The Department of Nuclear Engineering and Energy Conversions at University of Rome I "La Sapienza" has studied in the last years a "family" of power-split drivetrains provided with a planetary gear system: the **SIPRE** - an acronym in the Italian language: **S**istema **I**brido di **P**ropulsione con **R**uotismo **E**picicloidale (Hybrid-Propulsion System with Planetary Gear Set) - family. The third member of this family, the **SIPRE 3** [1], is proposed in this paper.

The planetary gear set is the heart of the SIPRE 3 system. Due to the planetary-gear-set (PGS) unit it is possible to share the thermal-energy driving torque between the electrical generator and the front axle; this is the main original characteristic that distinguishes the SIPRE 3 system from a traditional series-hybrid powertrain. In fact, such a behaviour, warranted by the presence of a PGS, allows the mechanical transmission of part of the ICE torque to the front-driving wheels in order to contribute to the vehicle traction together with the full-electric rear axle.

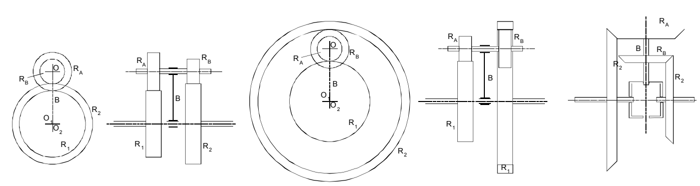


BP: battery pack; EM: electric motor; INV: inverter; MT: internal combustion engine; PGS: planetary gear set; EG: electrical generator; VR: voltage regulator

Figure 1: SIPRE 3 in the 4WD layout

POWERTRAIN DESCRIPTION

In order to explain the PGS kinetic and dynamic behaviour and its influence over the entire system operation in detail, it is necessary to illustrate the layout of the various mechanical linkages. The planetary gear train used can be chosen between three different configurations: the Rolls Royce, the Pickering and the differential one. The choice depends on the desired transmission ratio, with reversal or upward conversion.



Pickering (τ positive) | Rolls-Royce (τ negative) | Differential (τ negative)

Figure 2: PGS layouts

The main parameter that defines the PGS behaviour is its conversion ratio τ, which depends on the number of teeth in the sun and ring gear, and the principal relationship among the speeds of the axes is the *Willis* [2] one:

$$\tau = \frac{\omega_2 - \Omega}{\omega_1 - \Omega} \tag{1}$$

where ω_2, Ω and ω_1 are the rotation speeds, respectively, of the internal ring gear (the transmission shaft $\omega_{driving\_shaft}$), of the planetary carrier (the electrical generator $\omega_{generator}$) and of the sun gear (the internal combustion engine ω_{engine}). In the Eq.1 when $\Omega=0$ is

$$\tau_{|\Omega=0} = \frac{\omega_2}{\omega_1} \tag{2}$$

and τ is positive if the first and last gear rotate in the same direction (upward conversion) and is negative otherwise (reversal conversion).

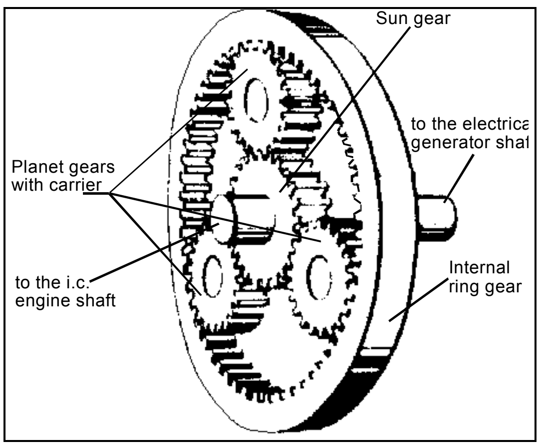


Figure 3: PGS links in the SIPRE 3

From the *Willis formula* the relationship among the various speeds can be conveniently derived as follows

$$\omega_{engine} = \frac{1}{\tau}\cdot\omega_{driving\_shaft} + \frac{\tau - 1}{\tau}\cdot\omega_{generator}$$

$$\omega_{driving\_shaft} = \tau\cdot\omega_{engine} + (1-\tau)\cdot\omega_{generator} \tag{3}$$

$$\omega_{generator} = \frac{\tau}{\tau - 1}\cdot\omega_{engine} - \frac{1}{\tau - 1}\cdot\omega_{driving\_shaft}$$

From these relations is clear that, unlike a traditional generator set used in series hybrid systems, the electrical generator of SIPRE 3 works at variable speed with a range of speed that is a function of τ. The *kinematics of the PGS thus supports two degrees of freedom*, so it is possible to freely select two different speeds (e.g. the ICE speed and the transmission shaft speed).

Other power-split powertrains with planetary gear systems have been proposed in the technical literature. In the Toyota Prius [3] the ICE is linked to the planetary carrier, the generator to the sun gear and the driving shaft to the ring gear. In the drivetrain proposed by researchers at Warsaw University of Technology [4] the ICE is connected to the sun gear, the generator to the ring gear and the driving shaft to the planetary carrier. The aim is always to select the engine's operating point independently from the vehicle's speed, exploiting the two degrees of freedom the PGS allows.

In order to understand the system behaviour completely, it is important to report the torque distribution over the three PGS axes. In fact in the dynamic field the PGS behaviour is quite different; the main relationship that describes the PGS operation is:

$$T_{driving\_shaft} + T_{generator} + T_{engine} = 0 \tag{4}$$

where the torque notation has the same meaning as the speed notation previously described.

From the Willis formula and the balance of powers in the device

$$T_{driving\_shaft}\cdot\omega_{driving\_shaft} + T_{generator}\cdot\omega_{generator} + T_{engine}\cdot\omega_{engine} = 0 \tag{5}$$

it is possible to come to the following expressions:

$$T_{engine} = \frac{\tau}{1-\tau}\cdot T_{generator}$$

$$\frac{T_{driving\_shaft}}{T_{engine}} = -\frac{1}{\tau} \tag{6}$$

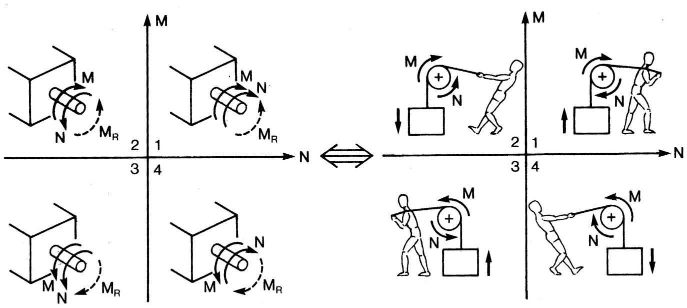
The dynamic problem is *completely settled* when just one of the three axis torques is fixed. For an automotive power unit the main condition can be the *driving torque* $T_{driving\_shaft}$ needed for the traction, so $T_{generator}$ and T_{engine} have to exactly match the Equations 6 and the choice of the value of the transmission ratio τ affects the kinematic and dynamic behaviour of this hybrid traction system.

It is important to note that the vehicle's dynamic behaviour is controlled via the brake and accelerator pedals, acting exclusively on the electrical traction equipment arranged on the rear axle. From this point of view *this vehicle is managed just like a full electric vehicle*. This is possible considering that the hybrid equipment acting on the front wheels, which supplies an additional traction torque to the vehicle and cooperates with the rear electrical traction, is characterised by a fully automatic operation without the need of an external management. Furthermore, the engine needs no starter because the generator can act to crank it. Because there is no reverse gear, vehicle reversing is a motor-only drive mode.

Looking at the relations among the speeds in the PGS, it is interesting to observe that the speed of the generator is zero when

$$\omega_{driving\_shaft}\Big|_{\omega_{generator}=0} = \tau \cdot \omega_{engine} \tag{7}$$

and the two degrees of freedom supported by the kinematics of the PGS allow the generator to operate in two different quadrants, depending on the engine's and vehicle's speeds, in generating (2nd and 4th quadrants) or motoring (1st and 3rd quadrants) mode (Figure 4). The generator/controller allows thus a bi-directional flow of power from the batteries to the PGS unit.



M: traction torque; M_R: resistance torque; N: rotation speed

Figure 4: The four operating quadrants of a motor/generator

The electric motor driving the rear wheels operates in the 1st (traction motor) or 4th (regenerative braking) quadrant. The electrical generator connected to the PGS planetary carrier operates in the 1st/2nd or 3rd/4th quadrants, depending on the sign of τ.

From the previous kinetic and dynamic equations it is easy to calculate the expressions for the power distributions over the PGS axes (Eq. 8):

$$P_{DS} = T_{driving\_shaft} \cdot \omega_{driving\_shaft} =$$
$$T_{engine} \cdot \omega_{engine} \cdot \frac{T_{driving\_shaft}}{T_{engine}} \cdot \frac{\omega_{driving\_shaft}}{\omega_{engine}} =$$
$$P_0 \cdot \left(-\frac{1}{\tau}\right) \cdot \left(\frac{\omega_{driving\_shaft}}{\omega_{engine}}\right)$$

(8)

$$P_{EG} = T_{generator} \cdot \omega_{generator} =$$
$$T_{engine} \cdot \omega_{engine} \cdot \frac{T_{generator}}{T_{engine}} \cdot \frac{\omega_{generator}}{\omega_{engine}} =$$
$$P_0 \cdot \left(\frac{1-\tau}{\tau}\right) \cdot \left(\frac{\omega_{generator}}{\omega_{engine}}\right)$$

where P_{DS} is the power that reaches the driving shaft, P_0 is the power supplied by the ICE and P_{EG} is the power absorbed by the electrical generator.

The advantages of the PGS operation, governed by the previous equations, are manifest when one analyses the ratio between the power mechanically transmitted to the front driving wheels and the total power supplied by the ICE; in fact, this parameter provides the exact amount of purely mechanical traction power available to the front vehicle wheels cooperating with the rear electric motor for the vehicle motion. In other words, thanks to the presence of a PGS, the electric motor has to supply a lower power than that necessary in a series hybrid drive train. Moreover, the load on the electrical generator is lower too, with evident benefits for the overall equipment cost.

A power ratio parameter can be mathematically expressed as a function of the PGS conversion ratio τ:

$$\rho = \left|\frac{P_{DS}}{P_0}\right| = \left|-\frac{1}{\tau}\right| \cdot \frac{\omega_{driving\_shaft}}{\omega_{engine}} \tag{9}$$

Assuming the speed ω_{engine} of the ICE fixed, the ICE power transmitted directly to the driving shaft increases linearly with the vehicle speed, related to $\omega_{driving\_shaft}$. At low speed the traction power is thus mostly supplied by the electrical drive. The PGS acts like a power-split device and a CVT (Continuously Variable Transmission) at the same time.

Another power ratio parameter is

$$\sigma = \left|\frac{P_{EG}}{P_0}\right| = 1 - \left|-\frac{1}{\tau}\right| \cdot \frac{\omega_{driving\_shaft}}{\omega_{engine}} \tag{10}$$

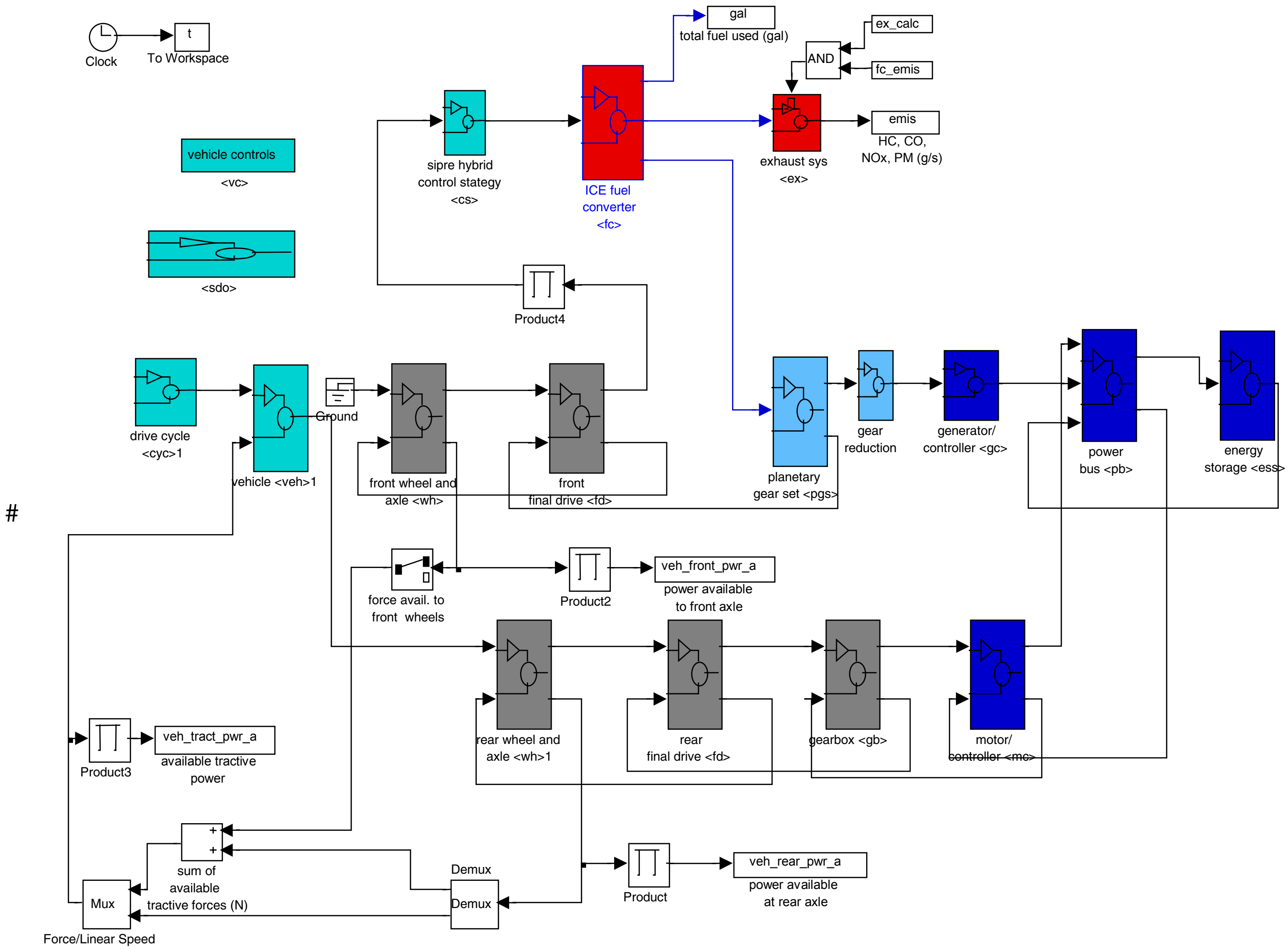


Figure 5: Simulink SIPRE 3 HEV block diagram's top level.

When the vehicle is at rest ($\omega_{driving\_shaft}=0$), $\sigma = 1$ in Eq. 10 and the vehicle is a series hybrid because the whole power generated by the ICE flows uniquely to the generator. At higher speeds the powertrain tends to behave like a parallel hybrid and increases the power flowing to the front wheels.

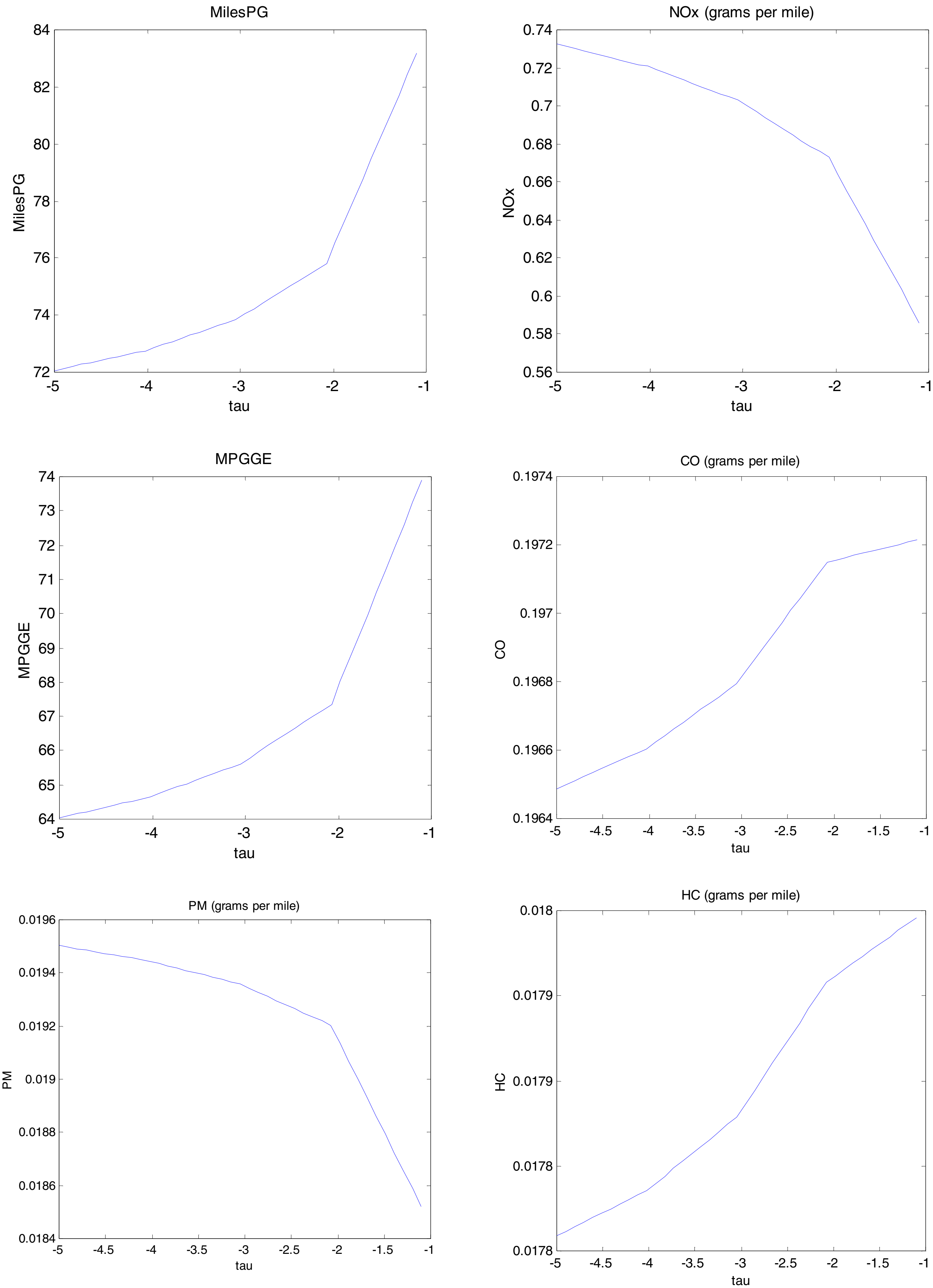
THE SIMULINK MODEL

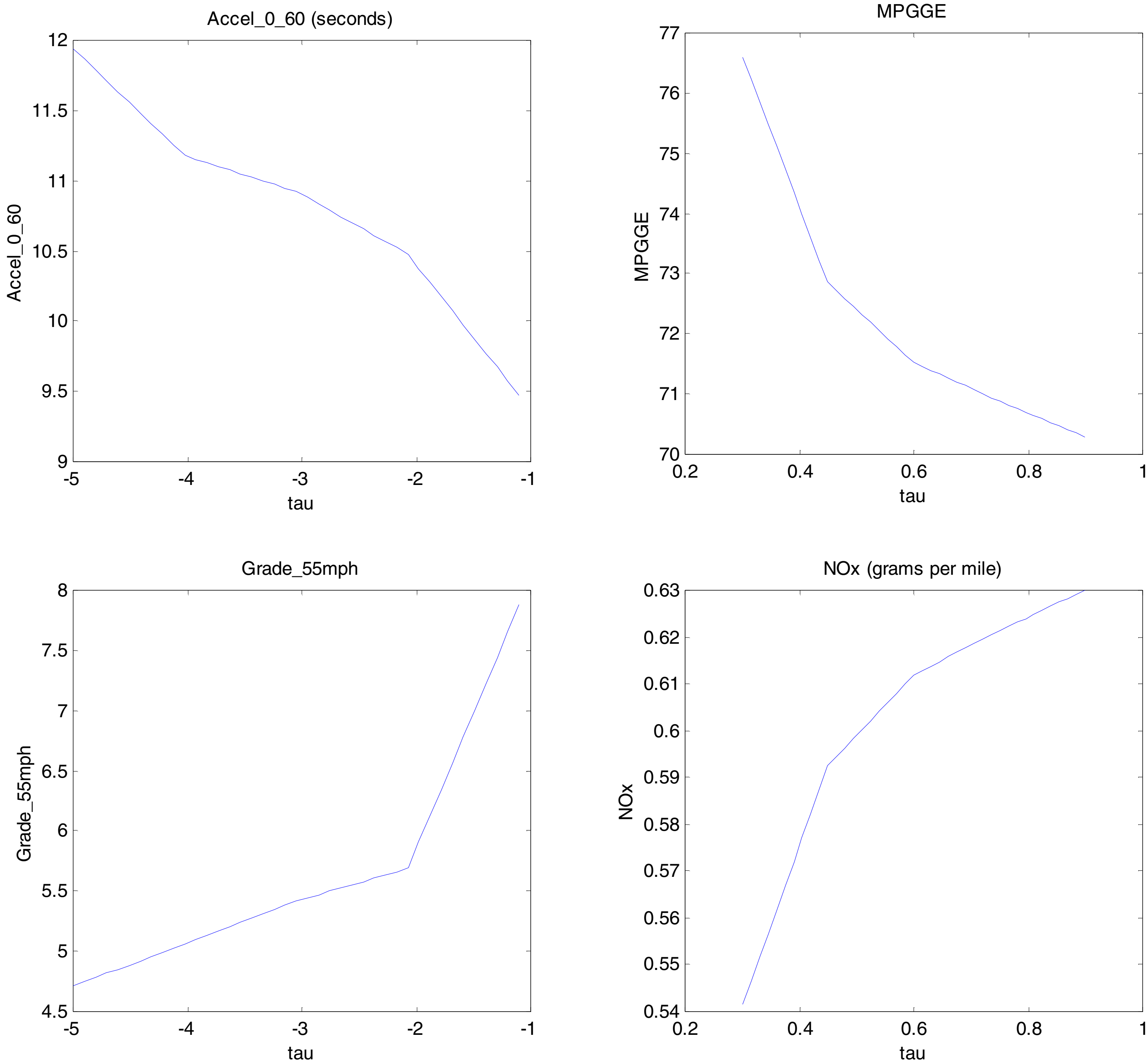
Figure 5 shows the Simulink model which allows ADVISOR to generate energy flows, emissions and consumption of the vehicle. The model describes the front and rear axles of a vehicle provided with a SIPRE 3 drivetrain in the 4WD layout and has been built modifying ADVISOR at the block diagram level, by programming in Simulink. Although ADVISOR relies heavily on a backward-facing approach for its operation [5], it is possible to reconnect ADVISOR block diagrams to model new vehicle types and add new component block diagrams, like the PGS one, which are related to a forward-facing approach. The generator/controller block diagram allows bi-directional power flow, depending on the sign of power and following the convention in Figure 4: negative power (the electrical machine operates as generator) flows from the PGS unit to the batteries; positive power (the electrical machine operates as motor) flows from the batteries to the PGS unit.

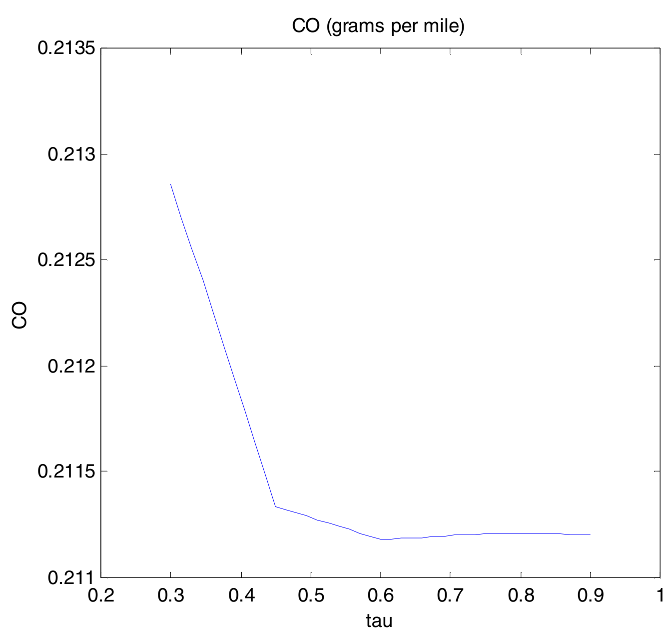
SIMULATION RESULTS

The vehicle used in the simulations was a PNGV-type vehicle. Its components and characteristics included:

- 28 kW CIDI engine (scaled from Fiat 100 kW 2.4 L Turbo Diesel Common Rail Direct Injection engine)
- Auxilec Thomson 32 kW PM traction drive [6]
- 22 kW generator/controller (scaled from Mannesmann Sachs 63 kW permanent magnet generator/controller [7])
- Twenty 18 Ah lead acid batteries (Optima spiral-wound VRLA, data from NREL tests)
- Mass of 1010 kg.
- Coefficient of drag (C_d) of 0.3
- Frontal area of 2 m^2.

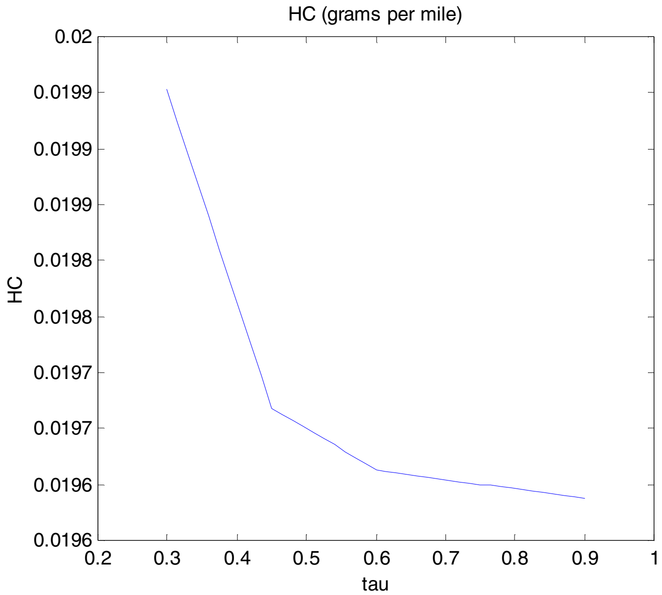

MilesPG
NOx (grams per mile)
MPGGE
CO (grams per mile)
PM (grams per mile)
HC (grams per mile)
MilesPG
NOx
MPGGE
CO
PM
HC
tau

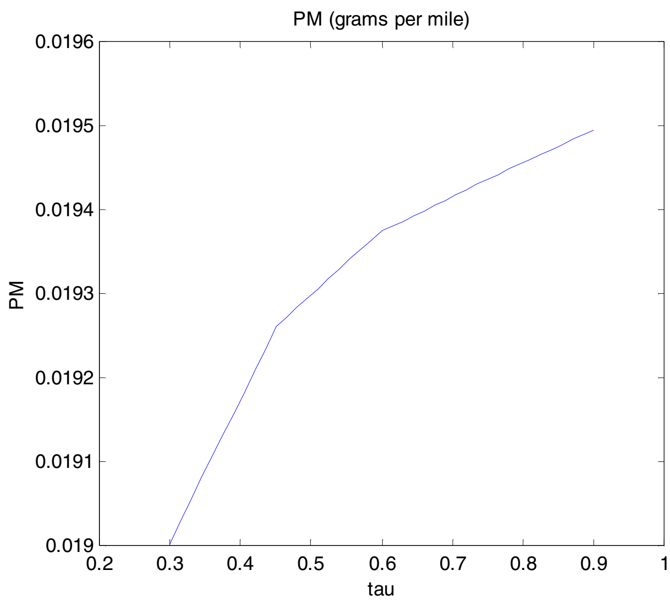




Figg. 6-13: Parametric study. Performances over the US FTP cycle when τ changes between (-5) and (-1.1).

We are testing for the time being a real-time control strategy inspired to a “dynamic” approach recently proposed [8]. In Figg. 6-18 we show the performance results obtained varying the PGS conversion ratio τ in a PNGV-type vehicle controlled with a very simple “static” power follower strategy: the optimum operational design curve in the ICE torque/speed map is calculated by equally weighting the importance of fuel economy and each emission component.





Figg. 14-18: Parametric study. Performances over the US FTP cycle when τ changes between 0.3 and 0.9.

DESIGN APPROACH

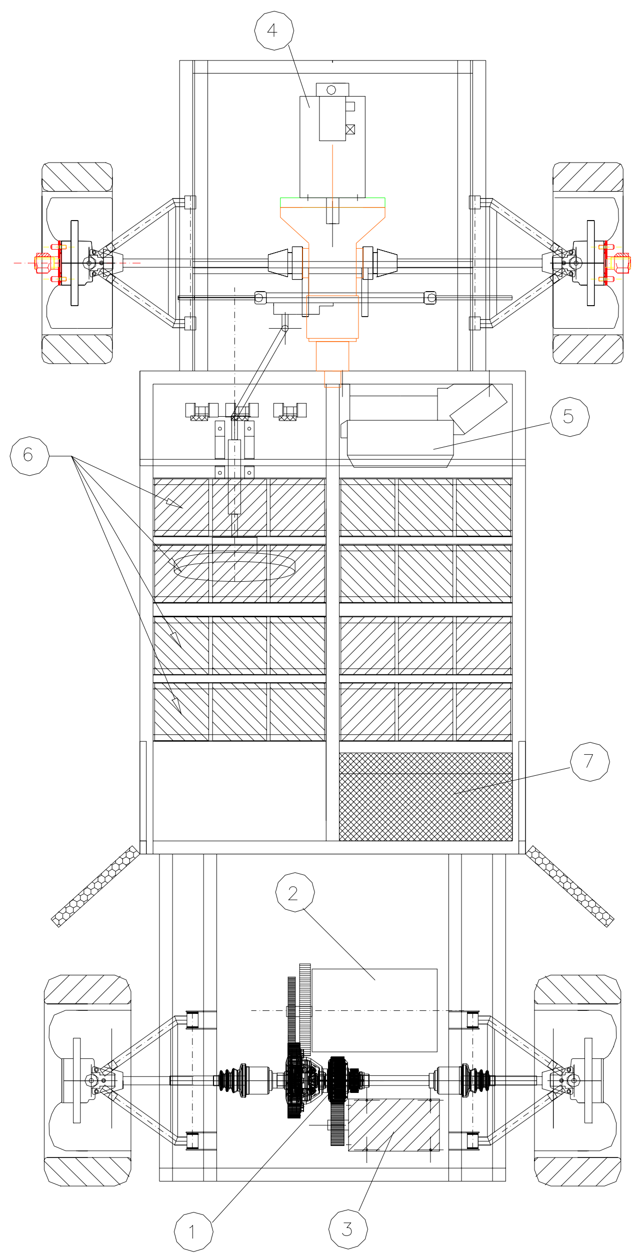
In order to give a detailed vision of the hybrid propulsion system here discussed, it is useful to present the design approach for the realization of a working prototype.
The Department of Nuclear Engineering and Energy Conversions of University of Rome "La Sapienza" has recently realized a hybrid sports-car prototype, called Kjara, in collaboration with the National Research Council (CNR); Kjara [9] is a parallel hybrid car and the aim of that project was to develop a laboratory vehicle useful to experiment various hybrid configurations.
The idea is to use the current layout, but adapted to a SIPRE 3 system, maintaining a big part of the system.
Kjara is a roadster and the powertrain characteristics, the arrangement of mechanical components, the architecture of chassis and suspensions are typical of a sports-car (see Figg.19-20).

Figure 19: Kjara vehicle prototype.

Figure 20: Kjara vehicle prototype on Lombardore (Turin) track.

The powertrain is composed by a thermal engine and an electric motor: the turbocharged diesel engine is installed in the rear, mid-mounted, transversally. It drives the rear wheels through a conventional 5-speed gearbox. The engine is a 85 kW Fiat 2.5 L turbocharged indirect injection diesel engine. The 18.3 kW electric motor is installed in the front, mid-mounted, longitudinally, and drives the front wheels by means of a transaxle 2-speed gearbox with differential. Its control electronics, manufactured by Celco Profil, is put on the dashboard by the right side of the steering wheel. The lead-acid battery pack is composed of 24 cells, each weighting 9.4 kg (total battery weight is 225.6 kg). Being the cells sealed, they can be put flatwise on one side under the two seats.
With such kind of powertrain, it is easy to design a quick conversion of the system to a SIPRE 3 configuration; in

fact, with the simple and quick substitution of the Diesel engine currently mounted on Kjara prototype with the planetary gear set group (see fig.21: PGS + ICE + EG + final drive, but on rear wheels), it is possible to switch to a SIPRE 3 propulsion system.

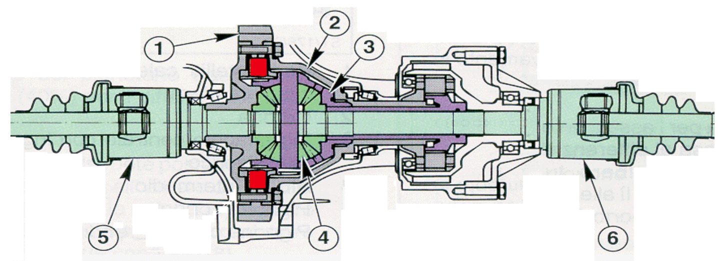


1, Planetary gear set with differential; 2, Diesel engine; 3, Electrical generator; 4, electrical motor; 5, electronics; 6, battery pack; 7, Diesel fuel tank.

Figure 21: Layout solution for the implementation of SIPRE 3 on Kjara vehicle prototype.

In figure 21 it is possible to see the design approach here proposed.
Maintaining the electric motor, its electronics and the battery pack, and mounting the PGS set with a little diesel engine and the electrical generator, it is possible in few hours of mechanical work to pass from the original parallel configuration to the SIPRE 3 system.

The design approach here proposed can be realized in short time and at an affordable cost (for a University it is very important !) using an existent PGS. The drawing in Fig. 22 represents in fact a feasible solution that uses a PGS with incorporated automotive differential, all derived from 1992 4x4 FORD ESCORT. This component, light and with a good transmission ratio, matches well the SIPRE 3 demands, and benefits obviously of a good reliability and quality. The adoption of this component is a very good opportunity for a prototype, cutting consistently the design and construction costs.



1, Sun gear carrier; 2, External case; 3, 4, final drive with differential; 5,6, axle shaft joints.

Figure 22: FORD PGS internal layout.

The FORD PGS internal layout, depicted in Fig.22, is provided with the sun gear jointed to the transmission shaft and to the differential, leaving for ICE and EG the internal ring gear and the planet gears carrier.
Thus, considering that the SIPRE 3 layout can be realized in any different combination of components which can be freely mounted on the three PGS axes, as previously explained, the solution given in Fig.22 is characterized by the Diesel engine joined to the internal ring gear and the electrical generator joined to the planetary gear carrier.
In this way a full SIPRE 3 equipment can be realized, in the four wheel drive configuration, needing only few mechanical modifications and starting from an easy available automotive component acting as PGS. So, using an existing hybrid car prototype it is possible to test on track all the simulation results ADVISOR can generate. The aim is to put on track and test the SIPRE 3 vehicle by the end of 2000.

CONCLUSION

A power-split hybrid drivetrain is analyzed in this paper. Its main characteristics are:

- vehicle reversing is a motor-only drive mode
- the generator cranks the engine
- the vehicle operates electrically when driving into restricted zones

- 2WD and 4WD layouts are available
- the generator can spin backwards

ACKNOWLEDGMENTS

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

ADVISOR:

ADvanced VehIcle SimulatOR

CIDI:

Compression Ignition Direct Injection

CNR:

Consiglio Nazionale delle Ricerche (Italian National Research Council)

EG:

Electrical Generator

4WD:

Four Wheel Drive

FTP:

US Federal Test Procedure, “city” cycle for city-highway tests

HEV:

Hybrid Electric Vehicle

ICE:

Internal Combustion Engine

MURST:

Ministero dell'Università e della Ricerca Scientifica e Tecnologica (Italian Ministry of Universities and Scientific and Technological Research)

PGS:

Planetary Gear Set

PNGV:

US Partnership for a New Generation of Vehicles

SIPRE:

Sistema Ibrido di Propulsione con Ruotismo Epicicloidale (Hybrid-Propulsion System with Planetary Gear Set

2WD:

Two Wheel Drive

VRLA:

Valve-Regulated Lead Acid

Use of *ADVISOR* for simulation of a Hybrid Electric Vehicle with a **Stirling Engine** as the Auxiliary Power Unit

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University of Calgary, Canada

Graham T. Reader
University of Windsor, Canada

UNIVERSITY of WINDSOR

UNIVERSITY OF CALGARY

Outline

1. Introduction
2. Background
3. Solution Design
4. Current Results
5. Conclusion & Future Work

Questions?

Introduction

- Consideration of environmental impacts in the life cycle of products
- Environmental regulation & commitment
- Automobile transportation system:
  - Number of vehicles, driving time
  - Local by-products: Congestion, air & land pollution
  - Global by-products: Acid rain, global climate change
- Increasing investment for environmental improvements on vehicles

Introduction (2)

- Hybrid Electric Vehicle (HEV)
  - optimization of power units functions:
    - ❑ Acceleration ❑ Cruise ❑ Stand by
- Stirling Engine (SE) powered HEV:
  - potential advantages over Internal Combustion Engines (ICE) powered HEVs
- ADVISOR: Cost effective HEV evaluation tool
  - Searching Strengths & Areas of improvement
  - Try new ideas

Background

- Stirling Engine.
  - It operates in a closed regenerative thermodynamic cycle.
  - Cyclic compression and expansion of the working fluid at two different temperatures.
  - Successful use in cryocooling and power applications.

Background

- Stirling Engine.

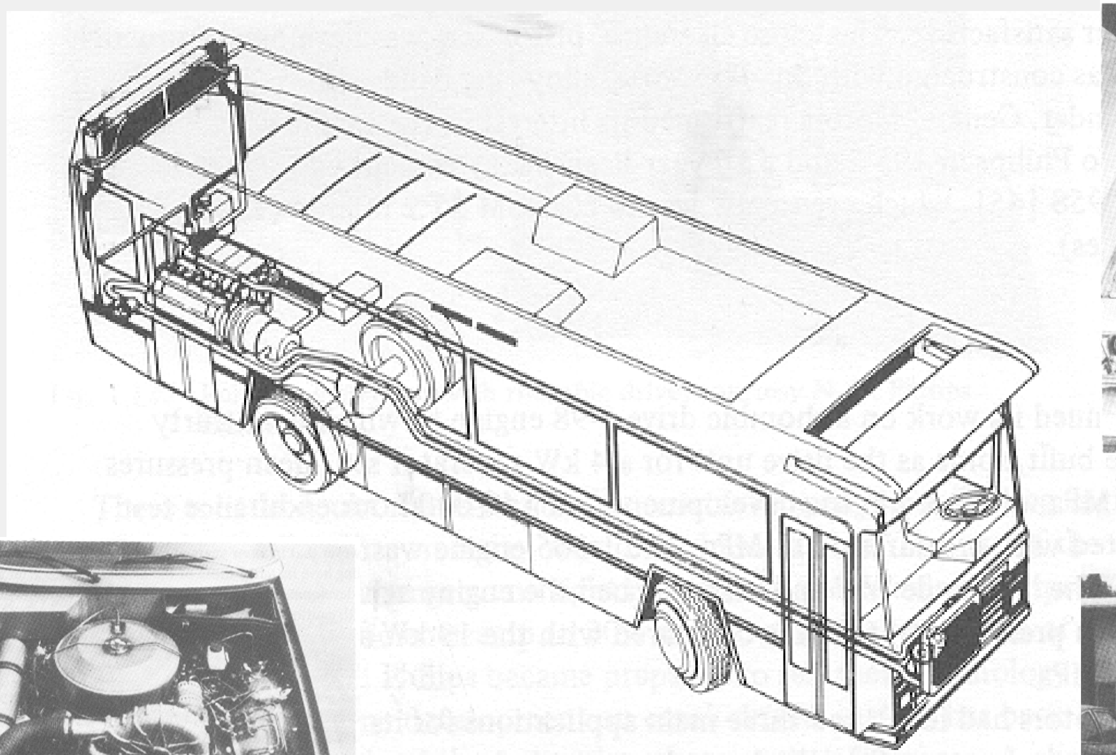
Southern California Edison (SCE)
Dish Stirling technology (MDC)
1987, Barstow, California.
13,000 hours, more than 100,000 kWh

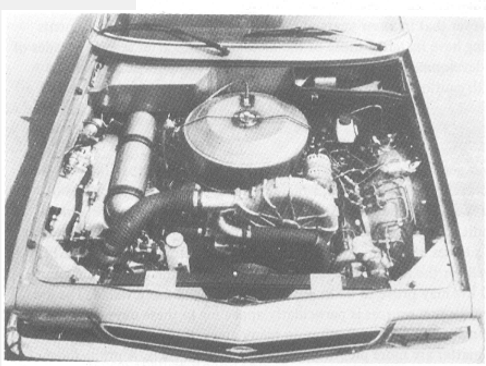
http://www.stirlingenergy.com/Pages/technology.html

http://www.kockums.se/productsandserva.html

Background

- Stirling Engine: Automotive Applications?





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Background

- Stirling Engine: Automotive Applications?

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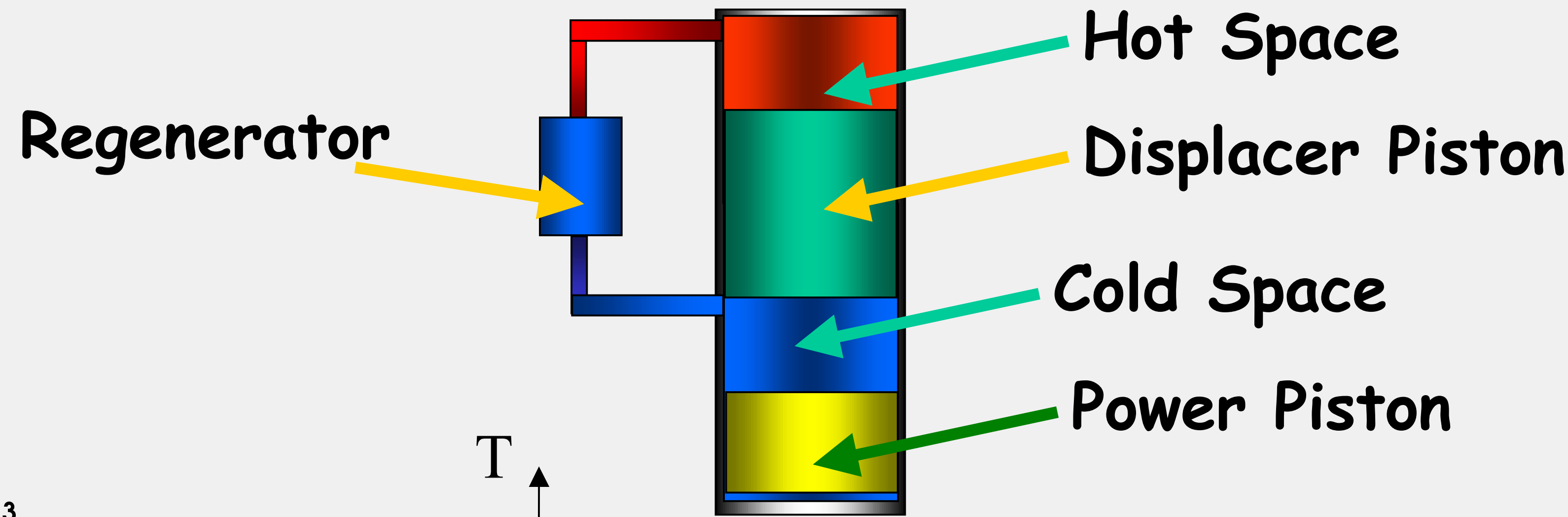
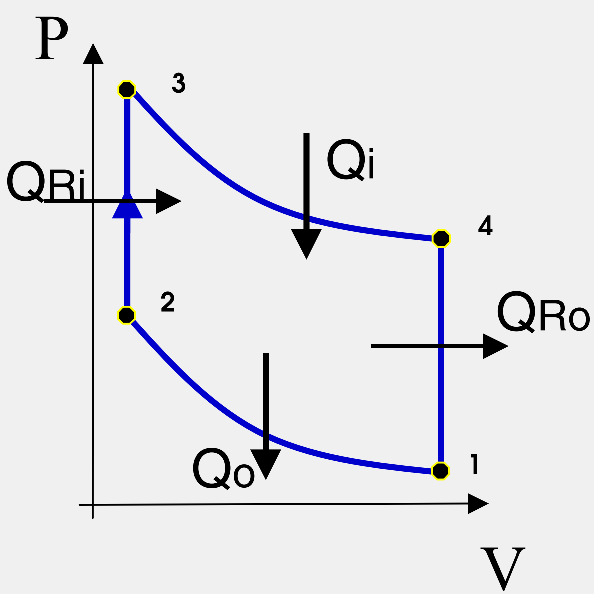
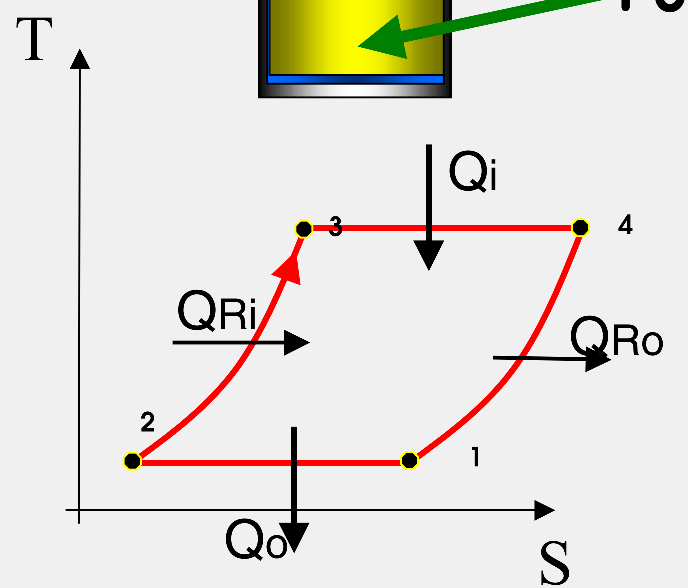
Stirling Cycle







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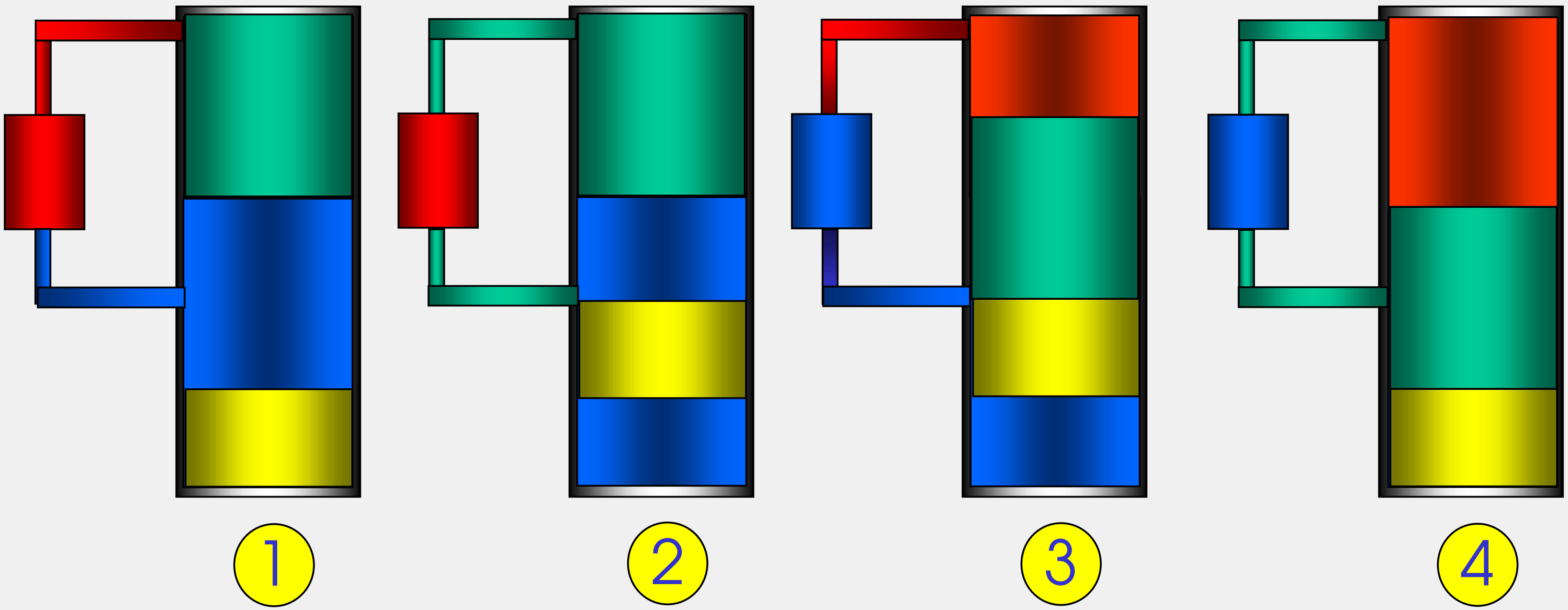
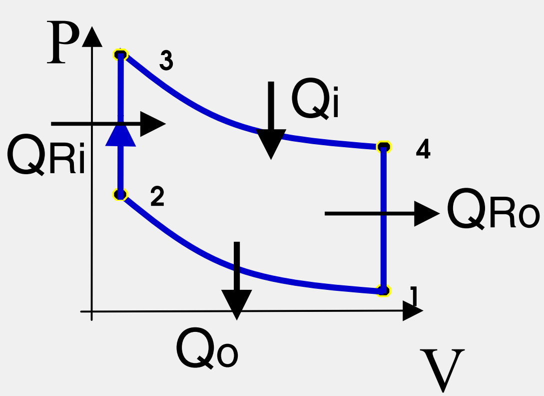
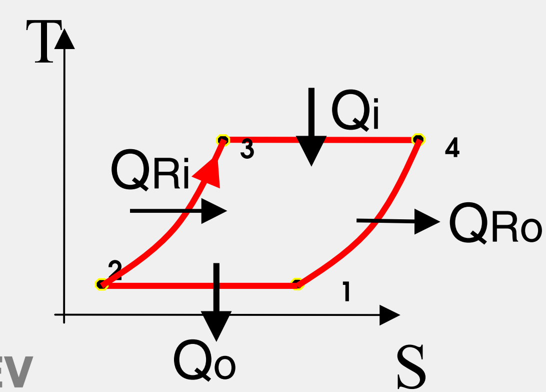
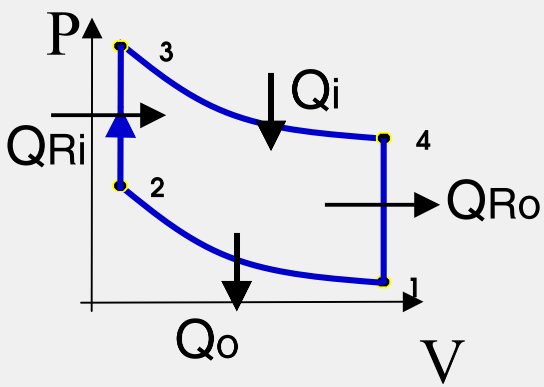
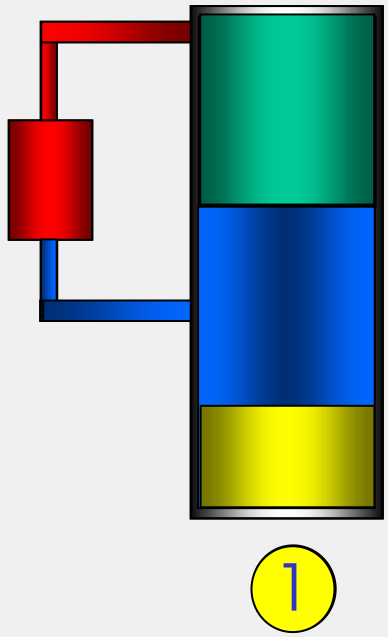


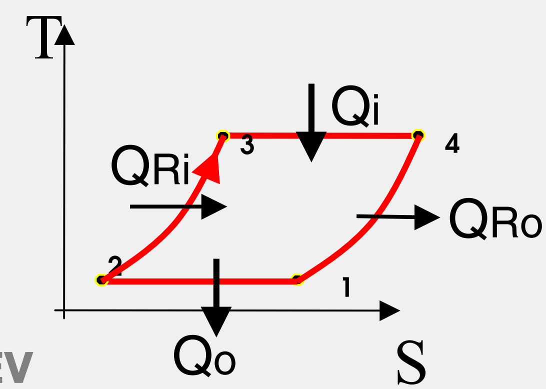




Stirling Cycle

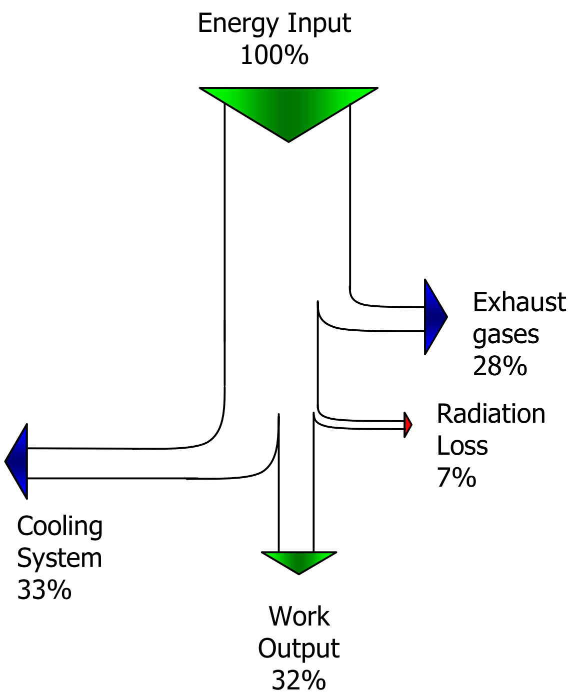




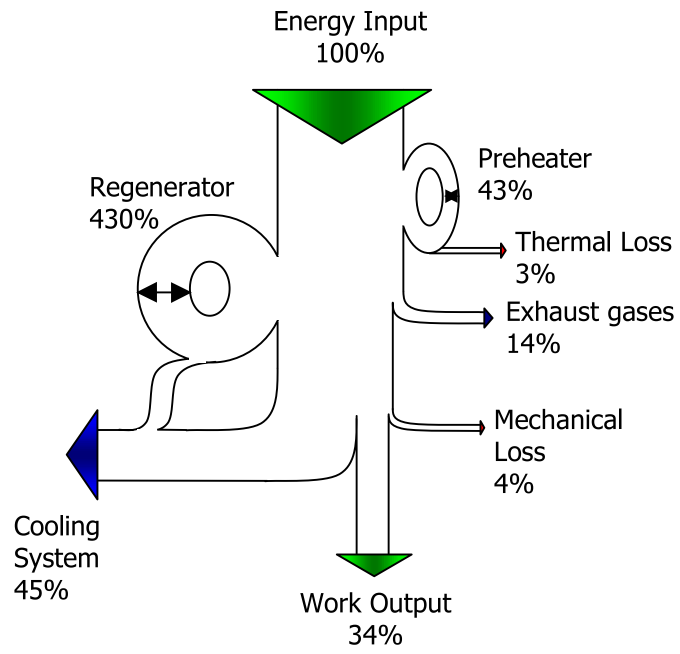


Energy Flow

- ICE



- SE



ADVISOR Simulation of SE HEV

SE Characteristics

- Multi fuel capability
- Highest theoretical thermal efficiency
- Higher efficiency than ICEs
- Quieter operation than ICE and gas turbines
- Lower vibration, emission of pollutants than ICE
- Cogeneration capability
- Regenerative braking capability
- Long operating life
- Extended maintenance periods
- Low oil consumption

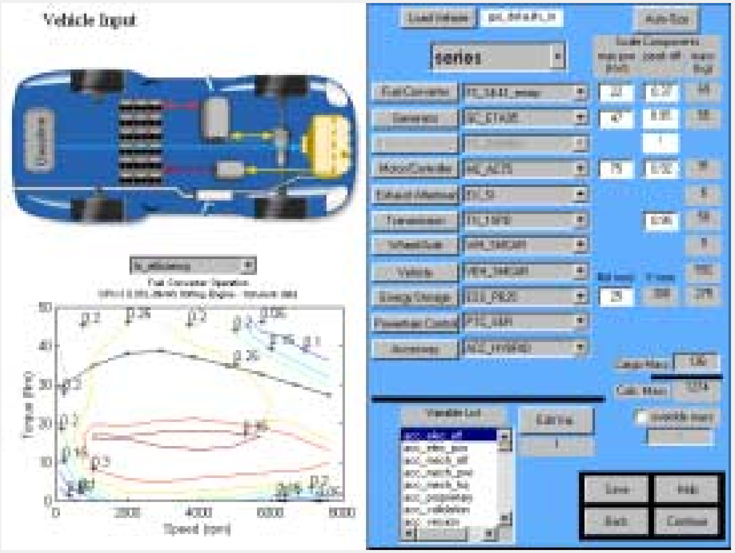
ICE - SE Comparison

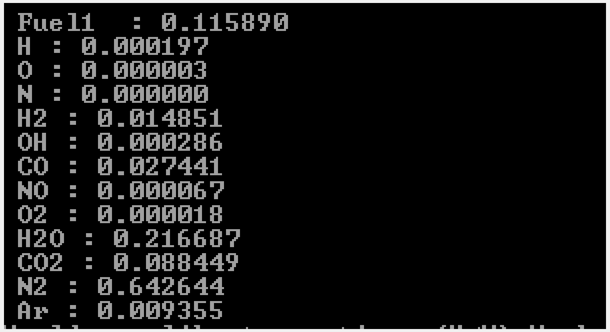
- Reliability
- Higher power to weight ratio (high pressure engines)

- High manufacturing & materials costs
- somewhat larger size than ICE
- Larger radiator than ICE
- Slower response than Otto, similar to Diesel
- Performance = Quality Manufacture
- Catastrophic failures (high pressure engines)

Solution Design

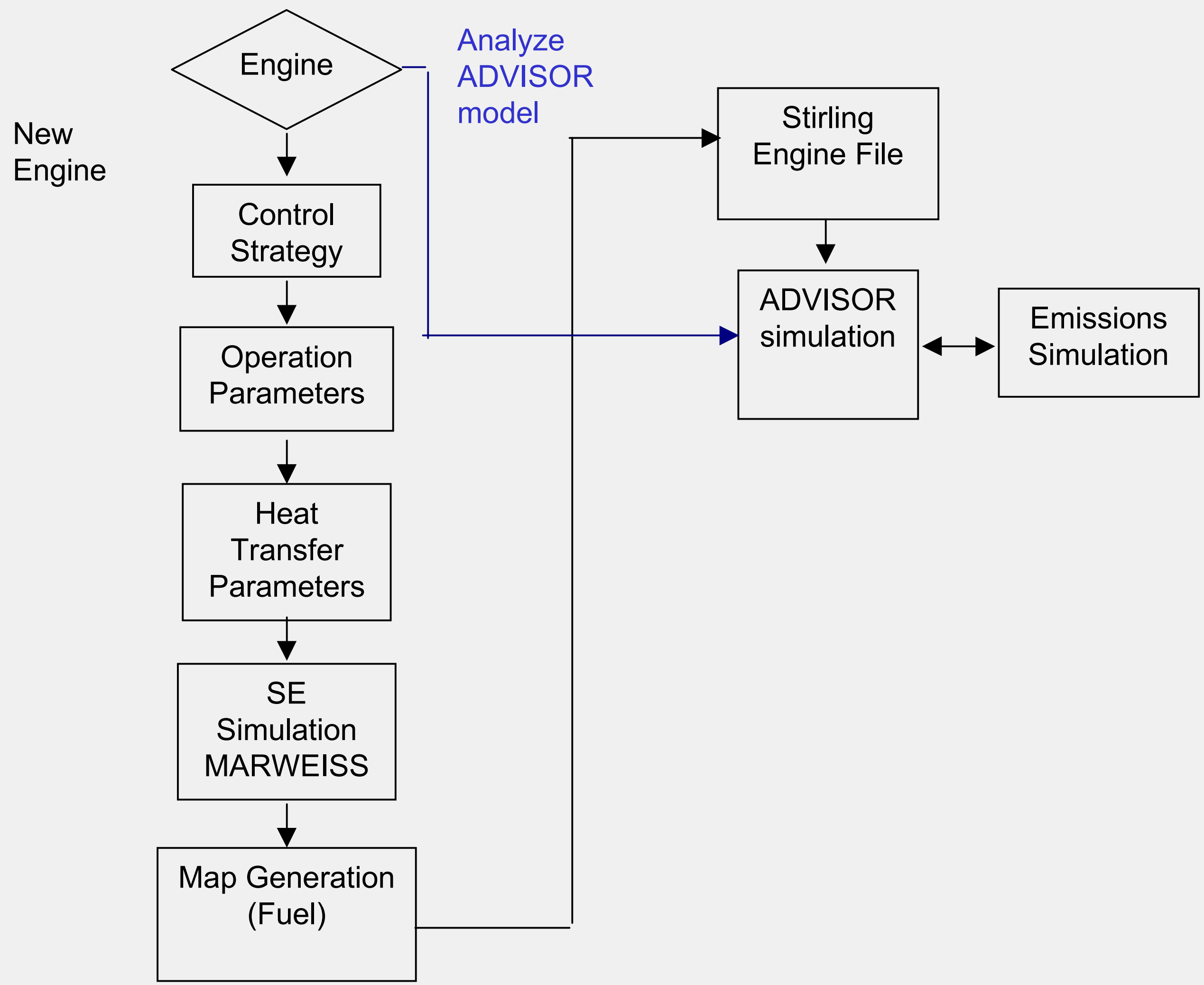
- ADVISOR
- MARWEISS
- Emissions calculation





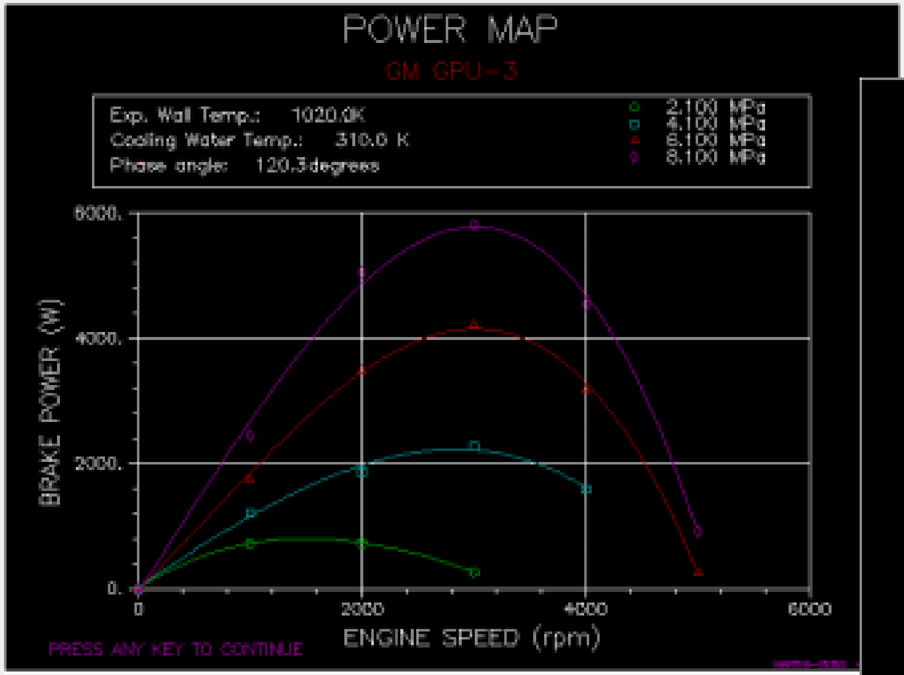
ADVISOR Simulation of SE HEV

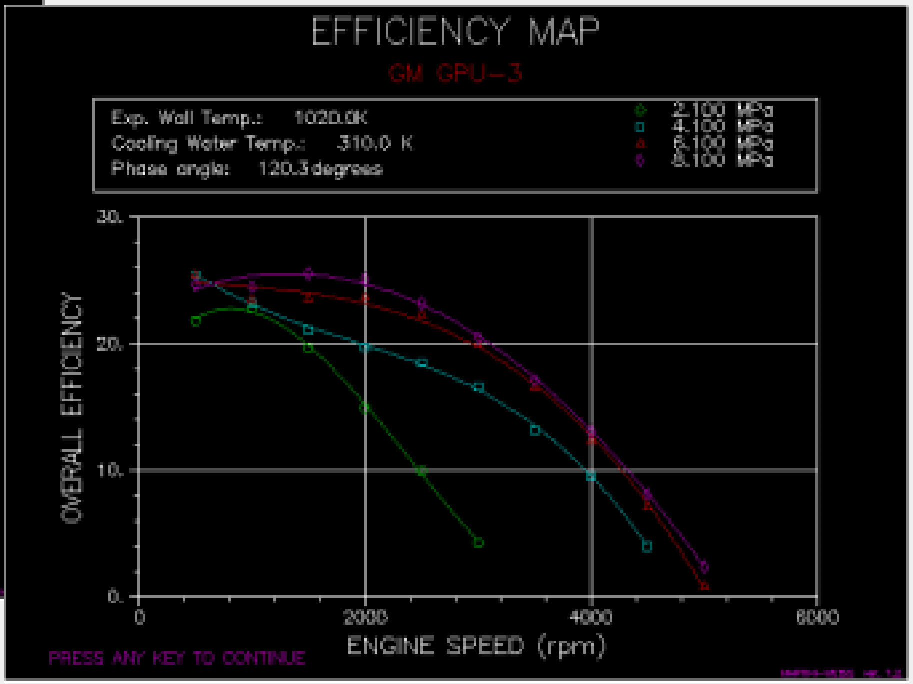
Solution Design



ADVISOR Simulation of SE HEV

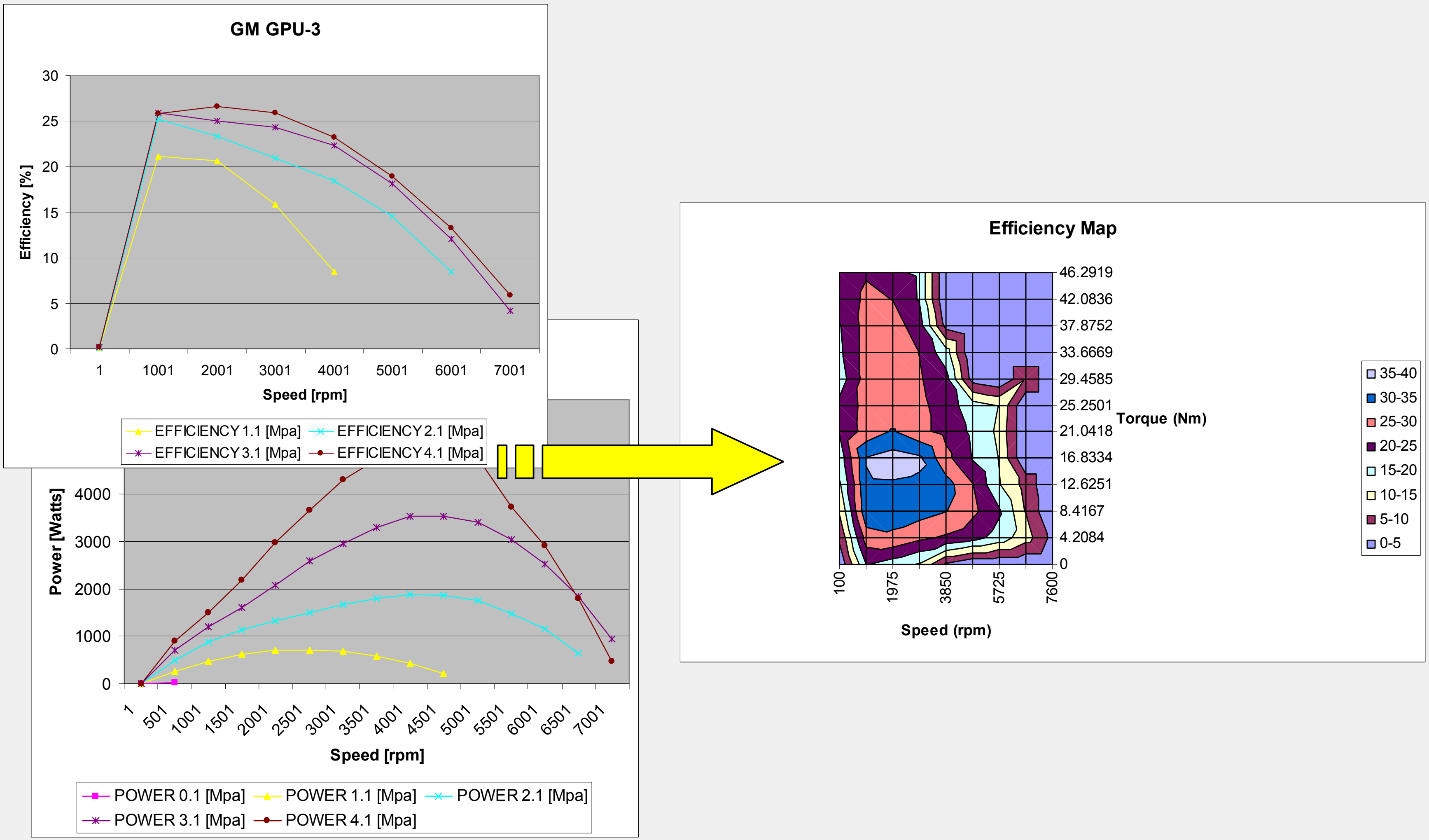
MARWEISS





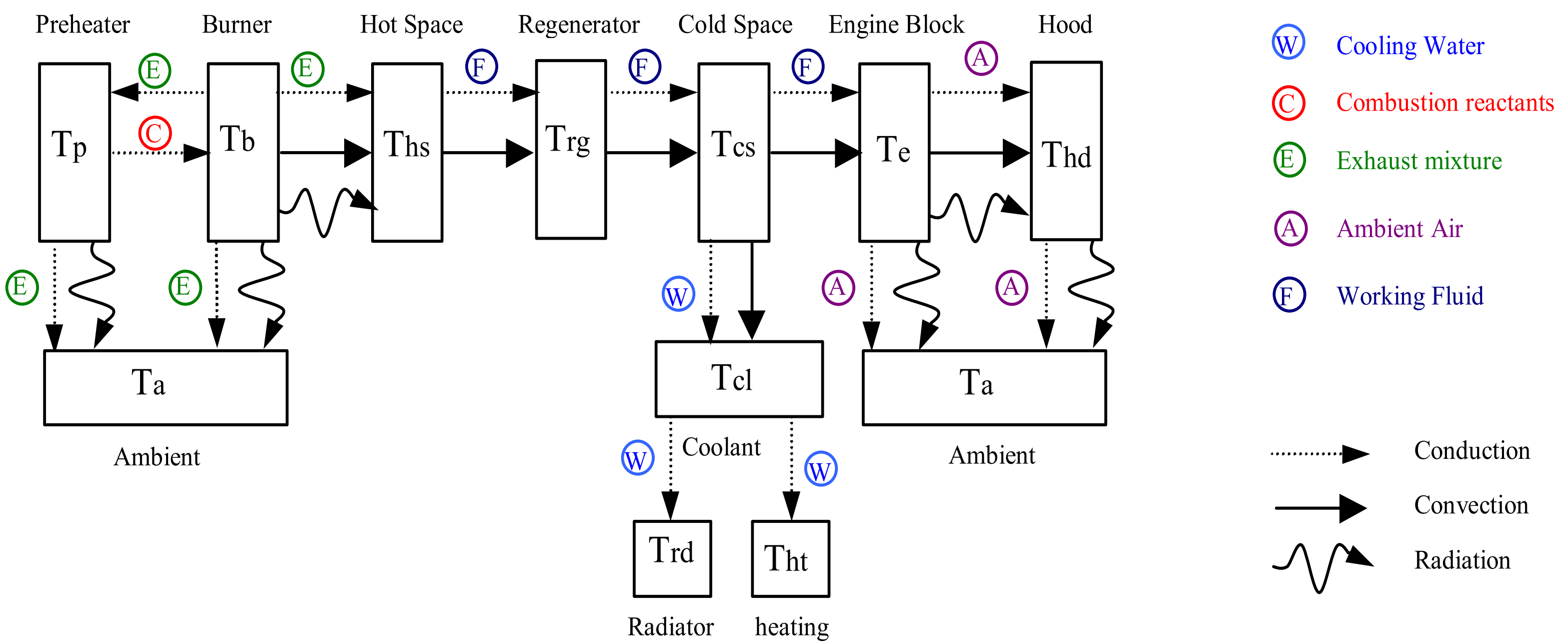
ADVISOR Simulation of SE HEV

MARWEISS

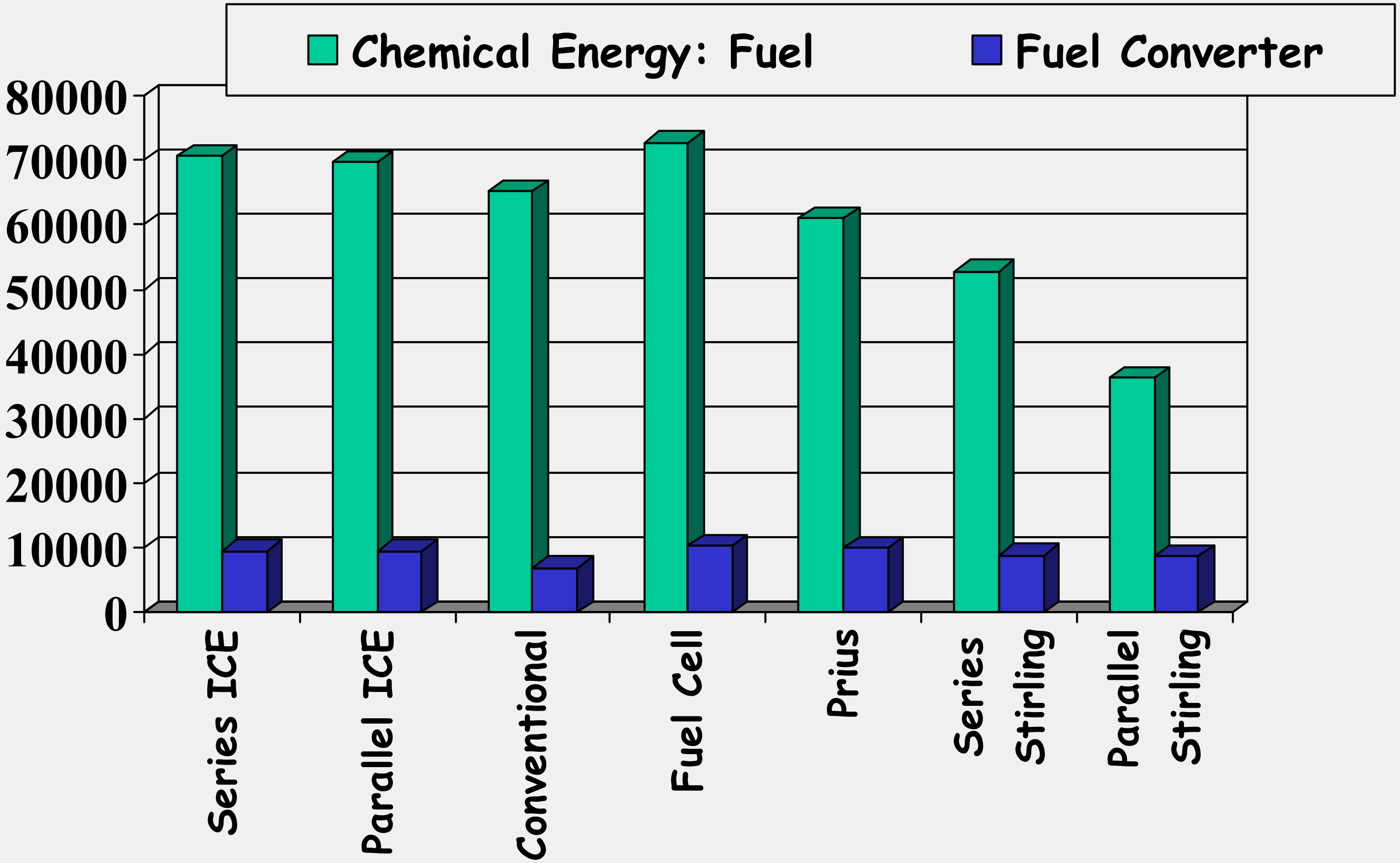


ADVISOR Simulation of SE HEV

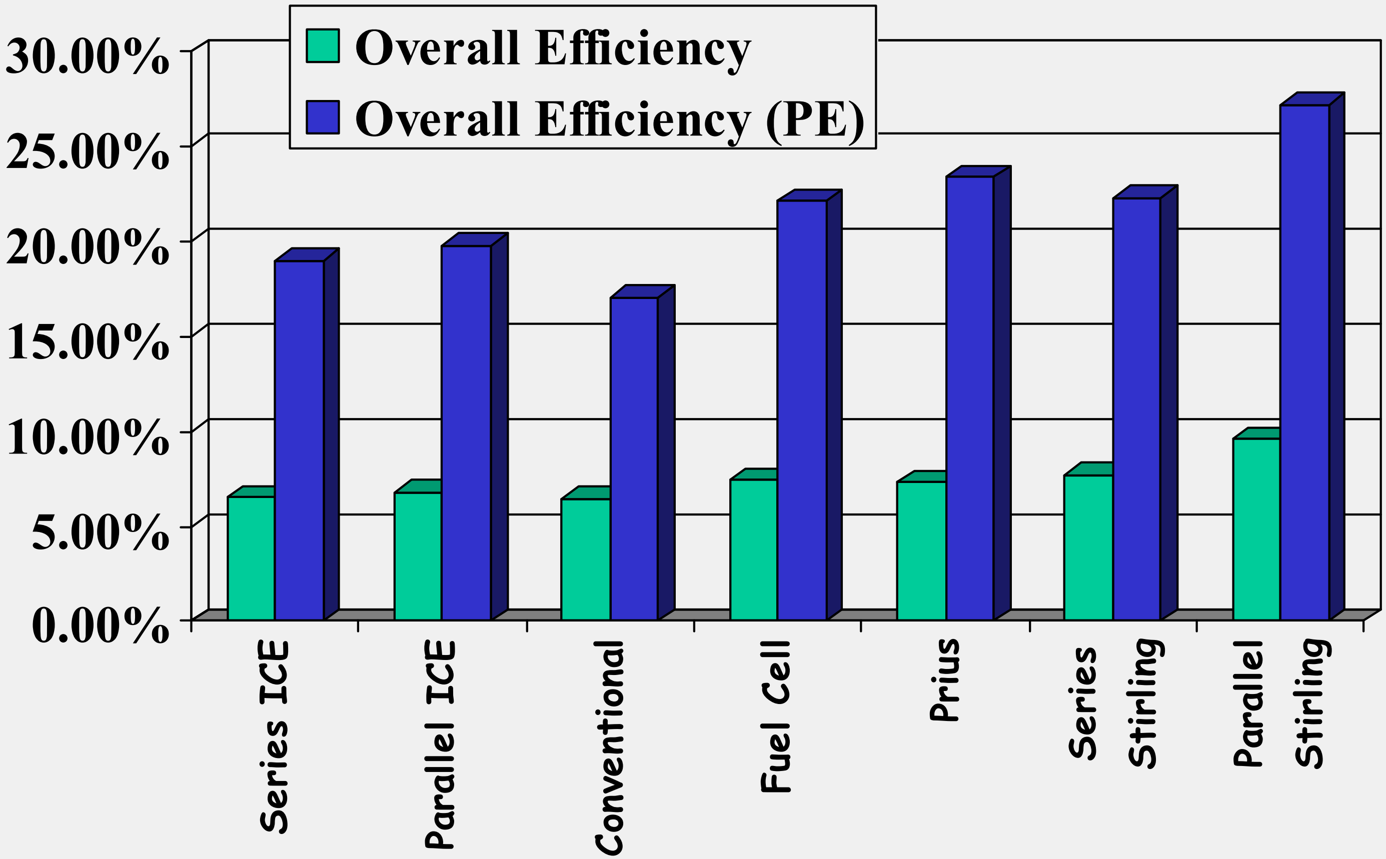
ADVISOR SE Thermal Model



Current Results

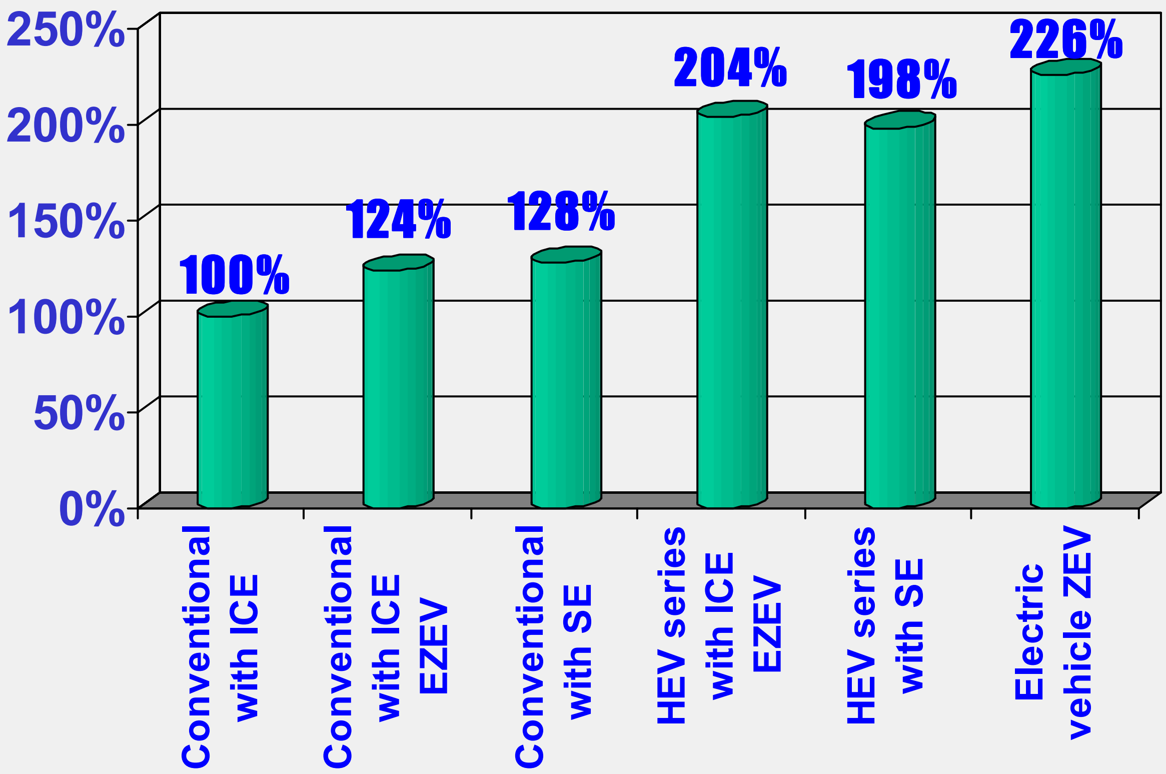


Efficiency



ADVISOR Simulation of SE HEV

Cost Analysis[a]



a : For a projected production of 10,000 units / year

Conclusion

- SE can be an alternative to ICE
  - Reduction of emissions
  - Improvement of efficiency.
  - High engine price: 150% ICE

    (with adequate production levels)
- Environmentally friendly automobile:
  - Adequate production levels of HEV and SE
  - Internalization of environmental costs
- Evaluation of SE as an APU with ADVISOR.

  Conventional Series Parallel Split

Future Work

- Experimental testing of the model:
  - Efficiency & fuel consumption
  - Engine characteristics (Torque, Speed, Power)
  - Emissions
  - Heat transfer model
- Integrate emissions simulation into ADVISOR
- Evaluate influence of mechanical efficiency on SE power map generated by MARWEISS.
- Evaluate configurations & components
- Optimize SE HEV.

Thank you!

Questions?

Use of ADVISOR for simulation of a Hybrid Electric Vehicle with a Stirling Engine as the Auxiliary Power Unit

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ABSTRACT

A hybrid electric vehicle combines the advantages of an electric motor and an energy storage system, with an auxiliary power unit - typically a chemically fueled unit. As a result, it reduces fuel consumption and adverse environmental impacts.

The aim of this project is to evaluate the performance of the Stirling engine use as the auxiliary power unit in hybrid electric vehicles and identify the characteristics that suggest mobility applications of the Stirling engine.

A simulation tool for assessing Stirling engine hybrid electric vehicles has been designed, based on these computer programs:
(i) ADVISOR, Advance Vehicle Simulator [1, 2]
(ii) MARWEISS, Stirling Engine simulation program [3]
(iii) EQUILIBRIUM, Emission composition Simulator [4]

Results obtained from this designed simulation tool, for conventional Stirling vehicles or hybrid electric-Stirling vehicles in series, parallel or split configurations, can be compared with other modeled vehicles such as, conventional, pure electrical vehicles, or hybrid electric powered with internal combustion engines or fuel cells.

To validate the simulation model, future work will compare findings with experimental data from a Phillips Stirling SE 102C power plant and examine findings with other Stirling engines.

INTRODUCTION

Environmental concerns are becoming a determinant factor in the life-cycle of products (design, production, distribution, use and disposal) all over the world. Regulation and voluntary commitment to control and mitigate adverse environmental impacts are continuously increasing.

Adverse environmental impacts caused by the intensive use of vehicles in big cities are evident. A steady rise in the number of vehicles and driving time in the world's major urban areas is pushing congestion, as well as air and land pollution to intolerable levels. The by-products of petroleum combustion - air pollution, acid rain and global climate change - point to the need to redesign the current automobile centered-transportation-system. [5]

Proposed measures in response to the environmental deterioration include urban planning and widespread use of public transit and alternative transports such as, bicycles and walking. However, it is predictable that the automobile will remain as the main way of transportation in the world major urban areas, urging to find ways to reduce its environmental effects.

In general, the environmental characteristics of vehicles are not considered as important as other factors, such as security, performance, life style (convenience, equipment), and cost (vehicle purchase price, fuel price) for the average consumer. Government legislation and cost reduction are the main driving forces for taking into account environmental issues in the design of transportation. The trend in the automotive industry is to design vehicles with lower environmental impact and increased efficiency, while satisfying customers' expectations.

The automotive industry has developed the technology needed to achieve the current environmental requirements, paying a price. There is an increasing cost for the environmental improvements to the customer that could eventually affect the expected performance of the vehicle. [6]

The Hybrid Electric Vehicle (HEV) constitutes an environmentally sound alternative to the conventional automobile due to the optimization of its power units for acceleration, cruise and standby of the vehicle, leading to reduced emissions and fuel consumption. Furthermore, a Stirling Engine (SE) powered HEV offers potential advantages over Internal Combustion Engines (ICE) powered HEVs: the ability to operate on different heat sources (multi-fuel capability), and the reduced levels of fuel consumption, noise, vibration and tailpipe emission related to the Stirling may overtake the projected goals for ICEs.

A simulation program is a cost-effective tool for performance evaluation of HEVs; it enables the definition of strengths and areas of improvement for achieving successful commercialization, reducing costs related to prototype development.

In this paper is summarized the current status of a graduate research project on the applicability of SE in HEV applications, to be concluded by December 2000.

The document is organized in the following sections:

I. **Background.** Overview of the SE and HEVs
II. **Solution Design.** Description of the SE HEV simulation model
III. **Results.** Current findings of the project, comparison of different configurations.
IV. **Future Research.** Description of future areas of research for this project.
V. **Conclusion.** Recommendations for simulation and application of the SE HEV.

BACKGROUND

The purpose of this section is to overview (1) the SE, its simulation methods and contributions to the automotive field, (2) the HEV, the simulator program ADVISOR and HEV trends.

THE STIRLING ENGINE

Overview of the SE

The Stirling cycle machine or SE was invented and patented by Robert Stirling, in Scotland, in 1816 [7]. The SE is a mechanical device, which operates in a closed regenerative thermodynamic cycle. It is based on the cyclic compression and expansion of the working fluid at two different temperatures. The flow is controlled by volume changes, and there is a net transformation of heat energy to mechanical work or vice versa [8]. It has been successfully utilized in cryocooling and power applications. [9]

The Stirling cycle has the same theoretical thermal efficiency as the Carnot cycle and a larger specific work output, although this potential has never been achieved. Today SEs present little advantage in terms of efficiency and power density over ICEs.

The inherent advantages of the SE over the ICE are mainly due to the engine's continuous external heating [10]. For comparison purposes the typical energy flow - diagrams of the SE and the ICE are presented below:

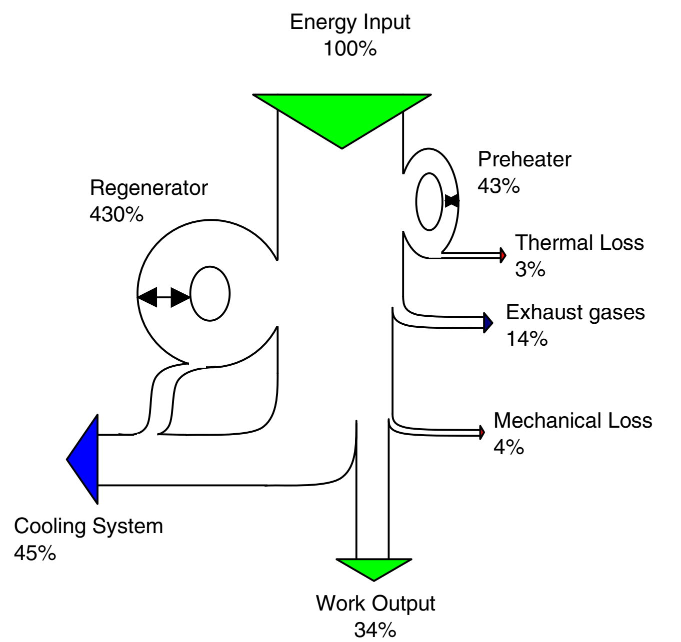

Figure 1. Sankey diagram for energy flow in a typical SE. After Walker [11], Reader [12]

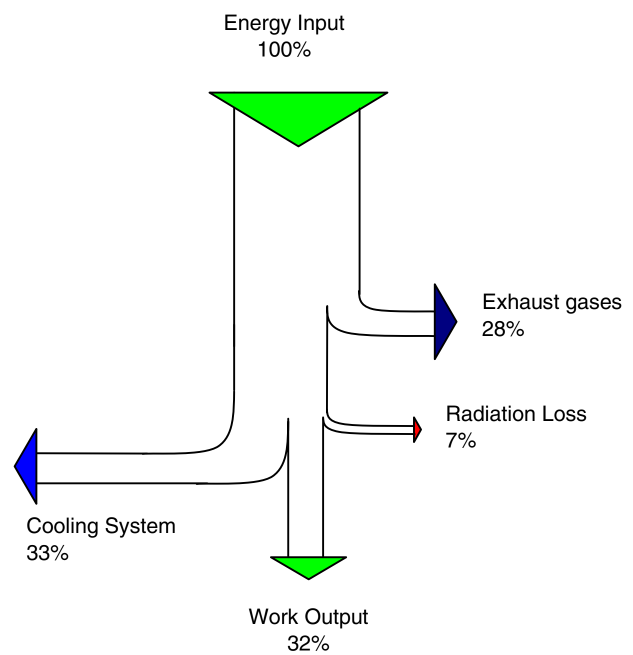

Figure 2. Sankey diagram for energy flow in a typical ICE. After Potter[13], Ganesan [14]

Around 70% of the lost energy in a SE is rejected via the cooling system, and 21% lost in the exhaust gases, while in an ICE 50% is rejected via the cooling system and 40% lost in the exhaust gases. This brings an advantage for cogeneration of heat (for the interior of the vehicle) and power with the SE. It also recalls the requirement for a larger radiator for the SE (usually double the size of an ICE radiator).

The SE represents a potential alternative to ICE in automobile applications. The main advantages are the:

- Ability to use any heating source
- Highest possible theoretical thermal efficiency
- Highest possible theoretical mechanical efficiency
- Quieter operation than ICE and gas turbines
- Lower vibration than ICE
- Lower emission of pollutants when using fossil fuels, because of their continuous combustion process
- Cogeneration capability: Heating interior of vehicle utilizing the energy kept in the engine's refrigeration system
- Regenerative braking capability. The engine operation can be reversed, transforming mechanical power at the output shaft into heat, for deceleration. Later on, this heat can be transformed back into shaft power for accelerating the vehicle
- Higher efficiency than ICEs
- Long operating life
- Extended periods between maintenance
- Low lubricating oil consumption
- Reliability (continuous working operation)
- Higher power to weight ratio when operating at high pressure

The main areas of improvement are the:

- High manufacturing costs with the present low level of production
- High materials costs
- size and weight, somewhat larger than ICE
- Larger radiator needed compared to ICE, with closed system cooling
- Slower response time compared to Otto engines, similar response as Diesel
- Performance depends on high quality manufacture
- Failures are catastrophic due to high pressurization on engine working fluid

Simulation of SE

The methods for analysis of SE are classified according to the assumptions and the mathematical theory that encompass them. They are classified in four main types:

1. Zeroth Order Design Methods: simple models based on an idealized mathematical model (Schmidt cycle analysis) and on engine experimental constants adequate for an initial approximation.

2. First order Design Methods, which start with limited information for calculating the output and efficiency of a given SE.

3. Second Order Design Methods; these take most aspects of the SE, and are more adequate for design. This methods assume that a relatively simple Stirling cycle analysis can be used to calculate the basic outputs and inputs, and that the energy losses can be deducted from the power output; the energy flows are calculated independent of each other without interaction.

4. Third Order Design Methods, or nodal analysis methods simulate the engine by dividing it in a given number of section employing nodes, and solving numerically the differential equations of Conservation of Energy, Mass and Momentum, for each of the nodes.

The third order methods are the most accurate and appropriate for modeling specific SEs, however, they require a longer computational and design time than other methods.

MARWAISS, a second order method is used in this project because of its capability to analyze different types of SE within a reasonable computational time. It is validated as a useful computer simulation tool with results close to test bed information, allowing modest confidence in the simulation and analysis of energy flow and efficiency.

MARWEISS or Martini-Weiss is a second order SE design aid developed by W. Martini and implemented on a PC by M. Weiss at the University of Calgary, Canada. Based on the Martini isothermal model, performs decoupled corrections for determining energy losses. It is written in FORTRAN 77, and includes input screens for the engine parameters. The results of the simulation can be visualized in graphical format and exported to a text file. [3]

MARWEISS utilizes the engine general dimensions, heat exchanger component sizes, drive system dimensions and miscellaneous parameters for performing the simulation. It allows the user to redefine a variety of dimensions, engine configurations, control strategies and operational parameters.

SE Vehicle applications

The main thrusts of the modern SE development have been automobile and cryocooling applications. The history of the modern SE started in the late 1930's, when Philips researched the development of a 1kW-power generator. In 1948 Philips designed a 149 kW engine, which was seen by Henry Ford II and other major automakers in Eindhoven, motivating an interest on the engine. Philips used hydrogen and helium for high-speed and high power density SE.

The main projects involving SE for automotive applications are condensed in the following list:

- General Motors-Philips program: From 1958 to 1970. Included GPU-3 6kW (Stir-Lec I series HEV), 4L23 187 kW (bus applications) [15]. Halted due to braking problem, high costs and GM team leader retirement.
- Ford - Philips program: From 1970 to 1980. Siemens - SE double acting 135 kW (Ford Torino). Complemented with Ford - Philips - ERDA program.
- Ford - Philips - ERDA program: from 1978 to 1980. Siemens - double acting SE 67kW. Halted due to problems in sizing the engine to the lines of production, and long warming up and cooling down time of the engine.
- Stirling Thermal Motors. From 1980 to present. 40kW and STM 4-120 4 cylinder Siemens - swashplate SE, with hybrid propulsion system, now team member on General Motors - Stirling Thermal Motors - DOE program.
- United Stirling AG Sweden: From 1968 to present. 4 cylinder 25 to 75 kW (automotive, marine, solar power generation, and battery charging Nacken class submarine of 1200 Tons) Submarine SE with an endurance of 6 to 8 times compared to Diesel engine. Automotive application halted due to high costs.
- Machinenfabrik Ausburg-Nurnberg (MAN) Motor Werke Mannheim (MWM) From 1968 to 1990's. Double acting Siemens - SEs (Military application on heavy vehicle engines and underwater power systems). Halted due to high costs and end of the cold war.
- Mechanical Technology Incorporated (MTI) - American Motors Company – DOE. From mid 1970's to late 1980's. 4 cylinder double acting engine with crank drive mechanism.
- General Motors - Stirling Thermal Motors - DOE program. From 1993 to 1998. STM 4-120 4 cylinder Siemens -swashplate SE (Partnership for a New Generation of Vehicles, PNGV). Currently carried out. Results have not yet been published.[16]

Several years of intensive research in SE produced engines that matched the achievements of several decades of even more intensive research in Otto and Diesel engines. The position of the SE in vehicle transportation seems optimistic because of the trends of the vehicle industry in searching environmentally friendly automobiles, and the natural capability of SE to operate with low levels of noise, vibration and emission of pollutants. However, the SE automobile projects have not been commercialized yet. The main areas for improvement include costs, required time for cooling and warming up of the engine, larger radiator required, matching of the engine to the automobile and sealing.

Cost is the major concern in the SE success; it varies between 1.5 and 15 times the cost of an equivalent Diesel, according to manufacturers' data and technical conferences. The cost of a SE prototype in US Dollars of 1981 ranges from \$2000/kW to \$6700/kW. This cost is practically unacceptable, when compared with the cost of \$25.5 /kW of Otto ICE [12]

In order to commercialize successfully the SE in the automotive industry, it must be a standard item, and not a prototype or exception item. Due to the current low volume of production, the SE requires specialized materials, tools and Fixed Capital Equipment that increment drastically the manufacturing cost.

With a production level of at least 400,000 units per year, according to studies documented by Reader [12], the comparative projected sale price for SE and ICE:

Table 1. Dealer selling price for automotive engines

Engine	75 kW $/kW	% Otto	112 kW $/ kW	% Otto
ICE Otto	25.25	100%	18.74	100%
Stirling	39.74	157%	28.92	154%

1981 USD (400,000 units per year) After Reader, G. Hooper C. (1983)

Even with less expensive materials and adequate production levels, the SE is likely to be 50% more expensive than Otto Engine. However, it is important to consider that because the engine's cost represents about 10% of the automobile's cost, the replacement of an ICE with a SE represents an increase of 5% on the cost of the vehicle.

HYBRID ELECTRIC VEHICLES

Overview of the HEV

A HEV is an alternative transport that has two sources of motive energy: 1) an electric motor, and 2) an Auxiliary Power Unit (APU). HEVs combine both sources with an energy storage system (ESS). Typically, the APU is chemically fueled -an ICE, gas turbine or a fuel cell.

As a result of the combination of the power units, HEVs reduce fuel consumption and adverse environmental impacts. The HEV capitalizes on the principle that a vehicle power plant must have three dissimilar functions: i) accelerate, ii) cruise, iii) stand by (when no power output is required: warming up, traffic lights, congestion).

In a conventional vehicle, the engine is sized to satisfy the acceleration requirement, utilizing excessive fuel for both, cruise and stand by functions. HEVs have two power plants working on series, parallel, dual or split configuration, to:

- Optimize power/energy consumption for acceleration
- Minimize energy consumption during cruise[17]
- Minimize or eliminate energy consumption during stand by
- Minimize pollutant emissions
- Provide regenerative braking capability
- Allow operation with alternative fuels; need not be dependent on fossil fuels.

The advantages of the HEVs over the electrical vehicles (EV) are:

- Lower weight and volume of the electric and energy storage units
- Higher global efficiency of the system, due to direct thermal to mechanical energy conversion
- Better vehicle performance (acceleration and speed) due to the motor/APU combination
- Increased autonomy range[18]

The disadvantages of the HEVs compared to ICE and EV vehicles are:

- Higher complexity in design and manufacturing
- Higher number of components
- More sophisticated vehicle electronic control strategies
- Higher manufacturing cost
- Higher weight and volume required for power units than ICE.

The HEV powertrain components are selected to minimize its disadvantages and achieve its advantages without appreciable loss in vehicle performance, range, or safety.

Simulation of HEV

The methods to analyze HEV employ a static or dynamic approach for vehicle control to optimize several parameters, such as efficiency, weight or emissions.

The simultaneous optimization of fuel efficiency and pollution emissions requires of strong mathematical algorithms in the computer simulations programs. ADVISOR performs forward/ backward analysis to review the validity of the information. Other methods currently in study, involve computer models with genetic algorithms that combine billions of options on the different parameters that determine the engine performance, for finding better results [19]

The ADVISOR program, launched in 1994 by NREL, considers dynamic vehicle operation conditions, for optimizing both energy efficiency and emissions, in conventional and advanced vehicles [20]. It is based on Simulink block diagrams and supported by Matlab data files that contain vehicle configuration, control, and performance data. The use of Simulink provides accessible documented code in a graphical environment, which makes modification relatively easy, helping ADVISOR to be well suited to collaboration between researchers and for distribution to the public.

The code incorporates several drive train types including electric, conventional ICE (spark ignited or compression ignited) and HEV in series, parallel and split mode with ICE or fuel cell as the APU. One of the objectives of this project is to include SE to the drive trains available.

ADVISOR allows the user to interchange a variety of components, vehicle configurations, and control strategies. Modification of data files to represent new or unique vehicle components is simple, and a friendly graphical user interface (GUI) allows manipulation of input files, test routines, and output plots [1,2].

Cost analysis on HEV

Mercedes Benz conducted a cost analysis for HEV in series configuration [21]. The following table contains a comparative cost analysis obtained from the study. It has been complemented with the projected production cost for a SE HEV, in series configuration.

Table 2: Production costs for different drivetrains

Drivetrain System	Production Cost (%)
Conventional with ICE	100 %
Conventional with ICE EZEV	124 %
Conventional with SE	128%
HEV series with ICE EZEV	204 %
HEV series with SE	198 %
Electric vehicle ZEV	226 %

Based on Mercedes Benz class C (10,000 units per year)
Complemented after Abthoff, et al. (1998)

For calculation of the cost of the SE HEV ($\mathbf{P}_{HS}$):

- $\mathbf{P}_{HIC}$: HEV ICE price, 204% conventional ICE.
- $\mathbf{P}_{ICE}$: ICE price, 10% price of conventional ICE
- $\mathbf{P}_{SE}$: SE price, for a production level of 10,000 units, would be around 280% the price of an ICE, according to studies by Jet Propulsion Laboratory [22].
- $\mathbf{P}_{EZEV}$: EZEV ICE equipment price, given the low emission of pollutants inherent to the SE, there would be a reduction of 24% basic vehicle price associated to EZEV ICE equipment.

Then:

$$P_{HS} = P_{HIC} - P_{ICE} + P_{SE} - P_{EZEV}$$

$$P_{HS} = 204 - 10 + 28 - 24 = 198\%$$

In conclusion, the cost of a HEV with SE would be very similar to the cost of the HEV ICE that complies with EZEV legislation. Environmental concerns themselves are not a reason for the general public to pay double for an alternative vehicle.

SE and HEV share a common future: In order to be commercialized successfully, they must first bring answers to common problems:

- Need to have adequate production levels to reach significant cost reductions in tools, materials and fixed capital equipment costs, independently of the APU
- Need to internalize environmental costs in transportation pricing [23] [24]

The implementation of pollution penalty measures (e.g. increased fuel taxes, licensing or driving fees) applied to vehicle use and ownership, can motivate the public interest towards environmentally friendly efficient vehicles. This will increase the research and production of such vehicles, and a subsequent price reduction.

SOLUTION DESIGN

GENERAL SIMULATION MODEL

This section describes the steps considered for integrating the simulation tools.

In order to predict the performance of a variety of SE, the simulation model is flexible allowing to model HEV or conventional vehicles, in any configuration.

The considerations for the model include:

- Multi-fuel capability of SE: Simple redefinition of the type and characteristics of the fuel employed
- Control method for SE: Capability for selection of the control method and generation of the corresponding power maps
- Reduction of NOx emissions: Consider effects in power, efficiency and emissions of the recirculation of combustion exhaust gases for reduced NOx emissions. The effects on power, efficiency and emissions should be considered

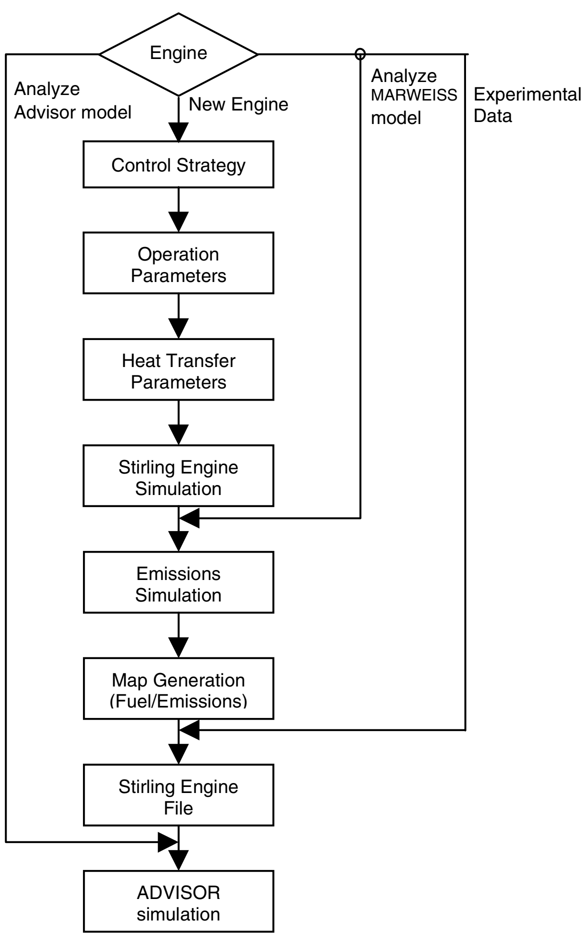

Figure 3. Methodology for simulation of SE HEV.

<u>SE selection</u>

The engine to be simulated can be selected from different sources:

a) Engine previously studied with ADVISOR, selecting the engine in the graphical interface of ADVISOR
b) Design of a new engine with MARWEISS. Define a new engine based on i) MARWEISS' engine parameter definition or ii) edition of an existing engine
c) Engine previously simulated with MARWEISS, selecting the text file with the SE simulation results (MARWEISS outputs for the desired engine)
d) Input experimental results of the SE in a text file, for selecting this file later in ADVISOR, as described in option a)

<u>Control Strategy.</u>

The control strategy is defined by the goal of the simulation, the most common options:

- Accomplish drive cycle
- Maximum Efficiency
- Minimum Emissions
- Minimum Fuel consumption
- Maximum Power
- Maximum Torque
- Maximum Speed

In ICEs, the power output is a function of the mass flows of air and fuel. Because of SE nature, the power output can be controlled in different ways. The most common ways are:[25]

1) Pressure level of working fluid
2) Stroke variation
3) Phase angle variation
4) Maximum compression / Expansion volume
5) Temperature of Hot / Cold spaces

The control variable determines the type of power maps that are required for the simulation. Most commonly, the power maps will be given as a function of:

i) pressure level and the angular speed, or
ii) phase angle and the angular speed.

<u>Operation Parameters</u>

Parameters defined to achieve objectives such as, emission levels, power output or efficiency.

1) Energy Parameters
   - Type and characteristics of fuel Employed
   - Fuel / Air ratio
2) Engine heater operation
   - Percentage of exhaust gas recirculation
   - Ambient temperature and pressure

Heat Transfer Parameters

These parameters include heat transfer coefficients and areas of the specific engine, utilized in the simulation of the heat transfer of the engine.

SE Simulation

As described in the background, it is employed the second order method MARWAISS. The general procedure of the program is shown in figure 4. MARWAIS is based on the Martini isothermal method, summarized here:

1. Given the hot and cold space temperatures and the engine dimensions, calculate basic power using Schmidt cycle analysis
2. Calculate basic heat input from power output, using Carnot Efficiency
3. Evaluate net power, net heat input, gas heater duty, and gas cooler duty
4. Calculate flow rate, cycle time for heater, corrected temperature drop for gas heater duty to be transferred, and effective hot space gas temperature
5. Calculate flow rate, cycle time for cooler, corrected temperature drop for gas cooler duty to be transferred, and effective cold space gas temperature
6. Recalculate steps 1 to 5 using effective hot space temperature for heat source temperature and effective cold space temperature for heat sink temperature
7. Repeat 6 until the effective calculated temperatures are steady

The power maps generated in MARWEISS tabulate the output power and the efficiency as functions of the engine speed, given different pressures of the working gas, in the case of engines controlled by working gas pressure. For phase angle controlled engines, the power maps tabulate the output power and the efficiency as functions of the engine speed, given different phase angles.

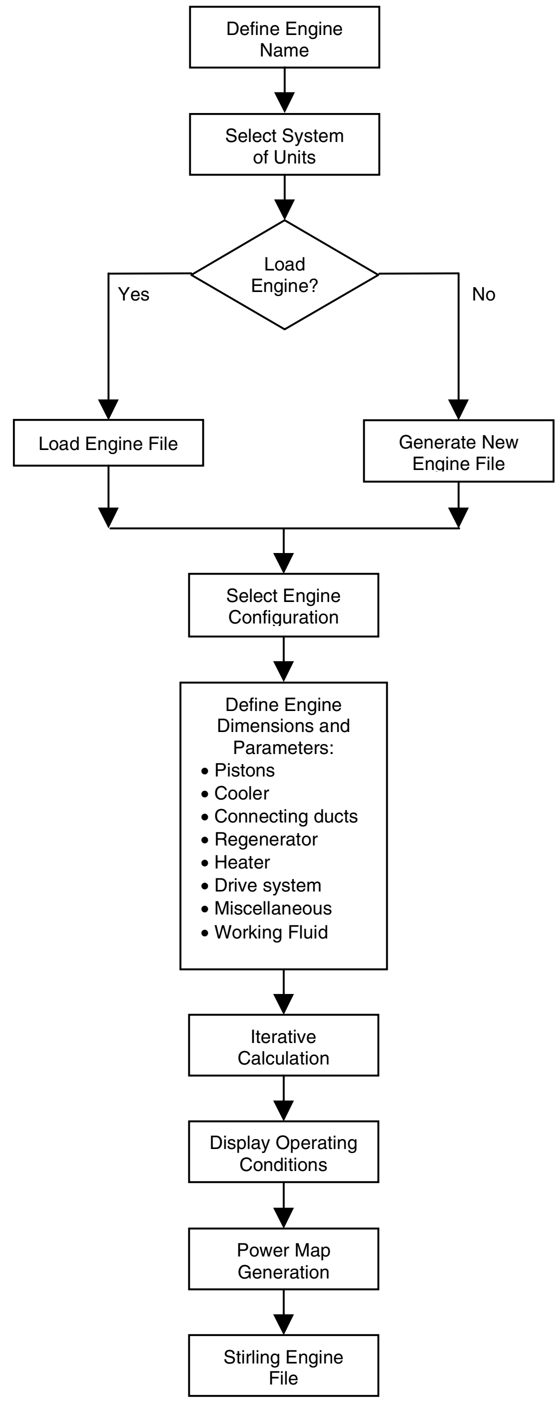

Figure 4. Flow diagram for MARWEISS SE simulator

Emissions Simulation

This part of the procedure consist of the calculation of the composition and properties of the combustion products at equilibrium temperature, utilizing a C++ code based on the program EQUILIBRIUM.

The calculation is done considering that the products and reactants are at constant pressure, and that the reaction takes place at adiabatic flame temperature. It is based in a work by Olikara and Borman [26] further developed by Liensch and Krieger [27], for modeling combustion on ICE at General motors research laboratories. Later it was programmed in Pascal language by Lane [4]. For validating the results obtained from this program, initially the results are being compared with experimental information found in the literature for SE, and will be confirmed in the future experimental work.

The values of molecular masses, specific heat capacities and enthalpies of formation, can be taken from a text file containing the Janaf thermochemical tables information for the products and reactants. Alternatively, this information can be obtained from the NASA polynomial interpolation equations.

The program EQUILIBRIUM determines the equilibrium composition, as a function of: the fuel / Air ratio, the ambient temperature, ambient pressure, type of fuel utilized and assuming that the reaction will take place in ambient air.

Inputs: Fuel/Air equivalent ratio, ambient temperature, ambient pressure, and number of atoms of Carbon, Oxygen, Hydrogen and Nitrogen in the fuel molecule

Outputs: Average molecular mass, specific enthalpy, specific internal energy, moles of fuel, and mole fractions of H,O,N,H_2,OH,CO,NO,O_2,H_2O,CO_2,N_2,Ar, unburned fuel.

Map Generation (Fuel/Emissions)

The power maps generated in MARWEISS, are transformed utilizing Matlab to the fuel consumption, power, torque and angular speed maps for simulation on ADVISOR. The methodology for 1) pressure controlled engine and 2) phase angle controlled engine are described below.

1) Pressure controlled engine

MARWAISS generates i) brake power map, ii) efficiency map, both as functions of angular speed and working gas mean pressure. **[$\underline{P}$=P(w,p), $\underline{\eta}$=η (w,p)]** Eqn. 2

1. Utilizing the values of brake power from the map, it is determined minimum and maximum, and generated a brake power vector, with a given number of elements
   [P]
2. Utilizing the Matlab interpolation function, from the brake power map and the pressure vector, it is obtained a mean pressure map as a function of the angular speed and the brake power vector (generated in step 1)
   [$\underline{p}$=p(w,P)] Eqn. 3
3. Utilizing the Matlab meshgrid and interpolating functions, it is obtained an efficiency map as a function of the angular speed and the brake power vector, utilizing the original efficiency map and the mean pressure map, obtained in step 2
   [$\underline{\eta}$=η (w,P)] Eqn. 4
4. Given that torque = brake power / angular speed, utilizing meshgrid and the map generated in (3), it is obtained a brake power map as a function of the angular speed and the torque
   [$\underline{\eta}$=η (w,T)] Eqn. 5

2) Phase angle controlled engine

MARWAISS generates i) brake power map, ii) efficiency map, both as functions of angular speed and phase angle. **[$\underline{P}$=P(w, α), $\underline{\eta}$=η (w, α)]** Eqn. 6

1. Utilizing the values of brake power from the map, it is determined minimum and maximum, and generated a the brake power vector, with a given number of elements
   [P]
2. Utilizing the Matlab interpolation function, from the brake power map and the phase angle vector, it is obtained a phase angle map as a function of the angular speed and the brake power vector (generated in step 1)
   [$\underline{\alpha}$=α(w,P)] Eqn. 7
3. Utilizing the Matlab meshgrid and interpolating functions, it is obtained an efficiency map as a function of the angular speed and the brake power vector, utilizing the original efficiency map and the phase angle map, obtained in step 2
   [$\underline{\eta}$=η (w,P)] Eqn. 8
4. Given that torque = brake power / angular speed, utilizing meshgrid and the map generated in (3), it is obtained a brake power map as a function of the angular speed and the torque
   [$\underline{\eta}$=η (w,T)] Eqn. 9

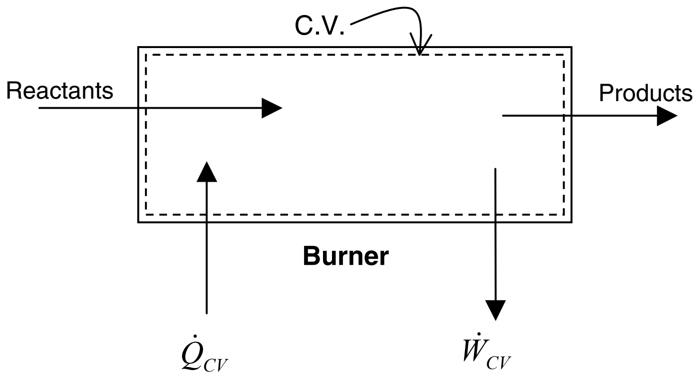

Figure 5. Control volume for burner

The fuel consumption map can be determined from the second law of thermodynamics, applied to a control volume surrounding the burner of the engine:

$$\frac{\dot{Q}_{CV}}{\dot{n}_F} - \frac{\dot{W}_{CV}}{\dot{n}_F} = \bar{h}_P - \bar{h}_R$$

$$\frac{\dot{Q}_{CV}}{\dot{n}_F} = \bar{h}_{PR}$$

and

$$\dot{m} = \frac{\dot{Q}_{CV}}{\bar{h}_{PR}}$$

From Eqn. 12, the fuel consumption map can be calculated given 1) the low heating value of the specific fuel, 2) the enthalpies of formation of the products and the reactants, and 3) the efficiency map.

$$fc = \frac{1}{\eta \quad \bar{h}_{PR}} \times 3.6 \times 10^6$$

Given 1) the molecular fractions of the combustion products, 2) the moles of fuel and 3) the moles of air required for combustion, the exhaust gas mass flow can be calculated.

$$\dot{m}_i = \frac{fc * M_i}{\sum_{k-1}^{n} M_k} \qquad \text{Eqn. 14}$$

SE File for ADVISOR

This module has as function assembly the maps for fuel consumption, torque, speed and emissions; writing them in a text file that ADVISOR can utilize as input file. Also writes the basic identification of the engine. The output file of this step can be edited for reflecting any other required change on the engine.

Simulate SE HEV in ADVISOR

For incorporating the SE in the fuel converter components of ADVISOR, it is required to define the heat transfer model, located under the fuel converter temperature calculation

HEAT TRANSFER MODEL

Heat is produced by the combustion of fuel in the burner and transferred to the hot space of the engine; it is transformed into work or transferred to the cold space by means of the working fluid. Being SE a thermal engine, the lower the temperature on the cold space, the better for the performance of the engine. However, there will always be radiation from the different parts of the engine to the environment, and conduction from the hot space to the cold space.

For optimization of the efficiency of the engine, many SE designs embody a preheater that works by heat transfer from the hot gases of the exhaust of the burner, to the air admitted into the burner.

The calculation procedure starts at the burner, determining in sequence the heat transferred from a given component to the next components, ending with the calculation of the heat transfer from the hood to the ambient and from the engine to the cooler.

The general equation for calculation of radiation:

$$Q_{x2y,r} = \varepsilon * \sigma * A * (T_x^4 - T_h^4)$$

For convection:

$$Q_{x2y,v} = h_{fluid} * A * (T_x - T_{amb})$$

For conduction:

$$Q_{x2y,c} = h_{cond} * (T_x - T_{amb})$$

For temperature differences:

$$T_x = \int_0^t \frac{Q_{in.x} - Q_{out.x}}{m_x * C_{p.x}}$$

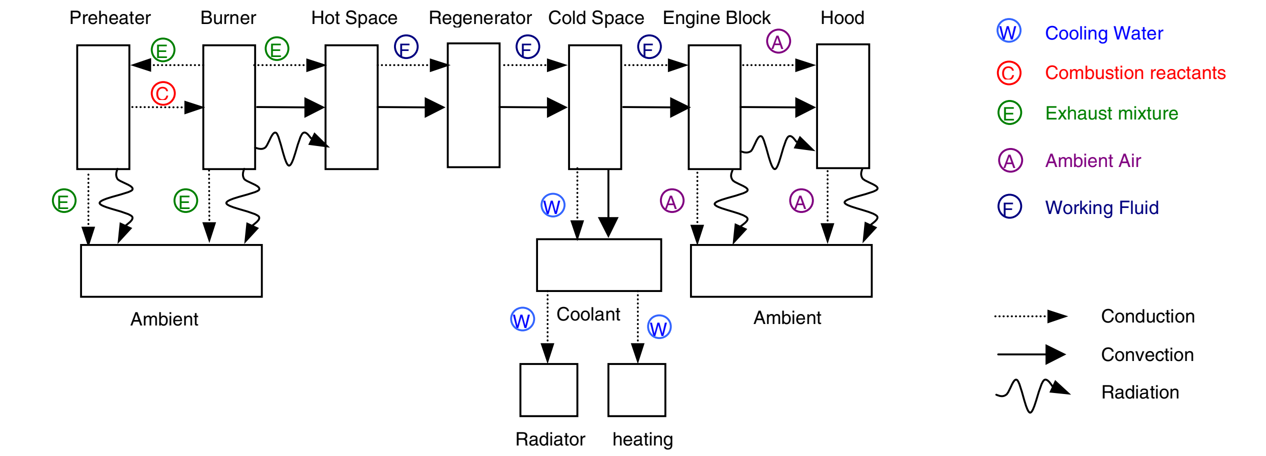

Figure 6. SE heat transfer model

RESULTS

The simplicity of ADVISOR for simulating vehicles with different configurations and components is an advantage over other HEV simulation programs. Once the model of a component of ADVISOR has been validated, it is simple and fast to perform simulations.

As an example for evaluation of the modules developed, it was performed a cycle of simulation routines with different APUs in series and parallel configurations, with a basic automobile arrangement. The following table shows the comparison on energy consumption for performing the same test routine, two cycles of the Federal Urban Driving Schedule.

The types of APU and configurations considered are:

1. HEV ICE in series configuration
2. HEV ICE in parallel configuration
3. Conventional ICE vehicle
4. HEV FC vehicle
5. HEV ICE in split configuration
6. HEV SE in series configuration
7. HEV SE in parallel configuration

Table 3 shows the energy balance after each of the components of the vehicle and the percentage of energy loss in each component, as a fraction of the total energy.

The ICE employed for the series and parallel configurations, was a Geo 41 kW engine. For the split configuration the ICE is a 1.5L Prius (Atkinson cycle) engine.

The fuel cell is an IFC 50kW net hydrogen fuel cell stack.

The SE employed is a GPU-3 6kW engine. This is a smaller engine compared to other engines. It was employed in the Sir-Lec I from GM, the first SE HEV [3]. It was selected for comparison of simulation results with published data.

Some results from the table, are the percentage of energy losses on the engine in descending order: Conventional vehicle (74%), series ICE (69%), parallel ICE (69%), split ICE (66%), fuel cell (63%), series SE (60%) and parallel SE (54%).

The overall efficiency, including potential energy: Conventional vehicle (17%), series ICE (19%), parallel ICE (20%), fuel cell (22%), series SE (22%), split ICE (23%), and parallel SE (27%).

The total energy used for performing the cycle: series ICE (27816 kJ), fuel cell (25666 kJ), series SE (24721 kJ), parallel ICE (22744 kJ), and parallel SE (22744 kJ), split ICE (21110 kJ), conventional vehicle (16825 kJ).

The results recall the importance of having a lighter vehicle to save energy; Even though the conventional vehicle had the lower efficiency of all the vehicles, it also used the least energy of all, because it was also the lighter vehicle.

Table 3: Comparison of drivetrains: Energy use, component efficiency and overall efficiency.

Energy Usage [kJ]	Series ICE		Parallel ICE		Conventional		Fuel Cell		Prius		Series Stirling		Parallel Stirling	
	Balance [kJ]	Use [%]	Balance [kJ]	Use [%]	Balance [kJ]	Use [%]	Balance [kJ]	Use [%]	Balance [kJ]	Use [%]	Balance [kJ]	Use [%]	Balance [kJ]	Use [%]
Fuel Converter	27816	69.2%	22598	69.2%	16825	74.2%	25666	63.3%	21110	66.1%	24721	59.8%	22744	53.8%
Energy Storage	22967	0.2%	22348	0.2%	16252		24375	1.8%	20190	0.9%	22751	3.2%	21701	2.0%
Motor / Controller (Power)	19692	2.5%	20498	2.5%	16252		20957	4.9%	18874	2.1%	18775	5.2%	18889	5.7%
Gearbox (Power)	18662	1.3%	19561	1.3%	15430	1.3%	19892	1.5%	18874		17771	1.6%	17895	2.0%
Wheel / Axle (Power)	17852	1.1%	18747	1.1%	14759	1.0%	19036	1.2%	18067	1.3%	17094	1.1%	17127	1.6%
Motor / Controller (Regen)	17481	1.6%	17549	1.6%	14270		18651	0.6%	17716	0.6%	16733	0.6%	16361	1.6%
Gearbox (Regen)	17412	0.1%	17502	0.1%	14236	0.1%	18582	0.1%	17716		16664	0.1%	16321	0.1%
Aux Loads	15522	2.6%	15612	2.6%	12368	2.9%	16686	2.7%	15827	3.1%	14778	3.1%	14437	3.9%
Braking	14410	1.5%	14492	1.5%	11133	1.9%	15473	1.7%	14545	2.1%	13739	1.7%	13419	2.1%
Aerodynamic loss	12298	2.9%	12380	2.9%	9023	3.2%	13361	3.0%	12894	2.7%	11627	3.4%	11307	4.3%
Rolling Loss	9459	3.9%	9522	3.9%	6940	3.2%	10276	4.4%	9998	4.7%	8966	4.3%	8697	5.3%
Potential Energy	0	13.0%	0	13.0%	-1	10.6%	-1	0	10	16.1%	8	14.6%	0	17.7%
Overall Efficiency	6.52%		6.78%		6.43%		7.43%		7.31%		7.75%		9.59%	
Overall Efficiency (PE)	18.99%		19.78%		17.07%		22.12%		23.37%		22.31%		27.24%	

$$\text{Overall Efficiency} = \frac{\text{Rolling resistance} + \text{aerodynamic losses}}{\text{Energy used [fuel} + \text{storage system]}}$$

$$\text{Overall Efficiency(PE)} = \frac{\text{Rolling resistance} + \text{aerodynamic losses} + \text{Potential Energy}}{\text{Energy used [fuel} + \text{storage system]}}$$

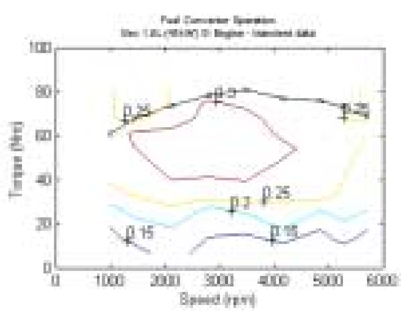

Figure 7. ICE spark ignited power map

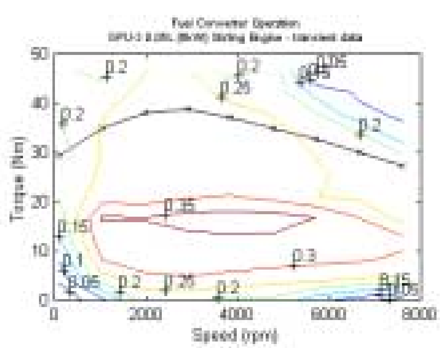

Figure 8. SE spark ignited power map

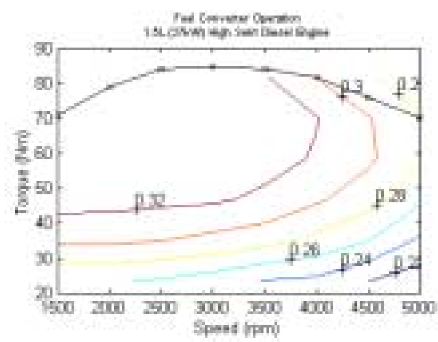

Figure 9. ICE compression ignited power map

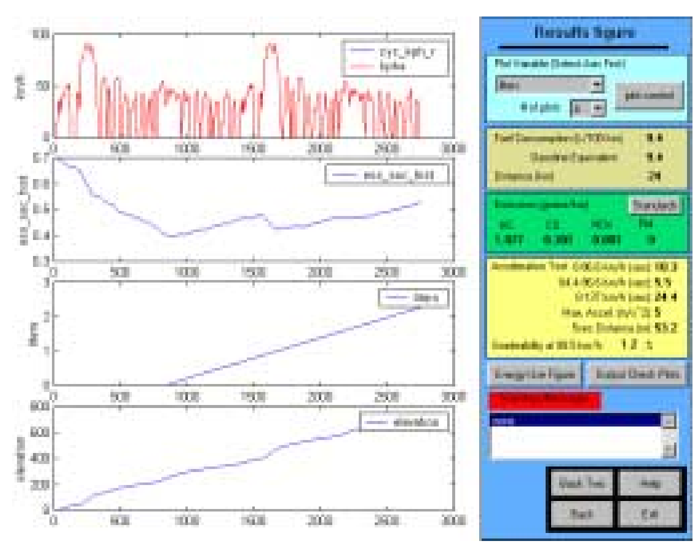

Figure 10. ADVISOR results figure.

FUTURE RESEARCH

- Experimental testing of the model
- Combustion process: Need to review emission levels, compared to experimental results
- Integration of combustion model into ADVISOR: Calculate emissions by time step, given that emissions change with engine temperature, pressure and Fuel / Air ratio.
- Evaluation of the influence of mechanical efficiency on SE power map generated by MARWEISS.
- Validation of the heat transfer model with experimental results
- Test of different configurations and components of the HEV, for optimizing a SE HEV.

CONCLUSION

According to Hitachi Car Eng. Co. (Japan) the ICE will remain as the main automobile engine for the following 25 years [28]. One may ask then, if an engine has shown such reliability and dominance on the market in such a manner; Why study other options? Considering the environmental regulation and transportation cost trends the question would be whether the ICE can meet all required goals without high increases in purchase price or complex maintenance requirements.

The exhaust gases of automobile engines are polluting the air in the major urban areas around the world. A steady rise in the number of vehicles and driving time in the world's major urban areas is pushing congestion, as well as air and land pollution to intolerable levels. In many countries, more than 50% of the air pollution is attributed to vehicle engines. In some cities, as Los Angeles, it can be even higher. In addition to air pollution and congestion, the automobile centered transportation contributes to other sources of annoyance, as noise, smell and, in case of diesel, soot.

The environmental concerns are producing a rethinking in the world transportation system, in spite of the trend to increase vehicle cost and the vehicle systems complexity.

From a technical point of view, alternative engines as the SE, gas turbine or the fuel cell, can be utilized as a replacement of the predominant ICE automobile engine, for reduction of emissions and improvement of efficiency. The main problem that they face, is ICE's competitive price. SE's multi-fuel capability, reduced emission of pollutants, and increased efficiency, are overcome by the high price of the engine. Even with adequate production levels, it is likely to be 50% more expensive than ICE, leading to an increment of 5% increment in vehicle price.

The HEV is an alternative transport that because of its double source of motive energy is able to reduce fuel consumption and adverse environmental impacts. The HEV promotes the optimization of the vehicle in its acceleration, cruise and stand-by functions.

SE automobile projects have not reached commercialization in the past. There is a need to match the engine to the automobile, look for cost reductions and optimize radiator size. Adequate production levels of HEV and SE, and the internalization of environmental costs in transportation price, can turn to reality the dream of an environmentally friendly transportation system.

The simulation tool introduced in this document for SE HEVs was designed based on ADVISOR HEV simulator, MARWAISS SE simulator and EQUILIBRIUM, composition simulator. The purpose of the tool is to evaluate the SE application as an APU, its advantages and areas of improvement.

Results obtained from the designed simulation tool, for conventional SE vehicles or hybrid electric-Stirling vehicles in series, parallel or split configurations, can be confronted with other modeled vehicles such as conventional, pure electrical vehicles, as well as hybrid electric powered with ICEs or fuel cells. ADVISOR allows quick testing of new components and different configurations of vehicles, making the simulation process efficient and easy to configure.

The next stage of this project is to validate the simulation model. It is desired to perform experimental studies of fuel consumption, heat flow, torque and speed characteristics, as well as emissions for present SE.

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Definitions, Acronyms, Abbreviations

ADVISOR:
Advanced VehIcle Simulator

APU:
Auxiliary Power Unit

CO:
Carbon Monoxide

DOE:
Department Of Energy

ECE:
External Combustion Engine

EGR:
Exhaust Gas Recirculation, engine feature for emissions reductions

ERDA:
Energy Research and Development Administration (now DOE)

ESS:
Energy Storage System

EZEV:
Extra zero emission vehicle

Fuel / Air equivalence ratio:

HC:
HydroCarbons

HEV:
Hybrid Electric Vehicle

HWFET:
Highway Fuel Economy Test

ICE:
Internal Combustion Engine

LEV:
Low Emission Vehicle

NOx:
Nitrous Oxides

NREL:
National Renewable Energy Laboratory

Phase angle:
Angle position between power piston and compression piston

PM:
Particulate Matter

PNGV:
Partnership for a New Generation of Vehicles

Preheater:
A heat exchanger user with fuel burners to transfer heat from the exiting combustion products to the input reactant air.

Regenerative:
A regenerative engine, is an engine that keeps heat rejected during part of a cycle in a component named regenerator, for using it in another stage of the cycle

Regenerator:
Element of a heat engine that keeps heat rejected from a fluid warmer than itself and releases heat to a fluid colder than itself

SE:
Stirling Engine

SOC:
State Of Charge

Swashplate:
A circular plate centered on and inclined to the axis of plate rotation used to transform reciprocating piston motion to rotary shaft motion. Usually associated with double-acting engines, but it can be used with single-acting engines.

ZEV:
Zero Emissions Vehicle

GW Hybrid Electric Sport Utility Vehicle Design for FutureTruck 2000 Competition

GW Transportation Research Institute
Vahid Motevalli, Ph.D., P.E.
Mohamad Syaifuddin

GW FutureTruck Design Goals

- FUDS and HWFET range - 452 km/300 miles HEV
- ZEV range - 125 km
- Acceleration (0-100 kph) - < 15 seconds
- Emissions - Federal Tier 2
- Equivalent Energy Efficiency - 60 mpg
- Curb Weight - 2,000 kg
- Aero drag, Cd - 0.4
- Gradeability - 5% at 90 kph
- Towing capacity - 900 kg

Estimated Energy and Power Requirement

CRUISING and GRADEABILITY	POWER (kW)
100 kph cruising	19.33
100 kph cruising at 6% grade	54.25
65 kph cruising	7.93
65 kph cruising at 6% grade	30.63
100 kph with 900 kg load	22.28
100 kph with 900 kg load at 6% grade	71.92
ACCELERATION	**POWER (kW)**
Peak power for 0-100 kph in 15 seconds	116.96
RANGE	**ENERGY STORAGE (kWH)**
Energy: 120 km ZEV range at 65 kph	14.64

Vehicle curb weight, $m_{vehicle}$ *= 2,000 kg*
Aerodynamic drag coefficient, Cd = 0.4
Frontal area, $A_{frontal}$ *= 2.4* m^2
Rolling coefficient, C_{rr} *= 0.012*

Rotational inertia coefficient, $C_{inertia}$ *= 1.2*

Vehicle Component Layout

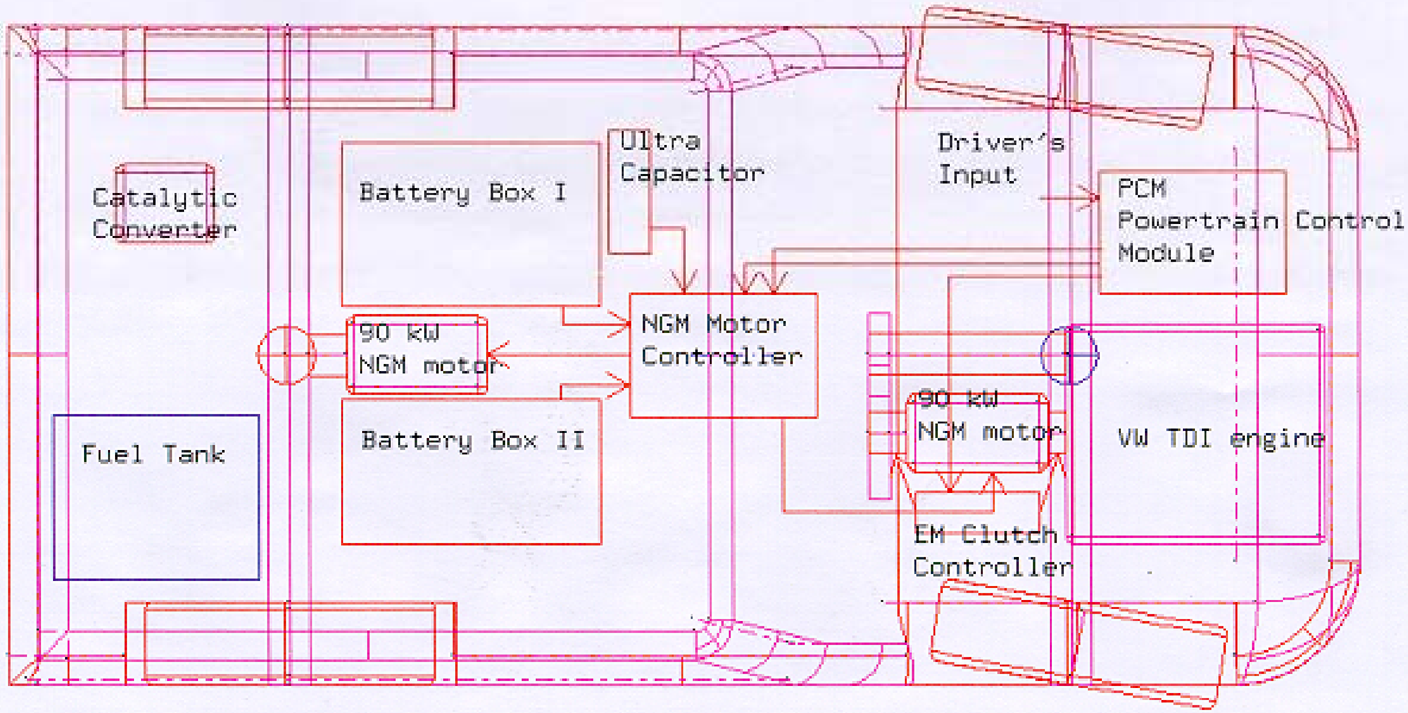


Figure 1. GW FutureTruck vehicle component layout

<u>Powertrain:</u>

Charge Sustaining Thermostat Series

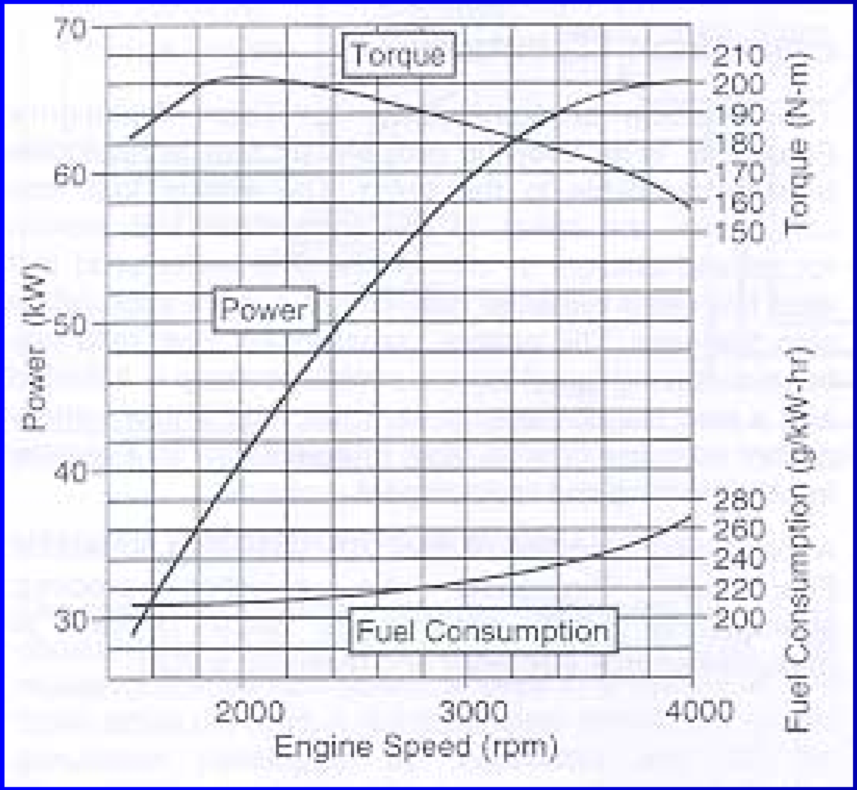
Motors: 1 90 kW DC electric motors at rear axle

Engine: VW 1.9 liter TDI

Motor/Generator: 1 90 kW motor/generator

Energy Storage System (ESS): NiMH batteries and ultracapacitors

VW 1.9 liter TDI characteristics



VW TDI specifications:

-Four-cylinder in-line diesel with direct injection turbocharged (TDI)

-60 kW at 3,300 rpm

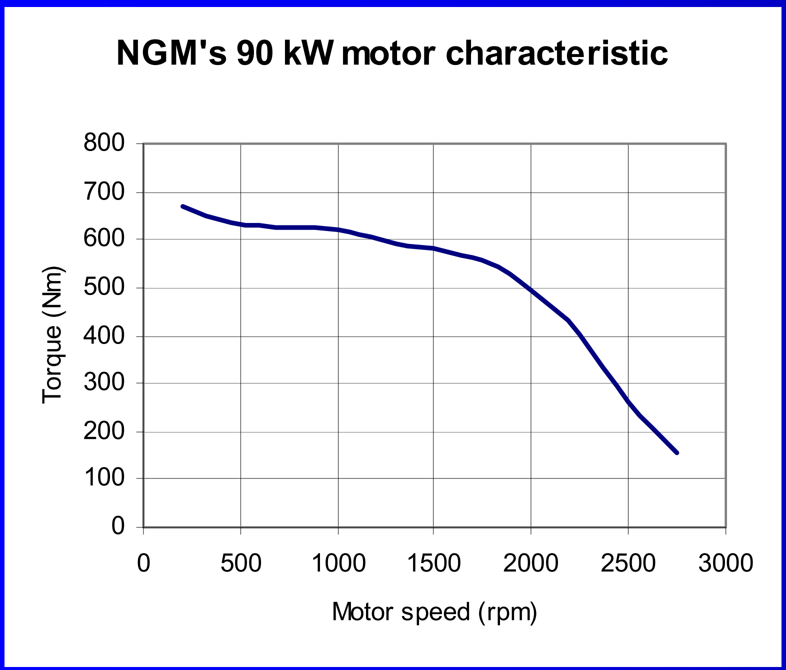
-Engine management system with EDC

-Sealed pressurized cooling system with oil cooler in coolant circuit

-Height: 637 mm, Width: 710 mm, Length: 545 mm

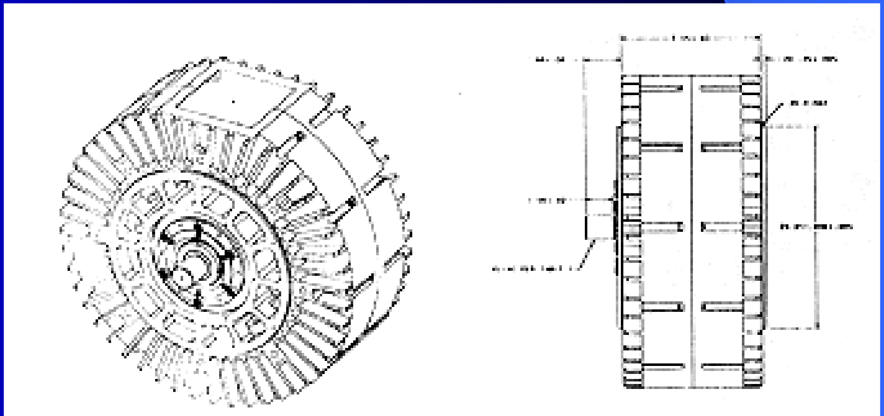
-Dry weight = 135 kg

NGM 90 kW DC motor
Model MDF-375/75-A1-BS



<u>MDF-375/75-A1-BS specifications:</u>

-Design Topology: Axial Flux, Dual Stator Fixed Air gap
-Overall size: 445 mm diameter x 189 mm length
-Weight: 84 kg
-Cooling: Forced Air
-Mounting: Face flange per outline
-Max rated current : 320 amps
-Rated DC Bus voltage: 312 V
-Mechanical speed limit: 3,000 rpm
-Rotor inertia: 0.17 kg-m^2



Energy Storage System
Ni-MH & Ultracapacitors

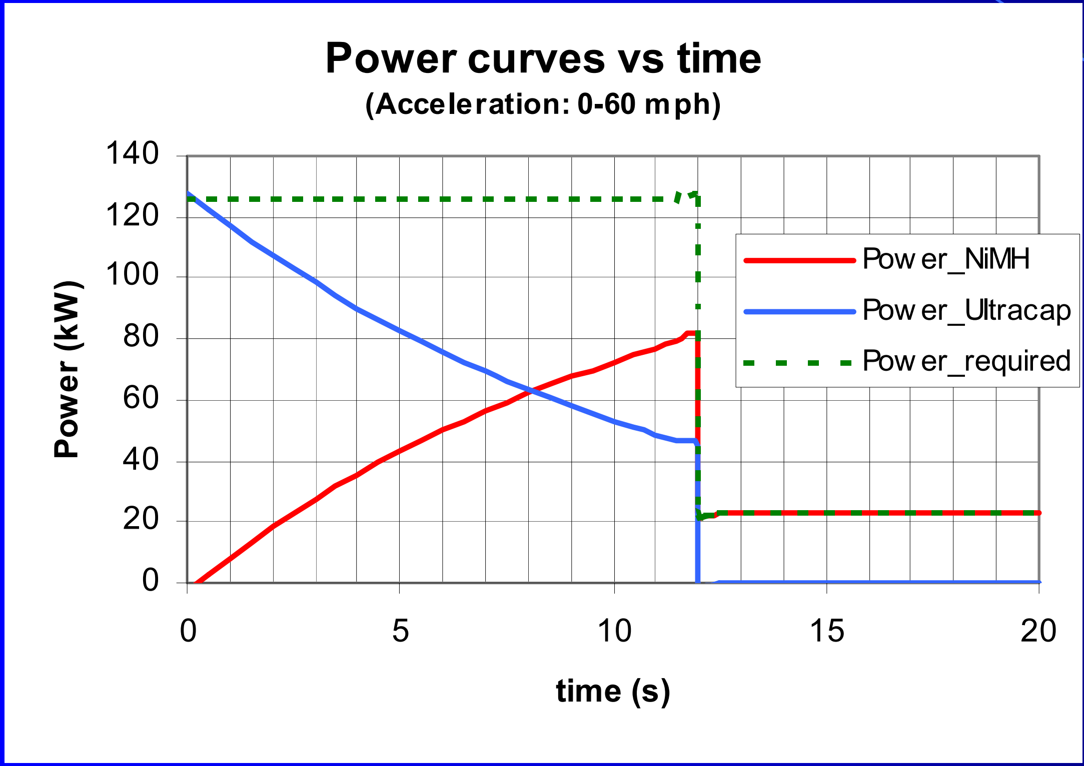
NiMH battery stack specification

Battery pack specification [30 kWh]	Ovonic NiMH
No. of modules	25
Mass (kg)	445
Volume (liters)	188.3
Power@20% SOC (kW)	97.8
Voltage (V)	330

Ultracapacitor stack specification

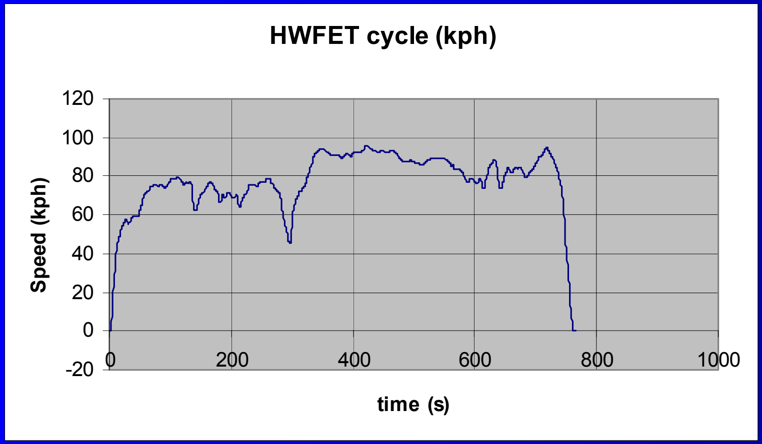
Ultracapacitor specification [130 kW]	**Pinnacle RIT Inc.**
No. of modules	3
Mass (kg)	1.3
Volume (liters)	1
Specific power (kW/kg)	100
Voltage (V)	300

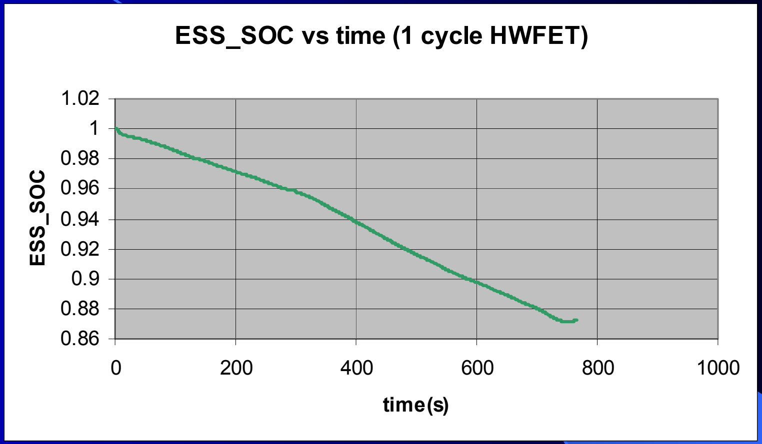
Power Requirement During Acceleration

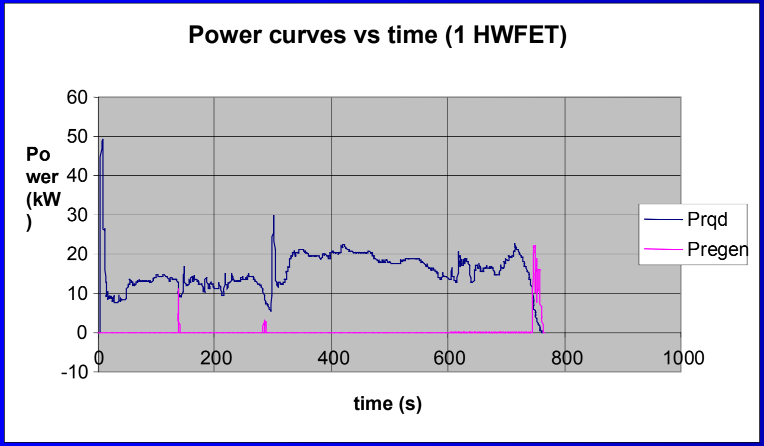


- High power demand > 120 kW
- NiMH batteries provides only maximum of 90 kW
- Ultracapacitor provides required power for acceleration

Simulation Results
HWFET Cycle

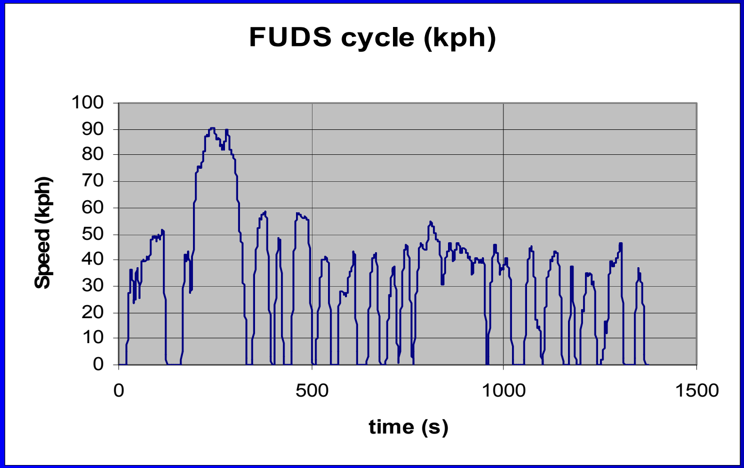


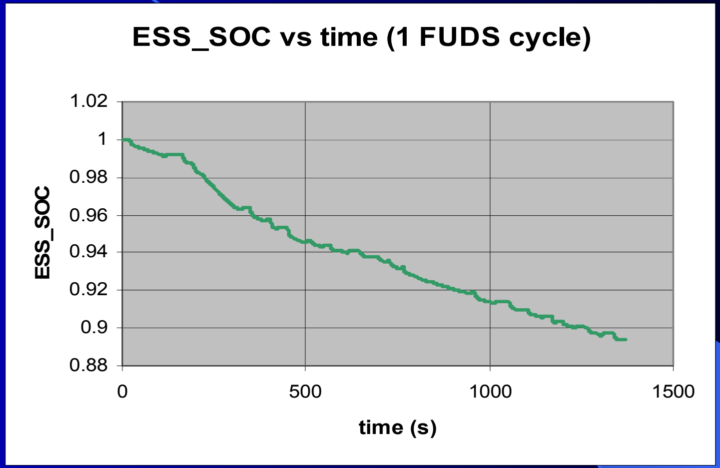


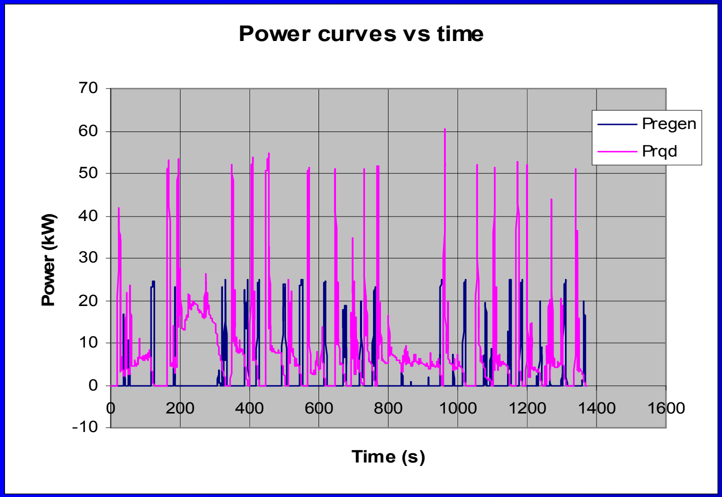


Simulation Results

FUDS Cycle







Summary

- The combined fuel economy prediction is 39 mpg (35.5 gasoline equivalent).
- The use of motor-generator at the front axle is unique and offers benefits of cost saving and mass reduction.
- The use of two transaxle motors allow four wheel drive mode without any need of transmission and transfer case.
- The hybrid energy storage system of NiMH batteries and ultracapacitors allows vehicle to achieve high performance and increase its range.
- Further study is required for component integration and modeling of the hybrid energy storage system.

GWU Hybrid Electric Sport Utility Vehicle Design for FutureTruck 2000 Competition

Mohd-Syaifuddin Mohd, Zeki Gokce, Vahid Motevalli, Kartik Bulusu
GW Transportation Institute, The George Washington University

ABSTRACT

The George Washington University is one of the several universities invited to participate in the FutureTruck 2000 competition. The competition challenges engineering students to convert a Sport Utility Vehicle (SUV) to meet the goals of attaining up to three times their current fuel efficiency, achieving exhaust emissions of Federal Tier 2 levels or below, and maintaining consumer acceptability in areas of performance, utility, and safety. In preparation for the competition, a design of a Hybrid Electric SUV was developed and evaluated. The evaluation of conversion of SUV was conducted by the GWU FutureTruck Team, focusing on the powertrain configuration, heat engine selection, energy storage strategy, control system strategy and electric drivetrain components. This paper describes the process, an innovative series hybrid powertrain configuration, and discussion of simulation performance characteristic of such a vehicle. Even though GM Suburban has been designated as the platform vehicle, this analysis was performed for a general compact SUV.

INTRODUCTION

To achieve the FutureTruck 2000 goals, the GWU Future Truck Team has set forth several goals which are listed in Table 1. The magnitude of these tasks can only be met through significant revision of the entire SUV system. Five technical targets are identified which are:

- Improve the fuel efficiency of the primary fuel converter
- Reduce the mass of the vehicle
- Reduce acessory system power loads
- Improve vehicle aerodynamic efficiency and reduce other dynamic losses
- Implement regenerative braking

Previous work on conversion of conventional vehicles into Hybrid Electric Vehicle (HEV) by other universities [e.g. 1,2,3] under the Department of Energy's (DOE) Future Car Challenge program, the Partnership for a New Generation Vehicles (PNGV) program and the HEV program in DOE have all pointed out the necessity of addressing all aspects of vehicle effeciency improvements as itemized here.

Table 1 - GWU FutureTruck design goals

PARAMETER	TARGETS
FUDS and FHDS range	462 km/300 miles HEV
ZEV range	125 km
Acceleration (0-100 kph)	< 15 seconds
Emission	Federal Tier 2
Equivalent Energy Efficiency	60 mpg
Curb weight	2,000 kg
Aero drag, Cd	0.40
Gradeability	5% at 90 kph
Towing capacity	900 kg

To improve fuel efficiency, the team has decided to propose an innovative series hybrid powertrain configuration. Details about the configurations are discussed in the following sections. With the selected configuration, potential mass reduction can be made by removing the existing engine block, transmission, and part of the driveshaft. The team has also considered replacing the existing Heating, Ventilation, and Air-Conditioning (HVAC) system with Thermoelectric Cooling (TEC) HVAC system. The TEC system is more efficient, capable of cooling and heating, using less power, has no CFC dependence and is lightweight compared to to the existing compression based system [4]. Other potential mass reduction is also possible through the use of composite material to replace the original body panels and hood. The aerodynamic performance of the vehicle can be improved by several measures: changing the vehicle profile and eliminating points where separation occurs, reducing discontinuity along the body line by inserting rubber trimming and covering the rear wheels, and eliminating the irregular underside surface by installing a floor pan. Table 2 shows the estimated energy and power requirement for the HEV-SUV based on the targets described before. The total power demand equation represents the energy consumption of a vehicle over a period of time. The equations used to calculate the power demand are [5]:

$$P_{total} = P_{aero} + P_{roll} + P_{hill} + P_{acceleration} \quad (1)$$

$$P_{aero} = \frac{1}{2} \rho_{air} A_{frontal} V^3 Cd \quad (2)$$

$$P_{roll} = m_{vehicle} g V C_{rr} \quad (3)$$

$$P_{hill} = m_{vehicle} g V \sin\theta \quad (4)$$

$$P_{acceleration} = a_{required} m_{vehicle} V C_{inertia} \quad (5)$$

where;

P_{total} = total required power

P_{aero} = power needed to overcome aerodynamic loss

P_{roll} = power required to overcome rolling resistance

P_{hill} = power required to climb hills

$P_{acceleration}$ = power required to achieve desired acceleration

Table 2 - Estimated energy and power requirement

CRUISING AND GRADEABILITY	POWER (kW)
100 kph cruising	19.33
100 kph cruising at 6% grade	54.25
65 kph cruising	7.93
65 kph cruising at 6% grade	30.63
100 kph with 900 kg load	22.28
100 kph with 900 kg load at 6% grade	71.92
ACCELERATION	**POWER (kW)**
Peak power for 0-100 kph in 15 seconds	116.96
RANGE	**ENERGY STORAGE (kWH)**
Energy: 120 km ZEV range at 65 kph	14.64

Vehicle curb weight, $m_{vehicle} = 2{,}000$ *kg*

Aerodynamic drag coefficient, $Cd = 0.4$

Frontal area, $A_{frontal} = 2.4\ m^2$

Rolling coefficient, $C_{rr} = 0.012$

Rotational inertia coefficient, $C_{inertia} = 1.2$

OVERALL DESIGN AND SYSTEM INTEGRATION

The team selected a charge sustaining series hybrid powertrain configuration. The benefits of a series configuration over a parallel configuration are [6];

i. the engine never idles, which reduces vehicle emissions and increases fuel efficiency,

ii. the engine drives a generator at an optimum performance setting, and

iii. a series hybrid does not need a transmission, which will reduce the vehicle mass.

Two highly efficient 90 kW DC motors will drive the proposed vehicle, one at the front axle and the other at the rear axle. The motor will be used to capture energy during regenerative braking. The front motor is used alternately as a driving motor when coupled to the frontal drive shaft or as a generator when coupled to a Volkswagen 1.9 liter compression-ignition direct injection (CIDI) engine. Figure 1 shows the vehicle component layout. An electromagnetic (EM) clutch system is used to engage and disengage the front motor to the drive shaft or the IC engine. Power to the motor will be provided by a hybrid battery pack consisting of Ovonic Nickel Metal-Hydride (NiMH) batteries and Pinnacle Research Institute, Inc. ultracapacitors. A motor controller from New Generation Motors Corporation will be used to control the desired speed or desired torque of the motor. An onboard CPU unit will be used as a Powertrain Control Module (PCM) which stores the control strategy algorithm of the vehicle.

HEAT ENGINE SELECTION

A 1.9 liter Volkswagen Compression Ignition Direct Injection (CIDI) engine has been selected for this design. It is a four-cylinder in-line diesel engine with turbocharger and direct injection. The CIDI engines were considered for their high thermal efficiency (>40 percent), operating flexibility, low start-up emissions, and demonstrated manufactureability and affordability, reliability, durability [7]. CIDI engine are also capable of increasing fuel economy by up to 35 percent [7]. Furthermore, in the series configuration that has been designed here, some of the undesirable effects known for the older designs in CIDI and not completely resolved in the current engines, such as particulate and CO emission as well as noise and vibration is minimized since the engine would be operated in a nearly constant rpm at an optimum setting (highest efficiency) and with least amount of transient problems. The selected VW engine has a good specific power with a compact design. Figure 2 shows the engine characteristics.

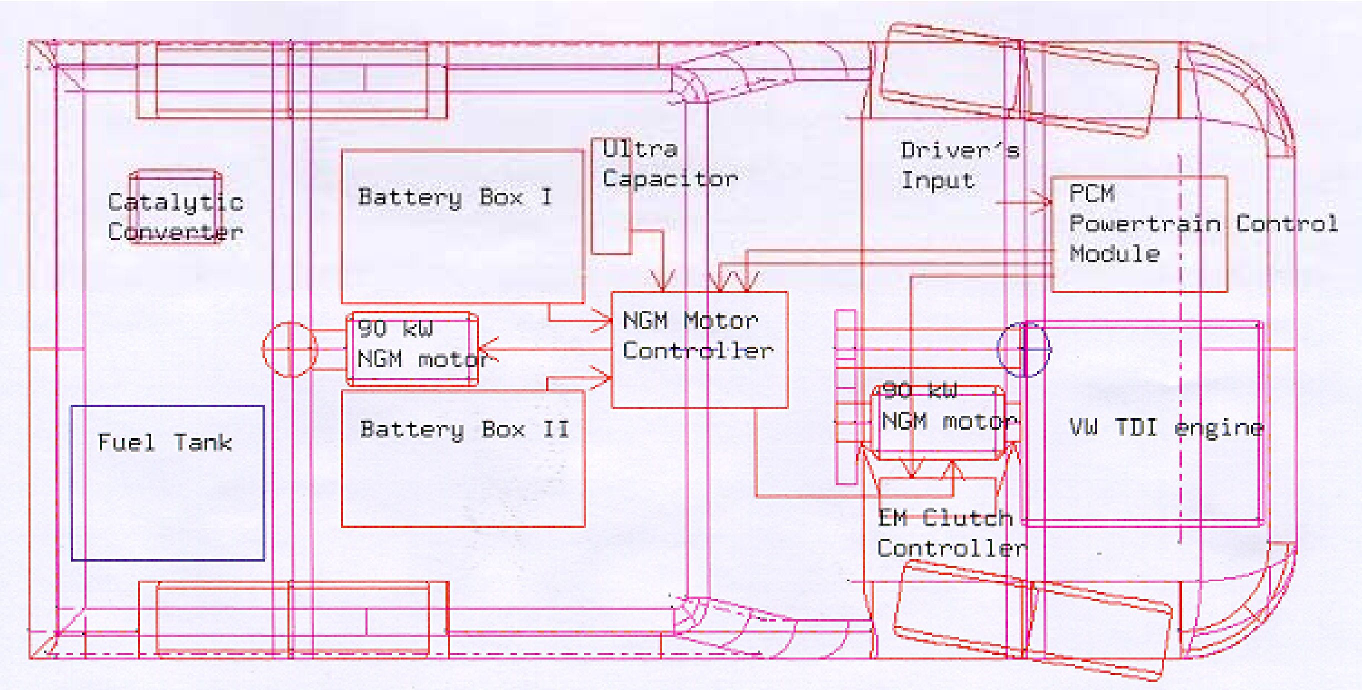


Figure 1. GW FutureTruck vehicle component layout

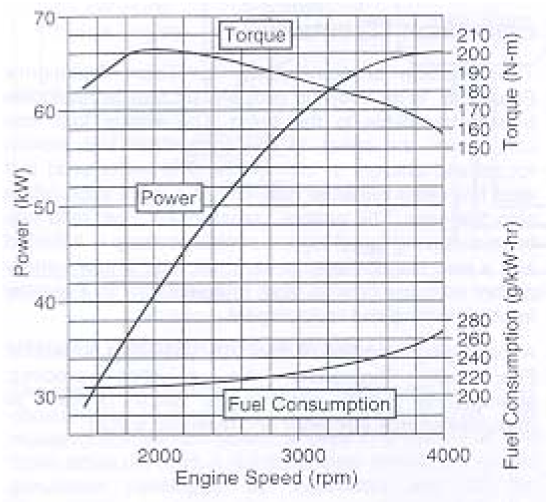


Figure 2 - Characteristics of a 1.9 liter VW CIDI engine [8]

ENERGY STORAGE DEVICE SELECTION

The GW team has decided to use a hybrid configuration of Ovonic NiMH batteries and Pinnacle Research Institute, Inc. ultracapacitors to achieve the power and energy storage requirements of the vehicle. During a short period of high power demand, ultracapacitors will provide the necessary power to the motors. We project that the NiMH battery stack alone will not be able to provide the high power required for hard acceleration (see Table 2) and would exceed the targeted mass limit. This has dictated the need of an ultracapacitor pack which has 90 times the power density of the batteries [9]. Other advantages of using ultracapacitors are that it takes less than 1 second to fully recharge the unit and also minimizes the battery size. The challenge is in coupling the ultracapacitors to the battery pack. Table 3 and 4 show the specification for the NiMH battery stack and the ultracapacitor stack, respectively.

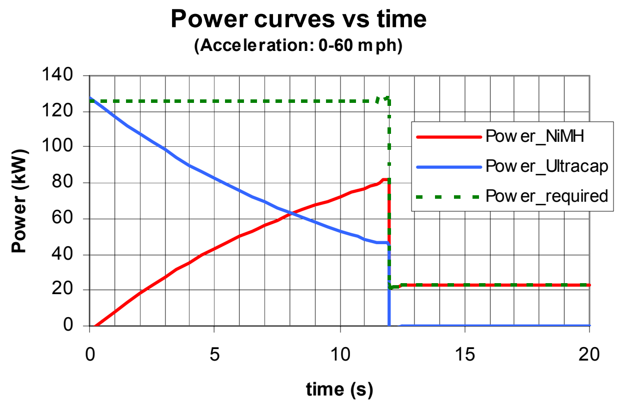


Figure 3. Power curves vs time during hard acceleration

Table 3 - NiMH battery stack specification

Battery pack specification [30 kWh]	Ovonic NiMH
No. of modules	25
Mass (kg)	445
Volume (liters)	188.3
Power@20% SOC (kW)	97.8
Voltage (V)	330

Table 4 - Ultracapacitor stack specification

Ultracapacitor specification [130 kW]	**Pinnacle RIT Inc.**
No. of modules	3
Mass (kg)	1.3
Volume (liters)	1
Specific power (kW/kg)	100
Voltage (V)	300

CONTROL SYSTEM DESIGN AND ITS COMPONENTS

The control system will consiste of power controllers for the electric motors and the on-board computer system also called a Powertrain Control Module (PCM). The new NGM-EV-C200 controllers will be used to control and power the 3-phase DC motors. The controllers have programmable logic capability allowing them to be optimized and matched with the motor characteristics. The overall system controller will be implemented on the on-board PCM. This computer will be designed to monitor the state of charge of the batteries and ultracapacitors, individual motor voltage and current, vehicle speed, temperature of various components, generator output, and will have various control functions including activation of the CIDI engine and generator, EM clutch engagement or disengagement, cooling fans, power limited cruise control, and motor controller.

The control strategy utilized is the thermostat series, which has the objective of operating mainly on electrical energy. The battery will be discharged until a low state of charge (SOC) is reached. The engine is then turned on to recharge the battery until a desired SOC is achieved. Advantages of this type of control strategy are that the engine can be set to operate at one point of torque and speed at which it is most efficient and least polluting. This prevents the engine from experiencing any transient load, which also should reduce the emissions. In addition, the operating point can be set for the optimum performance point of the electric generator by using a simple gear coupling. Another potential reduction to emissions can come from the addition of an electrically heated catalyst, which can be easily implemented to reduce cold-start emissions since there is ample knowledge of when the engine will come on [10].

ELECTRIC DRIVETRAIN

The drivetrain will consist of two prototypes 90 kW New Generation Motors Corporation (NGM) DC motors. Each one of the motors will drive the front drive shaft and the rear drive shaft. During low to average power demand, only the rear motor is driving the vehicle and the front motor is in the generator mode.

When the driver demands hard acceleration, the EM clutch system will disengage the generator from the engine and engage it to the frontal drive shaft. The power circuit is now reversed and has turned the generator into electric motor mode and will drive the frontal drive shaft.

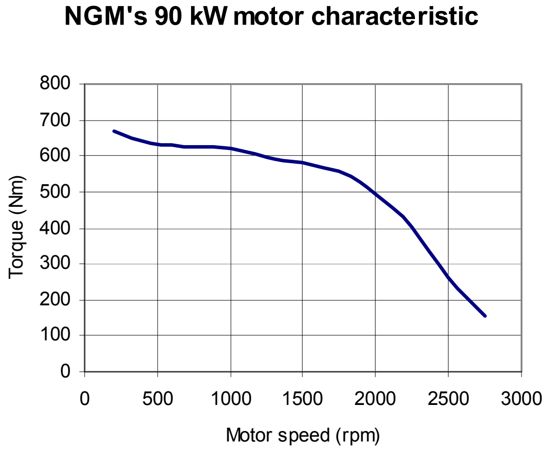


Figure 4 - NGM's 90 kW DC motors characteristic

The prototype NGM 90 kW DC motor is chosen because of its high efficiency (>90%), high specific power (each weigh only 55 kg) and capability to operate efficiently in regenerative mode. Figure 3 shows characteristic of the motor.

FUEL SYSTEM DESIGN AND MATERIALS SELECTION

The proposed vehicle will utilize the existing fuel system with only minor modifications to accommodate the new Volkswagen 1.9 liter CIDI engine. This has several advantages in that the fuel tank is optimally placed for crashworthiness, the fuel lines and connections are commercially produced and meet all federal standards, and the integration into vehicle is already achieved. This minimizes the need to make modifications in the layout and focuses the integration effort on new components. The only difference in the fuel system is that the flow rate is no longer regulated by the gas pedal and fuel pump, but rather will maintain a constant flow rate to the generator engine and will be activated by a signal from the PCM. The existing fuel tank can also be replaced with a smaller tank since the conversion vehicle will require less fuel to achieve the same driving range as the original vehicle.

Exhaust Emissions Control Design and Component Selection

The catalytic converter, muffler, and the tailpipe will have to be resized to accommodate the new CIDI engine. The design will address emission control to meet the Federal Tier 2 as required by the competition rules. Since the engine will operate at a constant speed for charging purposes only, high emissions typical of today's vehicle due to acceleration, deceleration, and time at idle are virtually non-existent.

PERFORMANCE AND ENERGY ECONOMY PROJECTION

The GWU team has used ADVISOR , a MATLAB-based dynamic simulation software to predict performance and energy economy projections of the proposed vehicle [11,12]. However, the software could not fully simulate the proposed design of the hybrid energy storage system of NiMH batteries and ultracapacitors. The simulation model does not include a ultracapacitor stack as specified in the vehicle design. This would not affect the energy economy prediction since the maximum power demand during the simulation of FUDS and HWFET cycles is below 50 kW and it is achievable by the NiMH battery pack alone (see Figures 5 and 6).

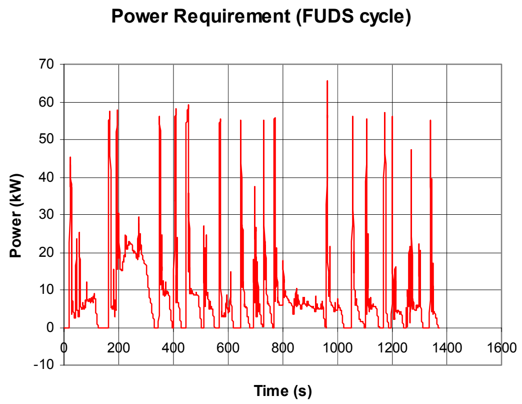


Figure 5- Power requirement vs time for 1 FUDS cycle

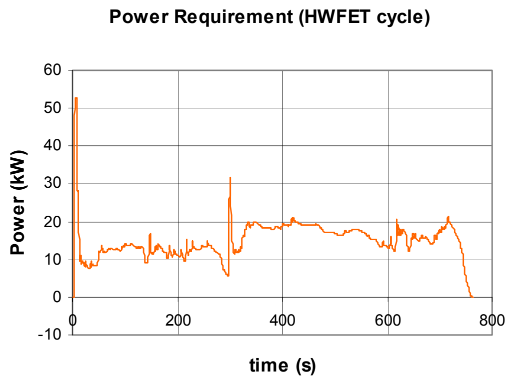


Figure 6- Power requirement vs time for 1 HWFET cycle

Assuming a 10% decrease in aerodynamic drag, an improved rolling resistance of 0.012, maintaning vehicle mass of 2,000 kg (model year 1999 Chrysler's Jeep Cherokee [13]) and using a series hybrid configuration, the results show that the vehicle is capable of achieving more than 39 mpg fuel economy (35.5 gasoline equivalent). This fuel economy projection is more than two times that of a typical SUV. With the addition of efficient regenerative braking and control system design algorithm, and mass reduction, this design vehicle has a potential of reaching the 3 times current fuel economy. Table 5 shows an example of simulation parameters and conditions used to predict vehicle performance and energy economy projection.

Table 5- Simulation parameters

Simulation Set-up Variables	Parameters
Drive cycle	HWFET (Highway Fuel Economy Test Drive)
No. of cycles	25 (256 miles)
Initial SOC of battery pack	95 percent
Maximum SOC	95 percent
Minimum SOC	30 percent
Control Strategy	Zero delta SOC Correct ($SOC_{final} = SOC_{initial}$)

The use of two 90 kW motors and an ultracapacitors stack allows the vehicle to meet the high power demand during hard acceleration. Ultracapacitors although having high power density, havw a limited energy storage capacity. Therefore, a hybrid configuration of NiMH batteries and ultracapacitors is proposed to meet the 300 mile range requirement. The greatest challenges will be in design and implementation of the EM clutch to use the front motor as the motor/generator and the coupling of the ultracapacitors and battery stack.

SUMMARY

The GWU innovative series hybrid conversion approach has a potential to meet and exceed the design goals outlined for FutureTruck 2000 competition. The use of highly efficient and compact DC motors as generator and driving motors is unique and offers benefits of cost saving and mass reduction. The use of two transaxle motors also allows the vehicle to operate in four wheel drive mode. The hybrid energy storage system of NiMH batteries and ultracapacitors makes it possible for the vehicle to achieve high performance and increase its range. A highly efficient CIDI engine will provide power to the generator only in its high efficiency region and low emissions. In addition, non-structural body parts will be replaced with lighter composite materials and the vehicle aerodynamic drag will be reduced through several measures.

CONTACT

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ADVISOR

Validation, Vehicle Development, and Applications

August 2000

Simulation of a Heavy-Duty Series Hybrid Electric Transit Bus

Jean BAVARD / Atef GAYED

ALSTOM

INTRODUCTION

ALSTOM

- ALSTOM & Urban Transport
- HEV Motivations
- Design Criterion
- Software Simulation via ADVISOR
- Results
- Conclusion

ALSTOM & URBAN TRANSPORT

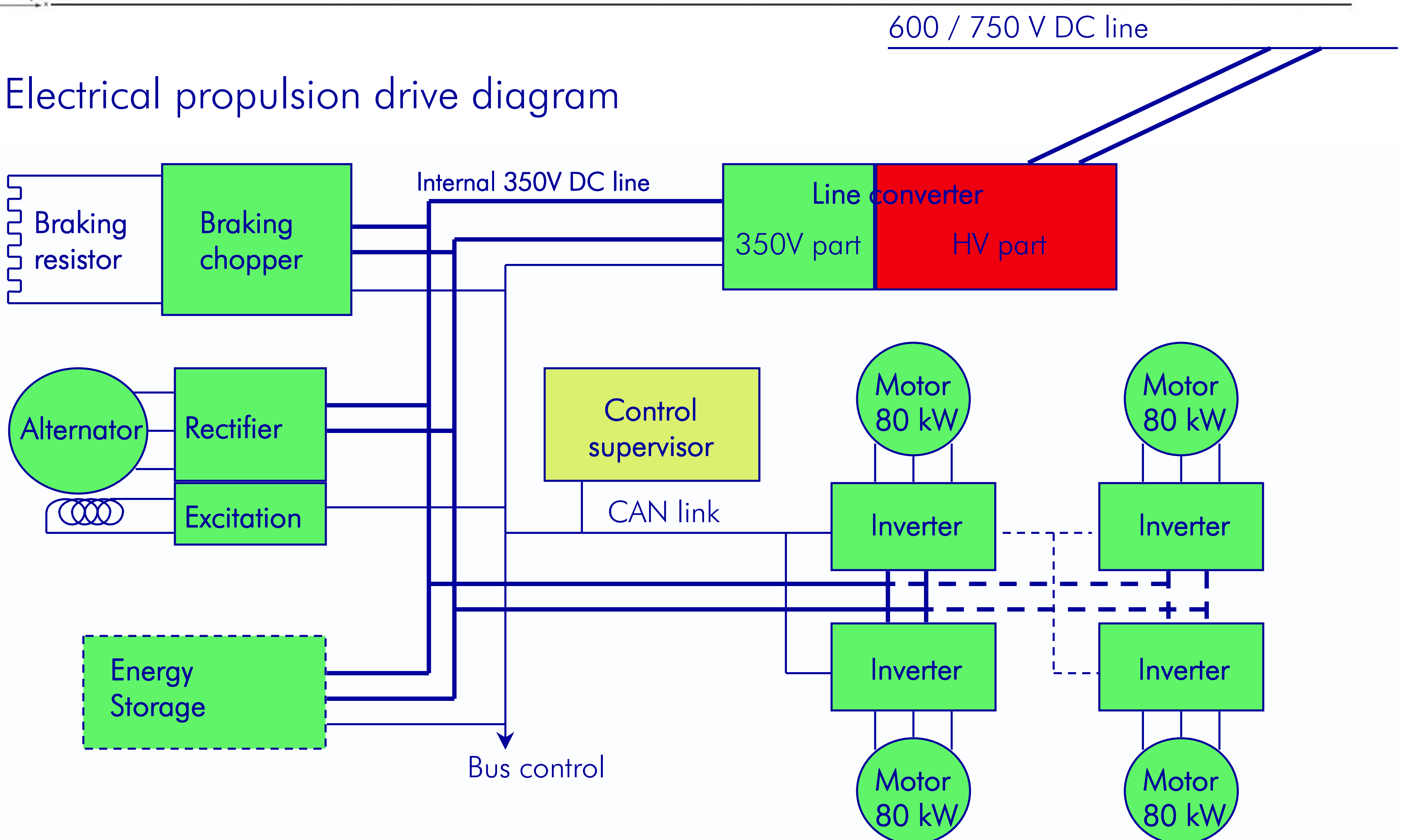
ALSTOM

- TROLLEYBUS ATHENS -

- TRAMWAY BORDEAUX -

Electric powered bus

Electrical propulsion drive diagram



GOALS

- HYBRID ELECTRIC BUS
  - Factory tests 2002
  - Prototype validation 2003
  - Mass production 2004
- FUEL CELL BUS
  - Demonstrator 2002

HYBRID ELECTRIC VEHICLES MOTIVATIONS

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- **GOALS :**
  - Pollutant Emission Reduction
  - Fuel Consumption Reduction
  - Better Comfort
- **Means :**
  - Energy Storage System
  - Energy Management
  - ZEV operating range
  - Electric Traction

BUS DESCRIPTION

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- 12 meters long
- 18 tons max. weight (15.2t for simulations)
- Performances :
  - easy starting up to 18% grade,
  - around 20 km/h for 15% grade,
  - 50 km/h with 5% grade,
  - 82 km/h on flat road
  - acceleration max : 1.5m/s^2
  - Jerk max=1.4 m/s^3 >>>> (Comfort)

DESIGN CRITERION

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- Series Hybrid Electric Vehicle
  - Maximize Energy Recuperation Possibility
  - ZEV Possibility.
  - Modular Assembly Possibility (1 or 2 axles)
  - Easy Fuel Cell integration
- Strategy
  - Maximize the electrical motor use in the Braking Phase
  - Optimize Engine Operating points

ENERGY STORAGE SYSTEM

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- Novel Battery Technology allow low SOC operating point
  - cs_hi_soc=.6 / cs_lo_soc=.4
- Sized to accept :
  - “Max.” Regenerative Power
- Zero Delta SOC
- ZEV
  - Battery Pack with High Power will have Relatively Large Energy Content.

Electrical Motor & ADVISOR

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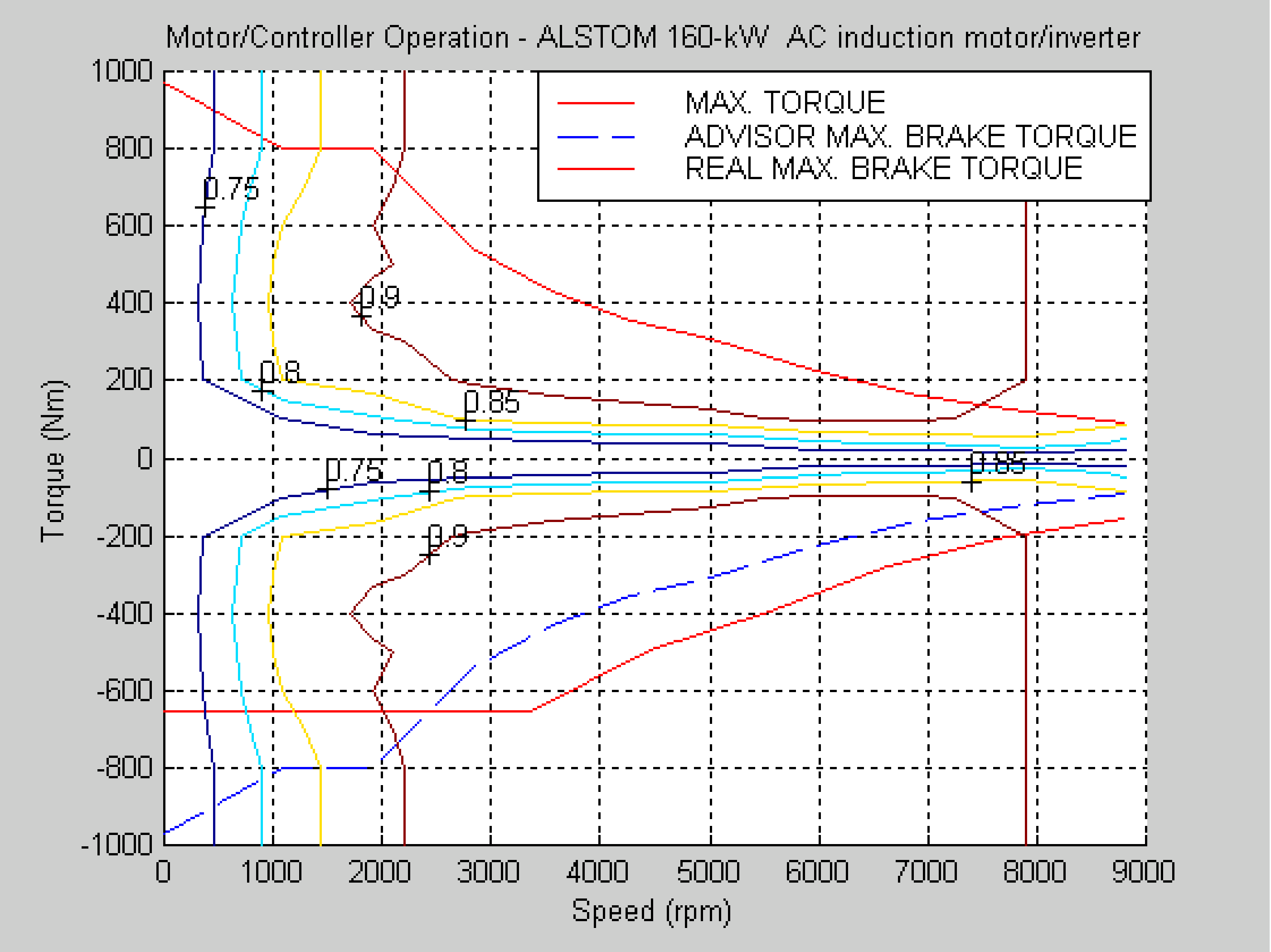
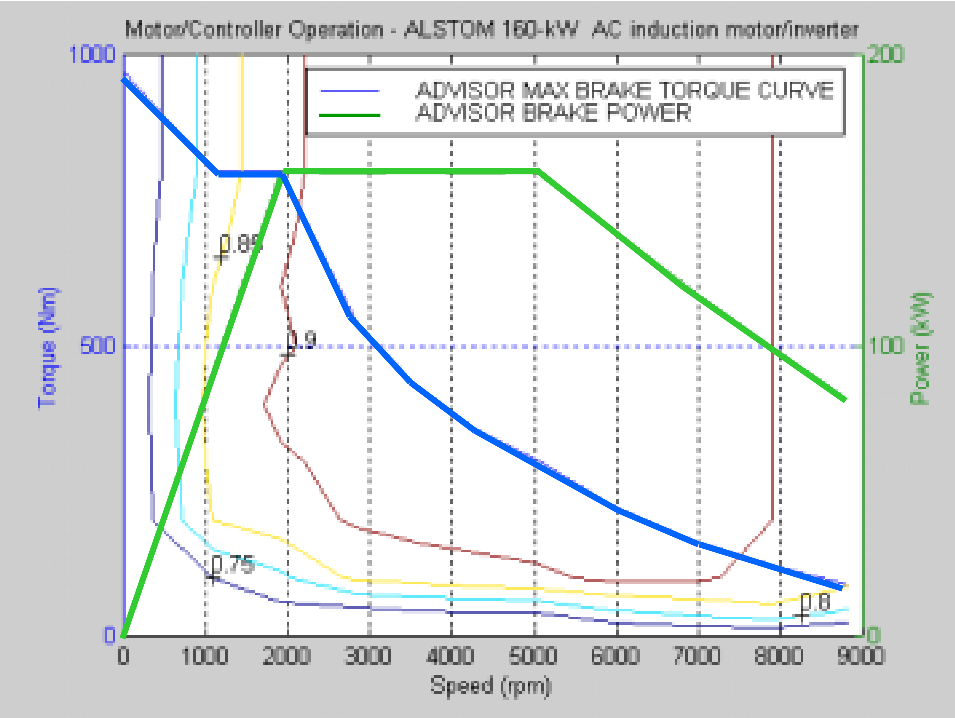
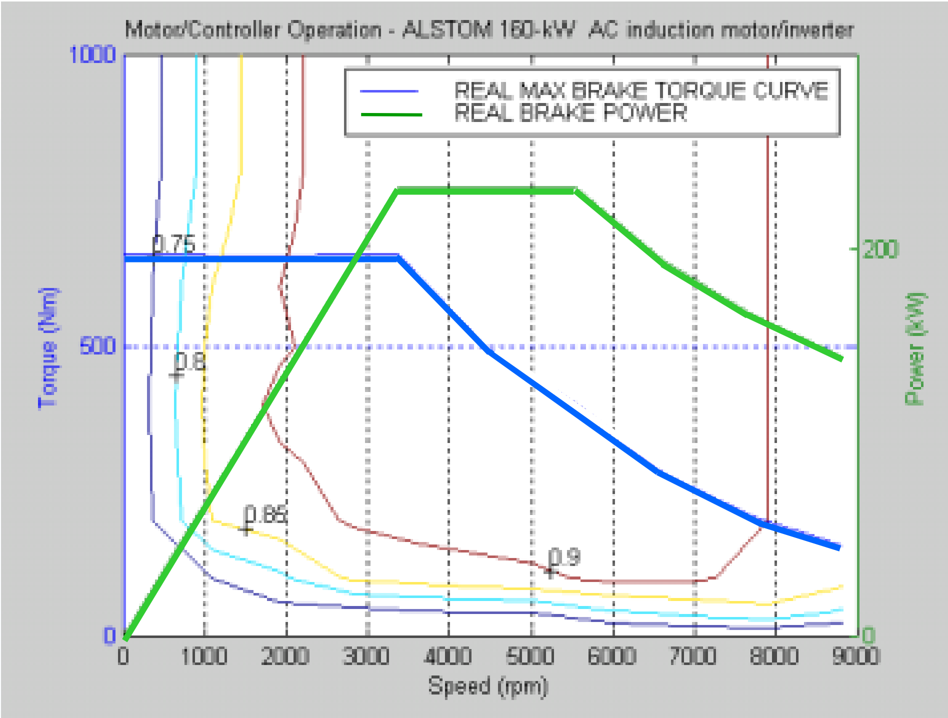


- Simulation of a Heavy-Duty Series Hybrid Electric Transit Bus -

Electrical Motor & ADVISOR





Original ADVISOR traction/brake effort and power

Modified brake effort and power

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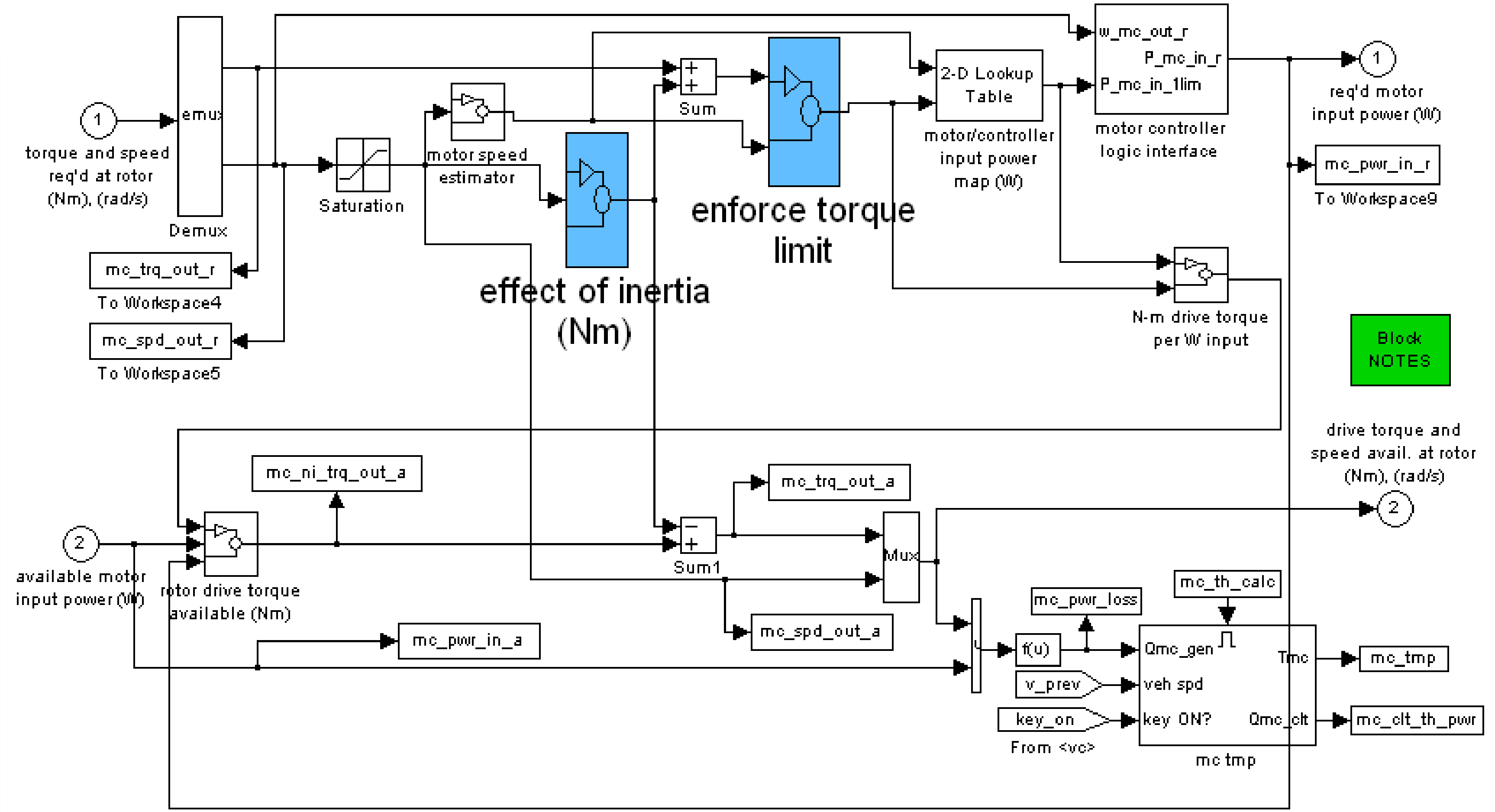
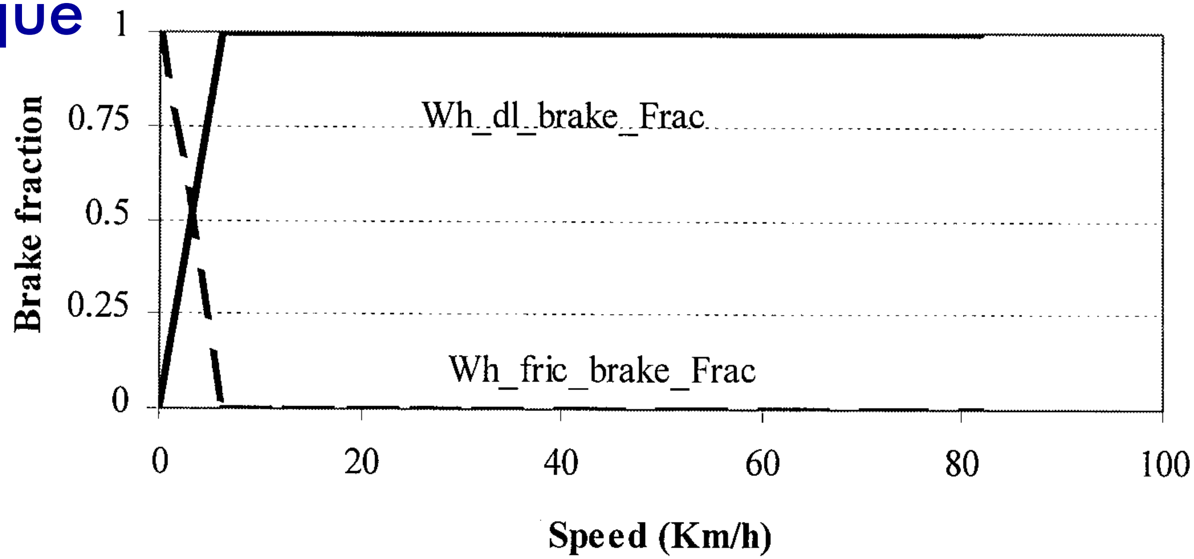
MC Bloc Diagram

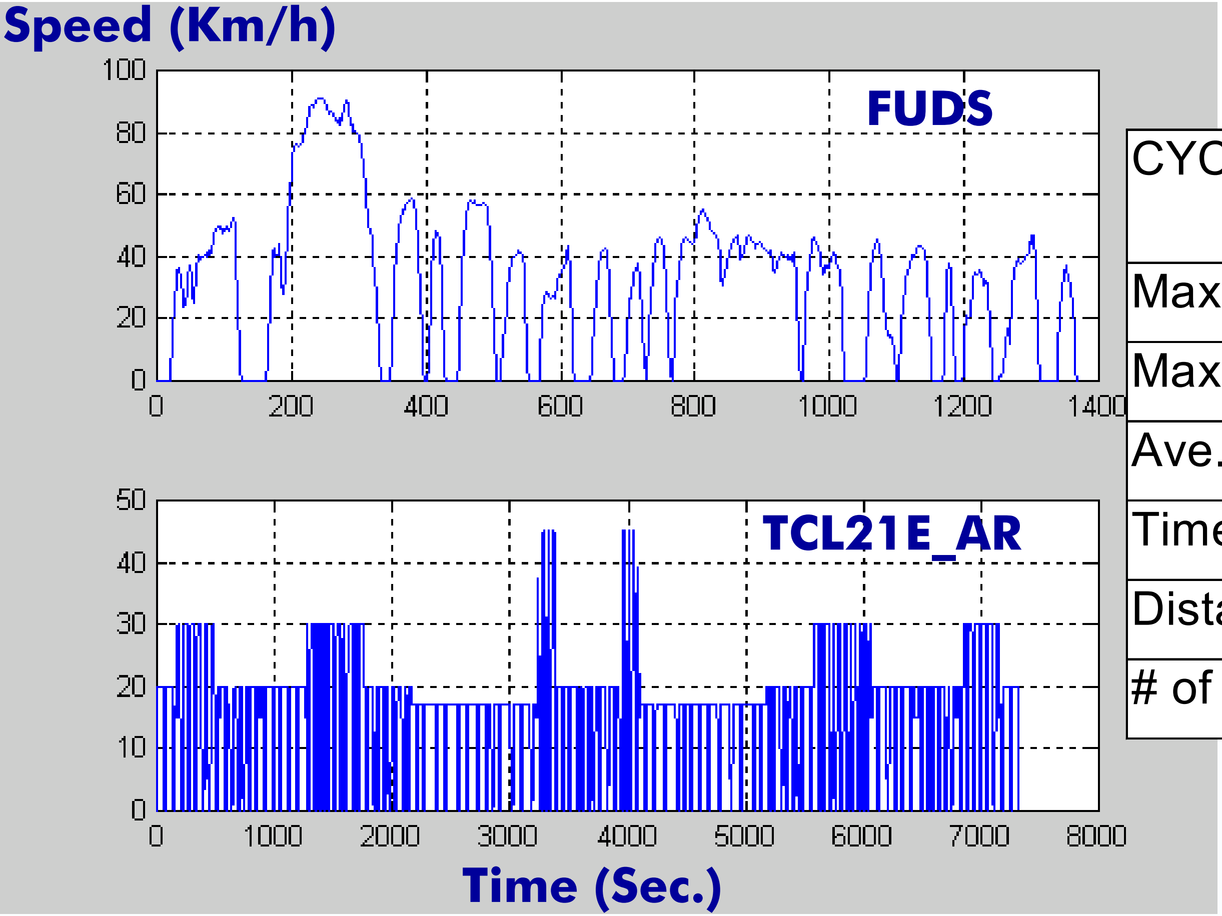


WHEEL & AXLE

- Maximize electrical braking
- Mechanical Brakes :
  - Very Low speed range
  - Braking Torque needed exceeds Electrical motor Torque



CYCLES



CYCLES	FUDS	TCL21E _AR
Max decel (m/s^2)	1.475	1.4
Max. Spd (km/h)	**91.2**	**45**
Ave. Spd (km/h)	**30.9**	**14**
Time (s)	1372	7332
Distance (km)	11.8	28.7
# of stop/km	**1.6**	**4.1**

RESULTS : FUDS / ST

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Energy Usage Table (kJ)

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	POWER MODE In	Out	Loss	Eff.	REGEN MODE In	Out	Loss	Eff.
Energy Storage	46113	34430	11616	0.75				
Energy Stored	67							
Motor/Controller	53951	45939	8013	0.85	22940	21978	962	0.96
Gearbox	45939	44203	1735	0.96	23069	22940	130	0.99
Final Drive	44203	44203	0	1	23069	23069	0	1
Wheel/Axle	44203	42321	1882	0.96	25618	25311	307	0.99
Braking							2242	

ADVISOR_MODIFIED

	POWER MODE In	Out	Loss	Eff.	REGEN MODE In	Out	Loss	Eff.
Energy Storage	47157	35184	12027	0.75				
Energy Stored	-54							
Motor/Controller	53934	45939	7995	0.85	24817	23008	1809	0.93
Gearbox	45939	44203	1735	0.96	24951	24817	134	0.99
Final Drive	44203	44203	0	1	24951	24951	0	1
Wheel/Axle	44203	42321	1882	0.96	25618	25279	339	0.99
Braking							328	

Gain Regen_Motor_in = 8.2%   Gain Mechanical brake=85.37%

RESULTS : FUDS / Regen Mode

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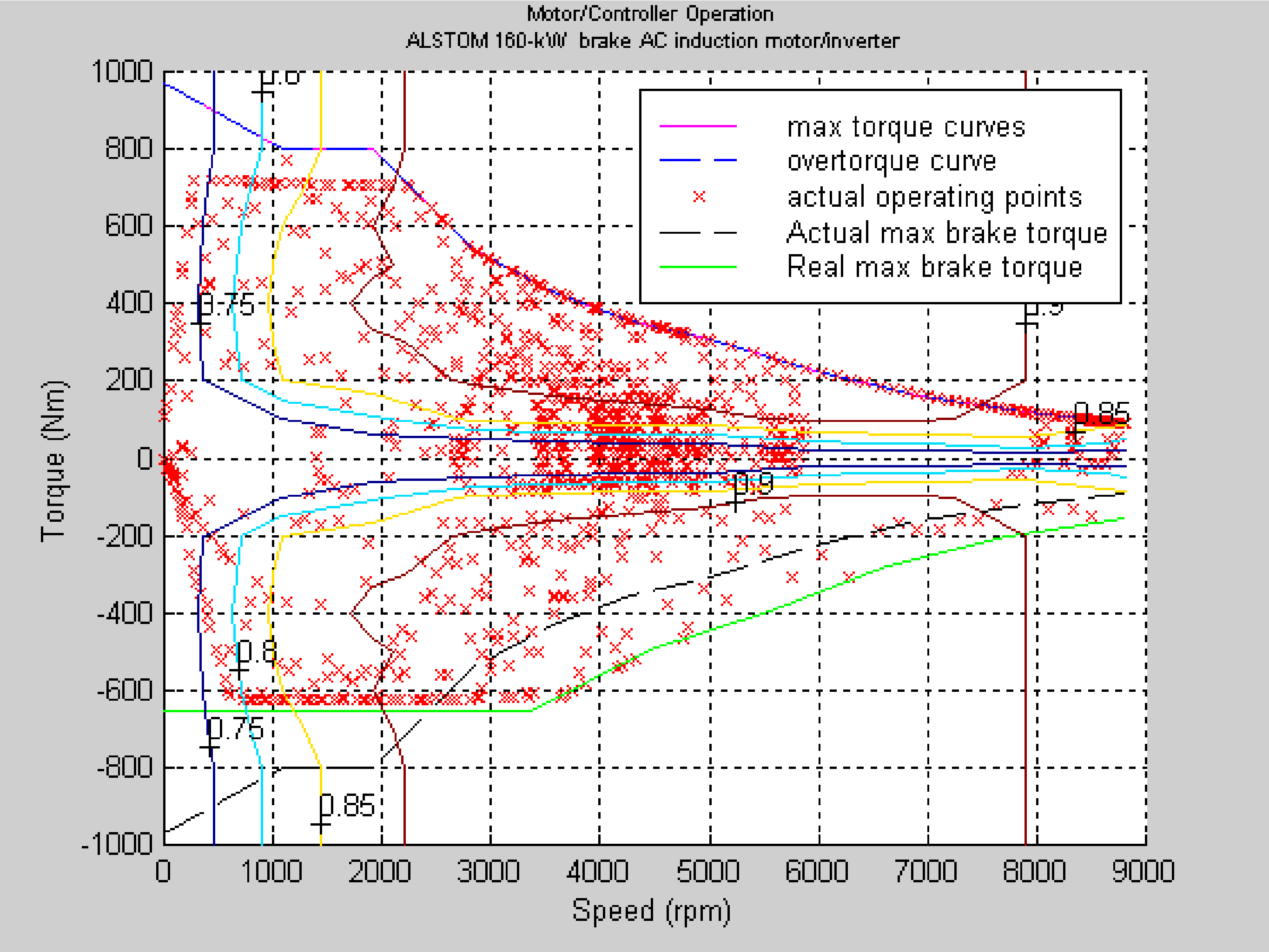
CYCLES	FUDS (ST)	FUDS (SFO)
max_veh_brake_pwr (kW)	266.5	266.4
Max_weh_brake_pwr (kW)	220	221
veh_regen_ energy (kJ)	25618	25618
Motor_regen_energy_in (kJ)	24817	24817
Motor_in/veh_regen_in eff.	96.87%	96.87%
Motor_regen_energy_out (kJ)	**23008**	**23399**
Motor_out/veh_regen eff.	89.8%	91.3%
Friction brake energy (kJ)	328	328
Gain in Friction brake loss eff	85.37%	85.37%
Fuel consumption (l/100km)	35	36.2

MC_160/230kW Operating Points ALSTOM



- Simulation of a Heavy-Duty Series Hybrid Electric Transit Bus -

CONCLUSION

ALSTOM

- Thanks to ADVISOR Teamwork
  - User facilities (modifications, adaptation, ...)
  - Friendly User Interface
  - but difficulties to know how a variable is used in order to make modification
- Continuing with ADVISOR :
  - Optimize pollution reduction
  - Optimize Control Strategy
  - Add interfaces with ALSTOM design tools

ALSTOM

www.alstom.com

Simulation of a Heavy-Duty Series Hybrid Electric Transit Bus

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Research & Development Engineer

ABSTRACT

Using ADVISOR simulation tool, the aim of this paper is to present a study concerning a series hybrid electric vehicles (S-HEVs) with both thermostatic and load follower control strategies. The vehicle being studied is a 12 meters, 18 tons transit bus. First, the weight the regenerative braking energy will be outlined. The importance of the electrical motor and the energy storage system and their impact on recovering this energy is highlighted secondly. Finally, this paper presents a comparison between the ADVISOR original version and a modified one that takes into account the real speed/torque map in the braking operation mode. Improvements due to the new braking version are presented.

INTRODUCTION

In urban areas, vehicles accelerate and decelerate frequently. As conventional engine drive vehicles waste all of their inertia energy as heat in braking, energy efficiencies from fuel to vehicle traction are typically less than 15% [1]. Therefore Electric Vehicles (EVs) and Hybrid Electric Vehicles (HEVs) which have re-generative braking feature are suitable for urban use from energy saving point of view in addition to the fact that they are zero or low emission possibilities. The amount of the re-generative energy that is fed to traction battery is one of the key parameters to evaluate the EVs and HEVs. Batteries or supercapacitors from one hand and the electric motors [2] on the other hand have an important role in recovering this regenerative braking energy.

Using ADVISOR, the aim of this paper is to present a study concerning a series HEV transit bus with both thermostatic and load follower control strategies. The effect of the regenerative energy will be outlined.

EV & HEV EFFICIENCY

Improving the energy efficiency of a vehicle can be made by three ways:

1. The reduction of the mass, tire rolling, aerodynamic and transmission losses receives great effort from the automobile engineers.

2. Optimization of each individual component efficiency of the system. This objective may be realized by properly selecting the component type, size, configuration and control strategy. Thus, all components work together in order to achieve the best overall efficiency required.

3. Recovering the kinetic and potential energies that are usually wasted in the form of heat in the brakes. This is an important approach to improve the vehicle efficiency especially in the city part of the bus duty cycle where stop and go driving is frequent.

Both point 2 and 3 are central goals of the EVs and HEVs research in general and ALSTOM in particular.

EV & HEV REGENERATIVE BRAKING

We can even say that both points have to be optimized together in order to achieve better efficiency and autonomy of EVs and HEVs. In fact, when braking,

1. Only the driven axle can be regenerative. Another part of the braking energy will be dissipated as heat by the friction braking system of the non-drive axle.

2. If the braking power exceeds the capacity of the regenerative braking system, the amount of the recovered energy is influenced by the part of the braking energy absorbed by the frictional brake system.

3. The recovered and recycled energy will be influenced by the losses due to the inherent physical properties and limits of each component used to produce and store this energy.

4. The braking energy recovery in emergency situation that can reach a deceleration up to 0.6g is not significant. This paper will focus on normal urban driving cycle.

SYSTEM DESCRIPTION

PERFORMANCES AND ELECTRICAL MOTOR

The series hybrid bus under study is 12 meters long and weighs 18 tons. Figure 1 shows the Alstom AC induction motor traction characteristics used during this study. It presents the sum of two hub motors of 80kW each implemented in a dual-mode bus (trolley or diesel/generator fed electric drive). It shows also the torque needed at different speeds in order to achieve performance for flat and different road grade (5, 10, 15 and 20%). The motor speed/torque characteristics achieve easy starting up to 18% grade, around 20km/h for 15% grade and 50km/h with 5%grade. Naturally it achieve 82km/h on flat road.

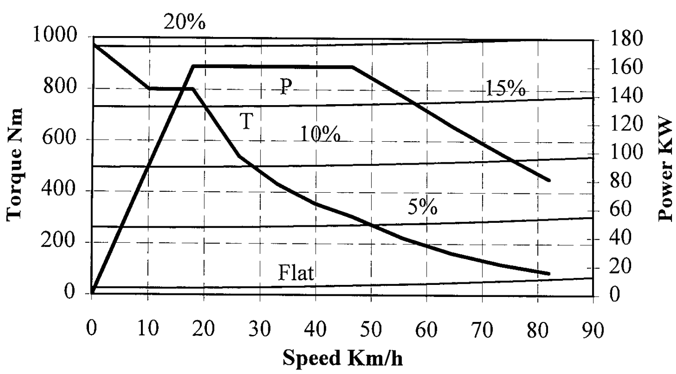

Figure 1: Electrical motor traction characteristics

Figure 2 shows the amount of the vehicle braking power with respect to its speed for different deceleration. Alstom has chosen to realize & use an AC induction motor that decelerates up to 1.5m/s^2 and can recover up to 230kW. The deceleration criteria had been taken symmetrical with the maximum passenger comfort acceleration. Alstom can meet, with other motor, greater deceleration in function of the bus specification. It must be noted that the motor torque/speed curve in the braking operation mode is different than that the traction side as assumed by ADVISOR. Consequently, this will lead to another maximum regenerative power than that of the traction power (160kW) as shown in figure 1 & 2.

Figure 2 shows also that the maximum braking power is proportional to the vehicle speed up to a key point "A ". Beyond this key point the regen_motor braking power stays constant for a while and then drops.

In general, by pushing the key point "A" to the left (minimizing the speed@maxpower), we can have better bus performances and thus better energy recuperation.

ALSTOM second stage program will be with a Permanent Magnet Synchronous Motor (PMSM) which will improve efficiency and regenerative power at high speed range.

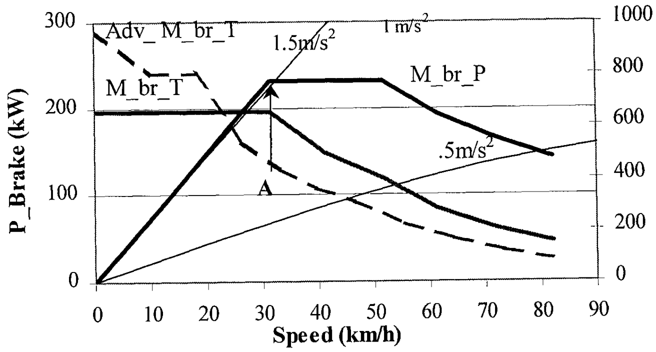

Figure 2: Electrical motor braking characteristics

ENERGY STORAGE SYSTEM (ESS)

The energy storage system (type, size, configuration and its control strategy) is one of the most important components in EVs and S-HEVs in order to improve fuel economy, overall efficiency and emission reduction.

We had used a novel battery technology during this study. It was sized in order to respect two criteria:

First, to be able to receive "all" the driveline braking power.

Second, to accept the genset power, when it is on, in the same time with the driveline braking power. (i.e. that the ESS can ensure alone the traction performances).

Respecting these criteria will lead to:

1. Oversizing the battery pack. Generally, with the chemical batteries available today having the required high power will also have a large energy content.
2. Have a zero emission possibility on the bus duty cycle (ex: down town) depending on the energy content of the battery pack.
3. Freedom to choose the genset operating point,
4. Better regenerative motor efficiency.
5. Improved fuel economy

GENSET

The genset consists of the internal combustion engine (ICE) or Fuel Converter (FC) together with a generator and power electronics (Generator Controller GC).

Genset is the set of power/speed combinations for a given vehicle where the maximum efficiency lies, where power and speed are limited by either the engine or the generator.

The FC is a diesel engine, which have 93 kW maximum power and 4000 rpm maximum speed, with 38% efficiency at 290Nm@2200rpm

The GC is a speed generator with a maximum torque of 290Nm, speed range up to 4000rpm.

WHEEL AND AXLE

The wheel drive line brake fraction (Wh_dl_brake_frac) and the wheel friction brake fraction (Wh_fric_brake_frac) are shown in Figure 3. These assume that the maximum brake force will be applied to the vehicle by the electrical motor in order to recover the maximum admissible of the braking power. The mechanical brakes will do the rest.

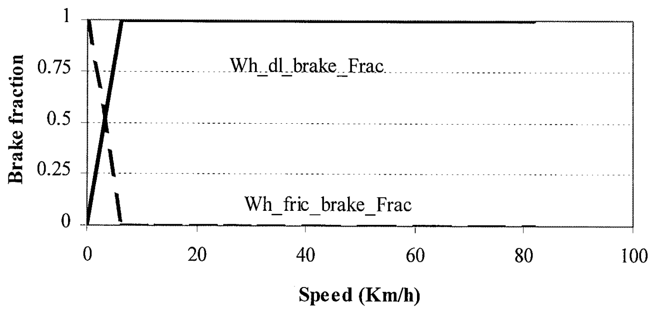

Figure 3: Distribution braking force on the front axle

AUXILIARIES: Assuming a continuous 6kW electrical

TRANSMISSION: 1 fixed speed

VEHICLE: 12m, 18t. Simulation results take into account that consumption is usually calculated for half loaded bus of 15.2tones.

MODELING & SIMULATION

Using ADVISOR, the component information presented above are the input data files for the S-HEV bus structure. This part must be designed as well as possible knowing the performances to be met.

CONTROL STRATEGIES PARAMETERS (CS)

Control strategies parameters are presented in the Table 1 with zero delta SOC target met for all cases studied:

cs_parameters	S. Thermostat	S. Follower.
cs_min_pwr	46kW	10kW
cs_max_pwr	46kW	70kW
cs_lo_soc	0.4	0.4
cs_hi_soc	0.6	0.6
Soc_init	0.5	0.5

Table 1: cs_parameters

The new battery pack technology used has approximately constant Open Circuit Voltage (OCV) over a wide SOC range. This allows a low SOC target. Consequently the energy storage system cs_parameters are chosen in order to recover the maximum admissible from the regenerative motor energy.

DRIVE CYCLES (CYC)

Figure 4 presents the FUDS, TCL21E_AR urban drive cycles. The last one represents a French drive cycle in Lyon City. These cycles have high dynamic variation. The maximum speeds are approximately 3 times the average speed as shown in Table 2.

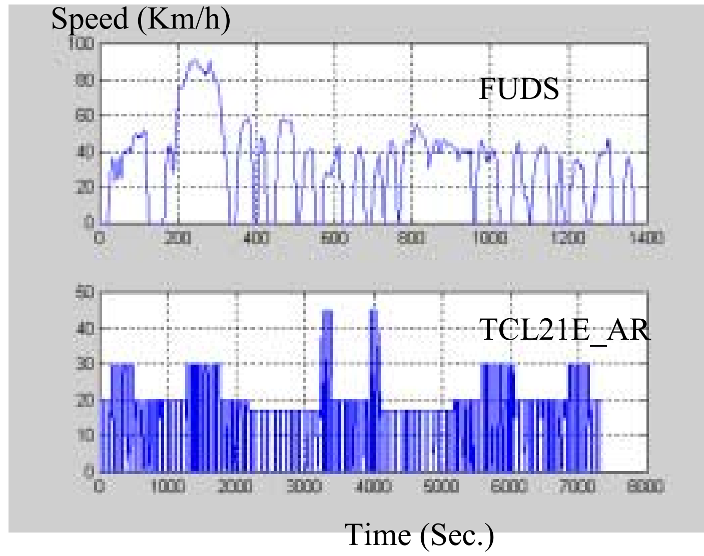

Figure 4: FUDS & TCL21E_AR urban driving cycles

CYCLES	FUDS	TCL21E_AR
max decel (m/s^2)	1.475	1.4
max_speed (km/h)	91.2	45
average_speed (km/h)	30.9	14
time (s)	1372	7332
Distance (km)	11.8	28.7
Numbers of stop/km	1.6	4.1

Table 2: FUDS & TCL21E_AR cycle data

CASE 1 : FUDS WITH ADVISOR ORIGINAL FILES

The ADVISOR original version assumes that the electrical motor has the same maximum torque curve in traction and braking operation mode (dotted lines Figure 5,6). Running the simulation with the above input files and conditions gives us the following results shown in Table 3 and Figure 5. We can note that the electrical motor is used over all of its speed and torque map range. The mc_trq is limited at high speed in traction and at medium and high speed in braking while it is not limited at low speed. The vehicle has a maximum braking power of about 266 kW. The wheel power is limited at the motor maximum admissible power (151kW).

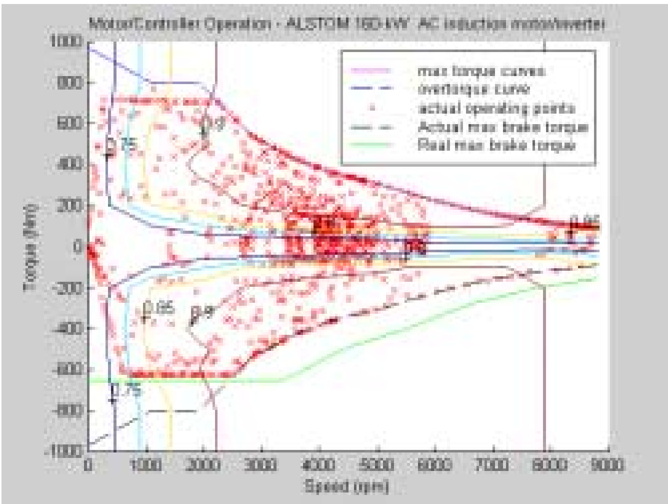

Figure 5: Motor controller operation for FUDS cycle with original ADVISOR version

The total vehicle braking energy is 25618 kJ. The motor_in kJ 22940 for both control strategies. The motor_in/veh_regen energy is about 89.5%. The motor can send to the battery pack 21978 kJ (series thermostat - ST) or 22027 kJ (series follower - SFO). The regen efficiency is about 86% and the brake losses are 2242 kJ.

CYCLES	FUDS (ST)	FUDS (SFO)
max_veh_brake_pwr (kW)	266.5	266.4
max_weh_brake_pwr (kW)	151.1	151.1
veh_ regen_energy(kJ)	25618	25618
Motor_regen_energy_in (kJ)	22940	22940
motor_in/veh_regen_in eff.	**89.5%**	**89.5%**
Motor_regen_energy_out (kJ)	21978	22027
motor_out/veh_regen eff.	**85.8%**	**86%**
Friction brake loss energy (kJ)	2242	2242
Fuel consumption (l/100km)	35.5	36.8

Table 3: Regen simulation results for FUDS cycle for both series control strategies with ADVISOR version

CASE 2 : FUDS WITH ADVISOR MODIFIED FILES

The ALSTOM AC induction motor used in this study has another speed/torque map, Figure 6, in the regenerative operation mode. This allows it to absorb 70kW (dot line) more than in traction mode especially in the medium and high speed range. Introducing this difference enabled us to approach the real motor operation and refine the simulation study and lead to the following results.

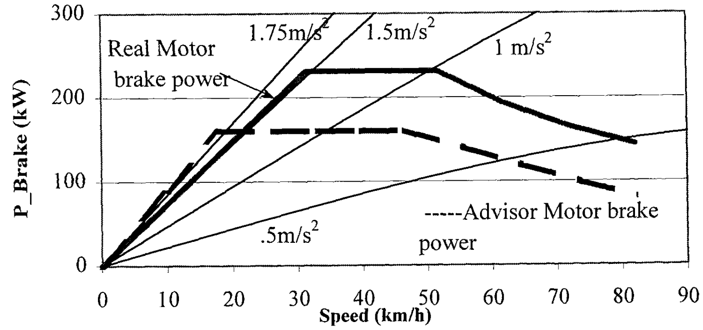

Figure 6: ADVISOR & real motor brake power

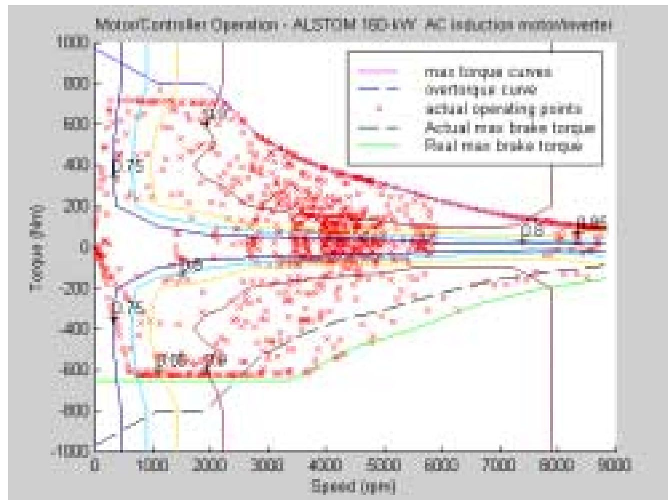

Figure 7: Motor controller operation for FUDS cycle with modified ADVISOR version

CYCLES	FUDS (ST)	FUDS (SFO)
max_veh_brake_pwr (kW)	266.5	266.4
max_weh_brake_pwr (kW)	220	221
veh_regen_ energy (kJ)	25618	25618
Motor_regen_energy_in (kJ)	24817	24817
motor_in/veh_regen_in eff.	**96.87%**	**96.87%**
motor regen_energy_out (kJ)	23008	23399
motor_out/veh_regen eff.	**89.8%**	**91.3%**
Friction brake energy (kJ)	328	328
Friction brake loss eff .	85.37%	85.37%
Fuel consumption (l/100km)	35	36.2

Table 4: Regen simulation results for FUDS cycle for both series control strategies with ADVISOR modified version

Table 4 and Figure 7show that while braking :

- the mc_trq is not limited
- the wheel driveline regen power can accept up to 221kW
- brake losses decreased by 85.37% for both control strategy.
- the regen to motor has increased by 8.18%
- the motor energy sent to the battery pack has increased by 4.6% (ST) and 6.2% (SFO).
- Slight improvement in fuel economy. The cs_parameters have to optimise in order to have a real gain for such point.

CASE 3: TCL21E_AR

Table 5 presents the simulation results for a thermostatic control strategy in the same conditions and parameters for the TCL21E_AR Lyon urban cycle. The first column presents the original ADVISOR version while the second is with the modified one. We can see the same conclusion as found for the FUDS cycles. The difference is the amount of energy recovered. The gain in the mechanical brake is about 52% instead of 85.3%for the FUDS cycle. This can be explained by the fact that the TCL21E_AR cycle has half maximum and average speed than the FUDS.

CYCLES	TCL21E_AR ADVISOR	TCL21E_AR Adv_Modified
max decel (m/ss)	1.415	1.4
max_veh_brake_pwr (kW)	236	236
max_weh_brake_pwr (kW)	151	222.75
veh energy (kJ)	41574	41574
motor regen energy_in (kJ)	38989	40018
motor_in/veh_regen eff. %	**93.78%**	**96.25%**
motor energy_out (kJ)	35763	36003
motor_out /veh_regen eff. %	**86%**	**86.6%**
Friction brake loss energy (kJ)	2018	967
Fuel consumption (l/100km)	35.4	35.2

Table 5: Regen simulation results for TCL21E_AR cycle for series thermostat control strategies for both original & modified ADVISOR version

CONCLUSION

In urban driving cycles, the friction brakes use a significant amount of energy. A well matched braking strategy with the electrical motor and the energy storage system characteristics allow the recuperation of a very large amount of the braking power.

First, the importance of the braking energy for EVs & HEVs was highlighted. Optimizing each individual component of the system from one hand and recovering the kinetic and potential energies on the other hand are the central goals of research for these structures. In the same time, the electrical motor and the energy storage system characteristics are of major importance to improve the regenerative recuperation. Consequently, introducing the real motor speed/torque map in the regenerative operation mode have allowed us to minimize the mechanical brake losses and thus improve the regenerative energy efficiency as presented for the urban FUDS and TCL21E_AR cycles.

ACKNOWLEDGMENTS

Special thanks to the ADVISOR team works specially Valerie JOHNSON for their precious help.

CONTACT

Jean BAVARD was born in Dijon, France in 1958. He received the B.Sc. degree in 1980 in general and electrical engineering from the Ecole Centrale de Paris, France. Since 1982 he joined the electrical traction department of Alstom-transport in Lyon and participated in the development of variable speed drives with alternative machines applied to railways and marines. Currently, he is in charge of traction drives applied to hybrid electrical bus. The main fields of interest are system control, energy management and power electronics.

Atef GAYED was born in Ismaïlia, Egypt in 1964. He received the B.Sc. degree in 1986 in power electrical engineering from Zagazig University, Cairo, Egypt. He received the Ph. D. degree in 1996 from Nantes University, France in the application of sliding mode control to variable speed drives. Since 1999, he participates as engineer for Alstom-transport in the railway and hybrid electrical bus fields. His research interest includes electrical motor control system, energy management and power electronics.

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1. Yimin Gao, Liping Chen and Mehrdad Ehsani, 'Investigation of the Effectiveness of Regenerative Braking for EV and HEV', SAE 1999-01-2910

2. Mellor, P.H. 'High Efficiency Drivbe-trains for Electric and Hybrid Vehicles' IEE 1999.

APPENDIX

ACRONYM & VARIABLE LIST

T (Nm)	Torque
P (kW)	Power
Adv_M_br_T (Nm)	**Adv**isor **M**otor **br**aking **T**orque versus motor speed
M_br_T (Nm)	real **M**otor **br**aking **T**orque versus motor speed
M_br_P (kW)	real **M**otor **br**aking **P**ower versus motor speed
SOC	**S**tate **O**f **C**harge
ST	**S**eries **T**hermostat
SFO	**S**eries **F**ollower
TCL21E_AR	**T**ransport en **C**ommun **L**yonnais (ligne **21** **A**ller **R**etour)

Hybrid buses - the benefits of matching to real routes

Mike Kellaway

Alan Ponsford

Background - UK market

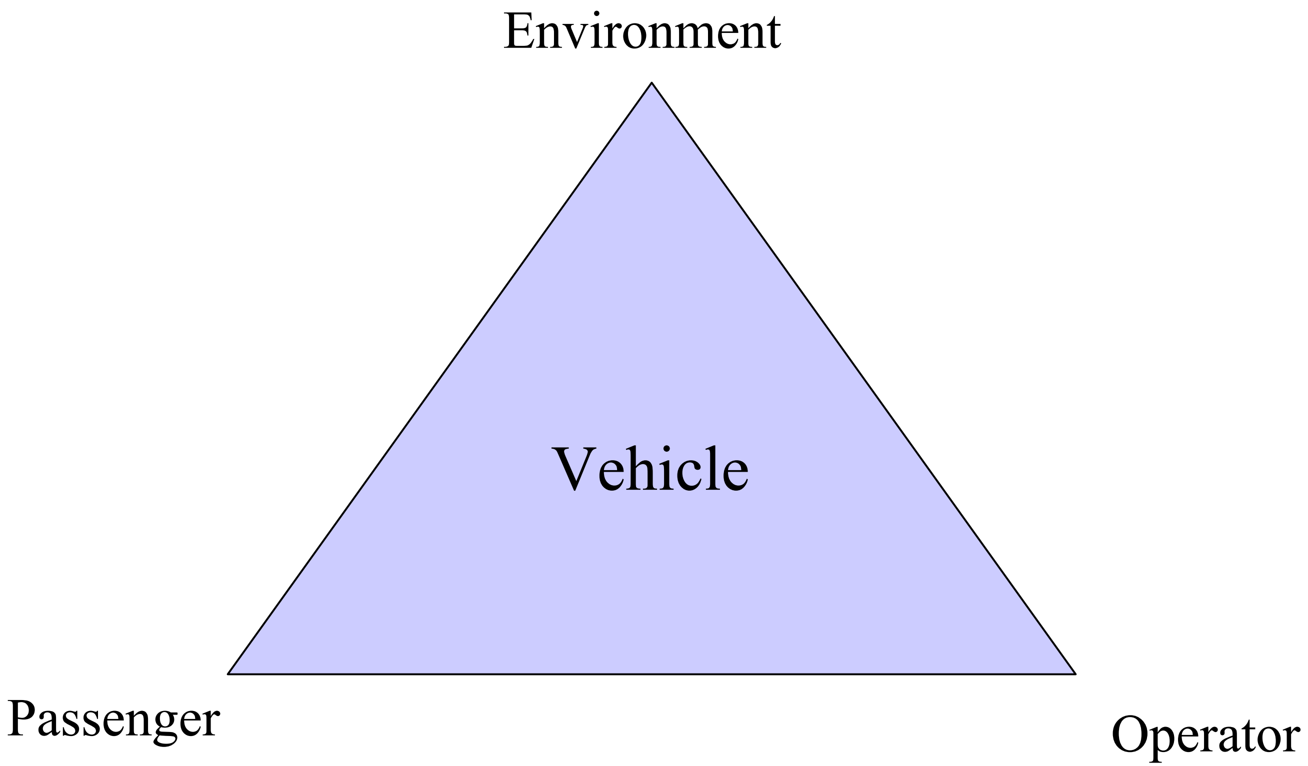
Dart

Classic

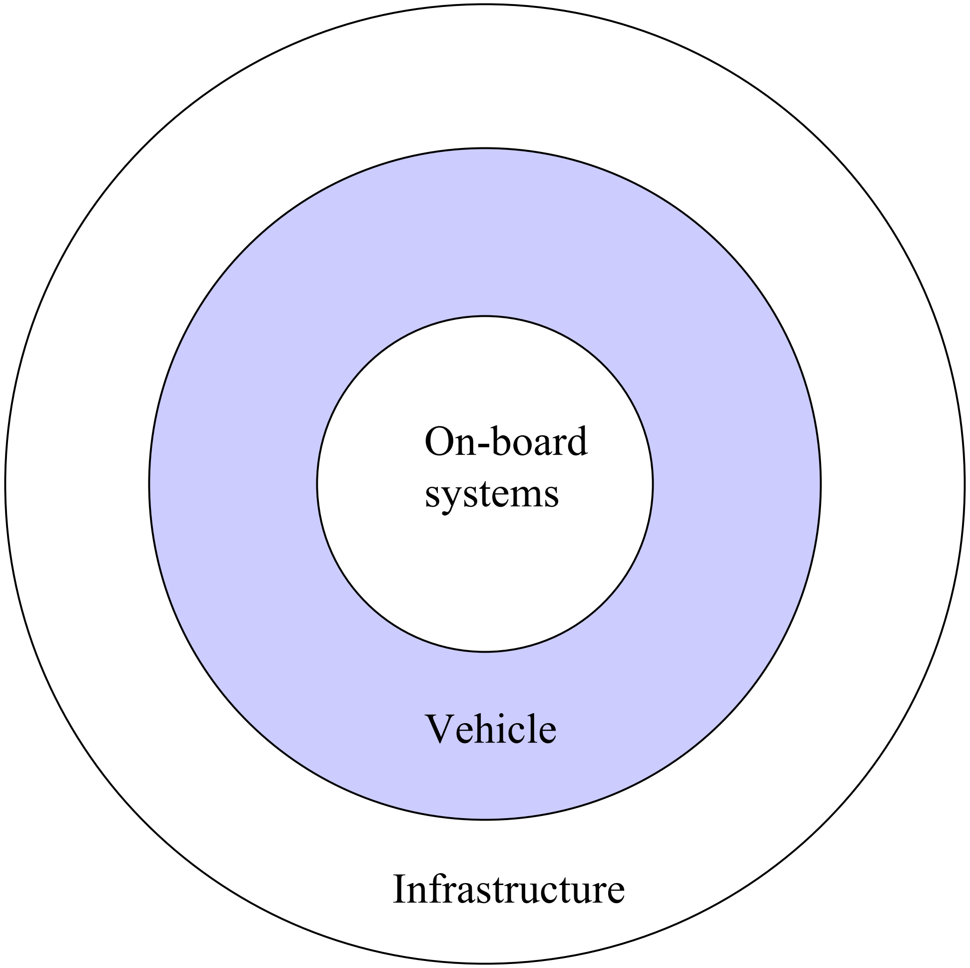
Dart SLF

newbus technology

Future Bus Requirements



Broad Scope



Challenges

- Energy use *Saving 16 to 60%*
- Emissions reductions
- True systems engineering
- Infrastructure links
- Real benefits to whole society

Series Hybrid Bus

- Energy source flexibility
- ZEV range possibility
- Compatible with realistic battery capability
- Offers both CO_2 and pollutant improvements
- Packaging flexibility
- Facilitates links to infrastructure
- Match to urban application

newbus technology

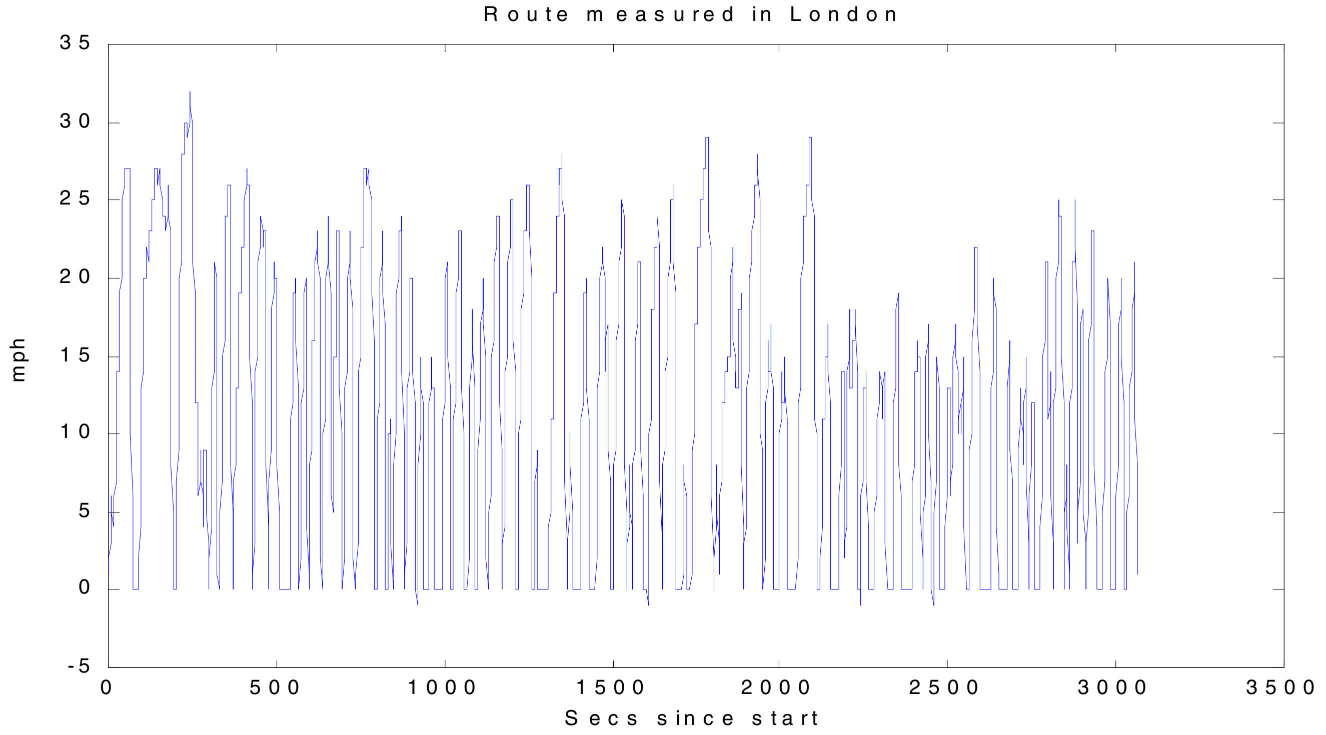
Performance envelope required

- Modern city profiles
- Attractors of low speed (energy, noise, pedestrians)
- Block time (gate to gate) is important parameter
- Opportunities to match vehicle to route

Real routes ?

- Objectives of standard cycles
- Measured data
- Real variability

Real routes



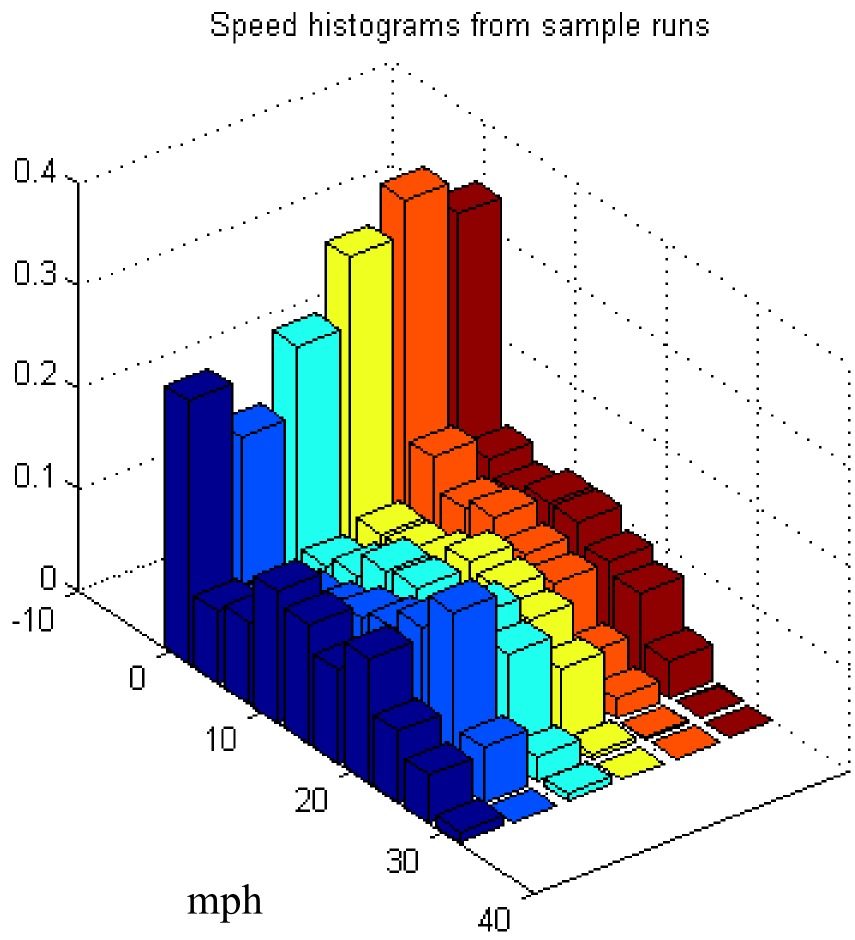
Route measured in London
mph
Secs since start
35
30
25
20
15
10
5
0
-5
0
500
1000
1500
2000
2500
3000
3500

Data gathering

- Limited data available from operators
- GPS
- Real-time GIS review during initial trials
- 3-axis accelerometers/grade estimation
- Custom logger with error-based filtering

Scatter

Payload
Traffic
Driver
Seasonal
…



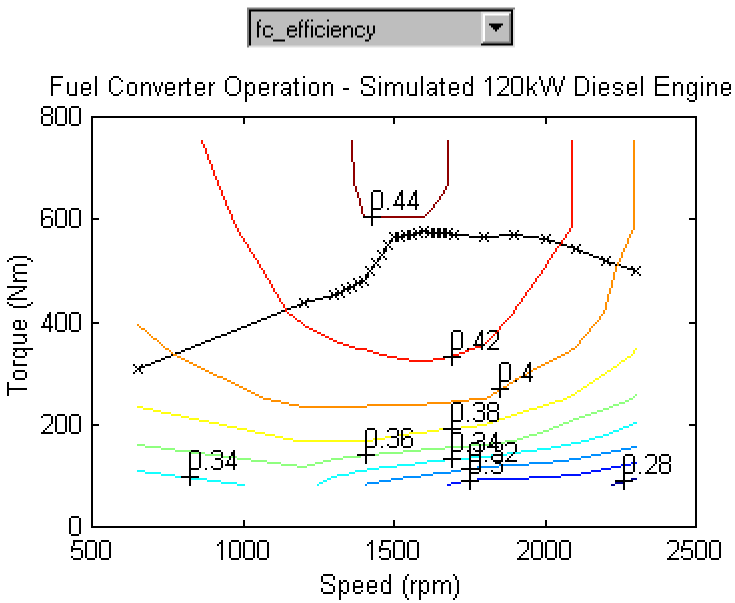
Modelling Strategy

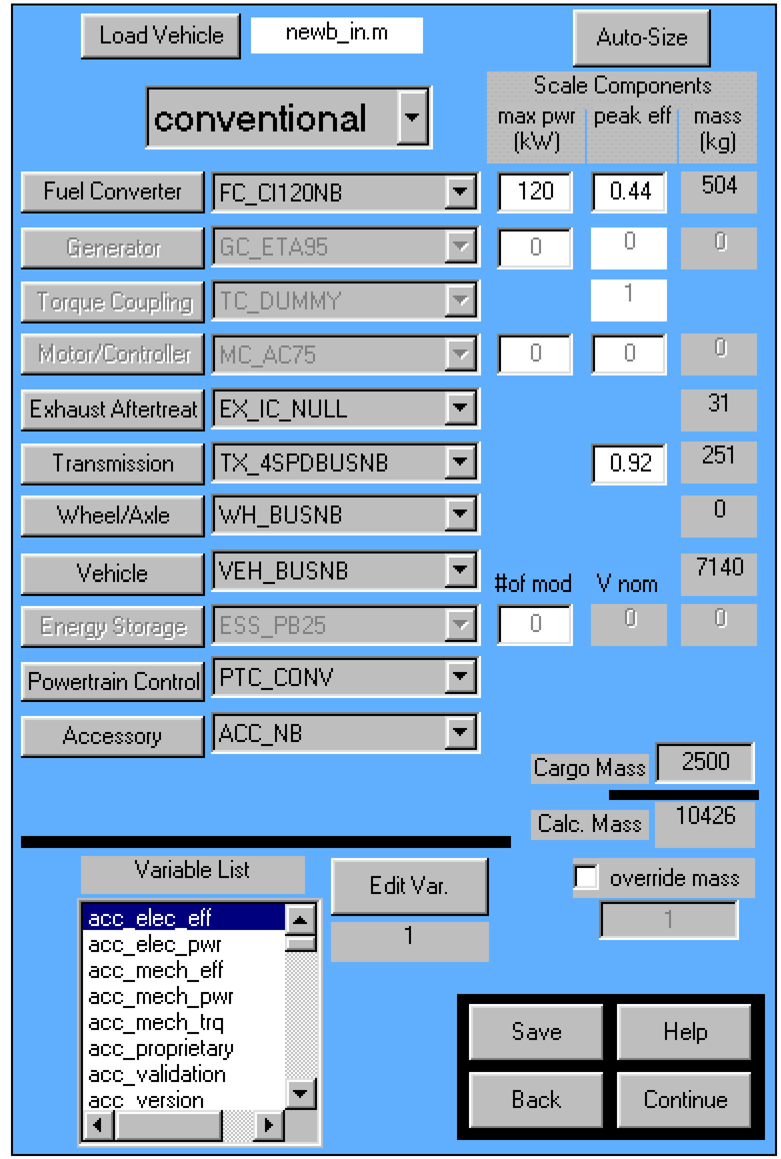
- Create model of existing conventional bus
- Exercise on collected route data to benchmark approach
- Develop hybrid bus model as a primary design tool
- Develop performance envelope reduction strategy

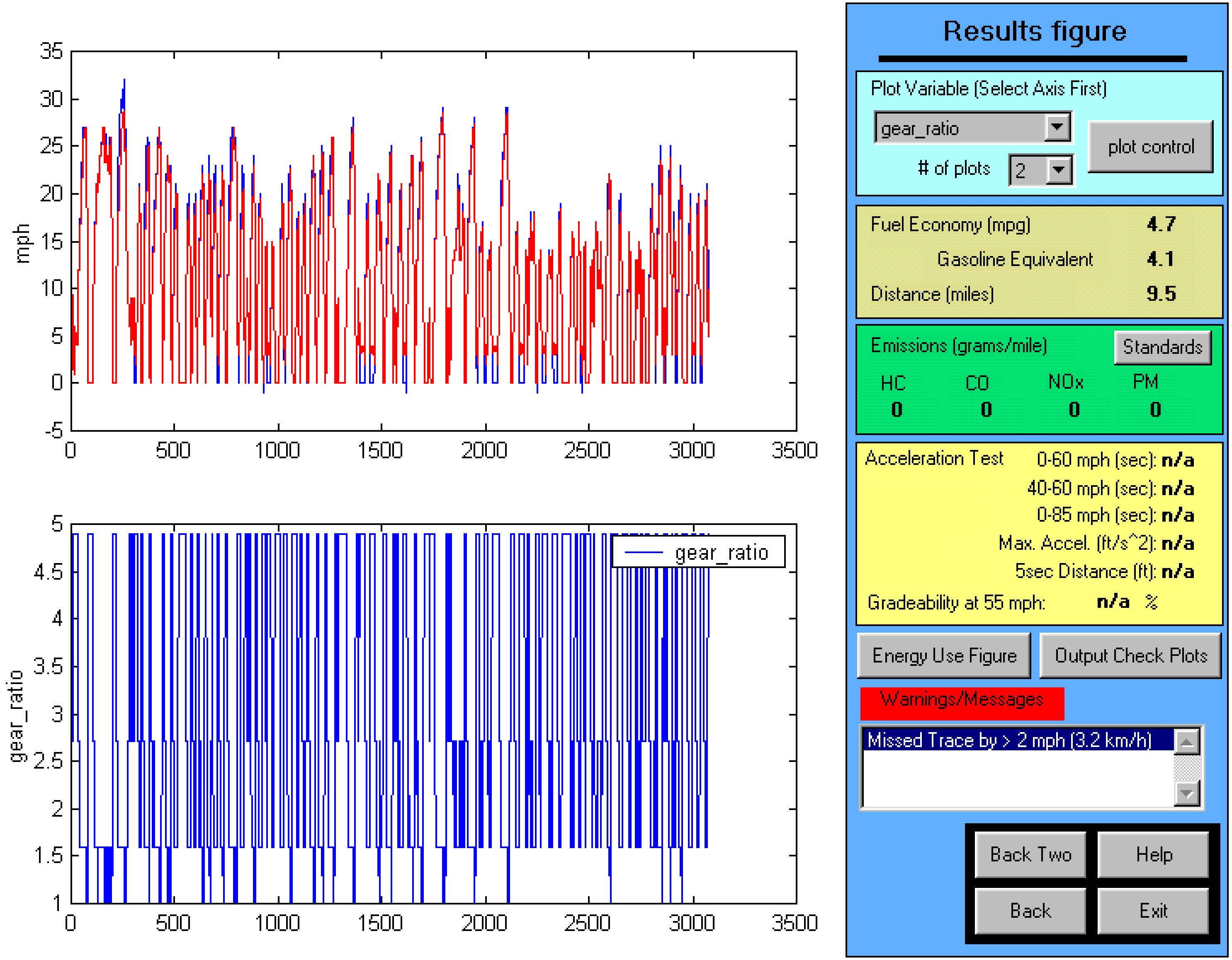
Why ADVISOR?

- Open source format
- Link to Matlab used for data processing
- Available models
- Excellent support resource available

Vehicle Input

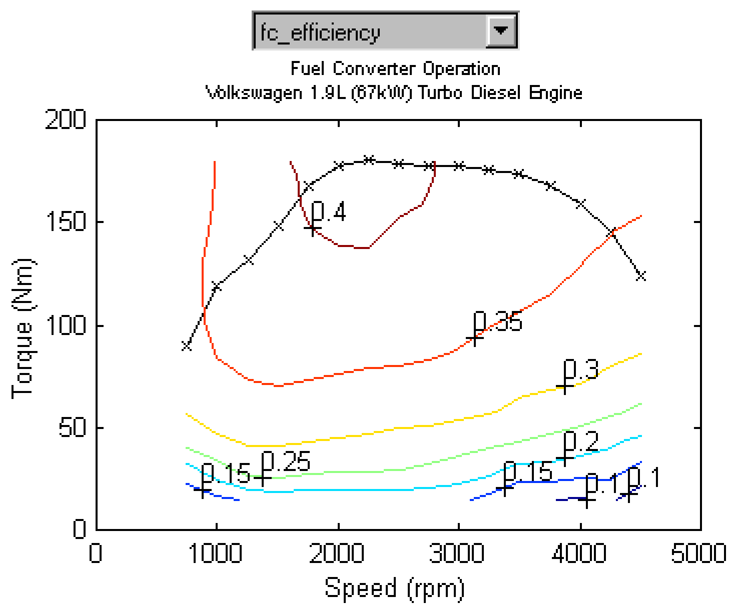


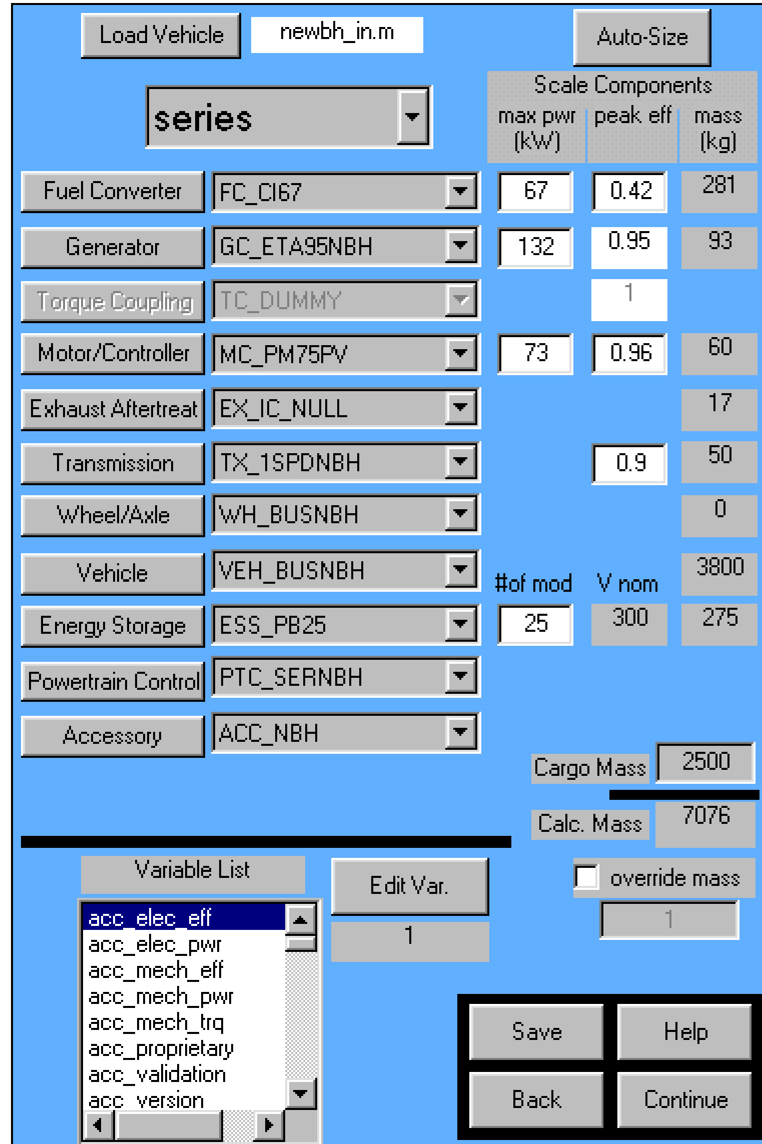


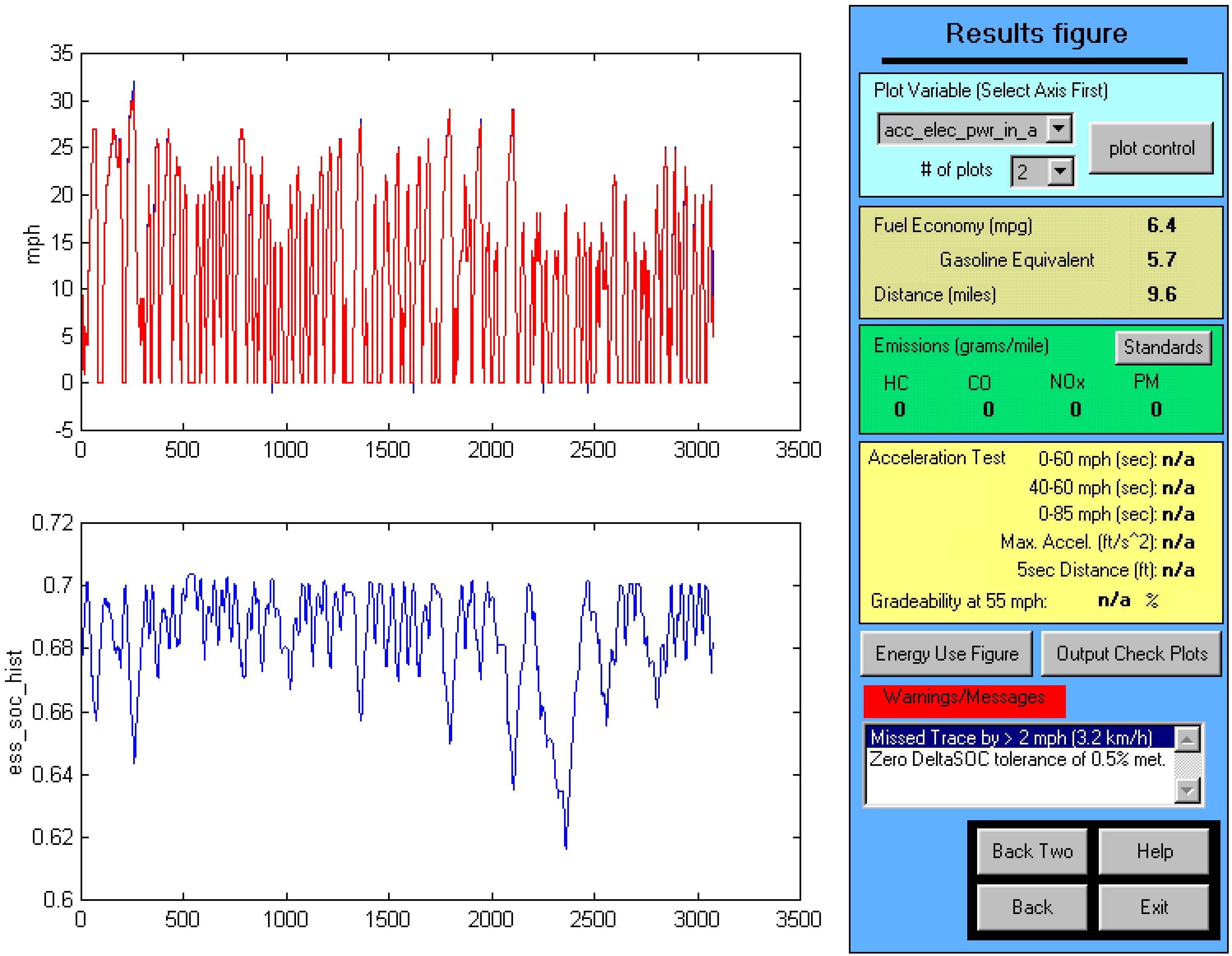


Results figure
Plot Variable (Select Axis First)
gear_ratio
plot control
# of plots
2
Fuel Economy (mpg) 4.7
Gasoline Equivalent 4.1
Distance (miles) 9.5
Emissions (grams/mile)
Standards
HC CO NOx PM
0 0 0 0
Acceleration Test
0-60 mph (sec): n/a
40-60 mph (sec): n/a
0-85 mph (sec): n/a
Max. Accel. (ft/s^2): n/a
5sec Distance (ft): n/a
Gradeability at 55 mph: n/a %
Energy Use Figure
Output Check Plots
Warnings/Messages
Missed Trace by > 2 mph (3.2 km/h)
Back Two
Help
Back
Exit
mph
35
30
25
20
15
10
5
0
-5
0
500
1000
1500
2000
2500
3000
3500
gear_ratio
5
4.5
4
3.5
3
2.5
2
1.5
1
gear_ratio

Vehicle Input





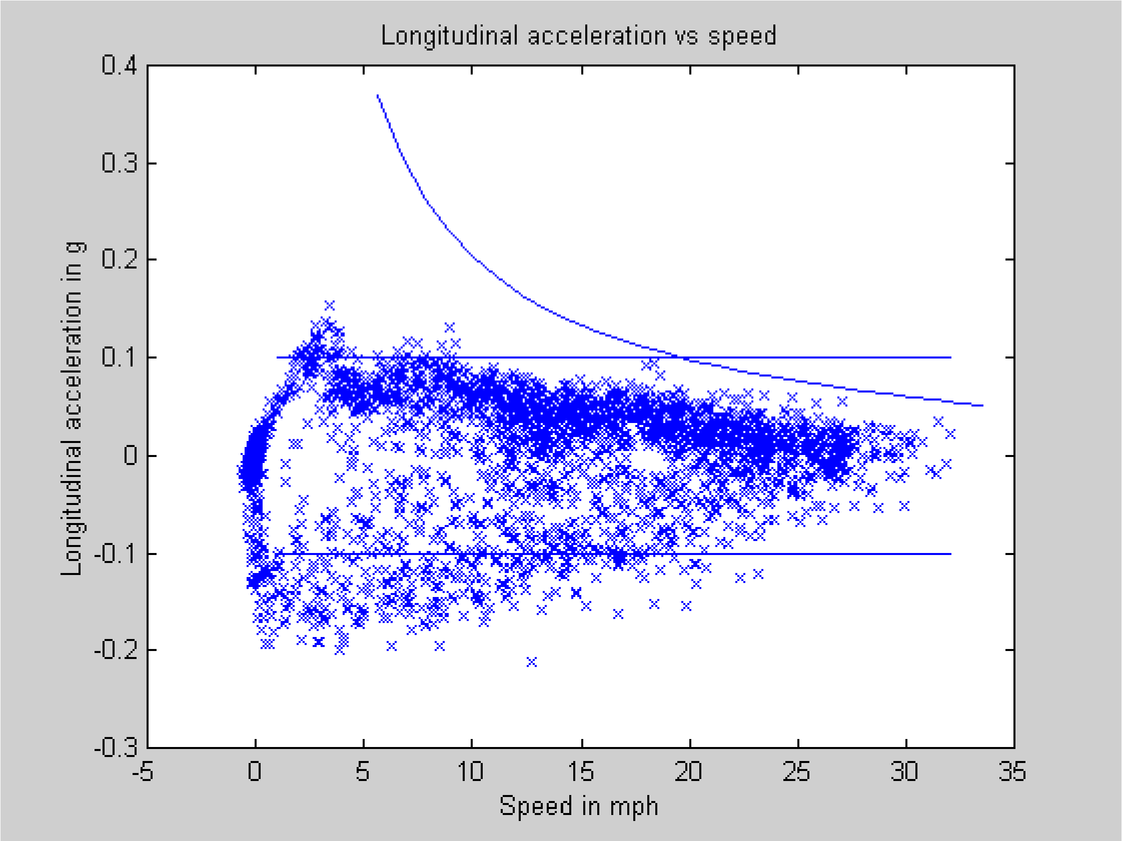


mph
0
500
1000
1500
2000
2500
3000
3500
-5
5
10
15
20
25
30
35
ess_soc_hist
0.6
0.62
0.64
0.66
0.68
0.7
0.72
Results figure
Plot Variable (Select Axis First)
acc_elec_pwr_in_a
plot control
# of plots
2
Fuel Economy (mpg) 6.4
Gasoline Equivalent 5.7
Distance (miles) 9.6
Emissions (grams/mile)
Standards
HC 0
CO 0
NOx 0
PM 0
Acceleration Test
0-60 mph (sec): n/a
40-60 mph (sec): n/a
0-85 mph (sec): n/a
Max. Accel. (ft/s^2): n/a
5sec Distance (ft): n/a
Gradeability at 55 mph: n/a %
Energy Use Figure
Output Check Plots
Warnings/Messages
Missed Trace by > 2 mph (3.2 km/h)
Zero DeltaSOC tolerance of 0.5% met.
Back Two
Help
Back
Exit

Modelling issues

- Fluid flywheel
- Payload
- Intermittent accessory load
- RWD
- Optimisation

Reduced-performance envelope possibilities



Findings

- ADVISOR simulation gave good fidelity compared with real-world fuel consumption for conventional design

- Reduced envelope designs offer significant and achievable benefits

- ADVISOR promotes insight into the key issues in optimising a design

Hybrid Buses – the benefits of matching to real routes

Mike Kellaway and Alan Ponsford
Newbus Technology Limited

ABSTRACT

Existing city buses are able to cover a wide operational envelope in terms of speed, acceleration and grade. This significantly exceeds the requirements of many routes particularly in flat, busy cities. The purchase and operating costs of a conventional bus are not particularly sensitive to performance level, but this is not true for a hybrid bus. Limiting the performance envelope of the bus can significantly reduce the size, weight and cost of the major systems on the vehicle. However it is essential to fully understand the real route requirements and to use accurate simulations to optimise the vehicle specification. This is being done using on-route measurements and ADVISOR simulations.

INTRODUCTION

Newbus Technology Limited are developing innovative hybrid buses based on a thorough evaluation of the vehicles' requirements and whole system design. Vehicle dynamic performance is one area being closely looked at.

Throughout the world, city buses are generally specified to be capable of relatively high speeds and climbing severe grades. In the UK, a typical modern vehicle can maintain around 50 mph on the level and climb a 25% grade fully laden. Clearly these are excessive capabilities in many city applications where traffic speeds are generally low and steep grades are not encountered. A typical London bus for example, such as that shown in Figure 1, will not exceed 30 mph in operation on almost all routes. The level of power available on the more recent designs is indeed sufficient to achieve longitudinal acceleration levels that can cause passenger discomfort, especially for standing passengers, if the vehicles are not driven carefully.

Because the purchase cost of a conventional bus is not heavily influenced by its power level, and in many markets fuel cost is not a prime concern, there has been little impetus to reduce power levels. In fact, drivers have expressed a strong preference for highly powered vehicles. There is also some concern that buses can accelerate quickly to match traffic speed.

In the design of a hybrid vehicle there is increased motivation to reduce the peak power level of the vehicle, as this has a significant influence on the size, weight and cost of all of the drivetrain components including the battery. There is also a significant efficiency benefit in avoiding the use of a large heat engine at low power levels. Reducing vehicle unladen weight further reduces the power requirement. In a future commercial environment, where fuel use is likely to become more heavily penalised, reduced fuel consumption will clearly become important.

As with any optimised vehicle, there is clearly a danger of unexpected performance shortfall. It is therefore necessary to collect representative data about actual in-service route dynamics and its variability. This then forms a qualified basis for careful simulation during vehicle design. It is only through working with statistical data during the simulation process that one is able to gain insights into the 'best' specification and to demonstrate the practicality and benefits of reduced envelope designs.

Figure 1 Picture of London bus on route

Measured data also provides a solid basis for 'what-if' investigations of more radical proposals such as limiting driver authority.

POTENTIAL FOR A REDUCED ENVELOPE BUS

Because a bus has a relatively fixed duty, there is scope to produce a range of vehicles with the performance of each model tailored to a class of routes. Whilst there are undoubtedly operational considerations such as a preference to be able to switch any bus to any route, in reality there are many cases where a vehicle remains on one type of route throughout its life. However, commercial considerations make it attractive to investigate whether the distribution of route requirements would support a single initial reduced envelope design that would cover a reasonable number of route applications whilst showing significant benefits. This can only be done by measurement of route characteristics.

It must be emphasised that there is no attempt to design a bus specific to a single route, rather a 'route class-specific' vehicle. Having said this, the Newbus designs will incorporate adaptive features to allow automatic tailoring to individual routes within the class.

IN-SERVICE DATA REQUIREMENTS

Although it is clear that many routes offer scope for a reduced performance envelope design, it is necessary to collect a significant sample of on-route dynamic data to allow the potential benefits to be studied by simulation. This can be divided into route topological characteristics and statistical on-route dynamics.

ROUTE TOPOLOGY

The gradients found on a route, their length and the speeds at which these are driven have a strong influence on both peak power and intermediate energy storage requirements for hybrid designs. It is therefore important to characterise a selection of routes in this respect. Initially, measurements are being made to establish typical cases and some idea of spread across the routes in a city. This allows the likely benefits to be identified before more extensive characterisation is carried out.

OPERATIONAL STATISTICS

It is also essential to investigate the distribution of dynamics on a single route caused by varying traffic conditions and as a result of different driving styles. It is important to understand the causes and scale of such real-world scatter. This is being carried out by measuring vehicle dynamics on selected routes for an extended period and identifying the variations within this. The objectives are to establish what are acceptable performance levels, how prevalent is 'over-driving' and how significant would be the effects on route timings of performance limitations.

DATA COLLECTION METHOD

Initial studies have been based on data collected for London Bus by Millbrook. These have allowed overall route dynamics and scatter on one typical route to be identified. These data were obtained from an instrumented vehicle in service.

To make it practical to collect what is likely to become large amounts of data it was important to develop a robust and low-impact data collection approach. It is also attractive to achieve the required level of accuracy without excessive cost, particularly as it may be necessary to monitor a significant number of vehicles in parallel. Finally, it was considered important to be able to collect the data remotely both to save time and to minimise the effect of such data collection on driving style.

The approach taken is to use a vehicle-mounted GPS receiver to collect 3 dimensional fix and time data. This is supplemented by 3-axis accelerometers that can be used to provide some data during any loss of GPS signal, for example in 'urban canyons' or under bridges. The accelerometers used are able to read gravitational force and can therefore be used to measure vehicle inclination when the vehicle is stationary or moving with constant velocity. The data is processed to give a 'most likely' set of readings before being stored in flash memory. A radio modem will be used to allow remote data access.

GPS data are recorded once per second, the accelerometer data are measured more frequently and filtered down to be recorded at the same rate as GPS data. This has the benefit of allowing peak accelerations to be captured and improves accuracy when integrating to estimate velocity and displacement.

DATA COLLECTION EXPERIENCE

Initial trials of the equipment have been encouraging, particularly the horizontal data. This was checked against a GIS map on a portable PC in real-time during initial data collection to allow the quality of the data to be assessed and to investigate the type of features that caused difficulty. In general a reasonable number of satellites were in view, even in city streets and the only difficulties came when passing under bridges. The route included a section along some relatively narrow London streets and there was some evidence of loss of precision caused by reflections from tall buildings. This is not thought to be a problem as such minor events can be processed out of the data. Although the results confirmed that achievable vertical GPS repeatability is quite good for measurements taken close in time, this is not sufficiently good to estimate grade. The use of full differential GPS is being considered, but may not offer enough improvement to be worthwhile.

The accelerometer pack gave good results which are clearly independent of the GPS data quality, however it proved difficult to reliably isolate gradient data from longitudinal accelerations on normal vehicle runs. Further work is under way to improve these measurements. Figure 2 illustrates the speed variation along the initial route measured. Figure 3 illustrates the variation in speed distribution from different runs on the same day.

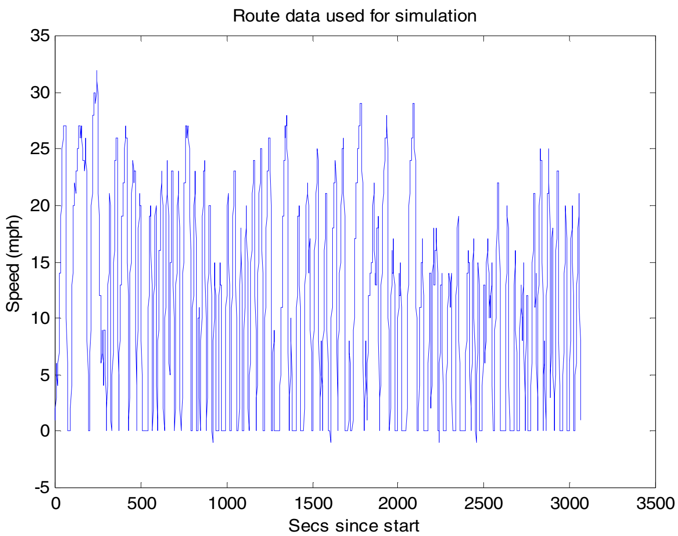


Figure 2 Measured route data used for simulation

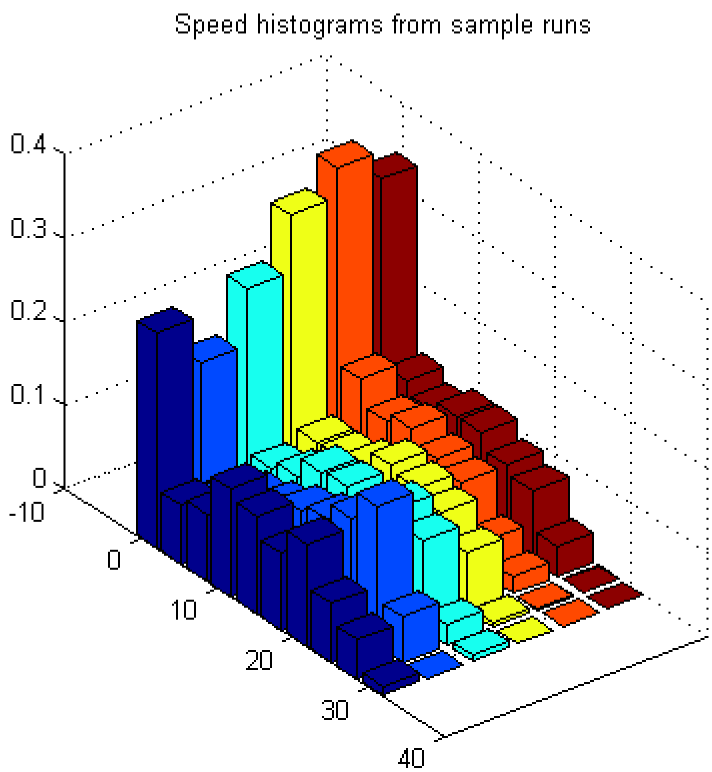


Figure 3 Fraction of time in different speed (mph) bands for consecutive runs

Following initial trials it was decided for future work to carry out an initial 'topology' measurement on each route, where precautions could be taken to ensure good grade information was obtained by stopping frequently along the route. The statistical data can be collected quite effectively in-service as planned. The GPS/accelerometer pack has proved itself effective for both types of measurement.

CHOICE OF ADVISOR

ADVISOR was chosen as the simulation tool for this project for a number of reasons:

- Its open-source format allowed visibility of the simulation process and ease of adaptation to specific requirements
- Processing of measurement data was performed in Matlab and was therefore easily linked to ADVISOR.
- The wide range of models available to allow work to be quickly started

ADVISOR SIMULATION STRATEGY

CONVENTIONAL VEHICLE

The initial route data was input as a cycle to an ADVISOR model with component models reflecting the design of a typical London diesel bus as shown in Figure 1. The fuel consumption derived from the simulation (5.52 mpg) compares well with actual values that are in the 5-6 mpg range for this type of route. The simulation's level of achievement of the demanded (measured) speed profile was also compared with likely load patterns during the day and confirmed that the simulation was giving a realistic model of the vehicle. Figure 4 illustrates the match at the selected payload. The ADVISOR results give fuel consumption in miles per US gallon rather than the figures above, which are in miles per UK gallon.

HYBRID VEHICLE

A hybrid simulation model was then created based on the Newbus hybrid design and used to investigate the performance of alternative hybrid designs.

ROUTE DATA

The use of real route data is preferred to standard cycles as the design is being optimised for representative routes rather than to a particular standard. This is more relevant for fixed-route vehicles such as buses. It is also important to include the effects of variability between drivers and different traffic conditions. An example of this is the change in speed profiles as the bus moves into the city centre.

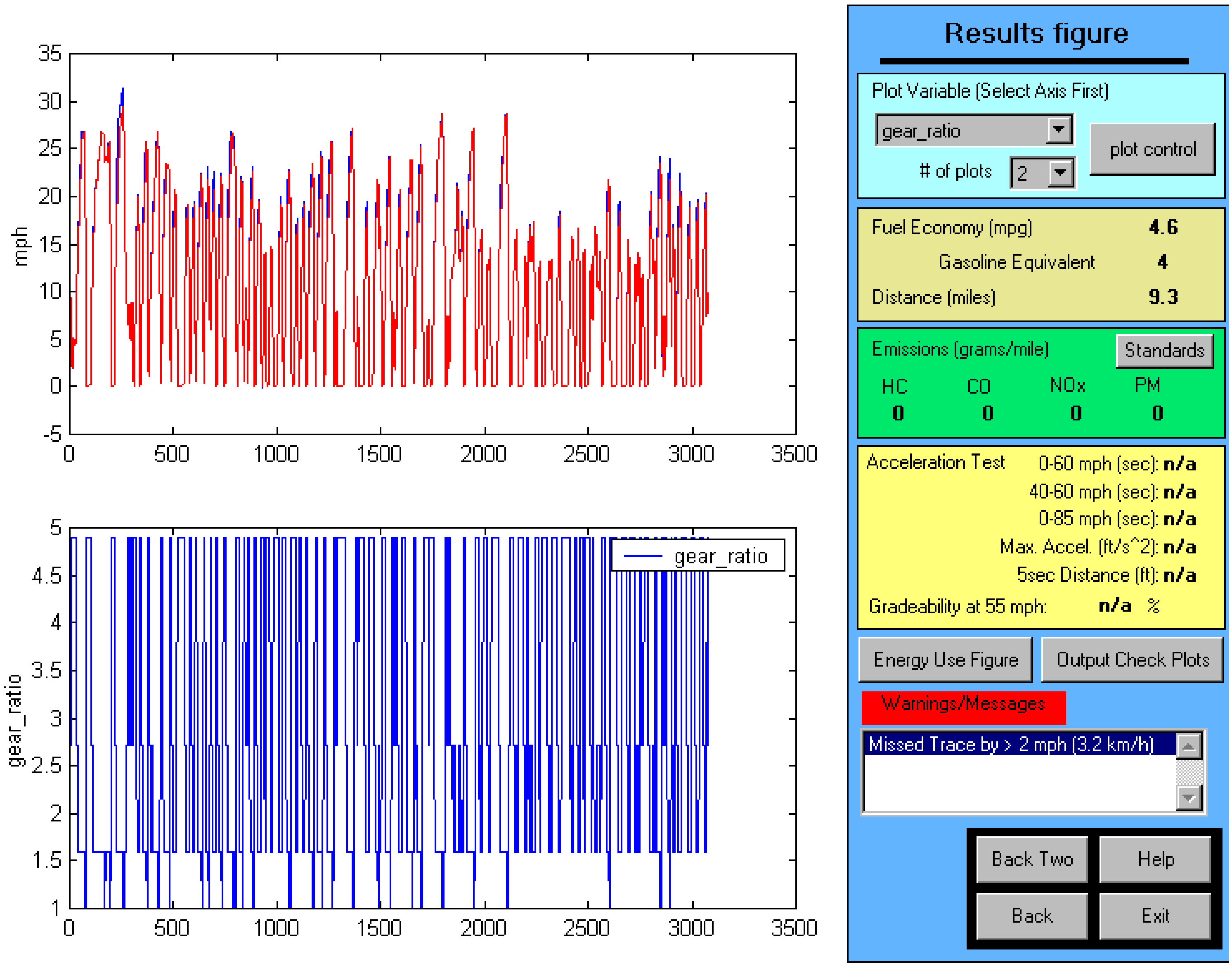


Figure 4 Results for conventional vehicle

ADVISOR MODELS

Initial vehicle models are derived from the built-in ADVISOR sub-system models, suitably modified to reflect the conventional and Newbus vehicle designs. As the development progresses it is anticipated that more of the elements will use Newbus-specific models. These will be particularly important for the Newbus custom hybrid controller, which incorporates a number of new features, and the battery model, which is to include a battery damage model to assess in-service battery lifetime. Some particular modelling issues arose during the work:

FLUID FLYWHEEL

The conventional bus uses a fluid flywheel rather than a torque converter and this was modelled as a manual gearbox with slightly higher numerical ratios in the lower gears combined with reduced overall efficiency.

PAYLOAD

The payload was set by running the model with increasing load until the best match with the measured speed was achieved. In reality the payload changes with time and at some time it would be interesting to look at changes in this as part of the simulation as it has a major influence on fuel consumption and the performance required.

ACCESSORY LOAD

It would be helpful to be able to model varying accessory loads as these can vary with engine speed and/or strategy. Without this the load tends to be overstated on the average or understated at the peaks. It is planned to capture real operational data in this area.

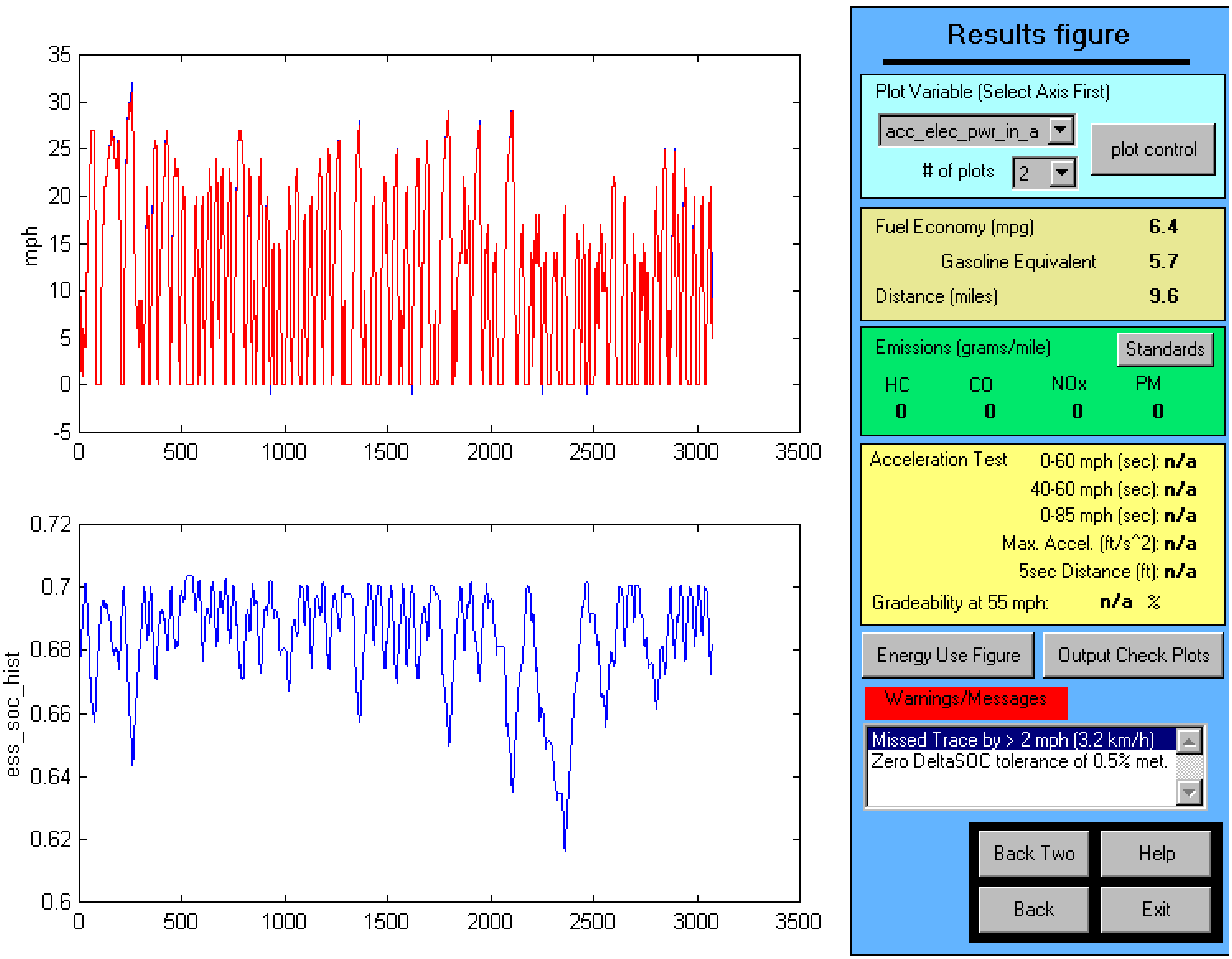


Figure 5 Reduced envelope hybrid results

REAR WHEEL DRIVE

It would be helpful to put this in explicitly. Even though this is almost certainly immaterial here, it would be comforting to know that everything was the correct way round.

FUEL CONVERTER 'SWEET SPOT'

Some effort was taken to match the generator and fuel converter to bring the fuel converter operating point to maximum efficiency at low operating speed. This may be possible in a more efficient way with more familiarity with ADVISOR.

MOTOR/CONTROLLER SPEED OPTIMISATION

The optimisation tool was found to be very useful in setting overall reduction ratio.

INITIAL FINDINGS

Initial results from the first ADVISOR hybrid models are shown in Figure 5. Significant fuel savings were possible in comparison with a 'full-envelope' hybrid design. As is generally recognised, it is necessary to carefully match the individual elements of the hybrid driveline to deliver the potential of each hybrid design.

The initial simulations confirm that a reduced envelope vehicle could service all sections of the route measured in London. In many cases the acceleration levels currently used offered no savings in route timing, but clearly reduced passenger comfort and increased fuel usage and emissions. There is therefore scope for further reductions by further reducing performance, though this clearly depends on the results of ongoing route measurements.

NEXT STEPS

The data collection technique is to be used in a number of UK cities to collect a representative sample of route data. This will then be characterised and used as simulation data for a new reduced power hybrid design. The use of carefully chosen actual route data will allow detailed assessment of the operation of the new vehicle and optimisation of its control strategy.

The process of in-service measurement coupled with detailed ADVISOR simulation will allow a thoroughly researched requirements specification to be drawn up for the vehicle with a high level of confidence of successful operational performance.

Future simulation work will include emission data and cover the spread between routes, drivers and time of day in more detail.

CONCLUSIONS

Initial results confirm the potential for a lower power hybrid design that offers lower purchase and operating costs, and reduced emissions in comparison with higher power hybrid designs. Ongoing work will develop this approach and allow the optimum power level to be specified taking environmental and commercial considerations into account.

The use of in-service dynamic measurements coupled with ADVISOR simulation is essential to allow this approach to be carried out with confidence.

By actually capturing measurements from vehicles in service it was possible to validate the data on a conventional vehicle before moving to a hybrid design.

The Newbus reduced envelope hybrid shows a reduction in fuel consumption of almost 40% over a conventional bus. This is achieved with battery cycling designed for long service life.

ACKNOWLEDGMENTS

The authors would like to acknowledge the assistance given with access to existing route data by Mike Weston of London Buses and Andy Eastlake of Millbrook Proving Ground. We would also like to thank the ADVISOR team for their advice and response to requests for additions to ADVISOR, in particular the addition of gradient input to the model.

CONTACT

Mike Kellaway can be contacted at mikek@newbus.com, Alan Ponsford at alanp@newbus.com. The Newbus Technology Limited website at www.newbus.com also contains further material about our work on Hybrid Buses.

DEFINITIONS, ACRONYMS, ABBREVIATIONS

GPS:

Global Positioning System

GIS:

Geographical Information Software

ADVISOR Modeling of a Fuel Cell Hybrid Electric Vehicle

Mike Ogburn
Mechanical Engineering
Virginia Tech

America's First non-OEM 5 Seat Fuel Cell Vehicle!

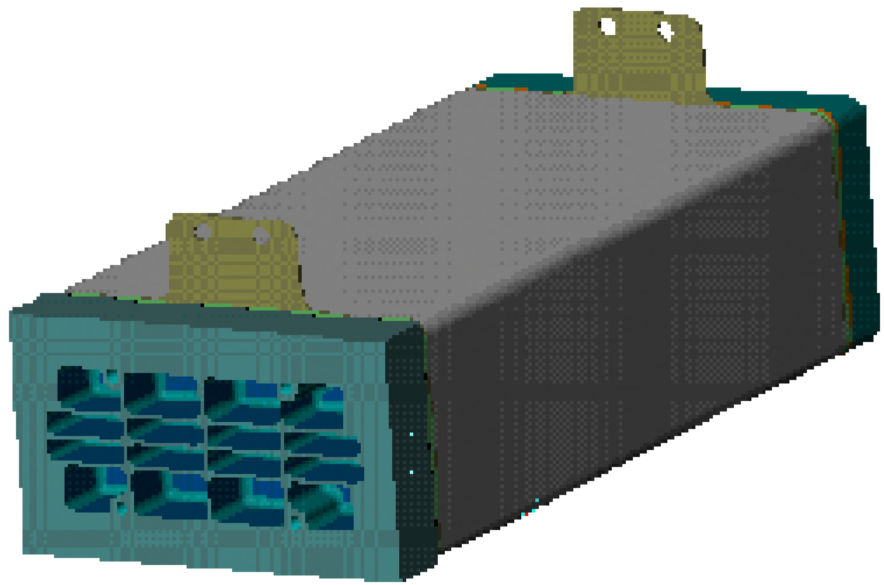
2nd Place Overall and Lowest Emissions, 1999 FutureCar Challenge

Overview

- Vehicle Layout and Design
- Fuel Cell Subsystems
- ADVISOR Model Development
- Experimental Data vs. ADVISOR Results
- Modeling of Proposed System Changes
- Conclusion

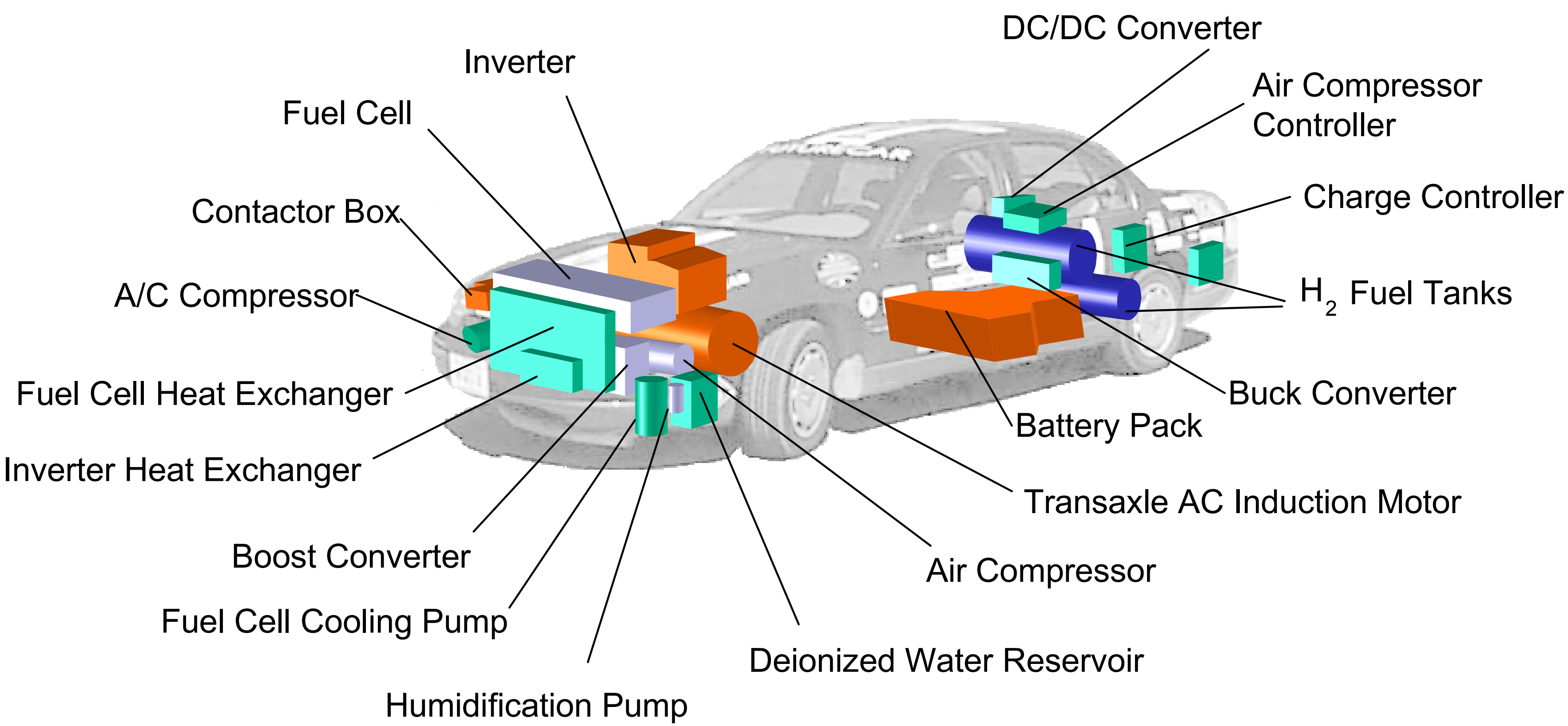
PEM fuel cells vs. internal combustion

- Power density (kW/kg) similar to IC engine
- Efficiency roughly twice that of an IC engine
- Zero emissions capability
- Low operational maintenance

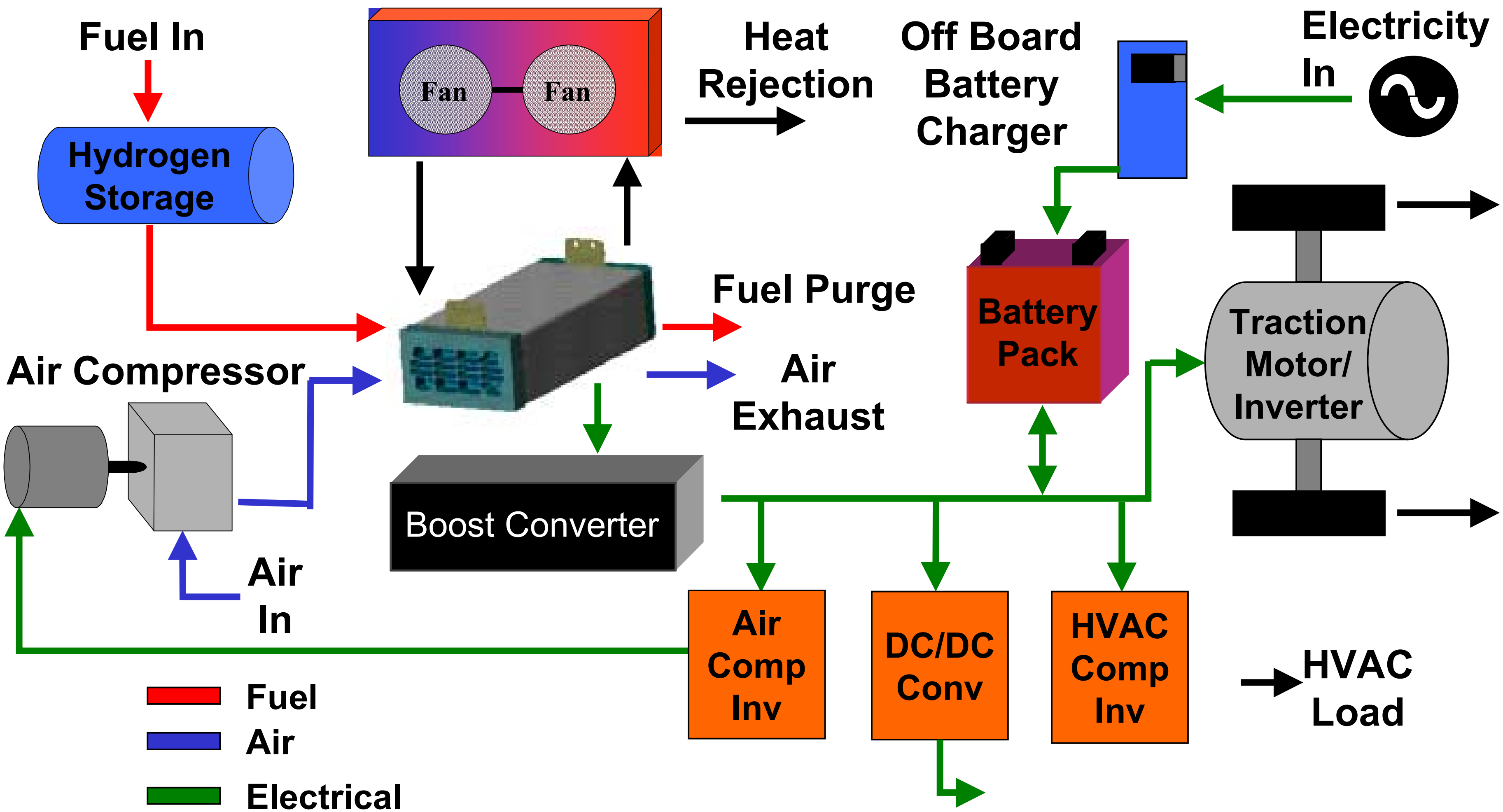


Energy Partners NG2000

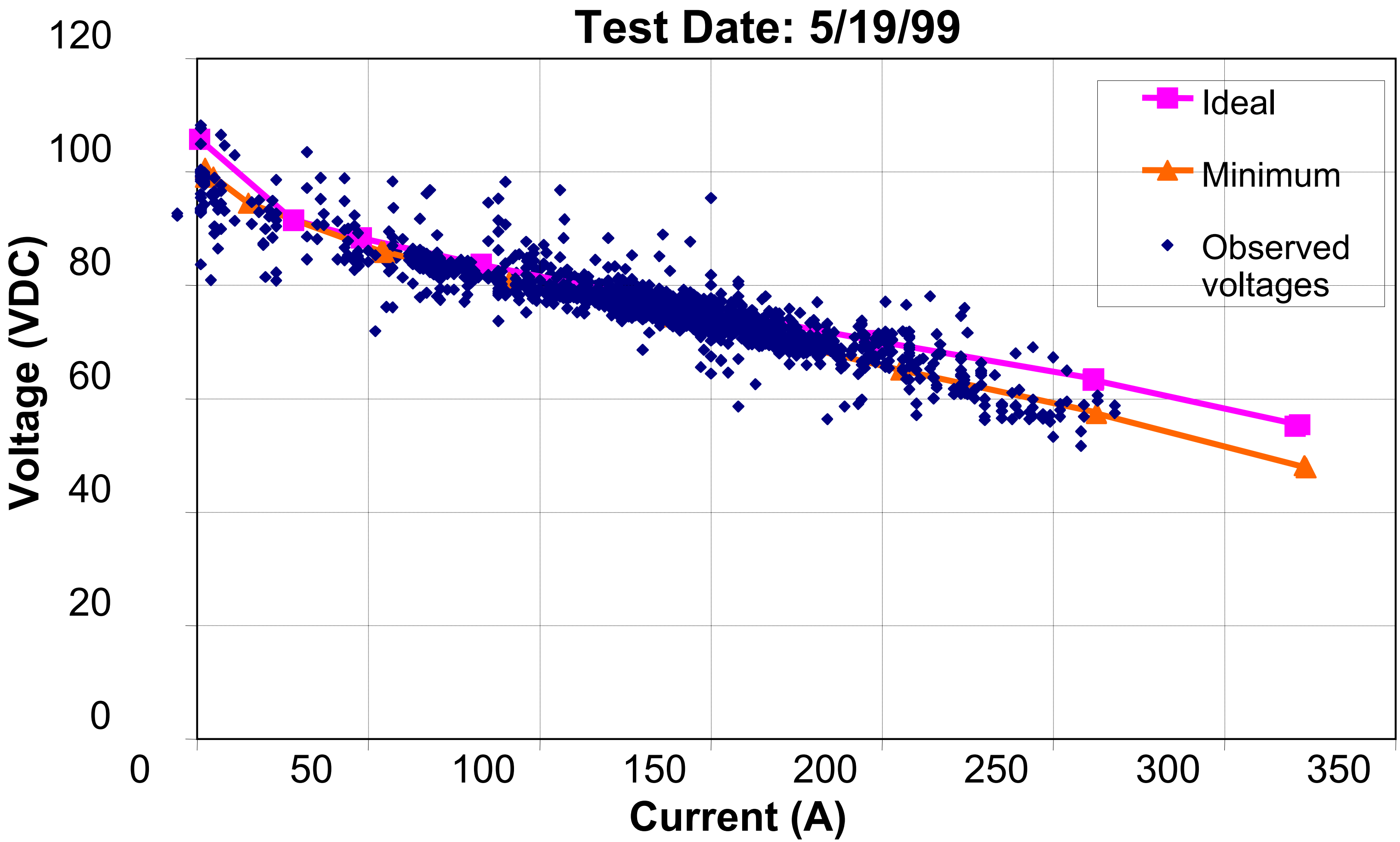
Packaging is one of the biggest challenges in Fuel Cell Hybrids

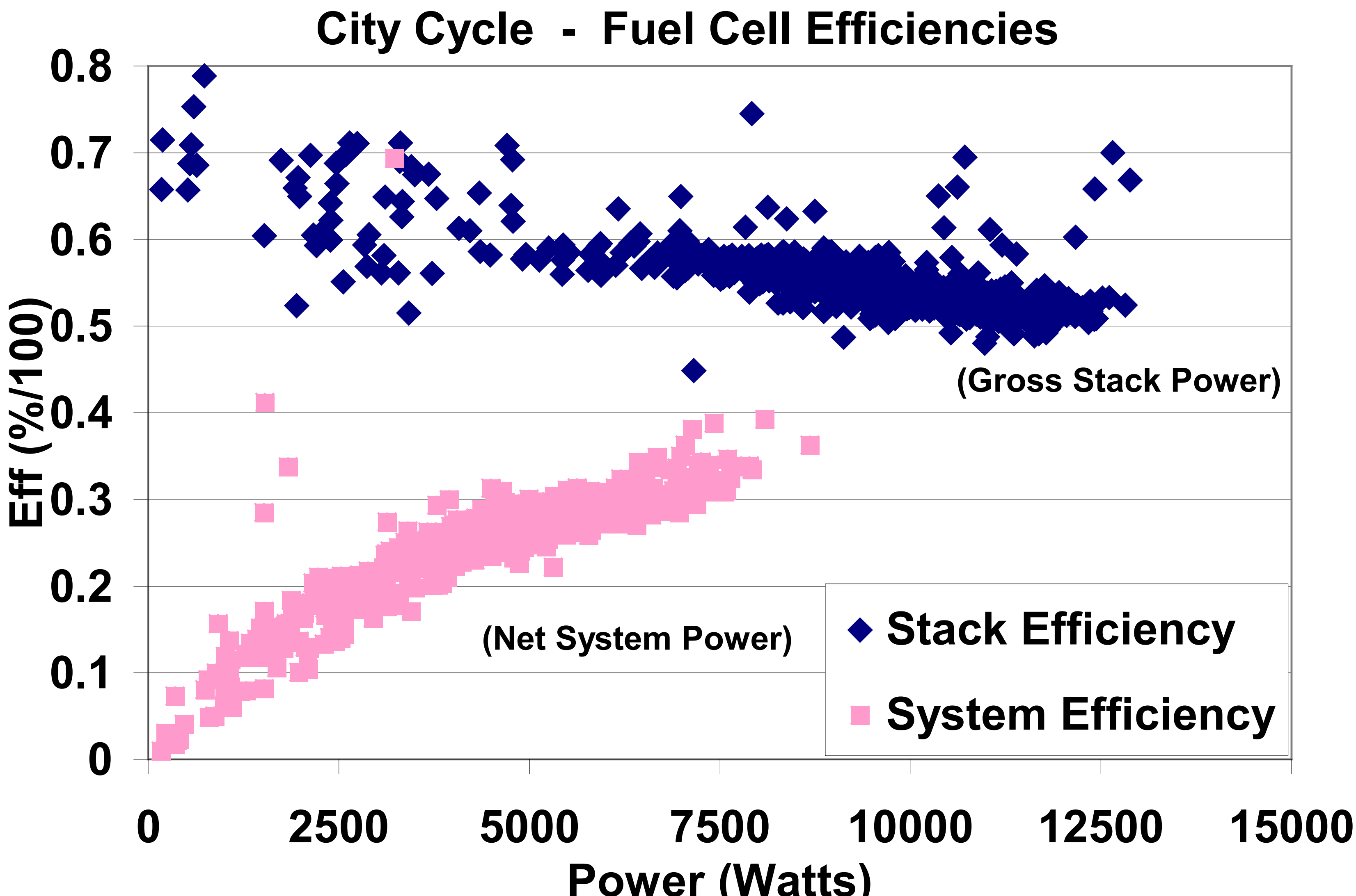


Energy Usage On a Fuel Cell Hybrid Vehicle



Test data shows that the system performed well




City Cycle - Fuel Cell Efficiencies
Eff (%/100)
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
2500
5000
7500
10000
12500
15000
Power (Watts)
(Gross Stack Power)
(Net System Power)
Stack Efficiency
System Efficiency

ADvanced ***V***eh***I***cle ***S***imulat***OR***

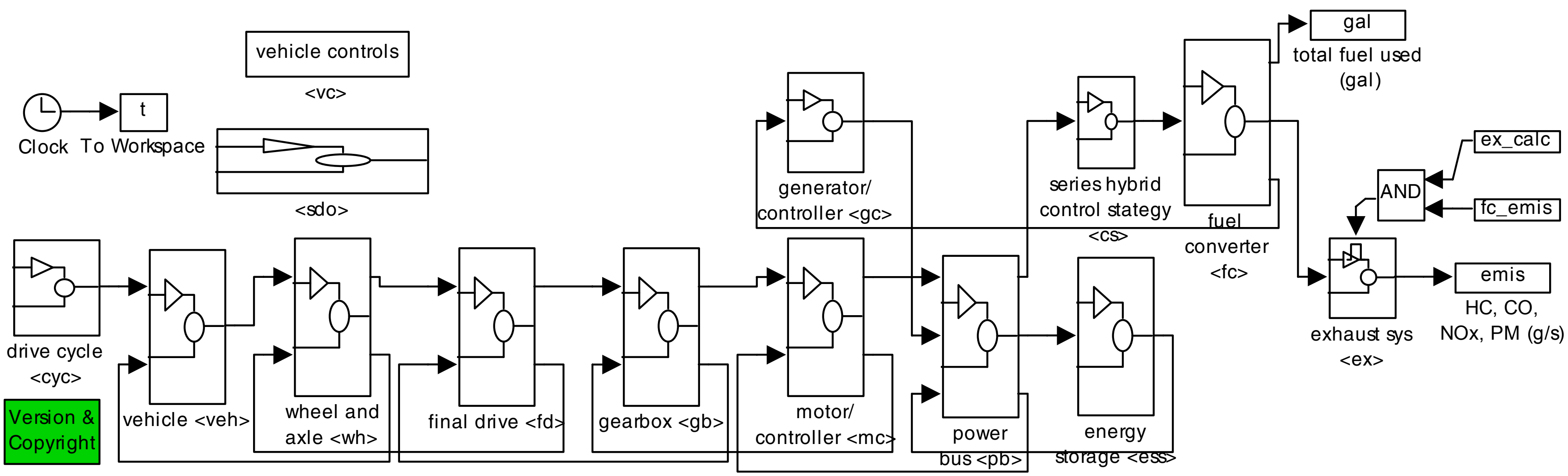
- Proven vehicle modeling platform for:
  - Vehicle Energy Use and Emissions
  - Powertrain Performance and Control
- Easy to use
  - User-Friendly Graphical Interface
  - Easily interchange and analyze:
    - Components
    - System Configurations
    - Control Strategies

AD**vanced **V**eh**I**cle **S**imulat**OR

- Uses Matlab and Simulink
  - Component building blocks
  - Data files load component specifications
- Other Features Include:
  - Parametric analysis
  - Sensitivity studies
  - Combined speed and grade traces
  - It's Free! *www.ctts.nrel.gov/analysis*

Series Hybrid Block Diagram

- EV Model + Engine and Generator
- Backward/Forward Framework

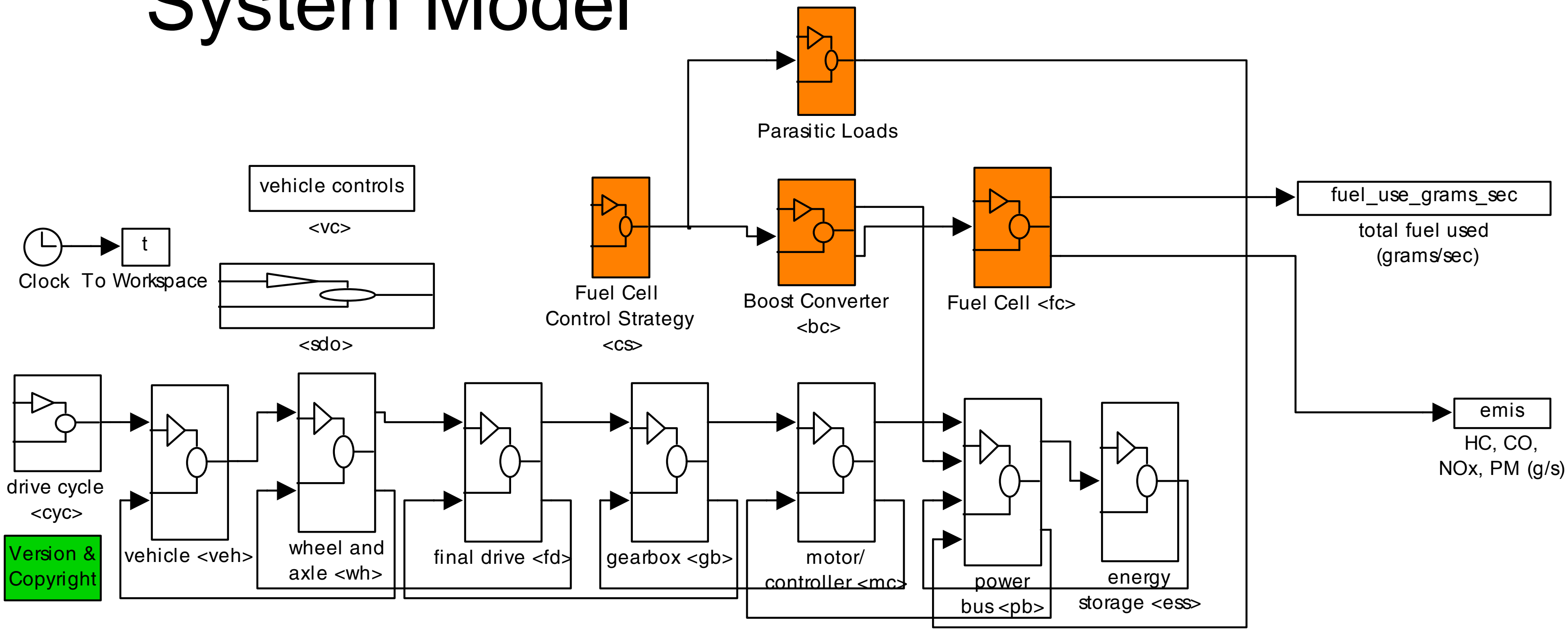


Developing a New Model

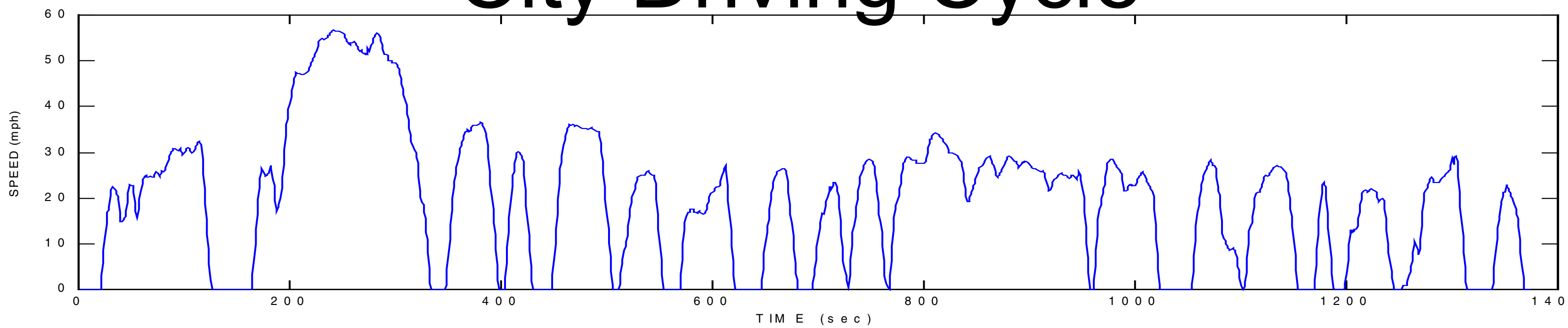
- 2 Years of Hybrid Modeling Experience
  - Validation of ADVISOR's HEV capabilities
  - Engine emissions mapping
- No Previous FCV Experience
  - Components tested by OEM and in house
  - Individual systems modeled as completed
  - Building-blocks for a full-system model

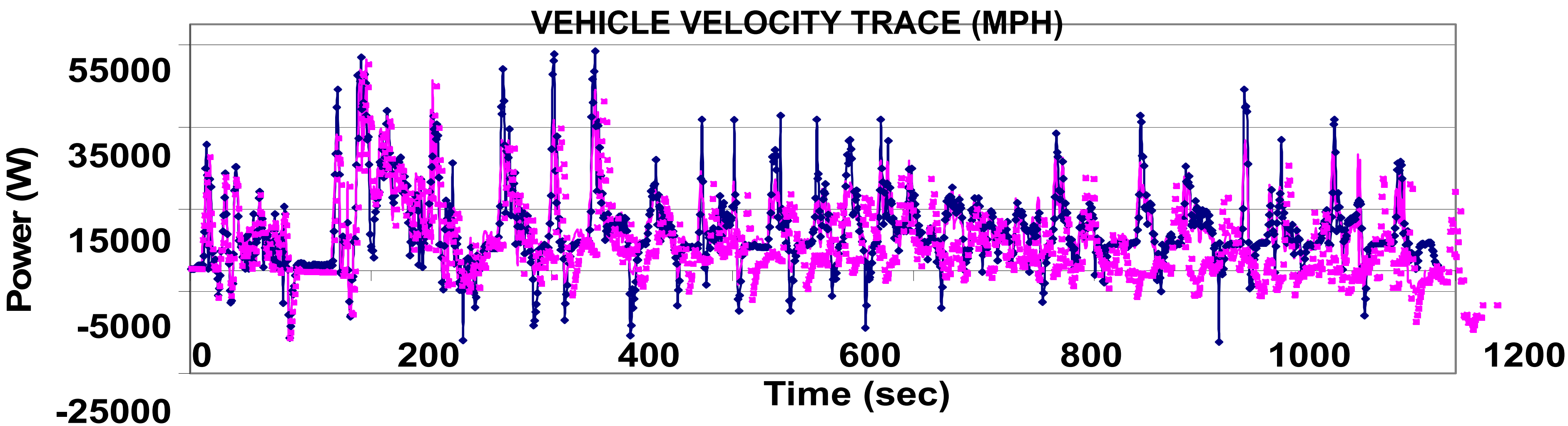
Fuel Cell Hybrid Block Diagram

- EV + Backward Looking Fuel Cell System Model



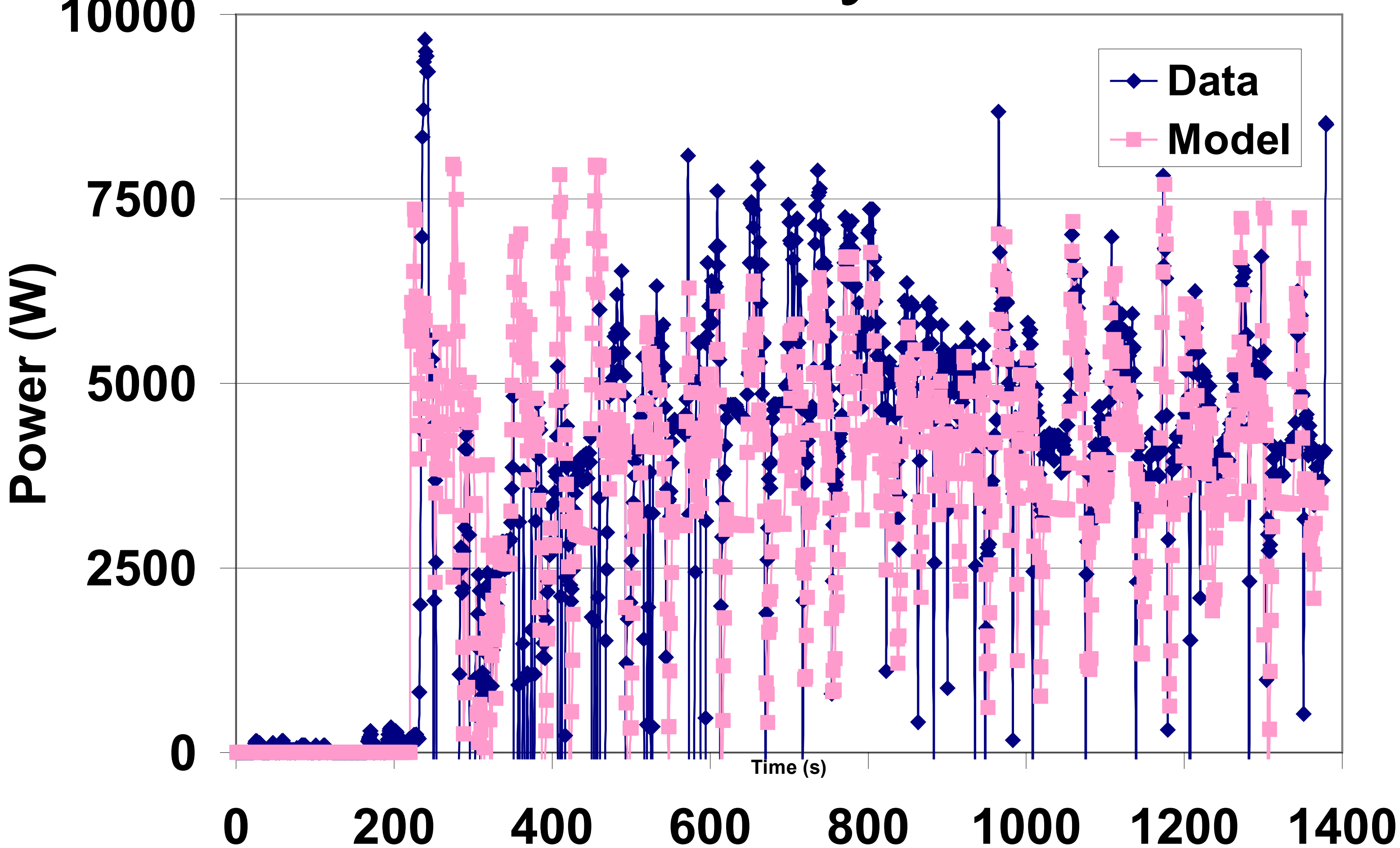
City Driving Cycle





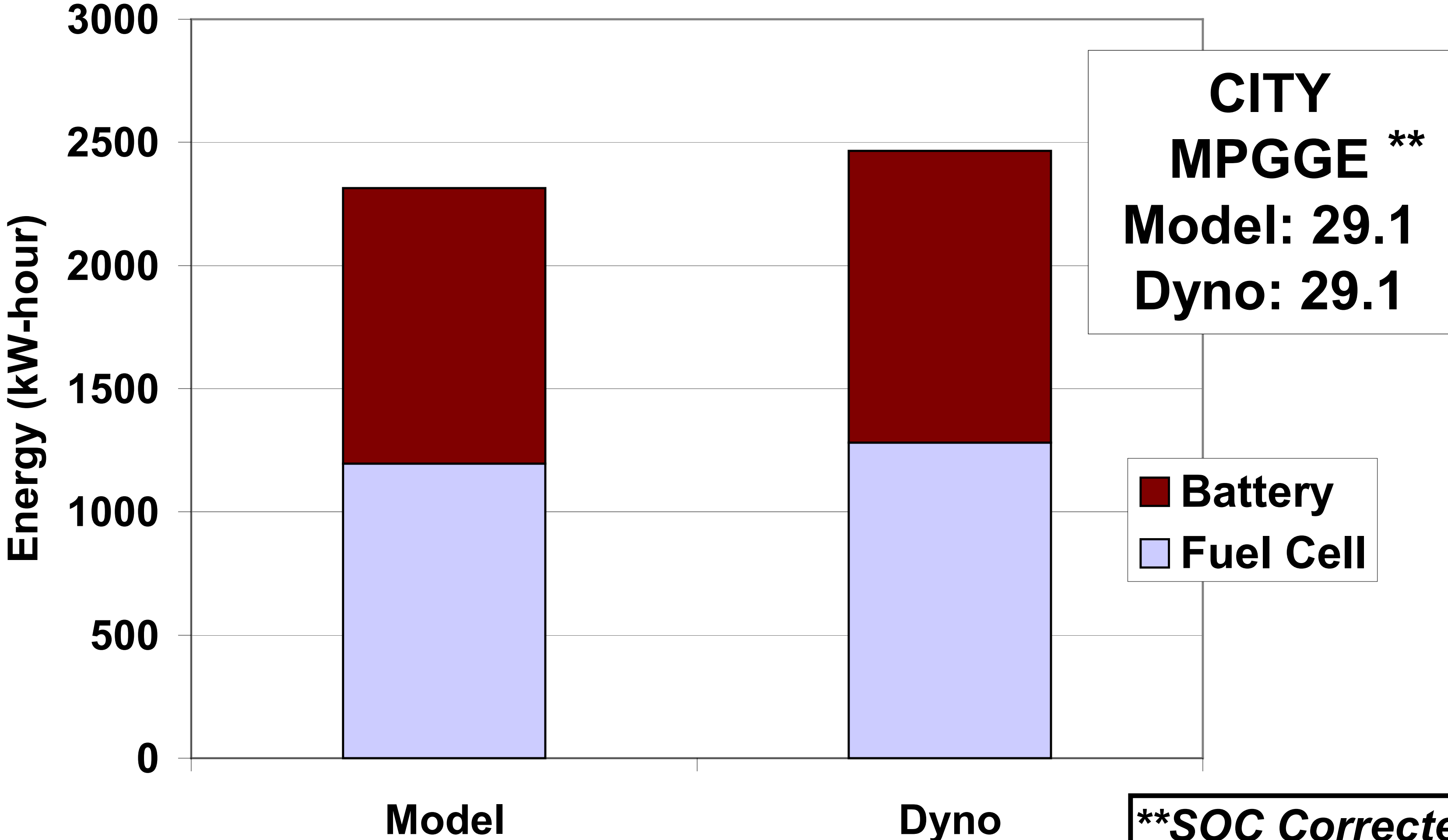
Motor Controller and Accessory Power (vehicle data and vehicle model)

Net Fuel Cell System Power



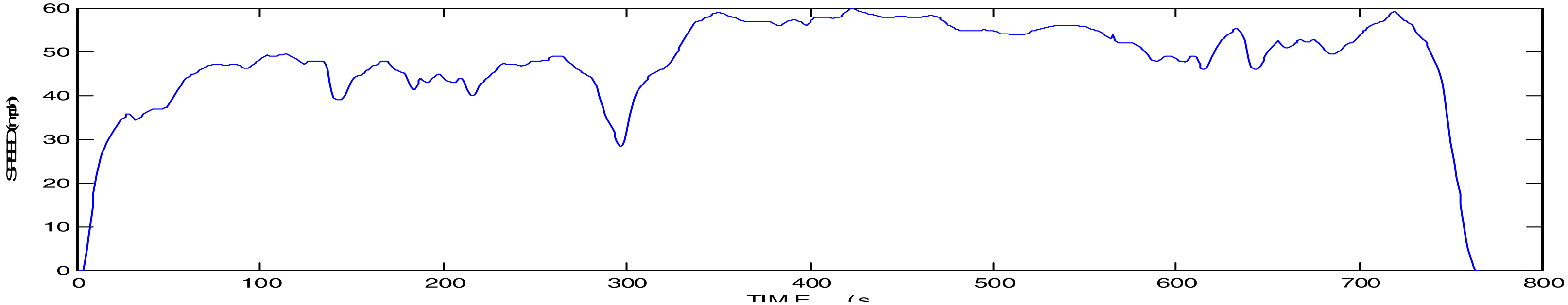
City Cycle - Energy Use

Energy Sourced for use by the Drive Motor

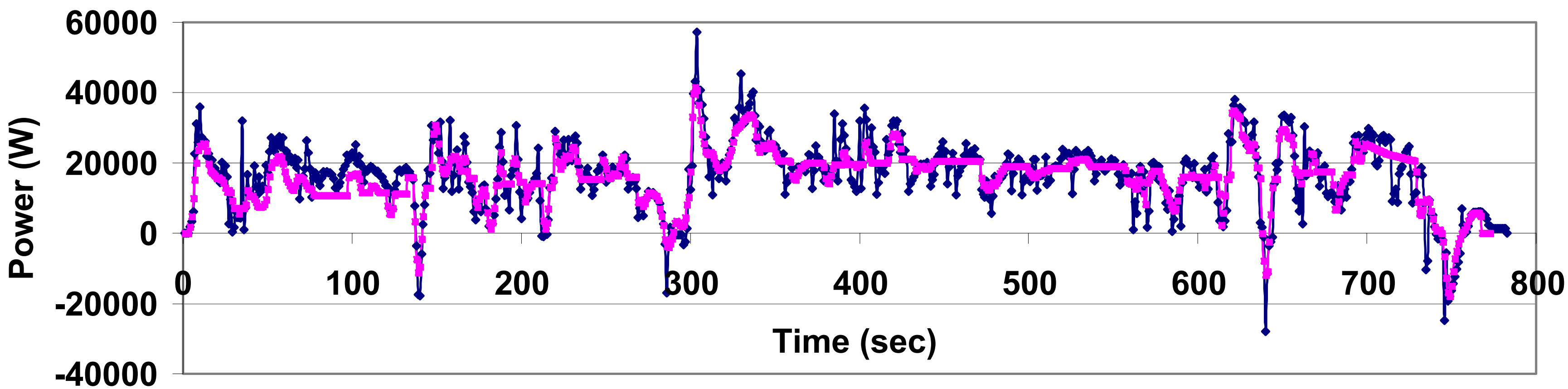


***SOC Corrected*

Highway Driving Cycle

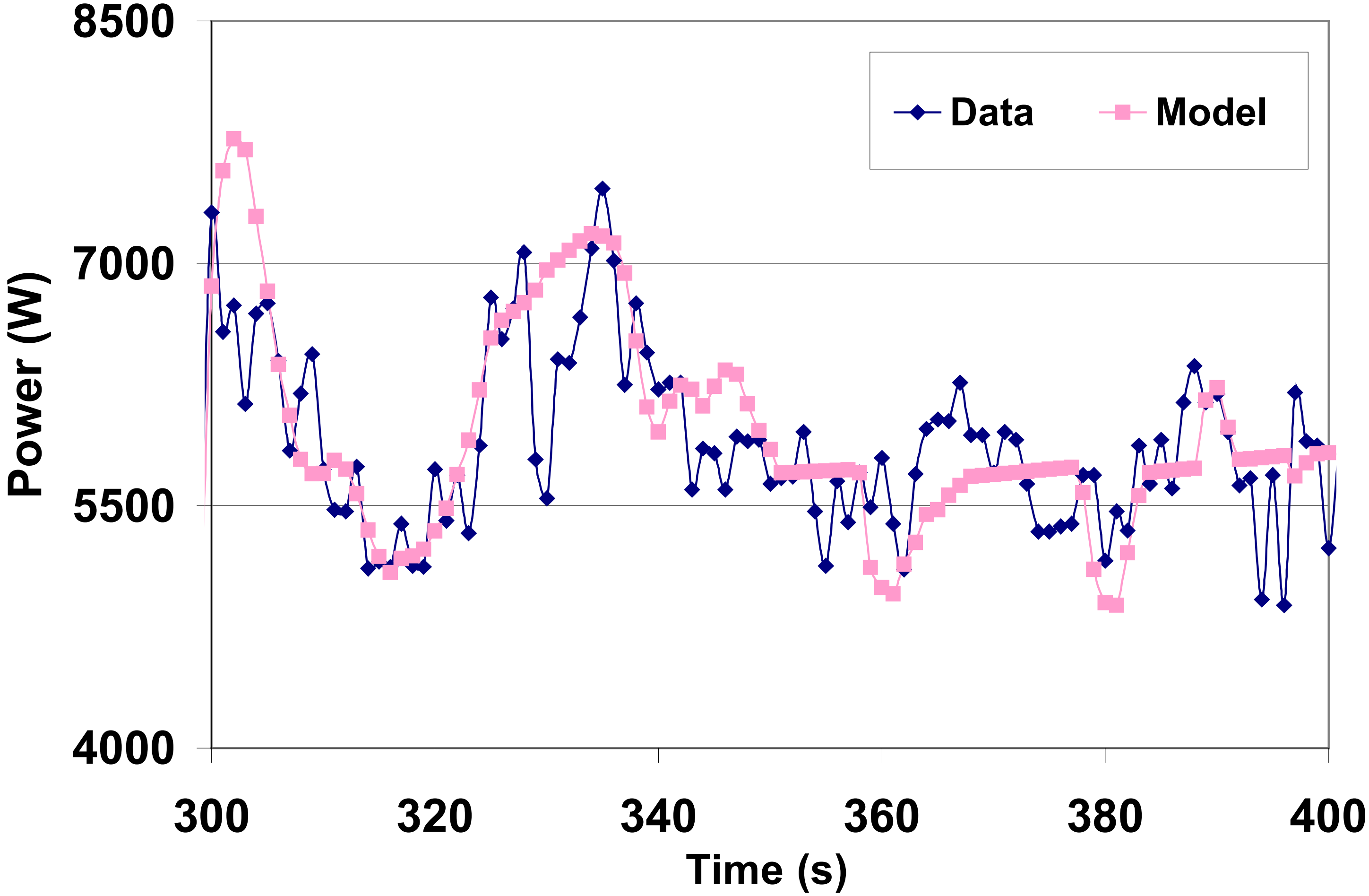


VEHICLE VELOCITY TRACE (MPH)

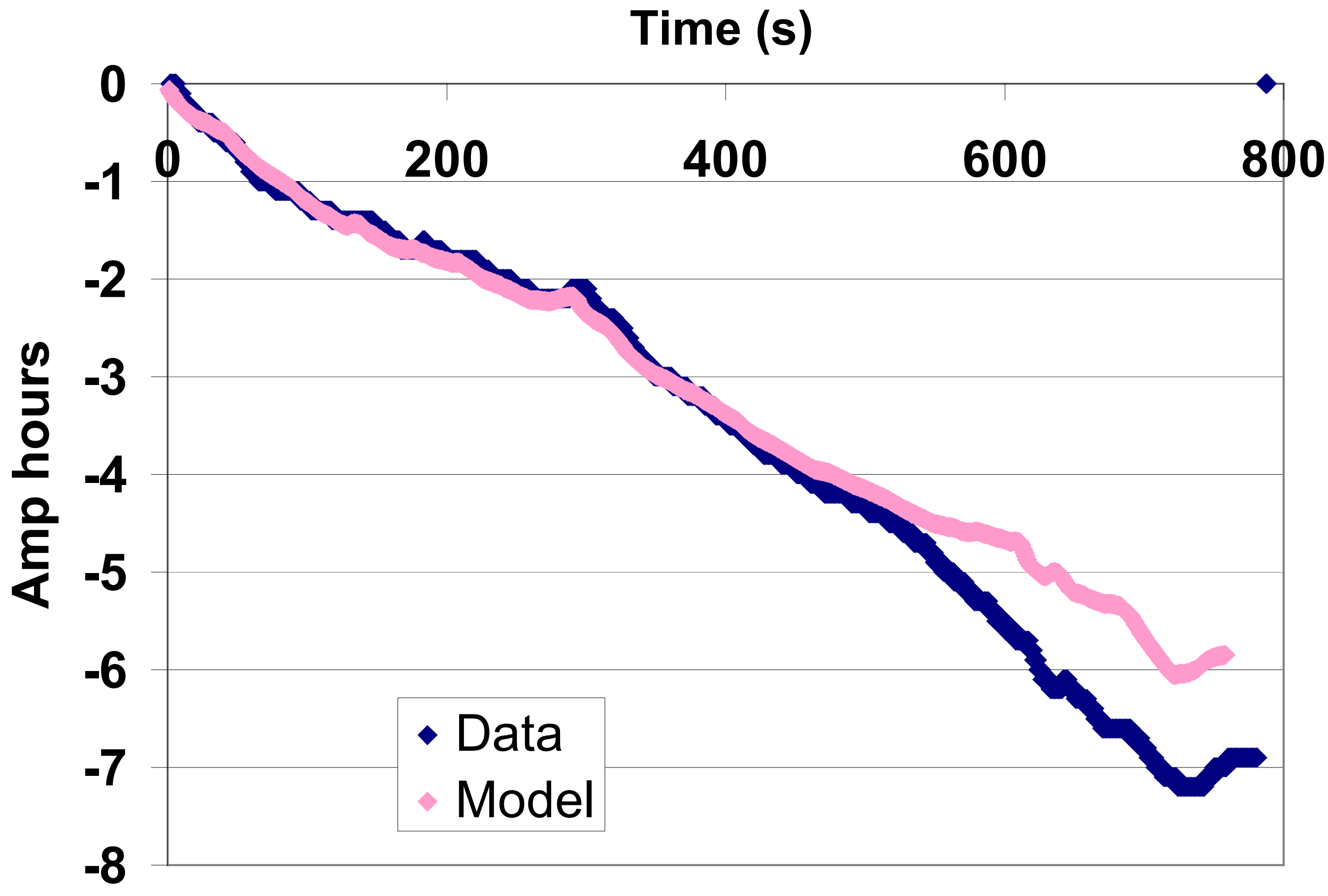


Motor Controller and Accessory Power (vehicle data and vehicle model)

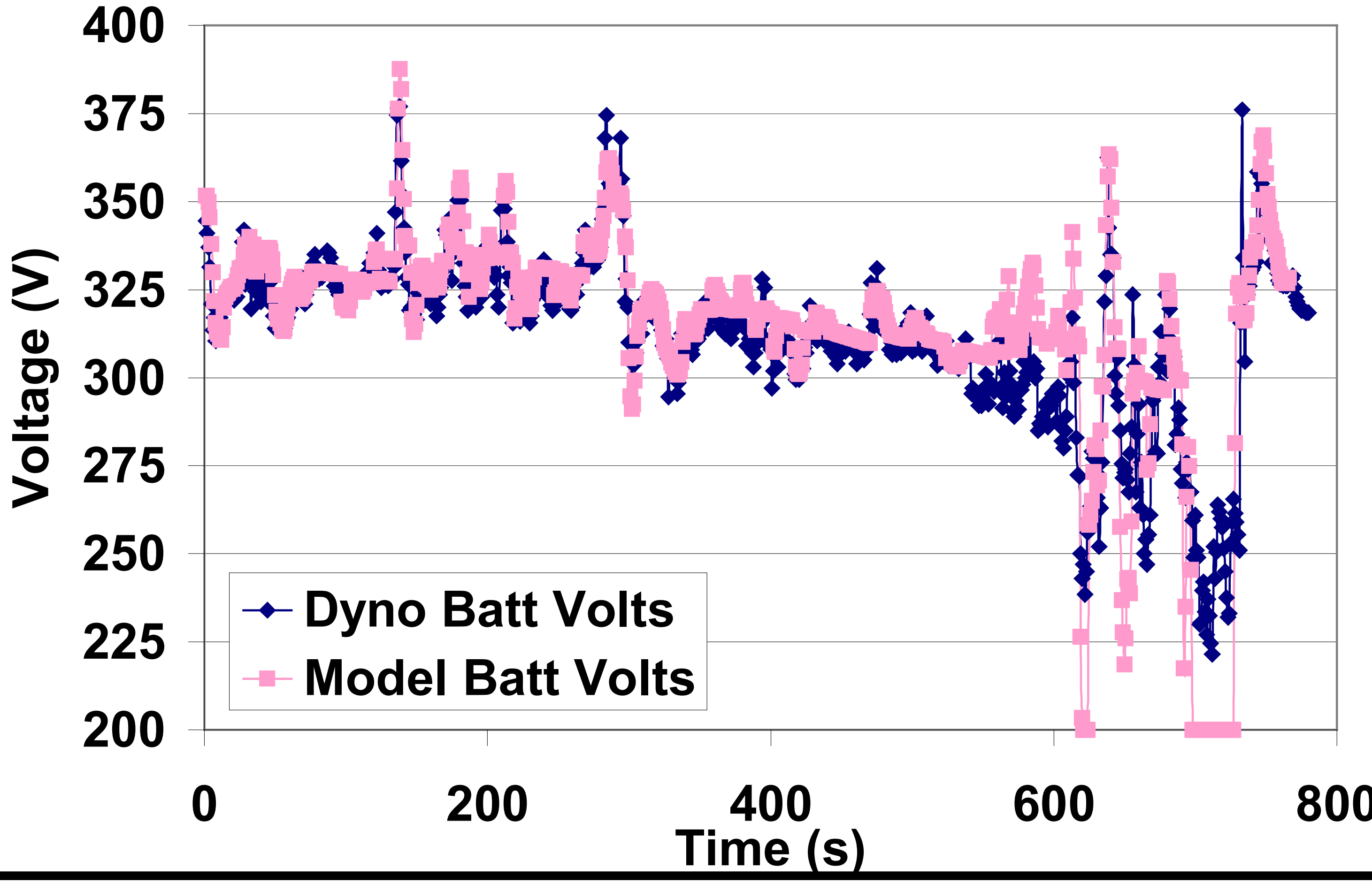
Second by Second Accuracy



Energy Storage System is Critical

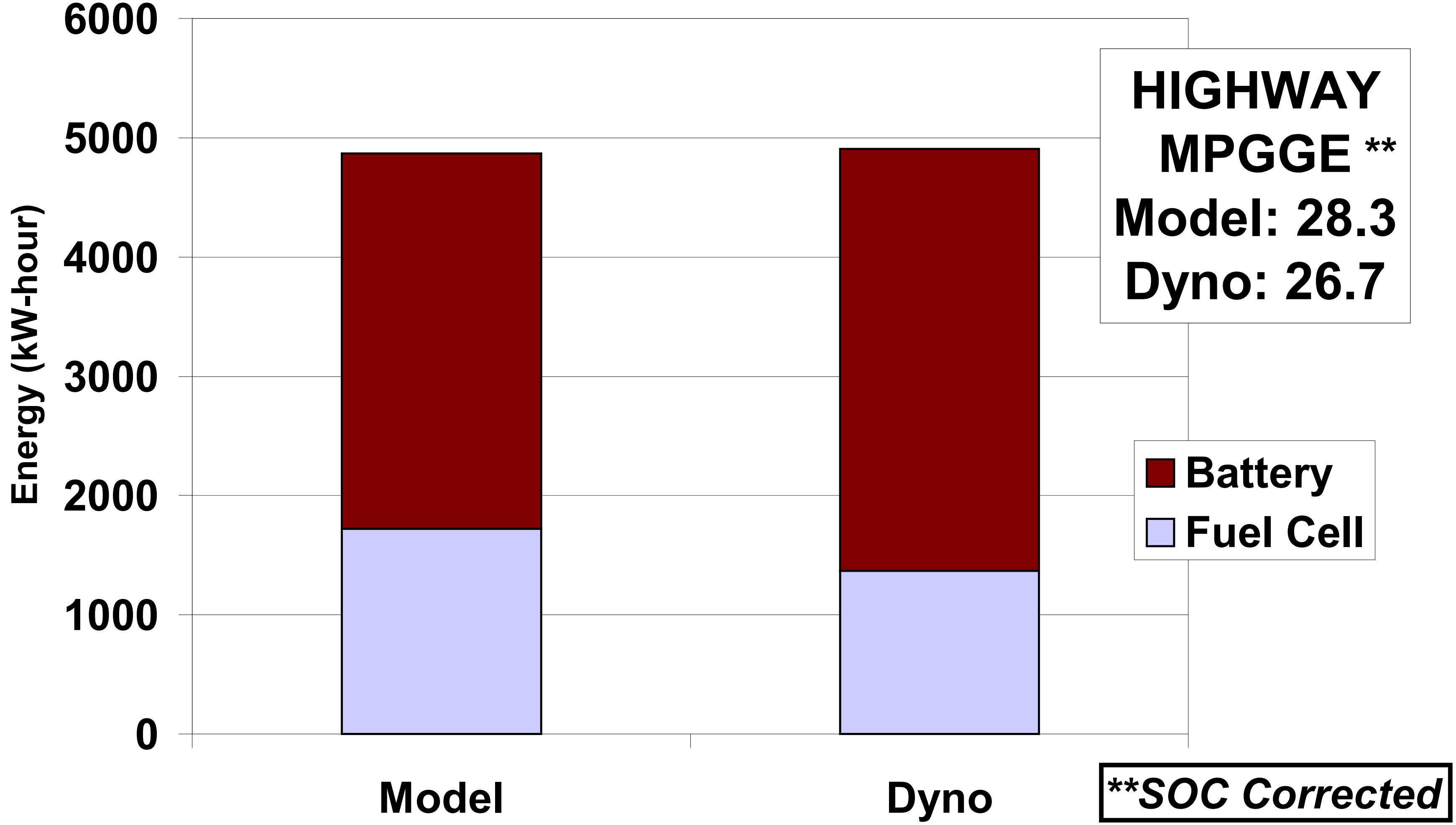


Energy Storage System is Critical



Highway Cycle - Energy Use

Energy Sourced for use by the Drive Motor

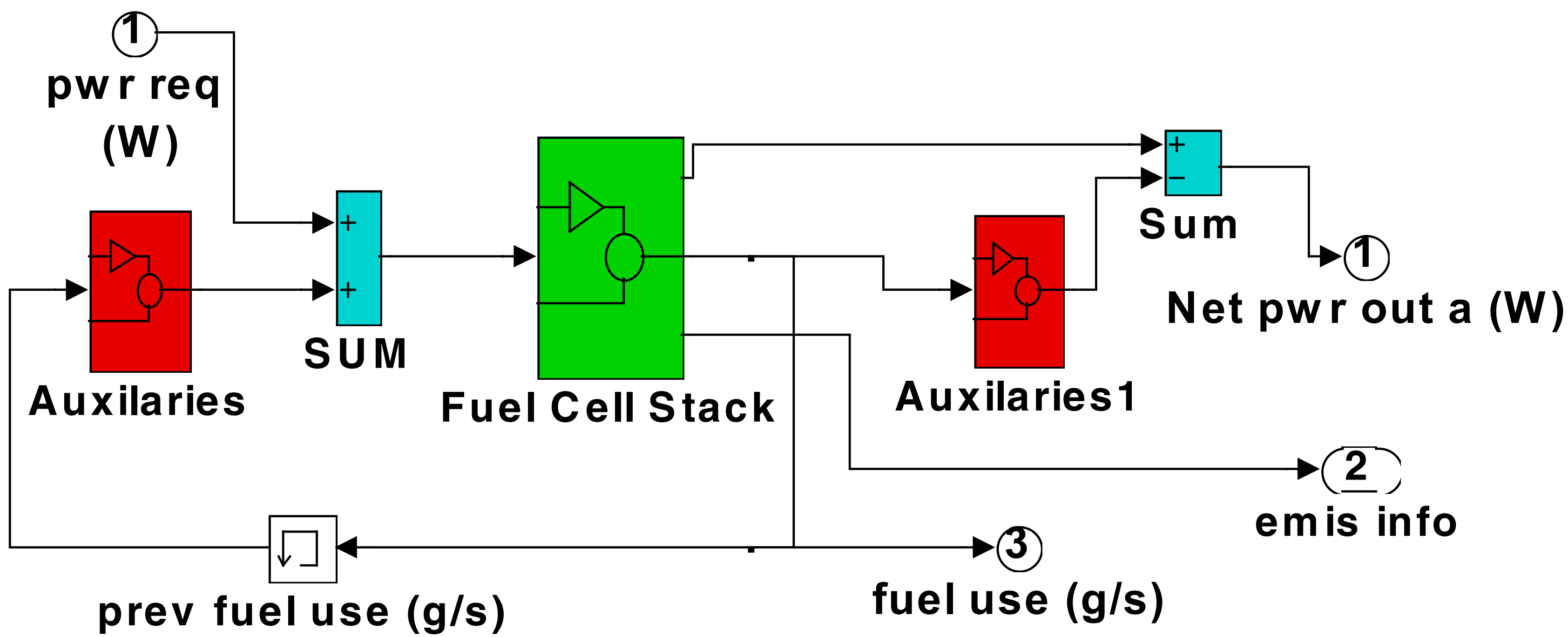


Model Pluses and Minuses

- Accurate for....
  - Trends and transients
  - Energy generation and energy storage
  - Identifying inefficient systems
- Lacking because
  - Not easily adaptable
  - No forward looking capabilites
  - Inter-system impacts not considered

Generalized Model

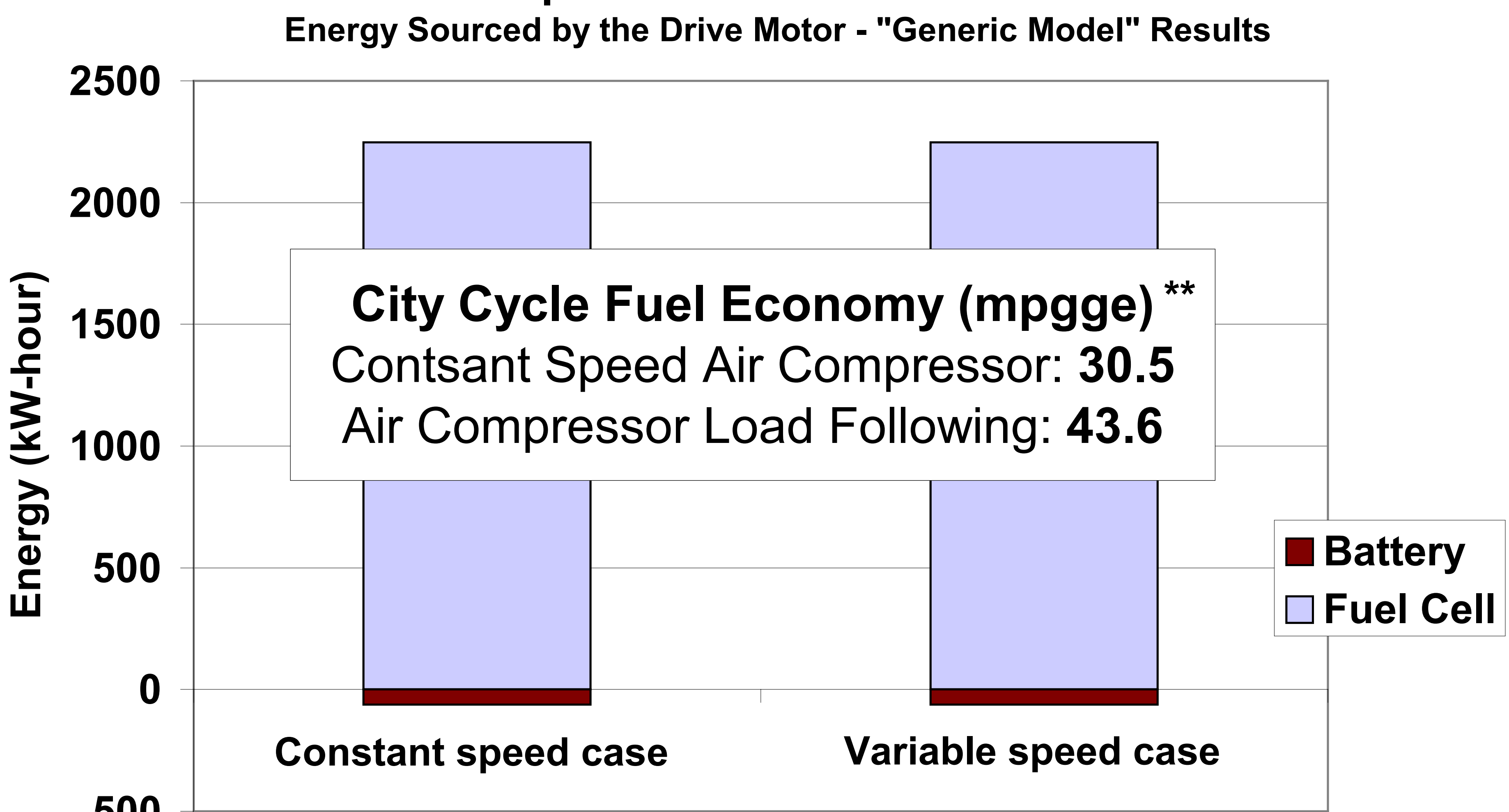
- Lumps Fuel Cell Accessories and Stack



"Generic Model" Advantages

- Restores Forward Looking Capability
- Eases Customization
- Stack Data Entry Options:
  - Polarization Curve
  - Power vs. Efficiency
  - Interface with Argonne's GCTool
- Load Following Accessories

Effect of Repaired Fuel Cell on Model Results

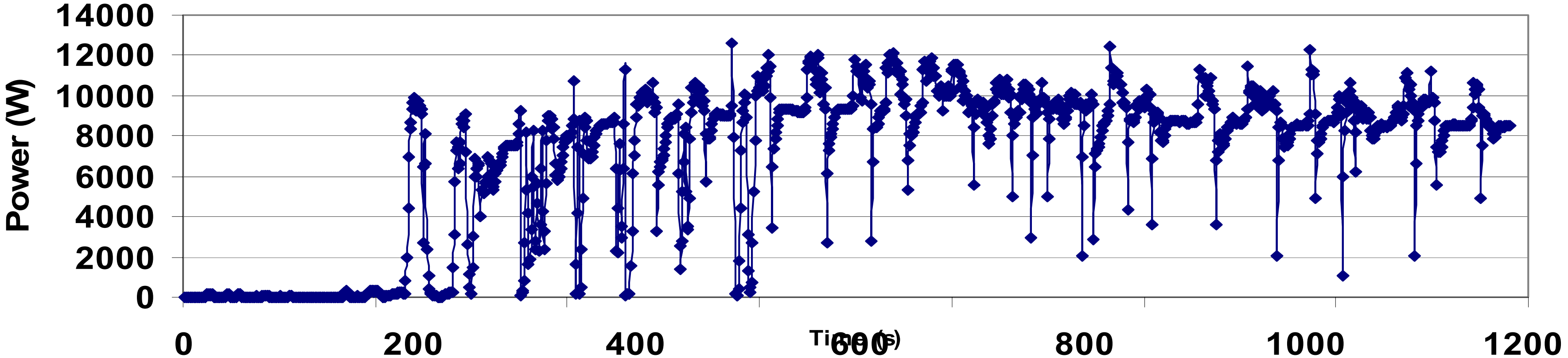


SOC SUSTAINING!

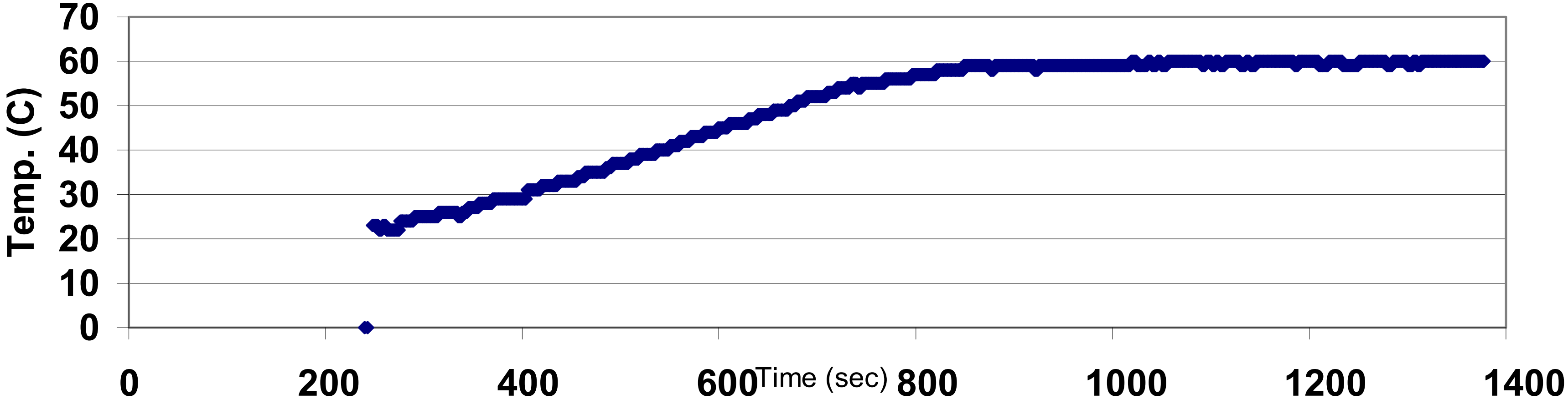
Future Work

- Further Testing of ANIMUL H2
  - Verification of as-designed performance
  - Load following efficiency improvements
- Thermal Modeling
  - Interaction between cooling and humidity
  - Methods to speed warmup times
- Investigate Effciency and Cost vs. Degree of Hybridization

City Driving Cycle - Thermal Data

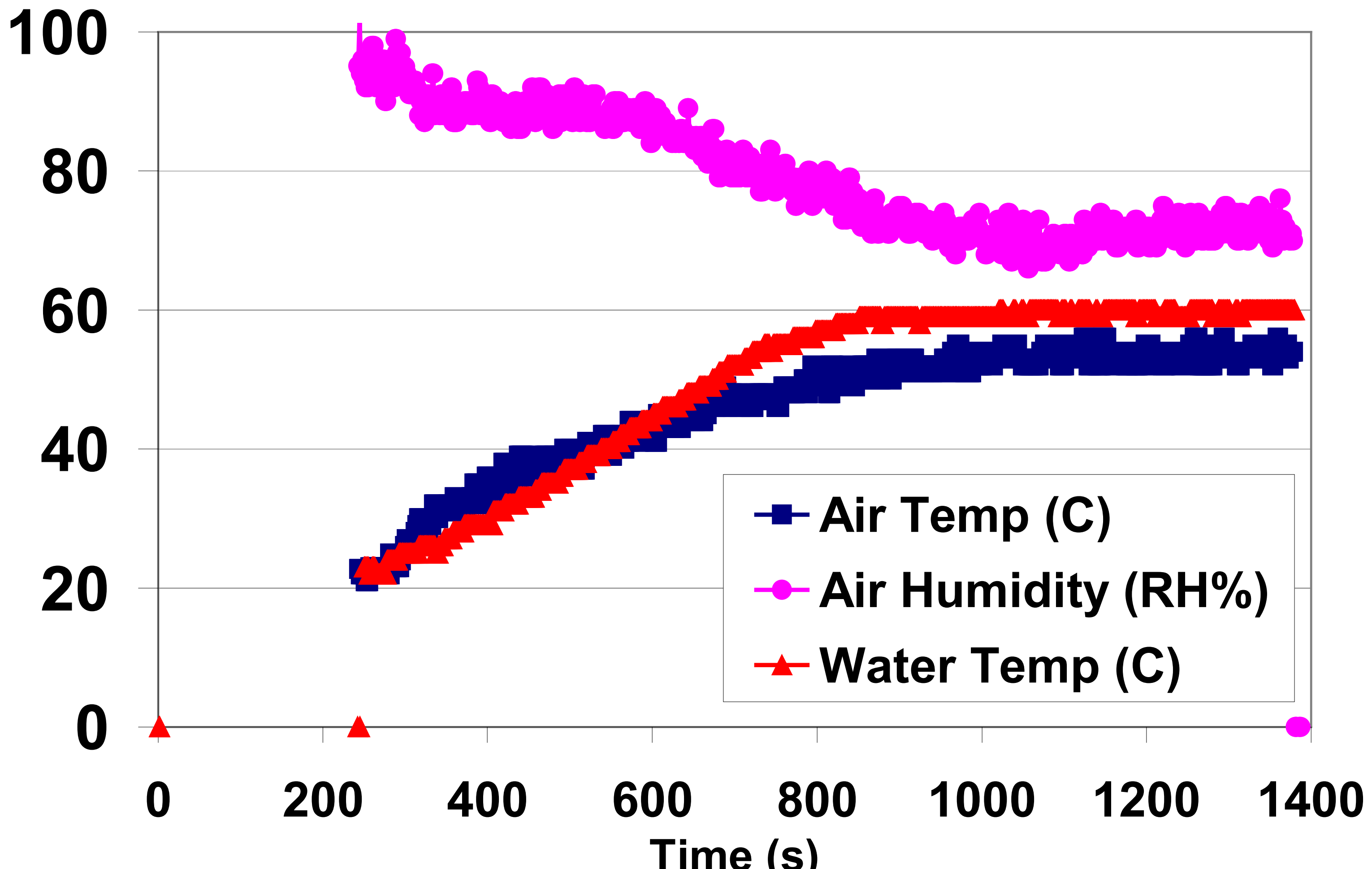


Fuel Cell System Gross Power



Fuel Cell Coolant Output Temperature

Transient Performance is Critical



Conclusions

- Developed accurate component models
- "Generic Model" Validated and Now Released in ADVISOR 2.2

Acknowledgements

- NREL Systems Analysis Team:
  Keith Wipke, Tony Markel, Sam Sprik
- HEVT, Dr. Doug Nelson, Energy Partners

ANIMUL H_2

The Hybrid Vehicle for the Next Millennium

http://fbox.vt.edu:10021/org/hybridcar

www.futuretruck.org

HEVT™

Hybrid Electric Vehicle Team of Virginia Tech

ANIMUL H_2

The Hybrid Vehicle for the Next Millennium

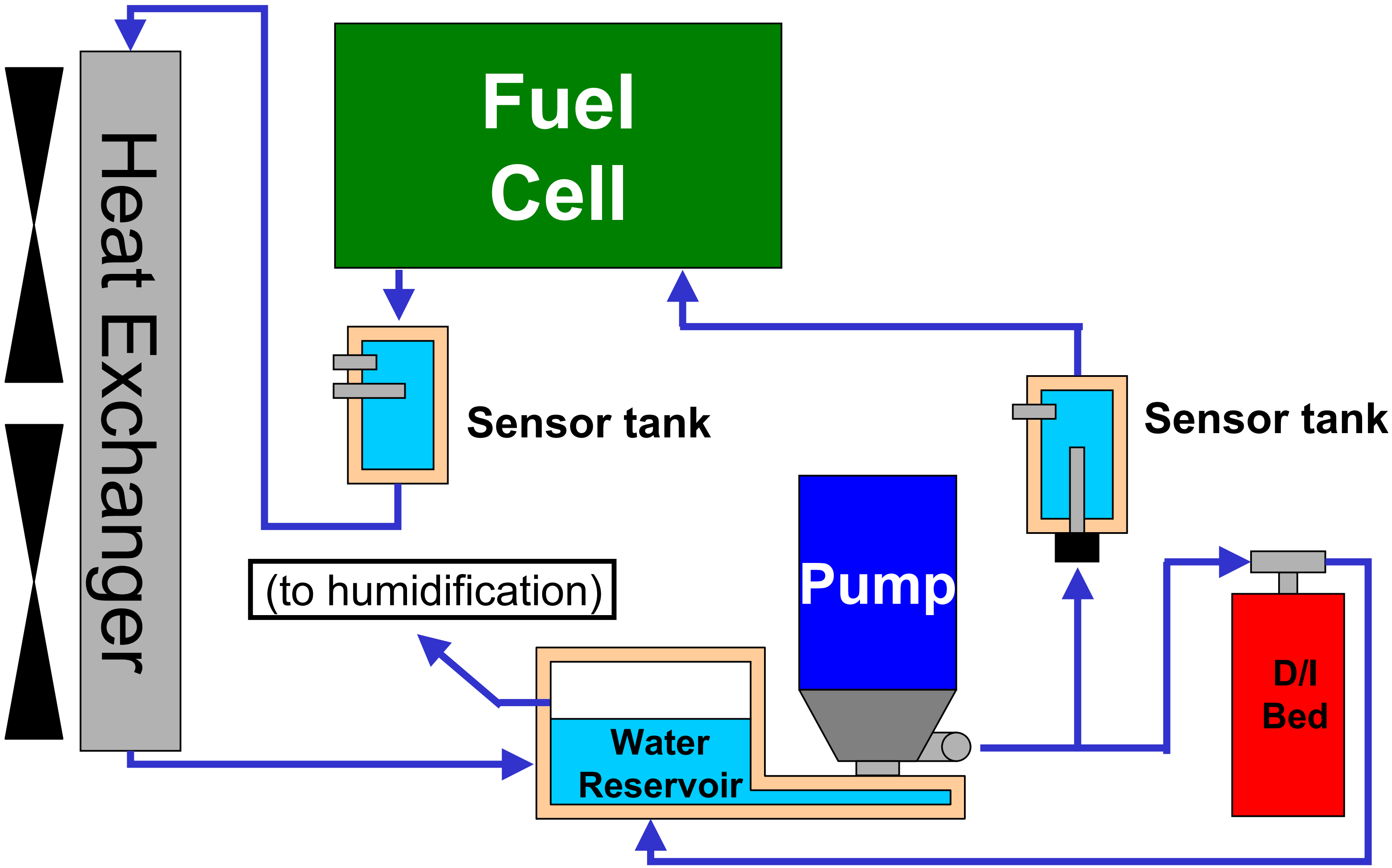
Additional Slides

Keys to FCV Success

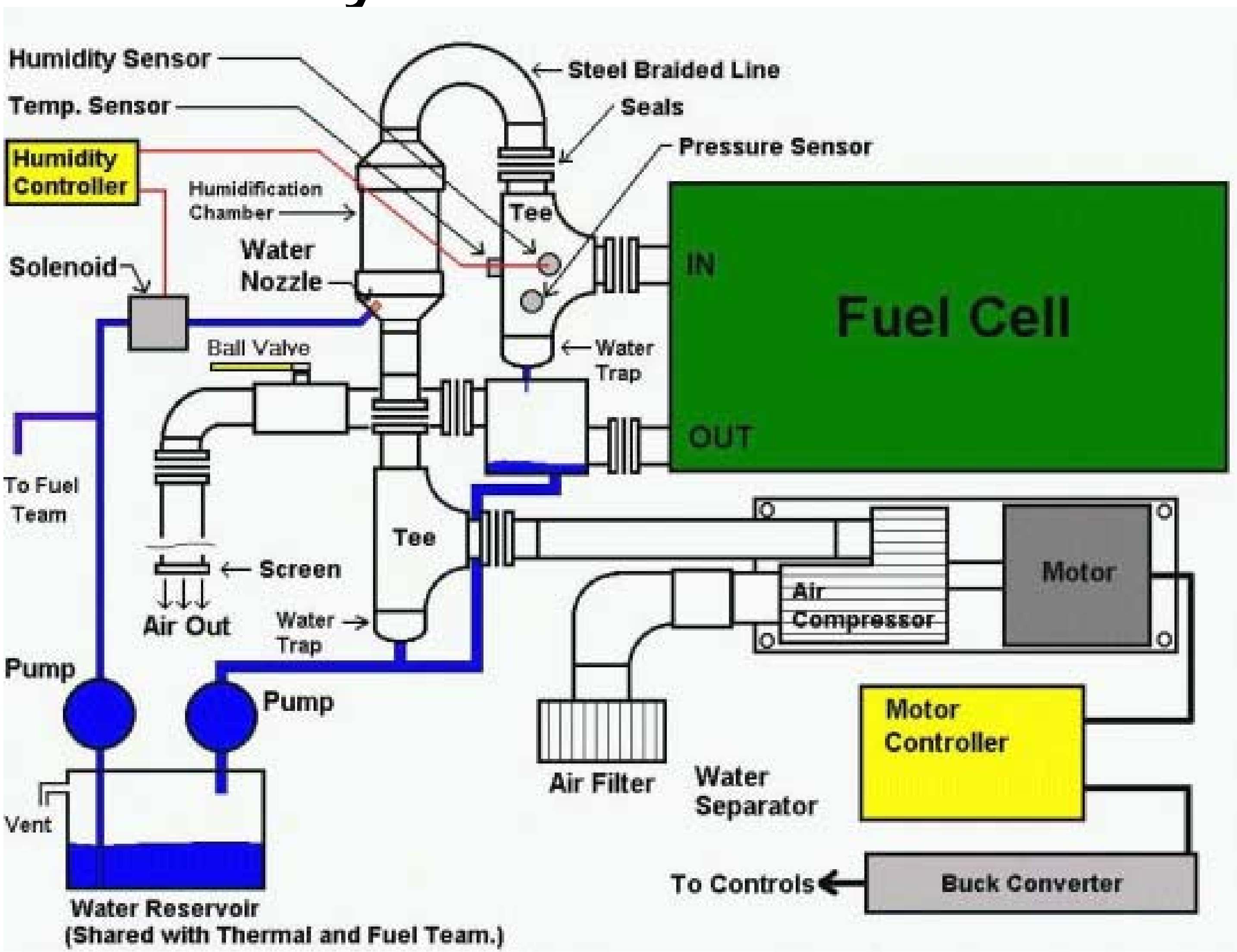
- Fuel Infrastructure!!
- Design for Manufacturability / Cost
- Weight Reduction = Efficiency + Range
- System Performance
  - Current customer expectations worldwide
  - Durability over 100,000 mi or 5000 hr
- Education of the public:

  If you build it, will they come?

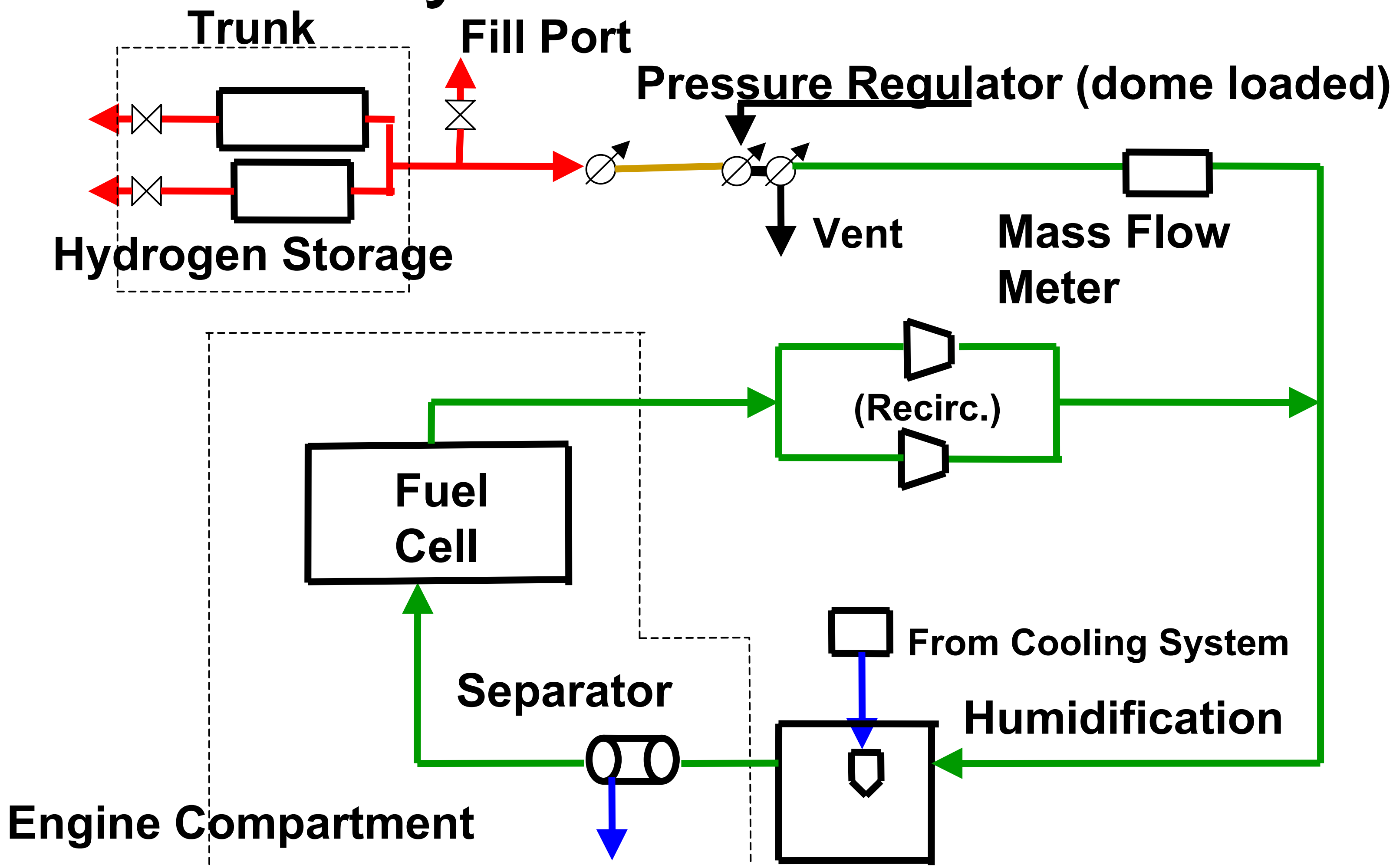
Thermal System Schematic



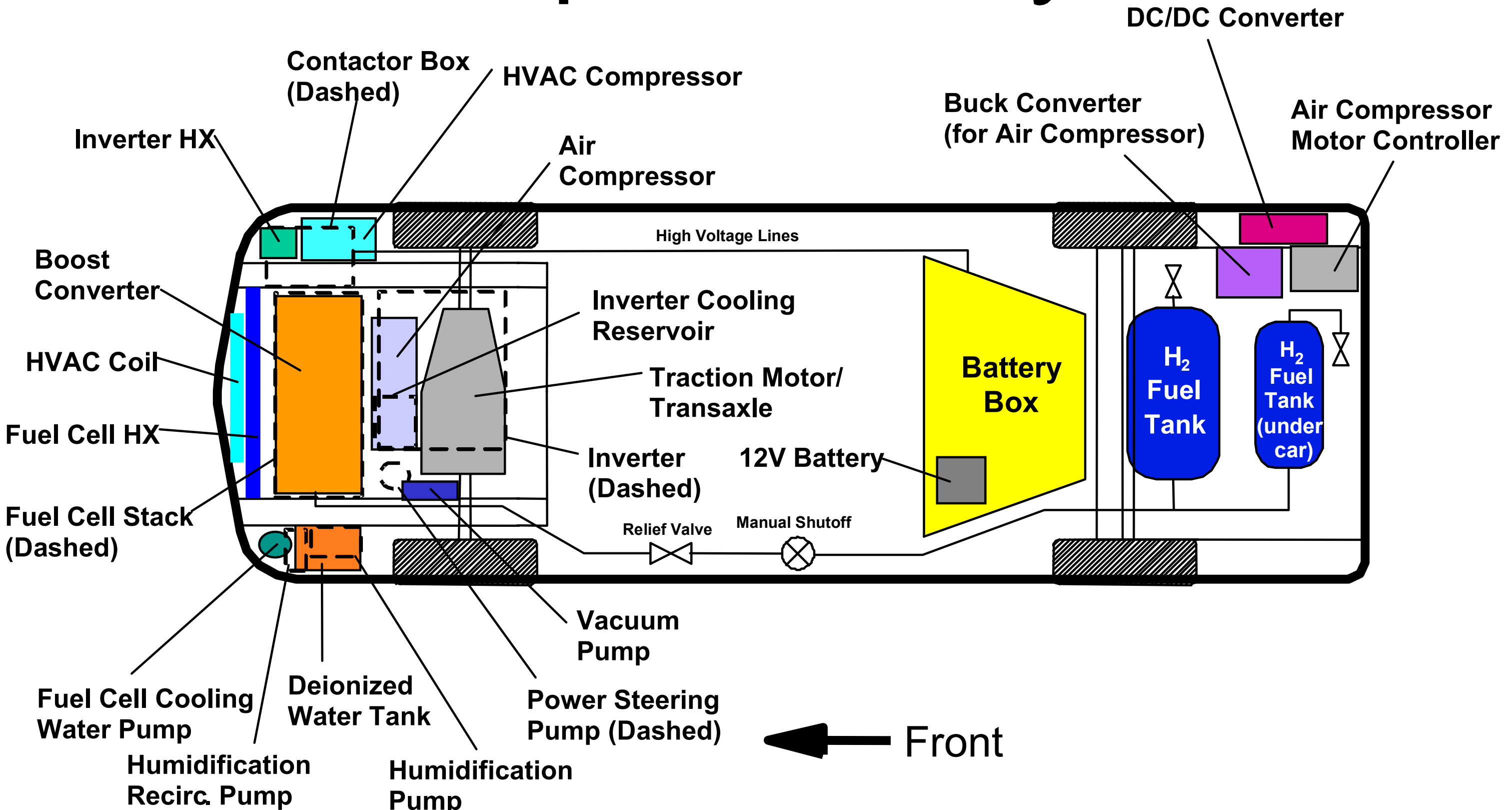
Air System Schematic



Fuel System Schematic



Component Layout



Note: Components denoted by a dashed line are located above other components

ADVISOR

Cosimulation:
Partnering with the Software Industry II:
Geometric and Mechanical Modeling

ADVISOR and Solid Modeler Integration

Mark Henault, ESS West, Inc.

The Integration of ADAMS/Car with ADVISOR, Realization of the "Functional Digital Vehicle"

Presentation (Joshi)

Paper (Spagnuolo)

Sandeep Joshi and Tony Spagnuolo, Mechanical Dynamics Inc.

INTRODUCTION

Mark Henault

ESS West, Inc.

- Working with NREL on integration of ADVISOR with Solid Modeling tools.
- Contact: mhenault@esswest.com
- Phone: 303-429-5005

OVERVIEW

- **Pro/HEV**
  - First integration of ADVISOR with Pro/Engineer
- **Functional Digital Vehicle (FDV)**
  - Next generation of ADVISOR integration with solid modeling & other tools (Pro/E, CATIA, Dyna, ADAMS, etc.)
  - Currently underway at NREL
- **Integration of ADVISOR with Solid Modeling Tools**
  - Why integrate
    - Packaging
    - Occupant Comfort
    - Crash/Structural Analysis
  - Current Status
  - Future Plans

What is Required for a FDV?

- **Power-train optimization (ADVISOR)**
  - Fuel economy
  - Emissions
  - Acceleration & driving performance
- **Vehicle dynamic optimization (ADAMS/Car)**
  - Handling/performance prediction
  - Durability prediction
  - Vehicle stability
- **Packaging – (1st order performed by Pro/HEV)**
  - Under hood
  - Trunk
  - Under vehicle
  - Vehicle center of gravity, air volumes, air flow studies, etc.
- **Occupant comfort (interior volume provided by Pro/HEV)**
  - Significant energy consumption for A/C & heating
  - Minimize energy while maximizing Occupant comfort
  - Not merely function of interior air temp & velocity of air
- **Crash & Structural performance (structure provided by FDV)**
  - Occupants safe?
  - 5mph vehicle damage?

Pro/HEV & FDV

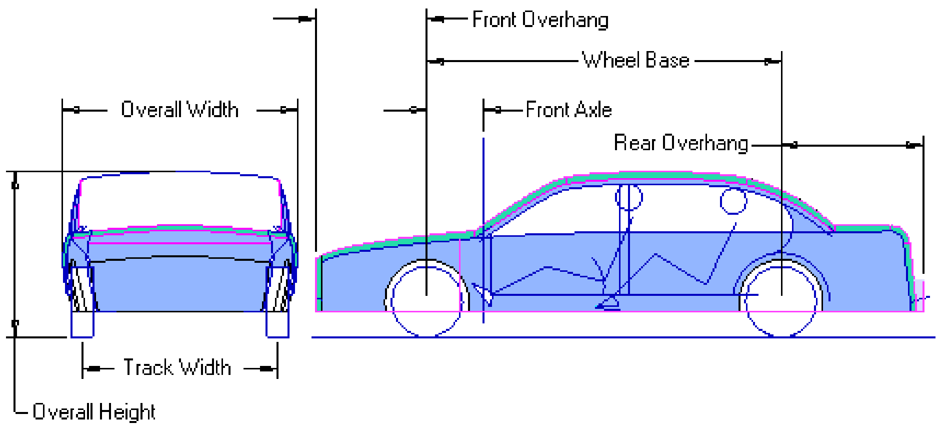
- Can recall “known” vehicle, modify “known” vehicle, or create a new vehicle from scratch in Pro/HEV.
  - Vehicle center of gravity
  - Vehicle mass
  - Packaging
    - Pro/HEV stores 250 dimensions to control vehicle configuration
    - Contains pre-defined suspension configurations to integrate with ADAMS (MacPherson in Pro/HEV, more planned for FDV).

Pro/HEV & FDV

- **Capture interior for CFD Analysis**
  - **Assigns boundary conditions for glass, etc.**
  - **Default conditions can be solved quickly**
- **Vehicle morph, generation of vrml files, e-mail notification, download files, visualize files**
  - **5 minutes plus download time**

Loading ADVISOR Vehicle into Pro/HEV

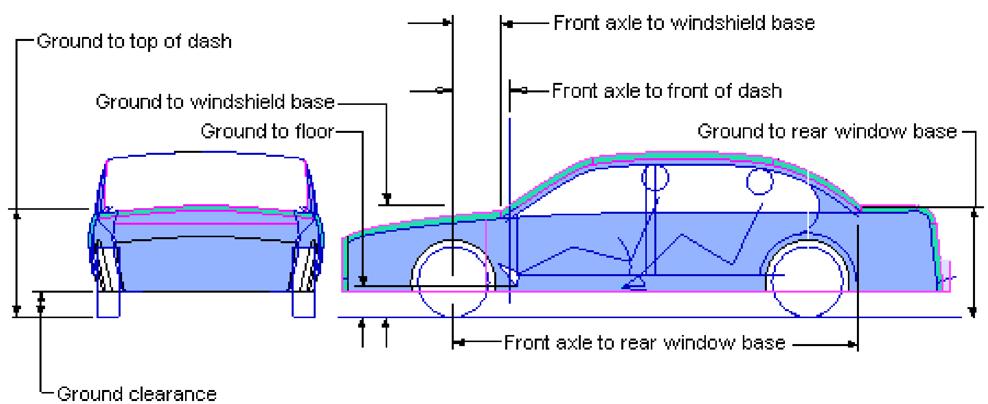
"What If" Studies



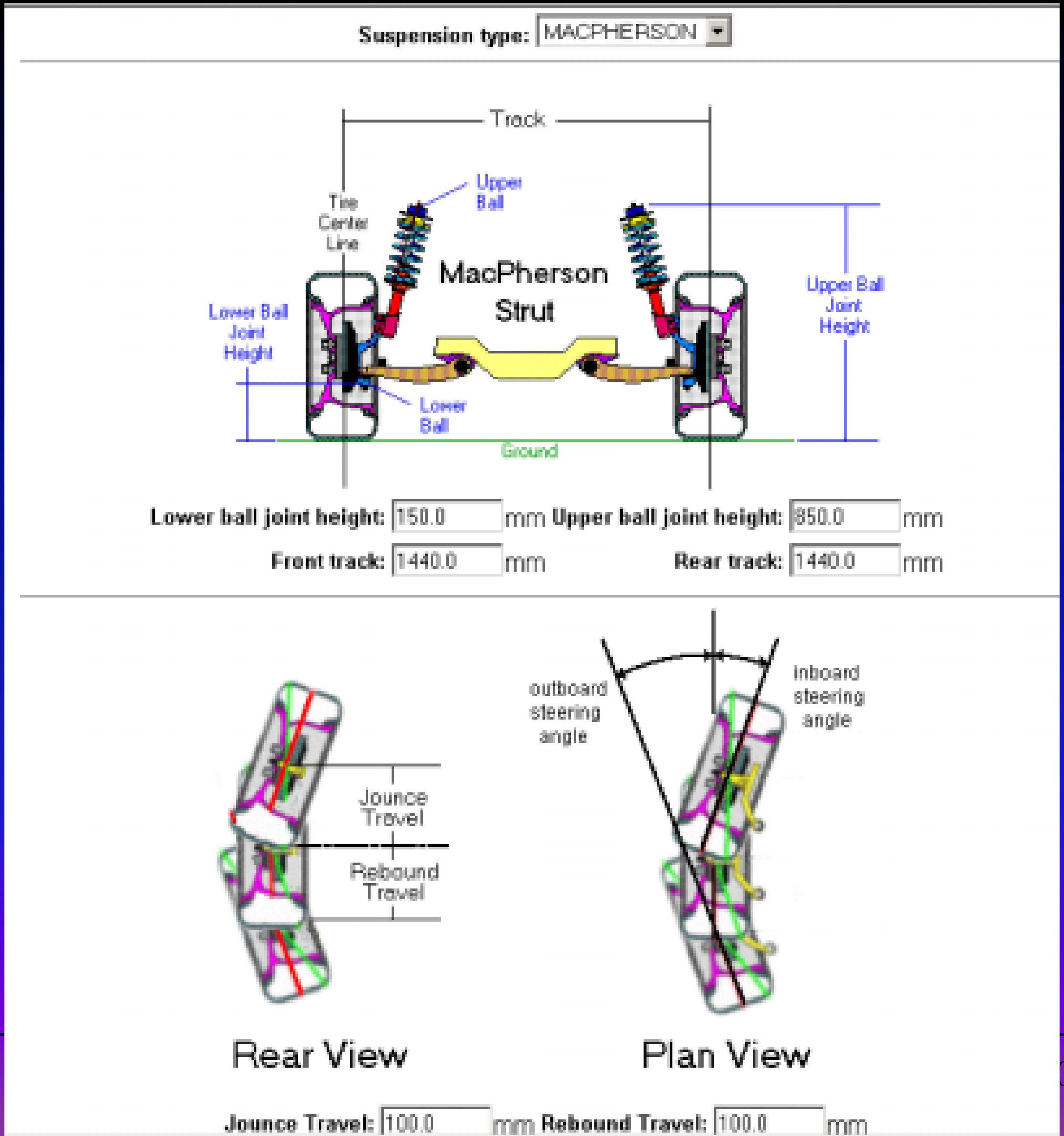
Overall Height: 1430.0 mm **Wheelbase:** 2640.0 mm

Front Overhang: 970.0 mm **Rear Overhang:** 970.0 mm

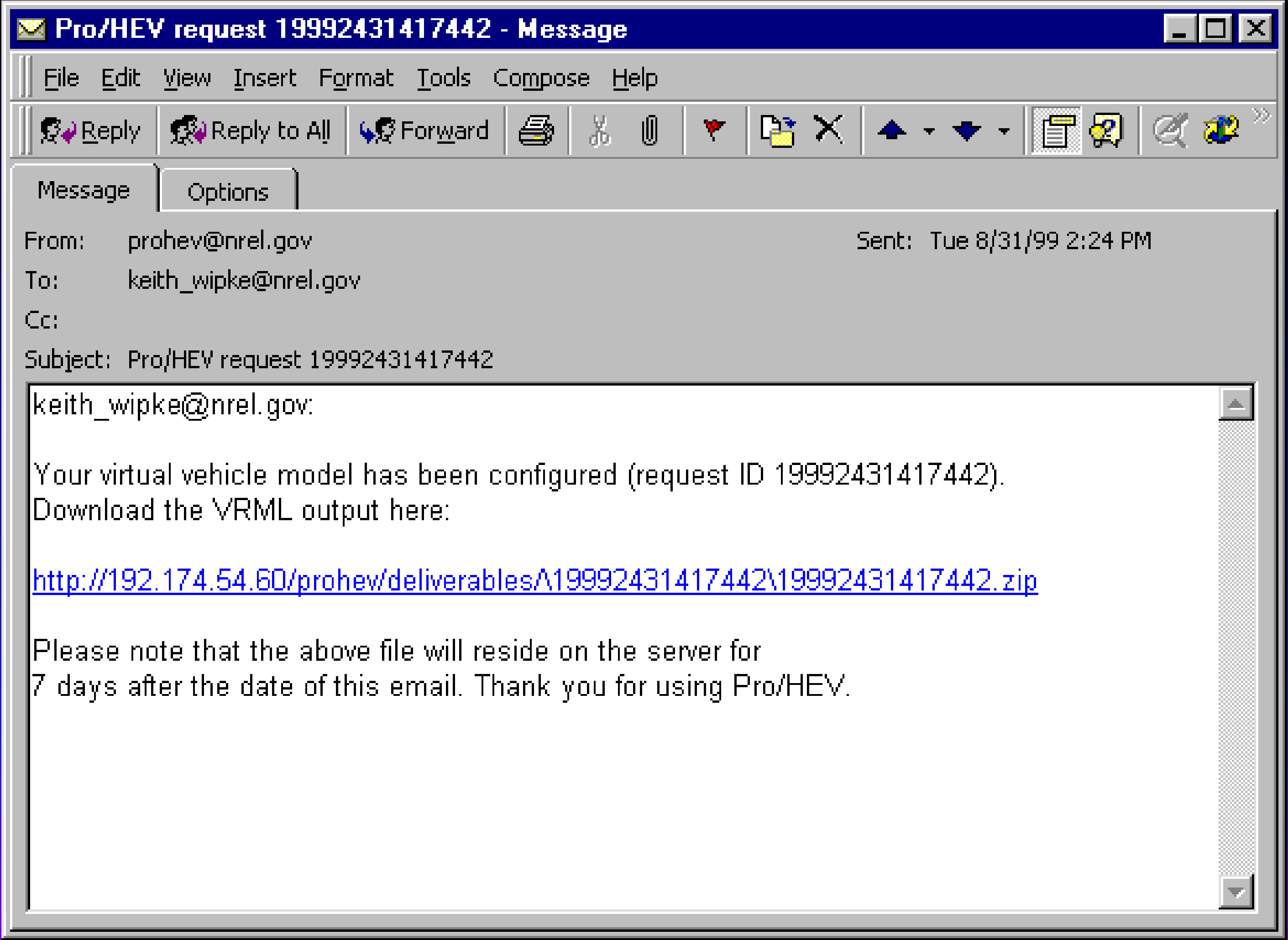
Distances and clearances:



"What If" Studies



E-mail notification of VRML files



Pro/HEV request 19992431417442 - Message

File Edit View Insert Format Tools Compose Help

Reply | Reply to All | Forward

Message | Options

From: prohev@nrel.gov — Sent: Tue 8/31/99 2:24 PM

To: keith_wipke@nrel.gov

Cc:

Subject: Pro/HEV request 19992431417442

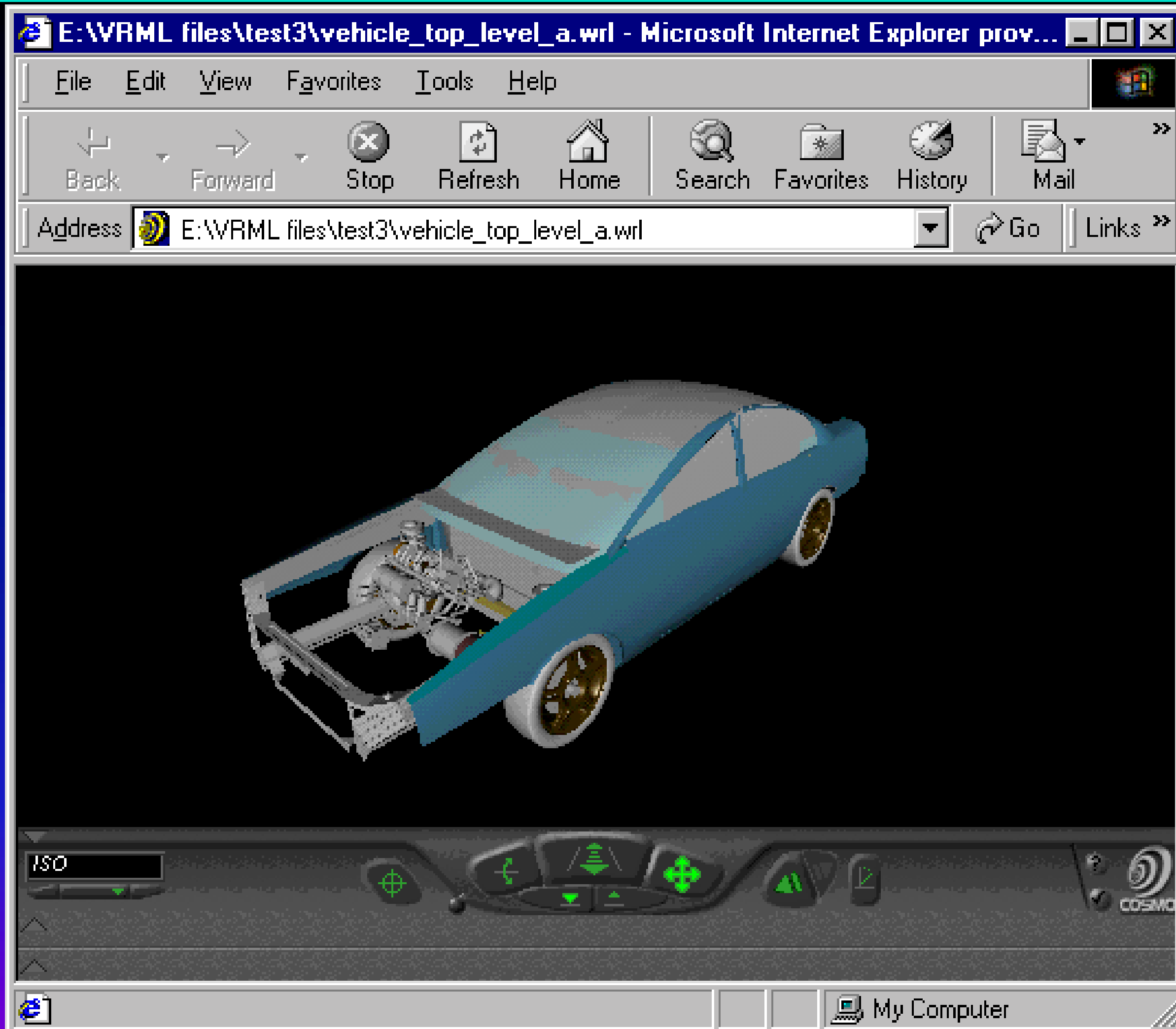
keith_wipke@nrel.gov:

Your virtual vehicle model has been configured (request ID 19992431417442).
Download the VRML output here:

http://192.174.54.60/prohev/deliverables/\19992431417442\19992431417442.zip

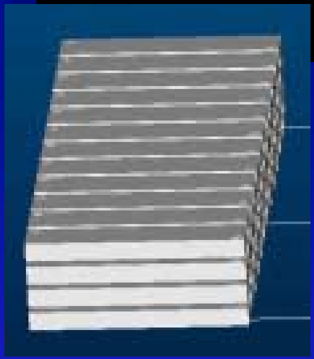
Please note that the above file will reside on the server for
7 days after the date of this email. Thank you for using Pro/HEV.

Visualizing VRML Vehicle

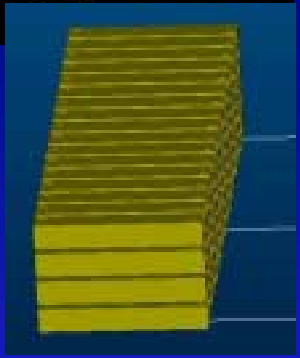


Battery Packaging Comparison

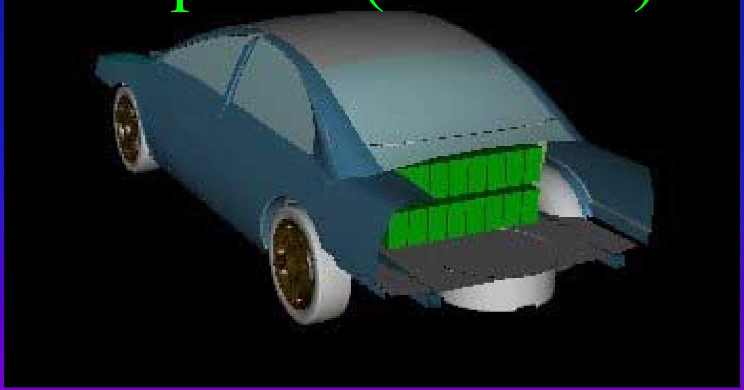
Prius (NiMH)



Battery "A" (Li-ion)

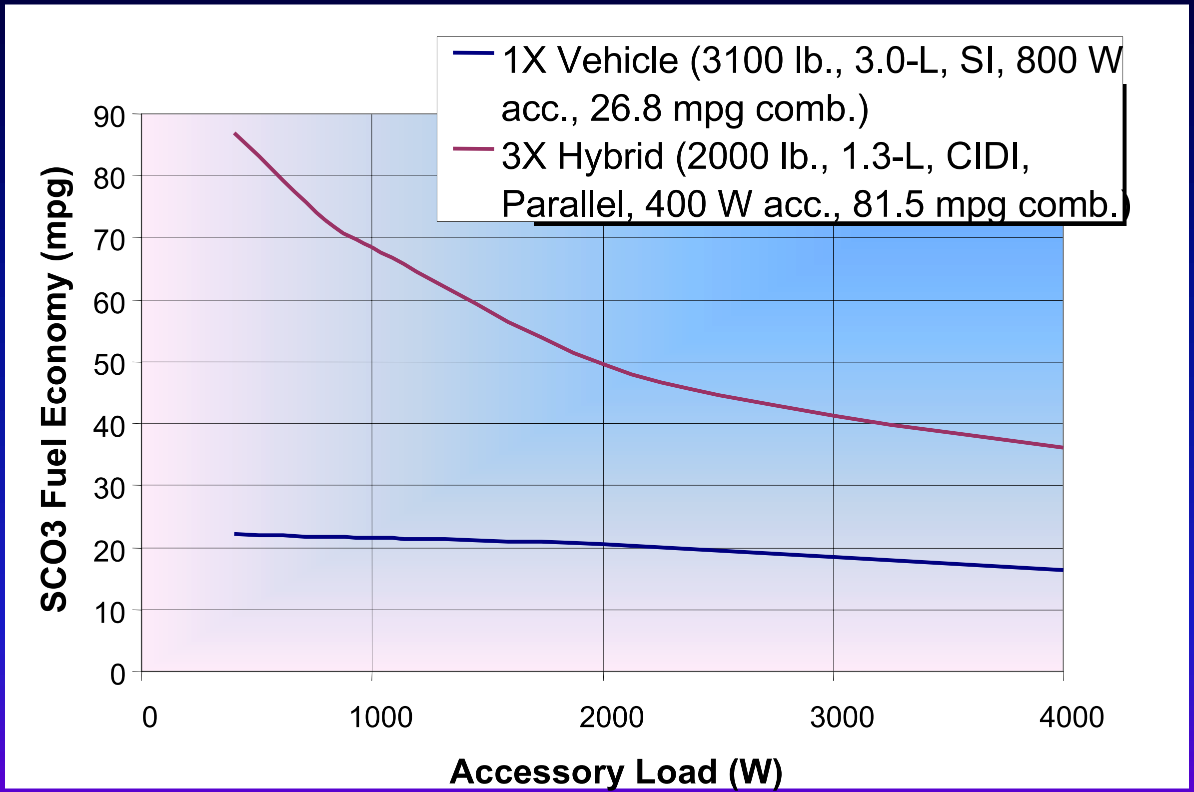


Optima (Pb-Acid)

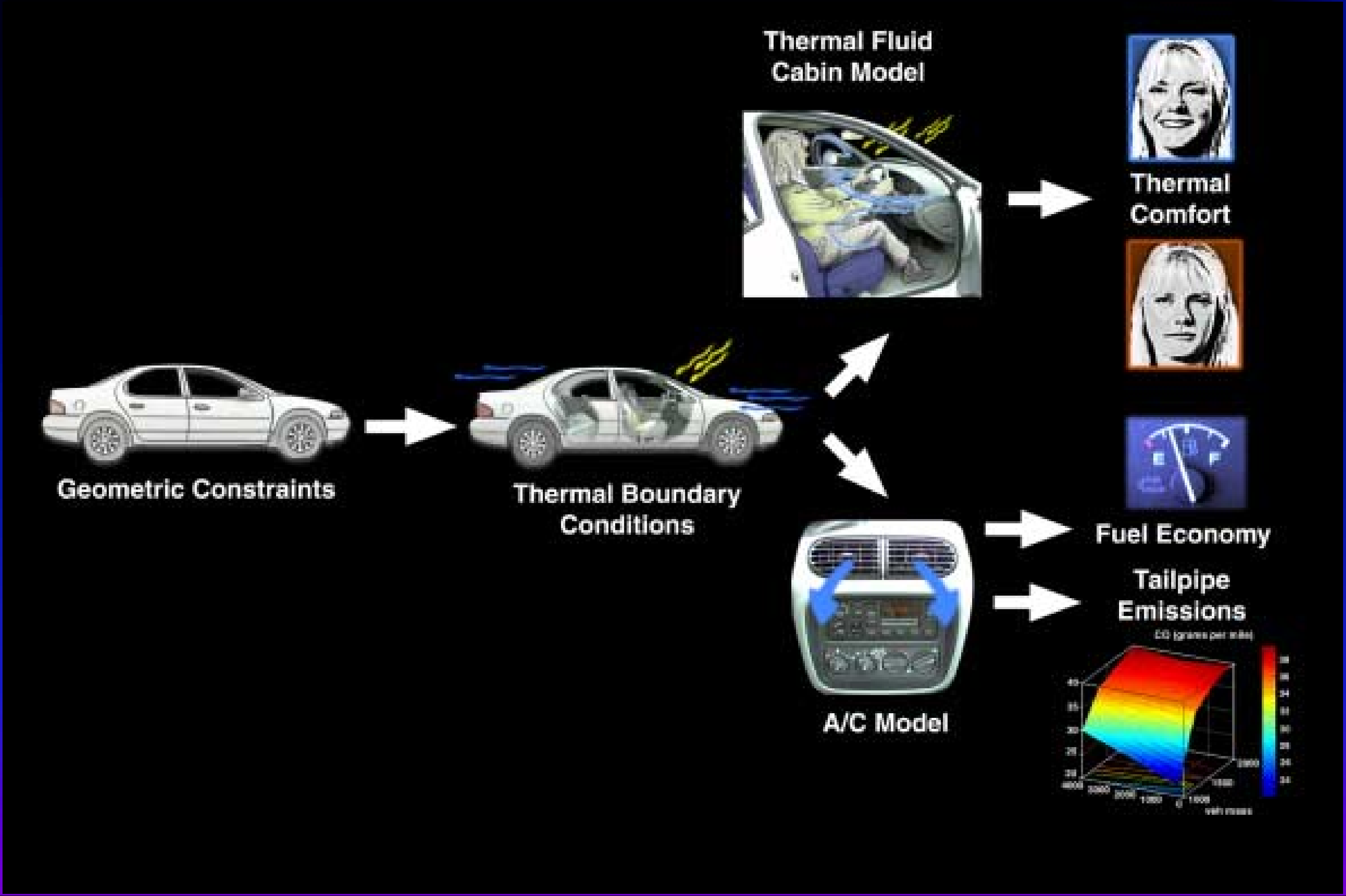


Why Worry About Aux Loads?

1 mpg => $4B annually



The Modeling Process

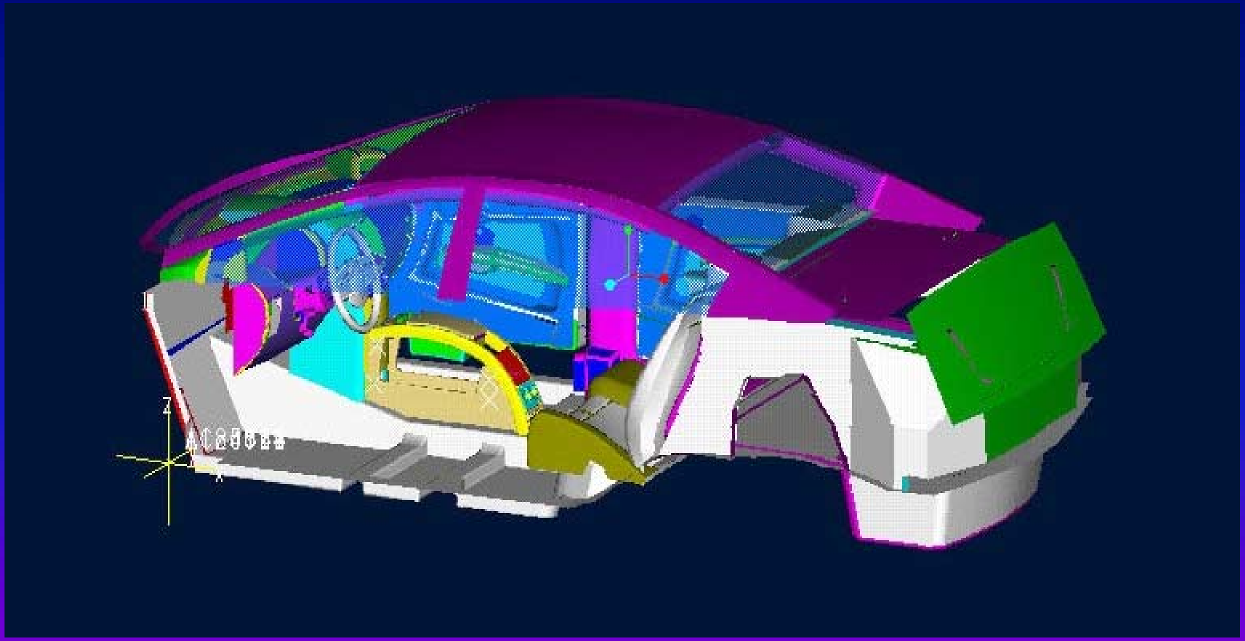


Five Step Analysis Process

1. Define interior air volume (CAD File)
2. Create mesh & assign thermal B.C. (ICEM-CFD)
3. Perform thermal/fluid analysis
4. Calculate transient thermal occupant comfort
5. Calculate fuel economy, and tail pipe emissions for specified drive cycles (ADVISOR)

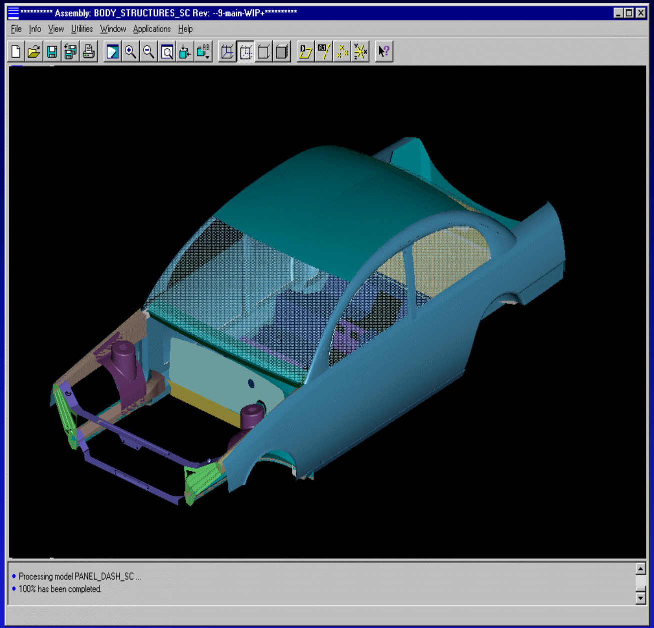
Step 1 – Define Interior Air Volume

- Traditionally get IGES data (partial) from OEM.
- Spend weeks cleaning up file to generate usable volume.
- Hope no major changes take place while working on the file.



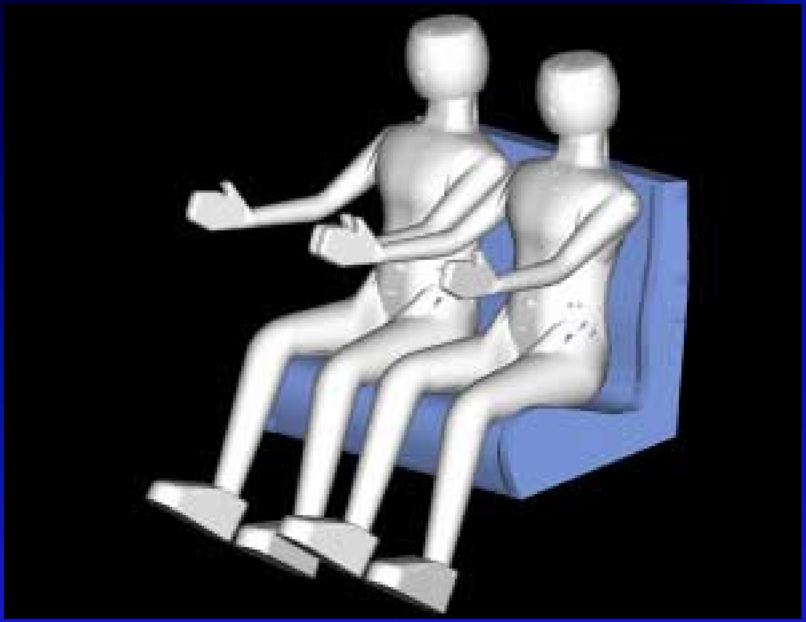
Step 1 – Using the FDV Approach

- Begin with Parametric vehicle.
- Morph vehicle to match given vehicle's interior (automatic for pre-defined vehicles)
  - Registers
  - Surfaces
  - Glass area
- Package Parametric Seats & Occupants (next slide).
- Generate Volume.

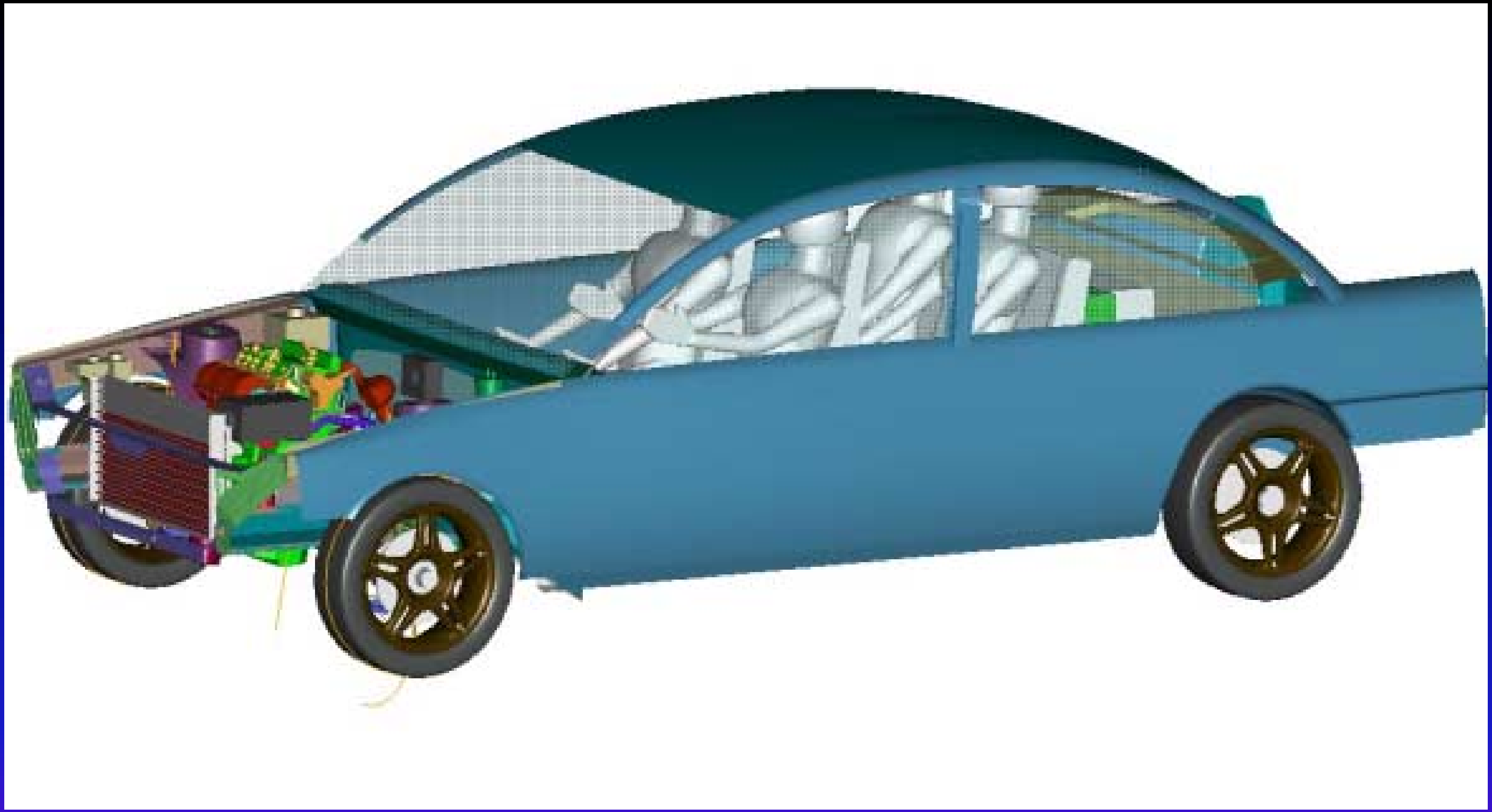


Step 1 - Digital Occupants

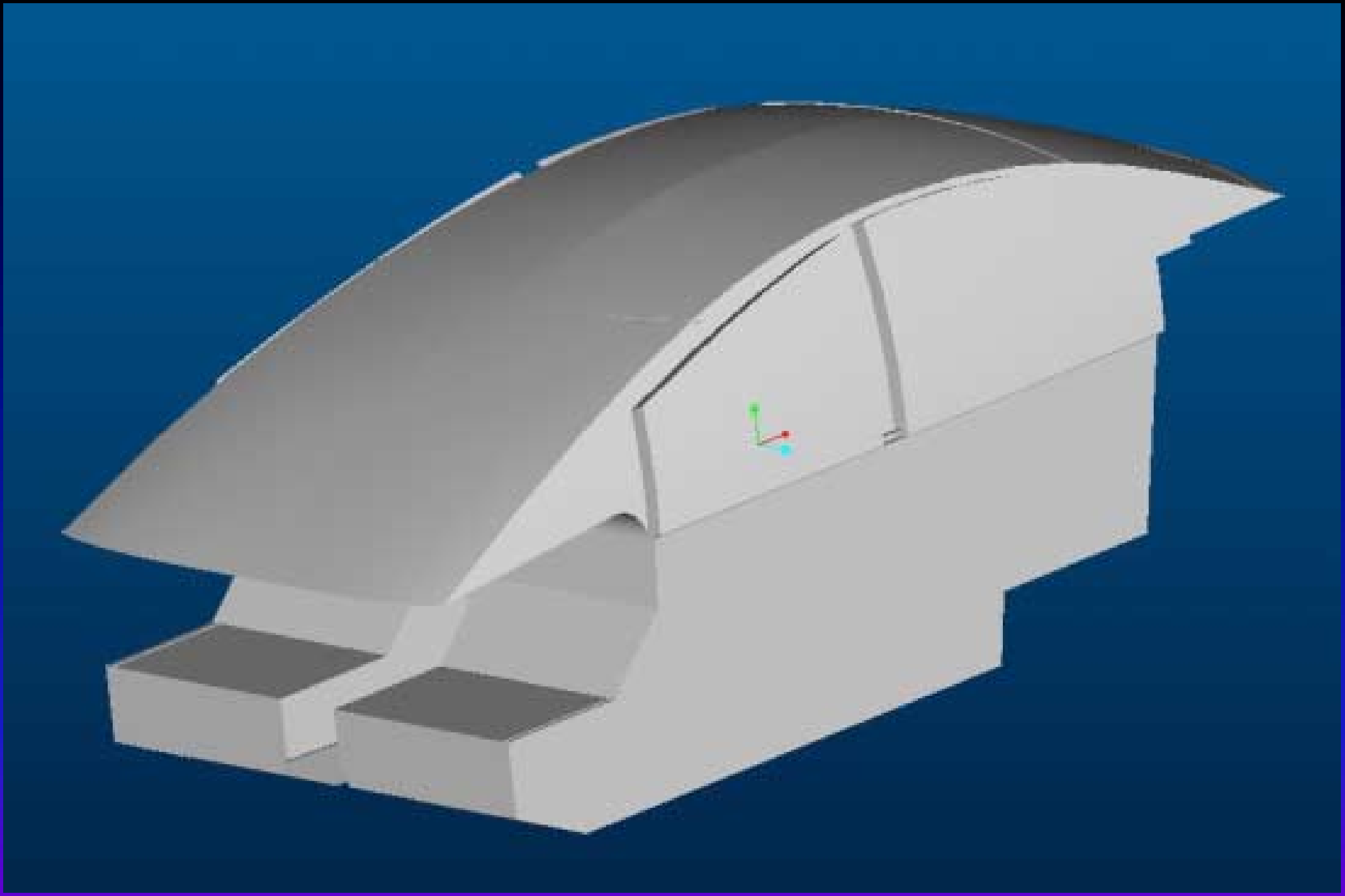
- Integrated digital manikin
  - links CFD and thermal comfort model
  - experimental validation of thermal comfort manikin



Step 1 – "Morphed" FDV

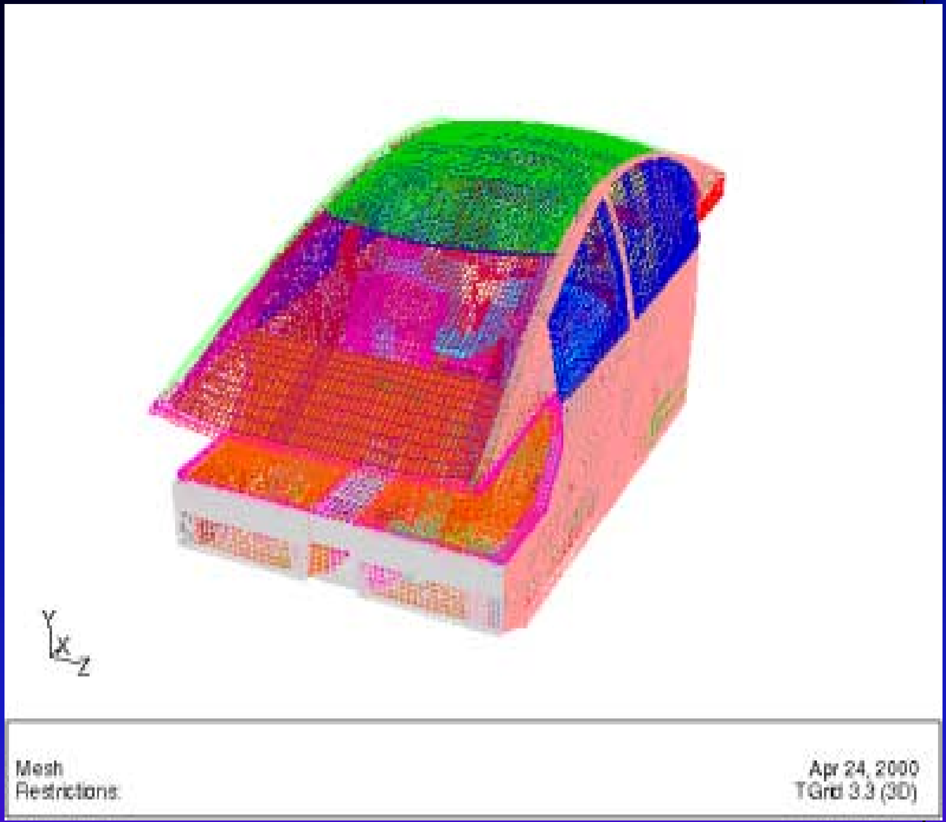


Step 1 - Interior Volume



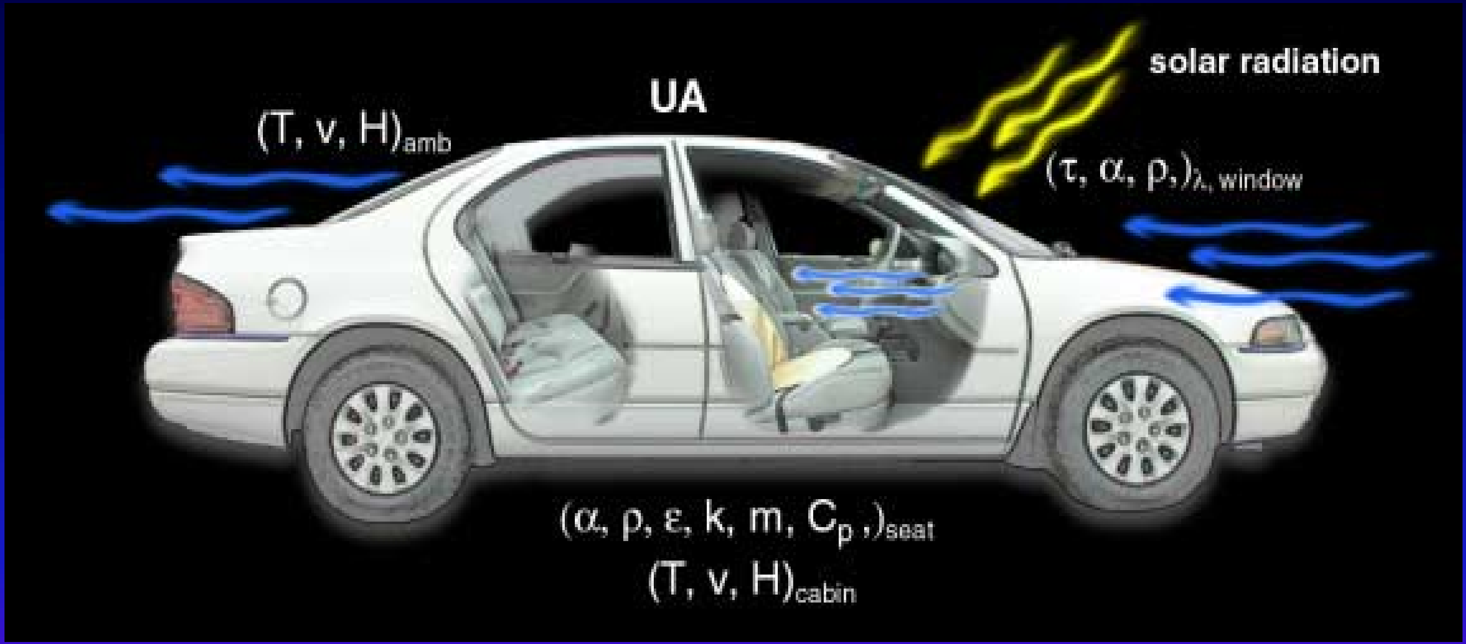
Step 2 - Mesh & Boundaries

- ICEM-CFD
  - Applies B.C. to vents, glass, body, etc.
  - Generates mesh of volume
  - Writes input file for analysis codes
  - Automatically launches thermal/fluid solver



Thermal Boundary Conditions

- Objective: **To specify the cabin thermal properties and boundary conditions.**

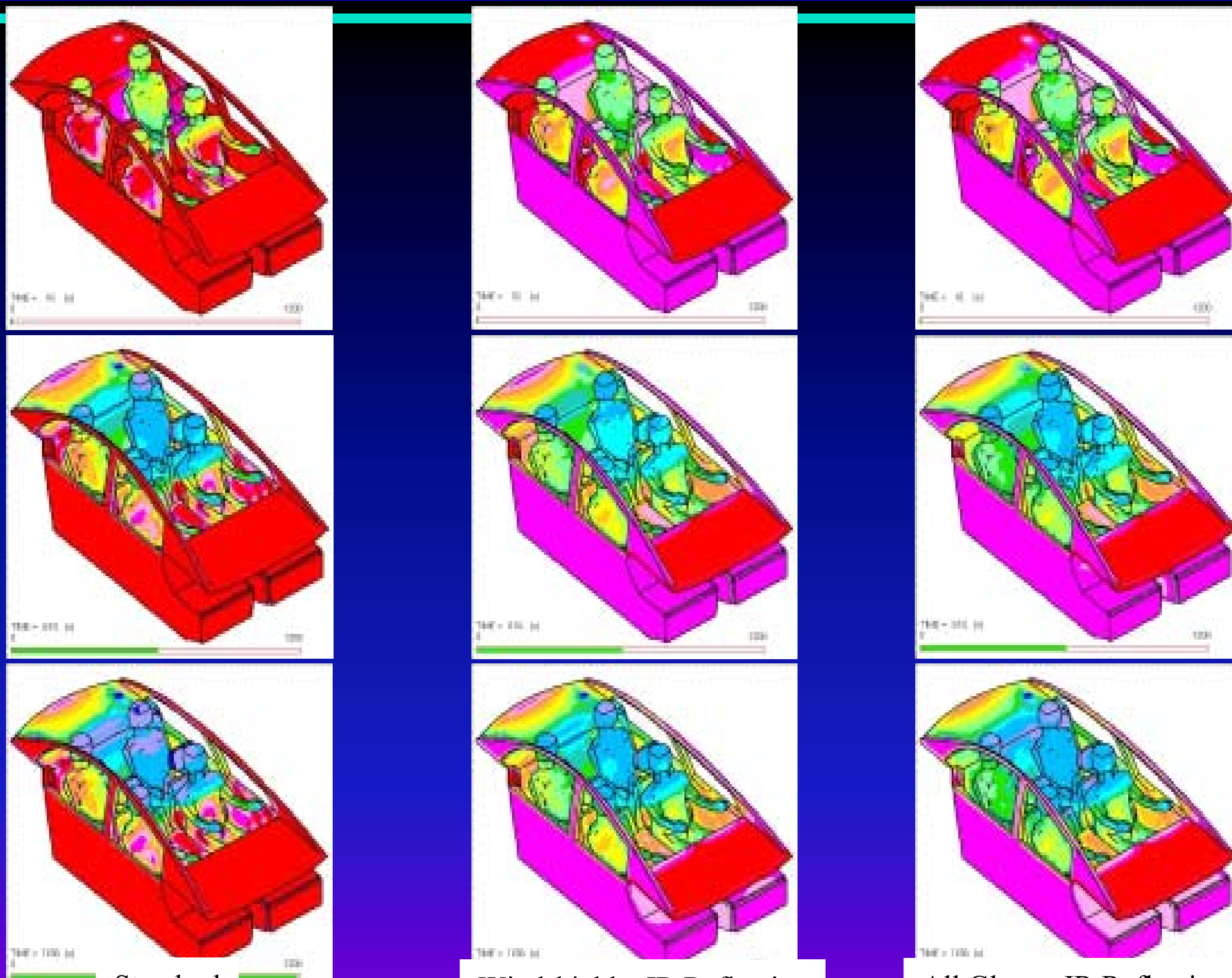


Step 3 - Perform Thermal/Fluid Analysis

- FLUENT, STAR/CD simulates thermal/fluid environment
- ICEM-CFD retrieves and visualizes results from thermal/fluid simulation
- ICEM-CFD generates input files for Occupant Thermal Comfort Model

- Interior Cool-down Animation

Results - 0, 10, and 20 minutes



T=0 min

T=10 min

T=20 min

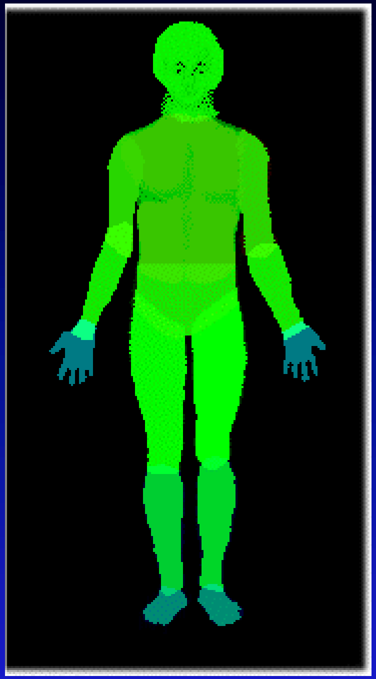
Standard

Windshield – IR Reflective

All Glass – IR Reflective

Step 4 – Thermal Comfort Prediction

- Thermal Comfort Model
  - Multi-segmented model
  - Clothing w/moisture and thermal capacitance
  - Data every 30 sec from ICEM-CFD for 20 min simulation
  - Transient solution
  - Advanced control strategies
  - Maximize comfort to thermally sensitive areas vs. uniformity



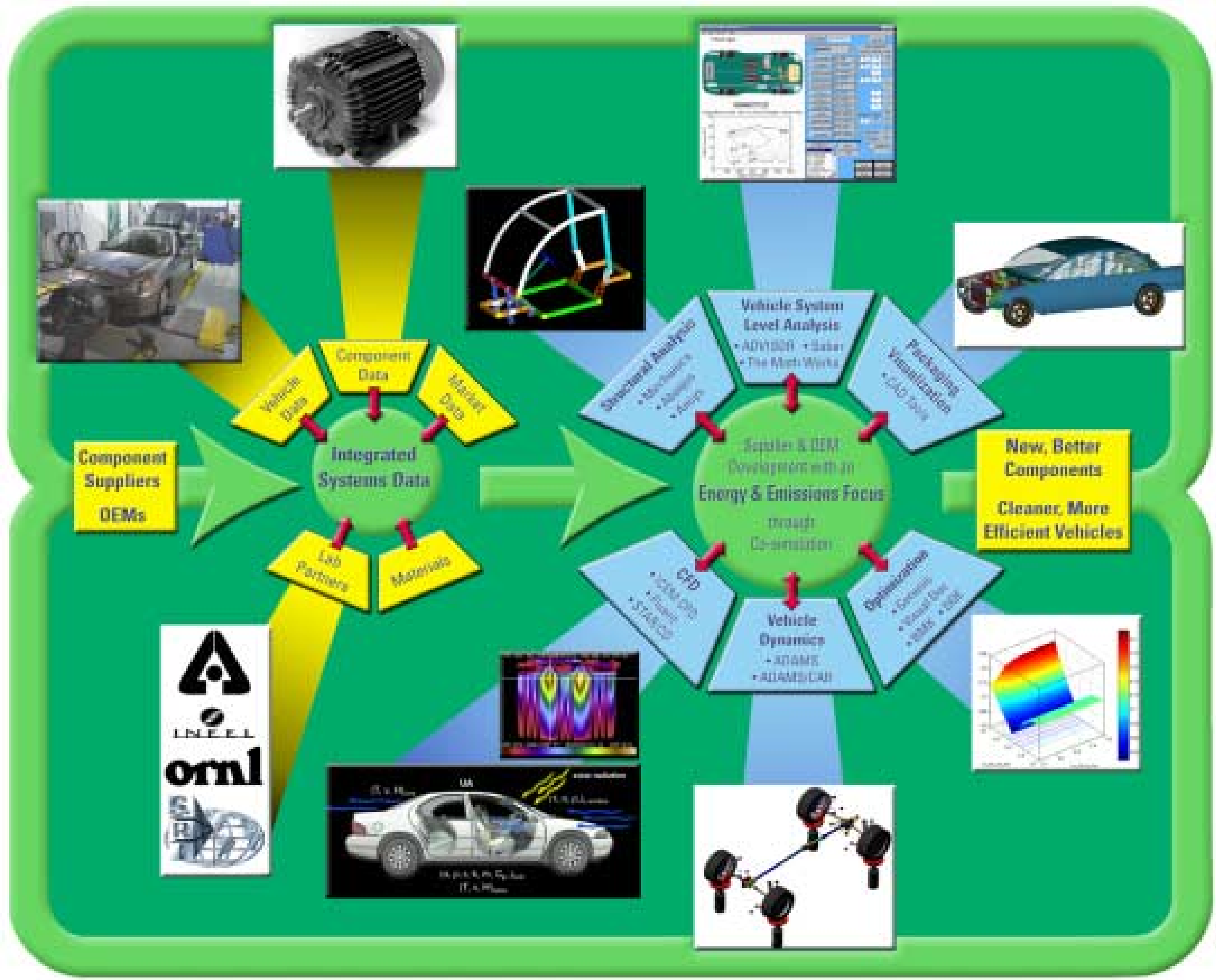
Step 5 – Vehicle Simulation, ADVISOR

- Fuel economy prediction for drive cycle
- Tailpipe estimate
- Transient A/C model w/boiling
- A/C size and performance for drive cycle

Summary

- **Brief Overview of the benefits of ADVISOR & Solid Modeling Integration**
  - Packaging studies
  - Mass & CG calculations
  - Interior volume generation for occupant comfort analysis & a/c sizing
  - Generation of geometry for future work (ADAMS, Crash analysis, etc.)

Future Direction: Functional Digital Vehicle



The Integration of ADAMS/Car with ADVISOR

Sandeep Joshi
Mechanical Dynamics, Inc.

Users Conference for ADVISOR
Costa Mesa, CA
August 24-25, 2000

ADAMS

Presentation Overview

- Introduction to Mechanical Dynamics, Inc. (MDI)
- Introduction to ADAMS/Car
- Interfacing ADVISOR with ADAMS/Car
- Closing Remarks

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ADAMS

Introduction to MDI

- Founded in 1977
- Pioneered the field of Mechanical System Simulation.
- ADAMS line of software products is the most widely used MSS software in the world
- Vehicle dynamics, general dynamics, controls, space structures, mechanism modeling, aerospace systems simulations, railcar and motor-sports applications
- Ten offices in the United States and wholly owned subsidiaries in several countries around the globe
- http://www.adams.com

ADAMS

Functional Virtual Prototyping

- Functional simulation of real-world systems
- Reduces time-intensive, costly, hardware build-test-refine cycles
- Improves quality (cut warranty and repair/maintenance costs)
- Managing risks through better information upfront
- “what-if” scenarios

Mechanical Dynamics

ADAMS

Presentation Overview

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ADAMS

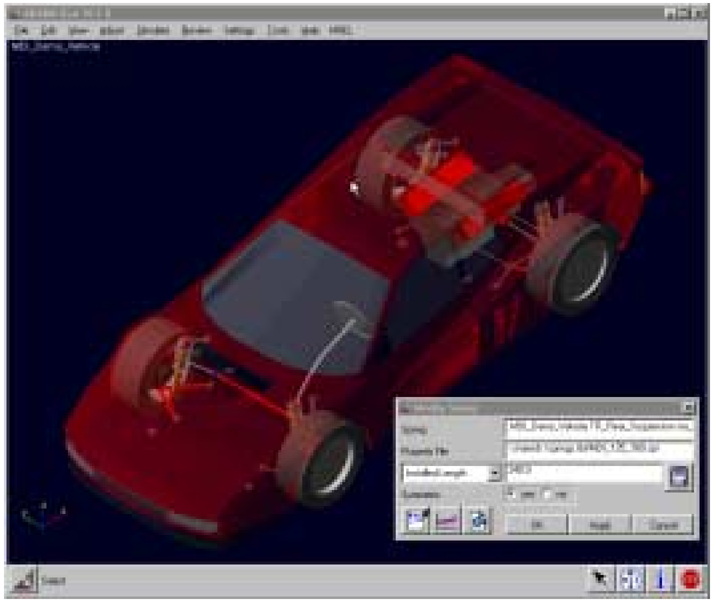
Introduction to ADAMS/Car

- Consortium of automakers including Audi, BMW, Renault, and Volvo
- Fully parametric
- Build and simulate virtual prototypes of vehicles and vehicle assemblies
- Software Modules: Suspension Design, Conceptual Suspension, Vehicle Dynamics
- Add-on Capabilities: Engine Simulation, Driveline Simulation, Tire Simulation, Driver Simulation

Mechanical Dynamics

Introduction to ADAMS/Car

- Interfaces seamlessly with other ADAMS products (including ADAMS/Insight for DOE)
- Demo ADAMS/Car
  - Two operational modes, Template Builder and Standard Interface
  - Kinematic and/or Compliant Subsystems
  - Flexible Bodies
  - Data Libraries
  - Curve Manager
  - Load Cases
  - Plot Configuration



ADAMS

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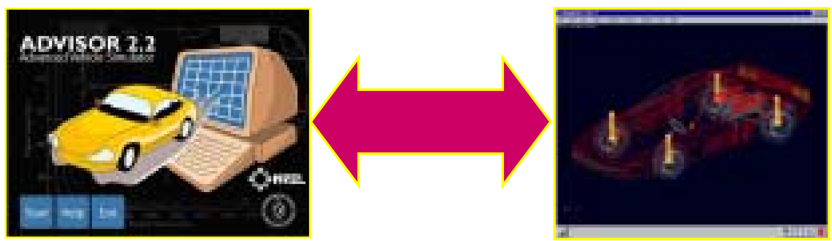
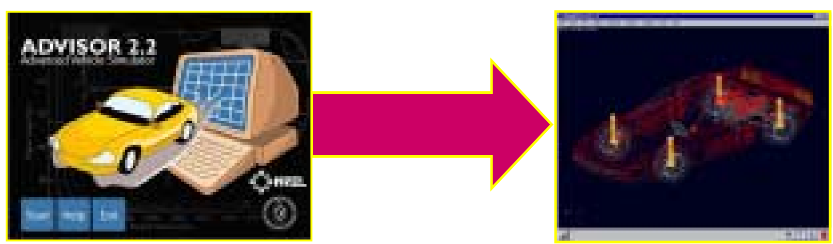
ADAMS

Outline of Interface

- Two interface approaches will be used:
  - ADAMS/Car - ADVISOR Cosimulation



  - Export to ADAMS/Car



  - Each approach has its own advantages and serves different simulation purposes.

Mechanical Dynamics

ADAMS/Car - ADVISOR Cosimulation

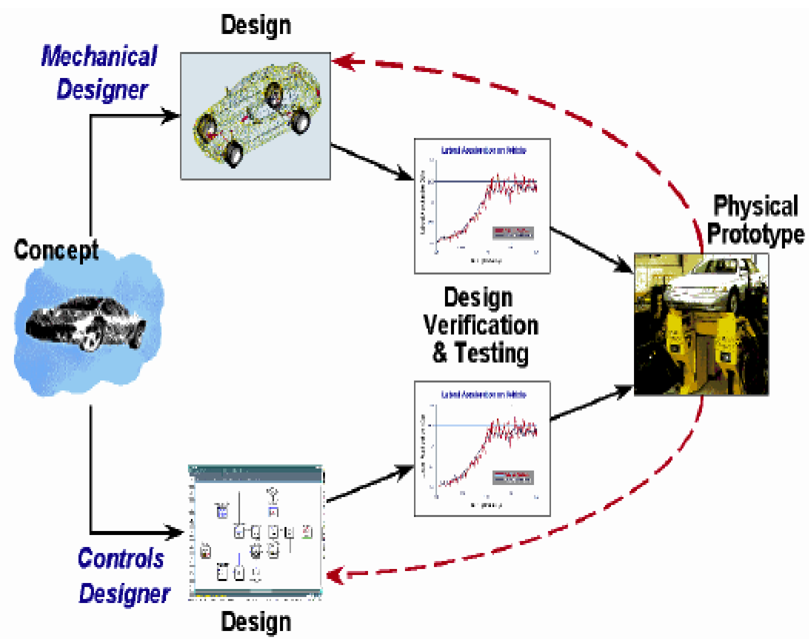
- Overview
  - Linking ADAMS/Car full vehicle model with ADVISOR model
  - Both ADAMS and Simulink solvers run together
  - Information passed back and forth between the two at each time step
- Method
  - ADAMS/Car full vehicle model using customized powertrain template
  - Use the ADAMS/Controls interface for exporting the plant
  - Modified ADVISOR model to work with ADAMS/Car model

ADAMS

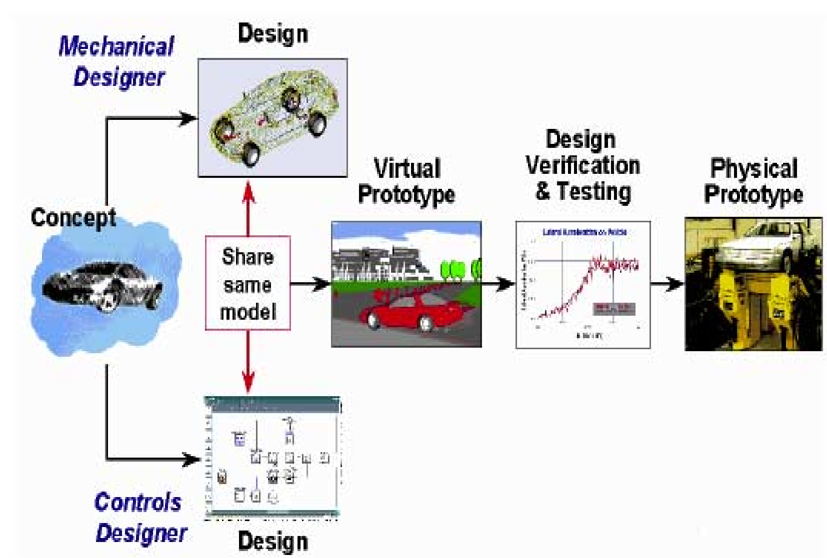
ADAMS/Car - ADVISOR Cosimulation

- General Benefits
  - Share Models

Design Process before ADAMS/Controls



Improved Design Process after ADAMS/Controls



Mechanical Dynamics

ADAMS

ADAMS/Car - ADVISOR Cosimulation

- General Benefits (contd.)
  - Verify combined effects of a control system on a non-linear non-rigid model
  - Eliminate risk of having control law developed for the wrong mechanical model
  - Add sophisticated controls to your ADAMS model
  - Generate mechanical system simulation models directly from your ADAMS data
  - Analyze results of the cosimulation either in the ADAMS or the control application environment

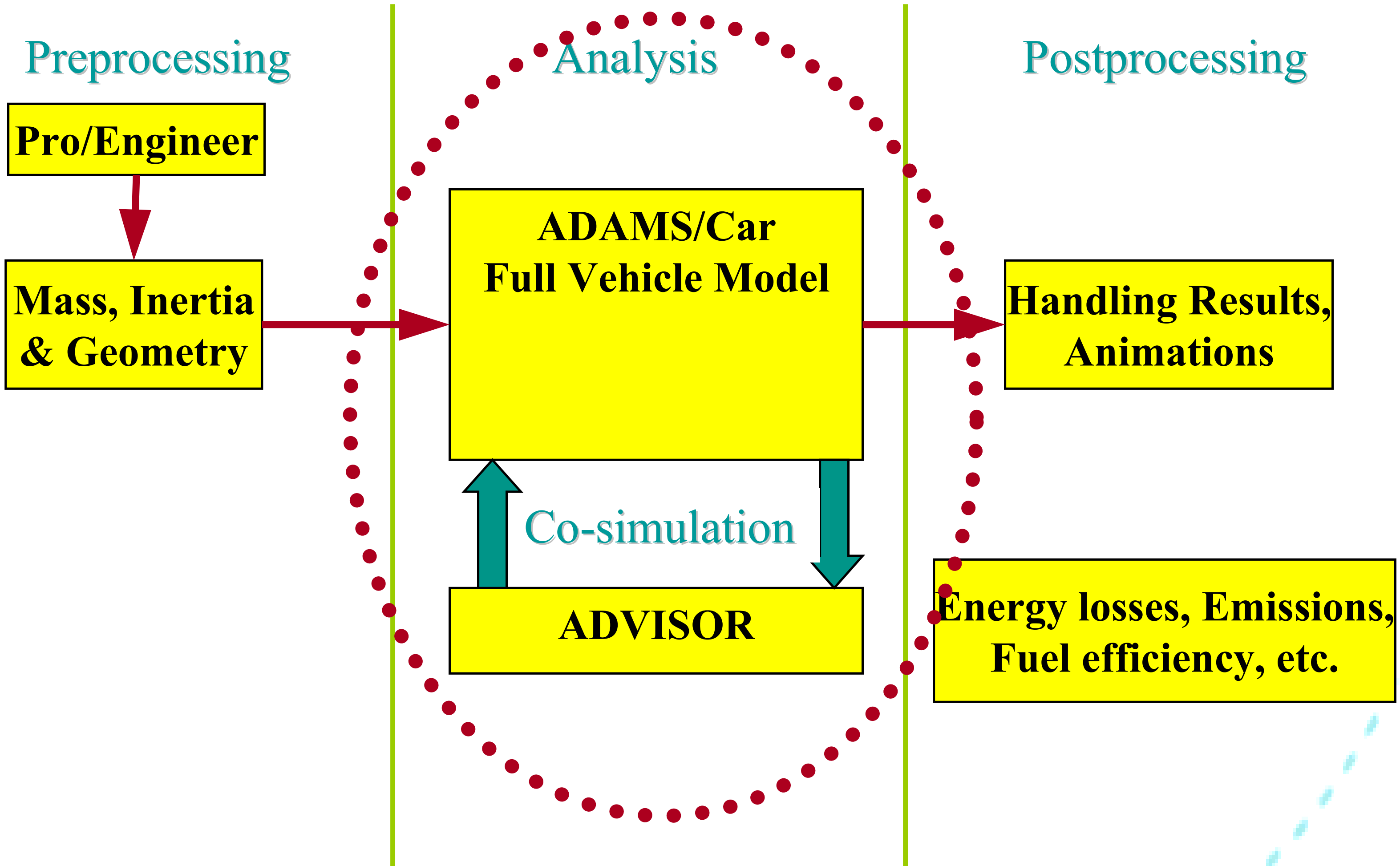
Mechanical Dynamics

ADAMS

ADAMS/Car - ADVISOR Cosimulation

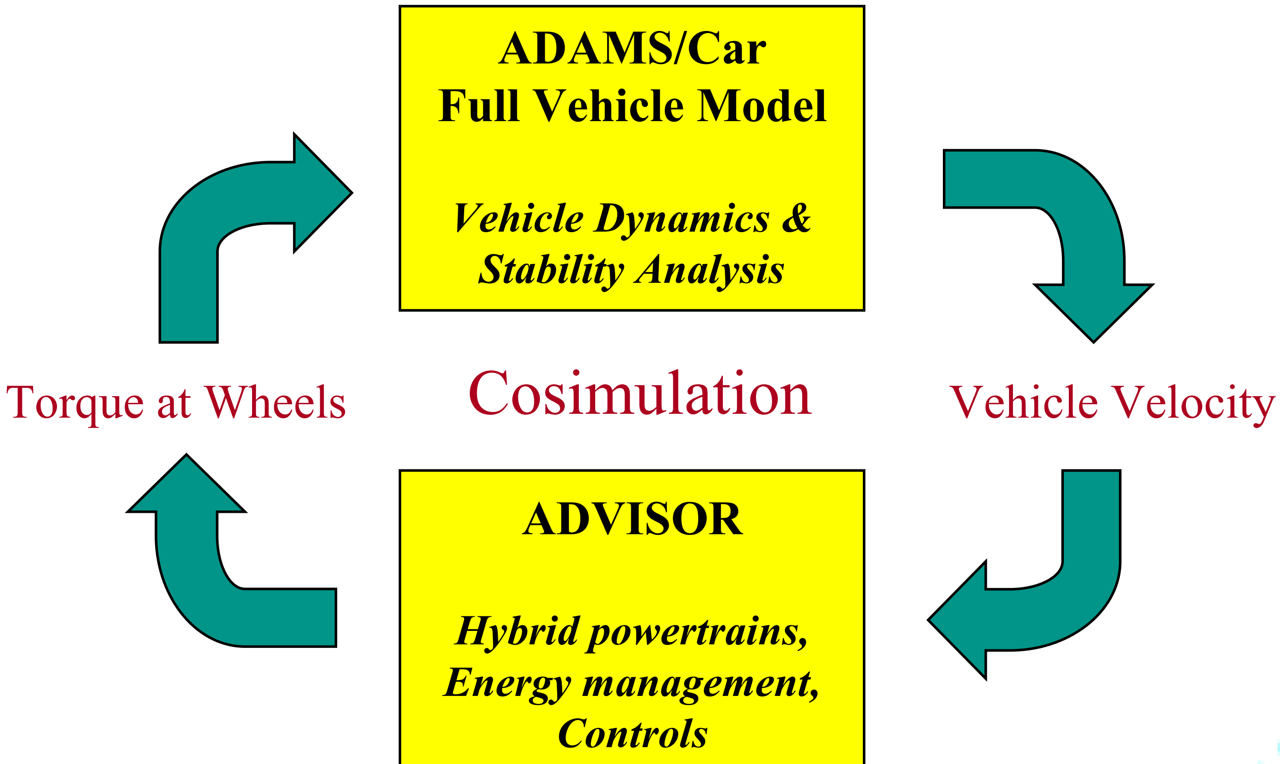
- Specific Benefits
  - Simulate 4WD/AWD powertrains
    - Torque split can be actively controlled by ADVISOR
  - Calculate energy losses during handling/durability events
    - Useful for trying minimizing losses for maximum fuel efficiency
  - Integrate accessory loads (like electric power steering) and look at their energy impact vs performance
  - Trade-offs to accurately assess impact of vehicle/component mass reduction and evaluating effect on dynamic performance

ADAMS/Car - ADVISOR Cosimulation



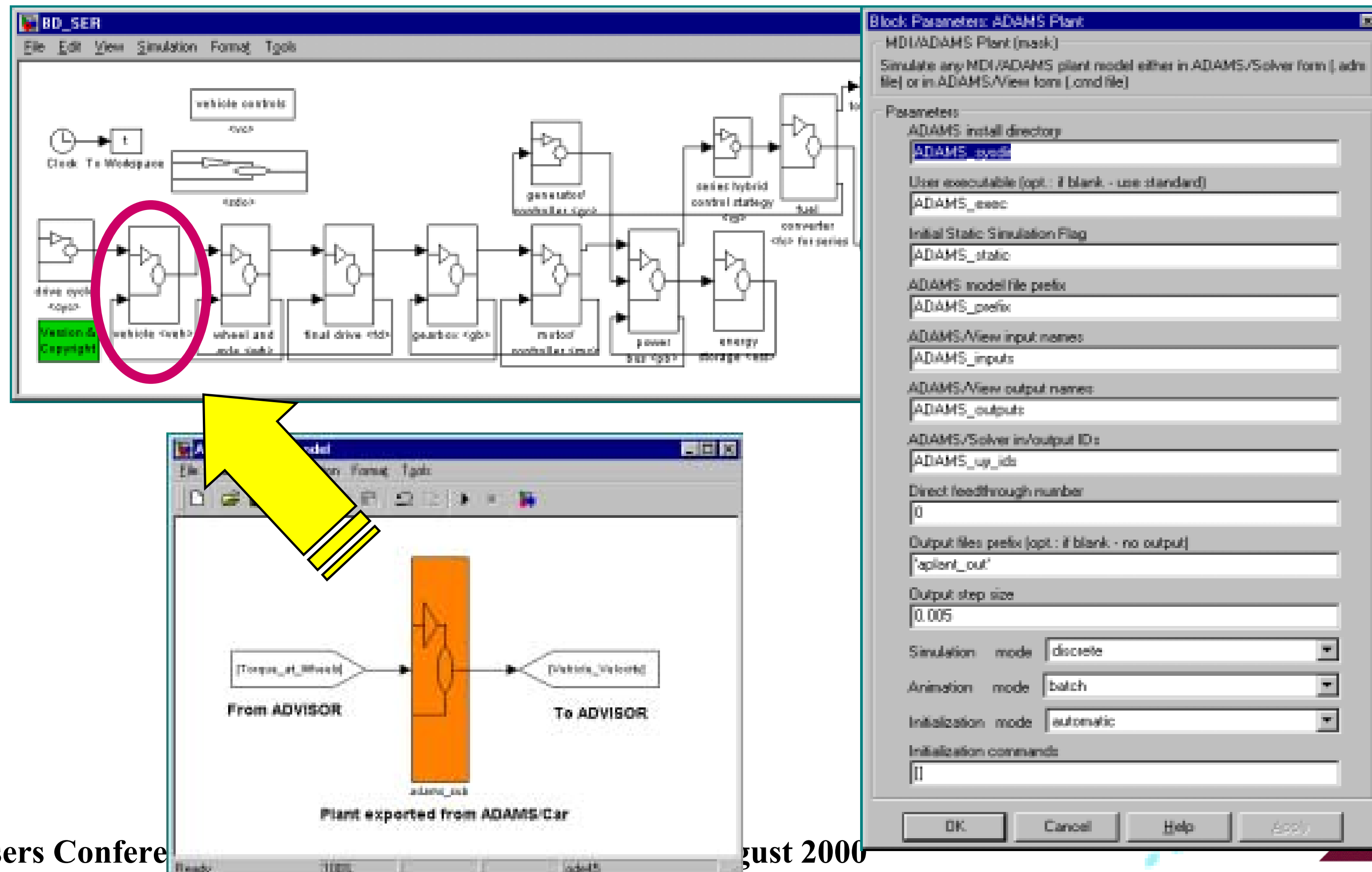
ADAMS/Car - ADVISOR Cosimulation

- Information Flow
  - The major variables exchanged are shown below. Additional information is also exchanged.



ADAMS/Car - ADVISOR Cosimulation

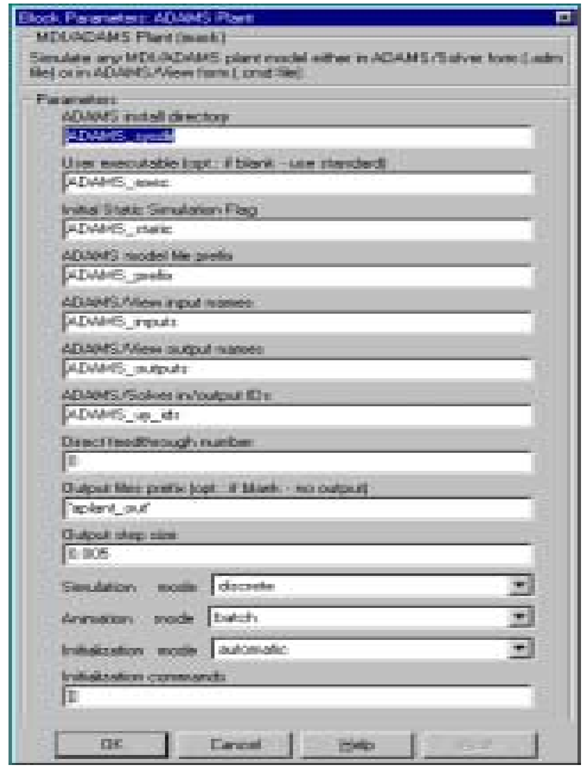
- Exporting ADAMS/Car Plant to Simulink



ADAMS

ADAMS/Car - ADVISOR Cosimulation

- Demo Cosimulation
  - ADAMS Plant Mask



- Results can be read back into ADAMS for postprocessing (animation and plotting)

Mechanical Dynamics

ADAMS

Export to ADAMS/Car

- Overview
  - ADAMS/Car full vehicle model with mass and inertia properties exported from ADVISOR
  - One way information flow to ADAMS/Car

- Method
  - Output mass and inertia properties from ADVISOR to ADAMS/Car
    - Optionally, geometry may be specified in web interface
  - Run standard handling maneuvers in ADAMS/Car

Mechanical Dynamics

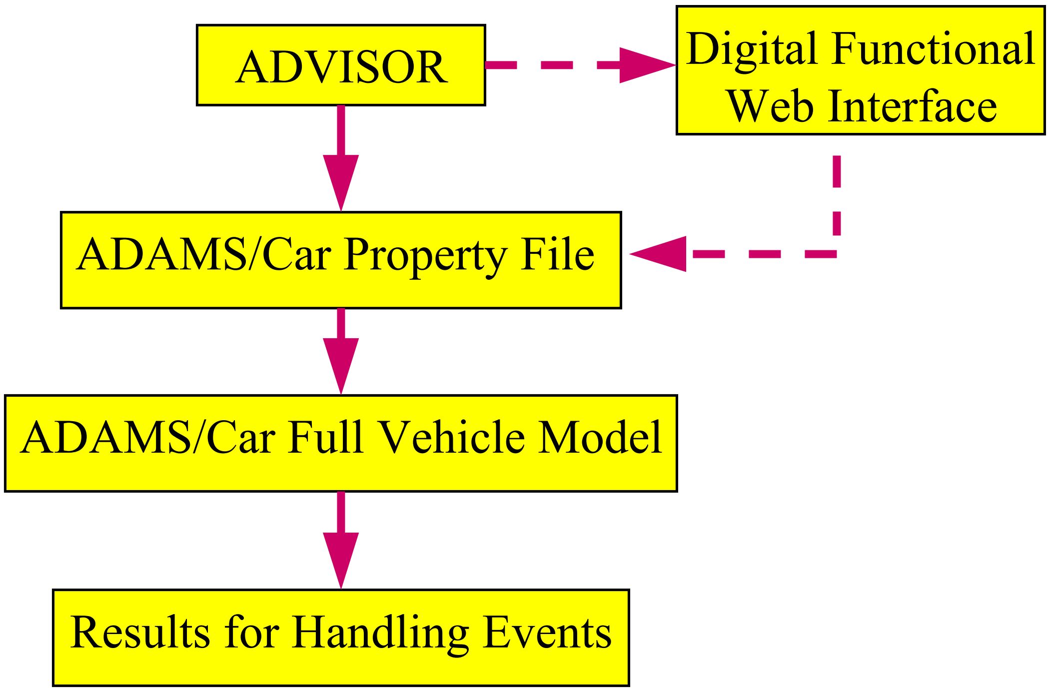
Export to ADAMS/Car

- Benefits
  - Faster simulations
  - Quick estimate of handling performance of hybrid vehicle
    - Example: allows analysis of battery pack location (often a large mass) and effect on handling

ADAMS

Export to ADAMS/Car

- Information Flow



Mechanical Dynamics

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ADAMS

Status

- Work in progress
- ADAMS/Car - ADVISOR Cosimulation
  - Proof of concept phase completed.
  - Need to modify ADVISOR to be used in the cosimulation mode
- Export to ADAMS/Car
  - Interface for reading in an ADAMS/Car property file into an ADAMS/Car full vehicle model completed.
  - Need to develop interface to write out these property files from within ADVISOR (or any other source)

ADAMS

Conclusions

- ADAMS is the world's most widely used mechanical system simulation tool.
- ADAMS is the de facto standard for functional system-level virtual prototyping in the automotive industry.
- Cosimulation is a proven technology that allows us to study the effects of a control system on a non-linear non-rigid mechanical system model
- As applied to this interface, cosimulation will allow us to simulate 4WD/AWD conditions, study energy losses in handling events, and include accessory loads in the model

Mechanical Dynamics

ADAMS

Conclusions (contd.)

- The "Export to ADAMS/Car" method will facilitate getting quick estimates on the handling behavior of hybrid vehicles

ADAMS

The Team

- MDI
  - Chris Gaddy
  - Sandeep Joshi
  - Rachael Kadell
  - Matthew Ma
  - Jennifer Peeples
  - Tony Spagnuolo
- NREL
  - Aaron Brooker
  - Terry Penney
  - Sam Sprik
  - Keith Wipke

Feedback

- Comments or questions?
- Contact Information
  - sjosh@adams.com
  - 949-786-0600 x100

The Integration of ADAMS/Car with ADVISOR, Realization of the "Functional Digital Vehicle"

Tony Spagnuolo
Mechanical Dynamics Inc.

ABSTRACT

As product complexity increases with hybrid electric vehicles (HEV) and competitive product development cycle times are reduced, hardware prototype creation and testing becomes one bottleneck in successful HEV launches. Due to this bottleneck, leading global manufacturers are feeling increasing pressure to rapidly institute enterprise-wide, simulation-based design and virtual prototyping practices that can insure greater product performance and quality in a fraction of both the time and cost required with traditional build-and-test approaches. This paper outlines the functional virtual prototyping implementations for HEVs and discusses the industry trends supporting such a shift. Specifically a connection between ADVISOR and ADAMS is outlined and discussed.

Figure 1. Moving from Physical to Virtual Prototyping

INTRODUCTION

There is a growing emphasis to develop hybrid electric vehicles (HEV), since they offer the opportunity to reduce energy consumption and emissions while still providing the consumer the utility of today's passenger vehicle. There are great engineering challenges in developing the practical power plants for hybrid electric vehicles; however, the ultimate challenge is consumer acceptance. Consumers have ever-increasing demands on ride, handling, durability and convenience features. Without a dramatic shift in market dynamics (e.g. a dramatic increase in fuel costs), it is unlikely that consumers will sacrifice their demands when selecting a vehicle in the future. Therefore, an HEV concept must demonstrate its ability to meet market requirements during the development process, or risk program cancellation.

The question is how does the automotive industry today deliver vehicles that meet customer expectations? If we look at one successful vehicle, the current BMW 3-series sedan came to market amidst a flurry of accolades and awards. "Perfection down to the last detail" was an overriding philosophy throughout the design process used to create this latest version of "the Ultimate Driving Machine." According to BMW Magazine [1], the development process involved five and a half years, 2.6 million man-hours, 130 hand-made system-level hardware prototypes created at a cost of roughly $350,000 per vehicle.

Assuming BMW has a competitive and representative vehicle development process, it is unlikely that a single HEV program will be able to afford such a process. However, without such a process it is likely that an HEV development program will not meet market standards. How can HEV program increase its confidence that it will meet market demands without the high cost of a physical prototype based development process? The answer is the Virtual Prototyping.

Simulation-based design practices allow product designers, engineers, and analysts to more quickly assess *form, fit, function*, and *manufacturability* of new products from concept design to production. No longer is it necessary to wait months to build a hardware prototype to make a small number of expensive modifications in order to assess proposed design changes. Instead, participants in the design process are able to construct accurate virtual prototypes, exercise the models through hundreds of tests with thousands of variations, and optimize the form, fit, function, and manufacturing characteristics in a fraction of the cost and time of traditional hardware prototype processes.

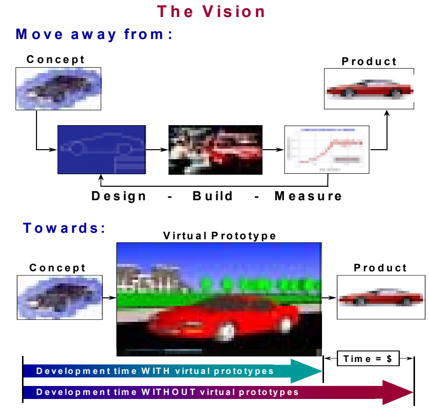

Figure 2. Moving from Physical to Virtual Prototyping

TRADITIONAL CAD/CAM/CAE VS. SYSTEM-LEVEL VIRTUAL PROTOTYPING

Traditional CAD/CAM/CAE practices throughout the 1970's and 1980's focused on a concept referred to as "art-to-part." Most engineering software activity was oriented toward the design, development, and manufacturing of higher quality parts. Detailed, three-dimensional solid modelers (CAD) allowed for quick part design and understanding of "form." Finite element software (CAE) made it feasible to perform detailed meshing and analysis of structural effects, thermal effects, and vibratory characteristics, or "function," of individual parts. Software aimed at improving "manufacturability" of parts (CAM) provided better control of machine tools, robots, mold procedures, stamping procedures, forging processes, etc.

These traditional CAD/CAM/CAE tools and processes were embraced and implemented throughout major industries, including the automotive, aerospace, general machinery, and electromechanical markets. For the most part, they lived up to their promise of dramatically improving part design. In the automotive industry, for example, automotive suppliers reported a 40% reduction in part defects over a recent five-year period. This significant improvement was accompanied by a corresponding drop in development and manufacturing costs attained through successful implementation of better CAD/CAM/CAE tools and processes.

Unfortunately, during the same five-year period that automotive part suppliers were achieving a 40% reduction in part defects, the vehicle manufacturers (OEMs) who were using these parts to assemble and market full vehicles experienced only a 20% reduction in warranty costs. In some sense, this was a surprise to many OEMs who expected a one-to-one correspondence between part defects and warranty costs. In retrospect, it seems perfectly sensible. ***Optimal part design rarely leads to optimal system design.*** For example, when perfectly good brakes are combined with a perfectly good suspension system and a fine chassis, the resulting combination often performs in a less-than-stellar manner. Clearly, the interaction of *form, fit, function*, and *assembly* of all parts in a product is a major contributor to overall product quality. We may be reaching levels of diminishing return in applying CAD/CAM/CAE technologies to part design. ***The big opportunity to increase quality and reduce time and cost has now shifted to the system level.***

More significant returns on investment can be realized today through the effective use of simulation-based design processes and ***virtual prototyping applied to system-level design***. Manufacturers now need a means to quickly assess *form* and *fit* of entire assemblies of three-dimensional solid models comprising a product (Digital Mock-Up). They need to be able to assess the operating *function* of the entire assembled product (Functional Virtual Prototyping), not just the component parts. And they need to investigate the entire *manufacturing* and *assembly* of the product (Virtual Factory Simulation), not just the creation of the parts. As global product manufacturers began to realize this fact over the last 2-5 years, it was natural for them to look for extensions to their traditional CAD/CAM/CAE systems to address system-level design. Part-focused CAD/CAM/CAE providers hurried to extend their software to address system-level designs with varying levels of success. But simple extensions of part design paradigms to system-level design often lead to impractical software products. For instance, as designers and engineers tried to construct large assemblies of solid models to facilitate system-level interference detection and virtual fly-through, the rendering performance of most traditional CAD/CAM/CAE systems became unacceptably slow (e.g., measured in hours). Similarly, engineers and analysts investigating system level operating performance attempted to combine all of their component finite element models and perform nonlinear finite element system simulations. These typically took Cray-weeks of simulation time to predict only seconds of real operating performance, thus making design trade-off investigations impractical. Similar problems occurred in

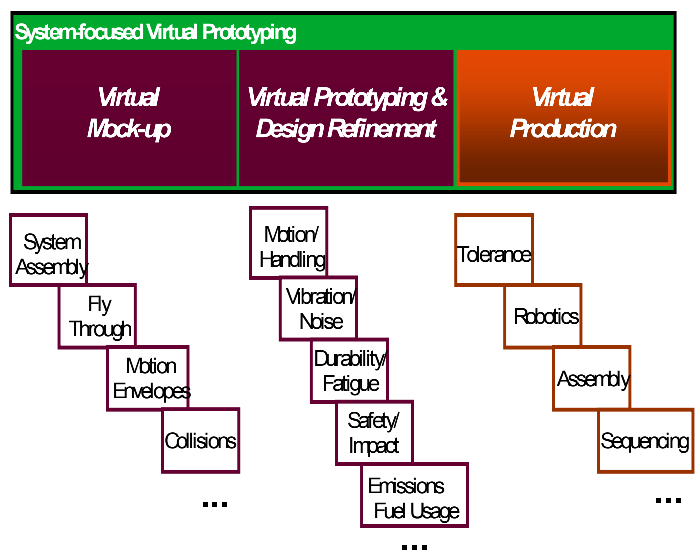

Figure 3. Technology Segments of System-Focused CAD/CAM/CAE

New methodologies, specifically oriented toward rapid system-level design, had to be adopted. The growth in simulation-based design tools has now shifted away from traditional CAD/CAM/CAE software and toward these newer system-focused solutions. Specifically, these system-level solutions include Digital Mock-Up tools to investigate product *form and fit*, Functional Virtual Prototyping tools to assess product ***function*** and operating performance, and Virtual Factory Simulation to assess *manufacturability* and *assembly* of the product.

Enterprise-wide, Product Data Management (PDM) is the "glue" that enables these system-focused solutions to be successful by making all of the up-to-date component data readily available and manageable.

Digital Mock-Up (DMU) solutions that make efficient use of tessellated three-dimensional component solid models were pioneered by Tecoplan, Engineering Animation, Clarus, and Division among others. These allow efficient design collaboration, mark-up, fly-through, and interference/collision detection. Integrated with Product Data Management Systems, these Digital Mock-Up products provide an excellent means to insure that all of the parts of the product will fit together properly and that the product will appear as specified.

Functional Virtual Prototyping solutions make efficient use of three-dimensional component solid models and modal representations of component finite element models to accurately predict the operating performance of the product in virtual lab tests and virtual field tests. Mechanical Dynamics pioneered this field with its ADAMS system simulation product line and is expanding its coverage through its partnership with MTS systems, nCode, and the solid modeling and finite element solution vendors.

Tecnomatix and Deneb pioneered virtual Factory Simulation. With these solutions, the entire manufacturing and assembly of products can be simulated, and field maintenance of products can be assessed as well.

The combination of Digital Mock-up, Functional Virtual Prototyping, and Virtual Factory Simulation provide a means for realizing an effective transition from hardware prototyping practices to software prototyping practices with all of the concomitant benefits. The remainder of this paper will focus on the subject of Functional Virtual Prototyping and the implementation of Functional Virtual Prototyping for HEVs.

FUNCTIONAL VIRTUAL PROTOTYPING

Effective Functional Virtual Prototyping (FVP) allows the full operation of the product to be considered and evaluated early enough in the design process to allow for "function" to truly drive "form" and "fit." It also allows multi-function optimization to be realized, such that a true balance can be obtained between competing functional requirements involving performance, safety, durability, cost, comfort, emissions, fuel economy etc. These two benefits were largely impractical in traditional development cycles involving extensive reliance on hardware prototypes. In addition to these benefits, functional virtual prototyping has proven effective in facilitating tighter and more successful relationships between manufacturers and their lead suppliers.

Deployment of Functional Virtual Prototyping typically involves five phases: *Build, Test, Validate, Refine*, and *Automate*.

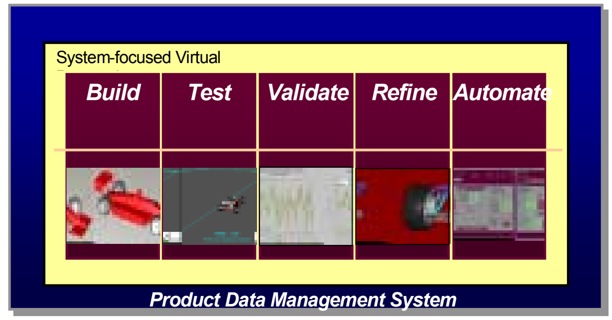

Figure 4. Five Phases of Functional Virtual Prototyping

BUILD

During the *Build* phase, virtual prototypes are created of both the new product concept and any target products which may already exist in the market. In the early concept stage, the virtual prototype models of the new product concept are kept simple and are most often driven by desired functionality data curves, rather than by specific product topologies. Appropriate target setting is, of course, very important. For example, the desired functionality data curves should be derived from a customer Quality Function Deployment (QFD) study that identifies the desired operating performance. For instance, in the initial design of a vehicle suspension system, the virtual prototype model often involves only the overall vehicle body and a set of vehicle suspension curves that relate the movement of the body to the movement of the wheels. These data curves embody the desired suspension characteristics. During later model refinement, specific suspension topologies are chosen (e.g., McPherson Strut) and the software optimizes suspension geometry and structural properties to yield the relationship described by the chosen curves. Similarly, to create models of target products, the actual target product is physically tested and its characteristics are accurately measured. This data is incorporated into a system-level model of the competitive vehicle to use later during the evaluation phases.

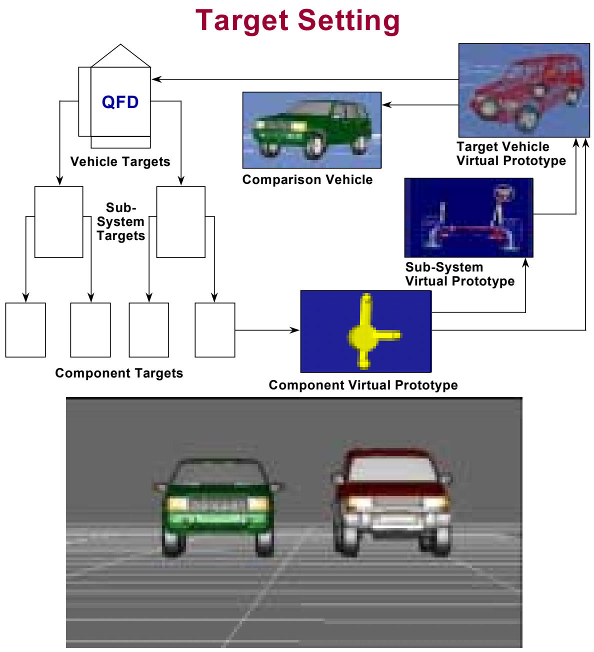

Figure 5. Target Setting via QFD

A modular system design process facilitates functional virtual prototyping and the manufacturer-supplier interaction. Clear inputs and outputs between various subsystems permit the development of multiple subsystem models with varying levels of model fidelity and complexity. These subsystem and system-level virtual prototypes are comprised of rigid and flexible representations of component parts connected through mathematically defined constraints. The geometry and mass properties for the parts are derived from component solid models; while the structural, thermal, and vibratory properties are derived from component finite element models or experimental tests. The most effective implementations of virtual prototyping begin in this Build phase with a close cooperation between engineering analysts and test engineers. Also, up-front planning of the product parameters that may be varied in the design cycle and how manufacturers and suppliers are going to share models, can be tremendously helpful.

TEST

Perhaps the single most important axiom for successful functional virtual prototyping is to ***simulate as you test.*** Testing of hardware prototypes has traditionally involved both lab tests and field tests in various configurations. With virtual prototyping, we need to create virtual equivalents of the lab tests and the field tests. By doing this, we greatly facilitate model validation through testing, and we break down the cultural barriers to the adoption of virtual prototyping practices. With regard to lab tests, successful virtual prototyping dictates that we need to construct virtual test rigs that reproduce the test procedures and boundary conditions of the real fixture and machine. With field tests, we need to construct models that represent the actual operating conditions of the product in the field. This will involve virtual test tracks in automotive.

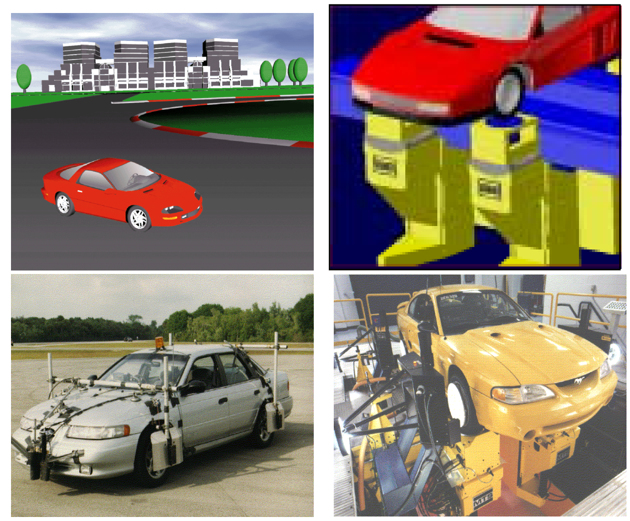

Figure 6. Field and Lab Testing: Vritual and Physical

Effective implementations of Functional Virtual Prototyping require a tight synergy between physical testing of hardware prototypes (components and systems) as well as simulation-based testing of virtual prototypes (components and systems). Testing requirements vary during the different stages of the design process. At the outset of a new product design based on virtual prototyping, hardware testing is instrumental in two ways. First, component tests are performed using various real component alternatives. These tests provide good characteristic data for a complete system-level virtual prototype model. Secondly, full system hardware tests are conducted using target products. This allows for the simultaneous development of virtual prototypes of competing products so that performance comparisons can be made throughout the design and development cycle.

Then, during concept design, virtual testing is used to exercise the new system model through a limited number of actual test scenarios such that performance data can be collected and validation can be performed. For companies that are initiating new virtual prototyping processes, it is imperative that they build a first system-level physical prototype at this stage in order to insure confidence in the simulation model. Companies who have been through this process a number of times have learned how to validate the modeling assumptions such that a physical prototype is unnecessary at this stage.

Once initial validation has been achieved by correlating the test results of the physical and virtual system prototypes, the true value of virtual prototyping begins to become apparent. Thousands of system variations, component choices, parameter choices, and tolerances can be examined through simulation and the results can be used to confidently make design choices about the new product. This will be discussed later in the section entitled “Refine.”

Testing remains an important part of functional virtual prototyping throughout the design cycle. Virtual testing is conducted continuously. Physical testing is introduced at various stages to either re-validate the model after significant refinement or to test certain configurations of the product containing design parameters outside of those for which the model has been validated.

VALIDATE

The importance of accurate validation of system-level models and modeling assumptions should not be under-emphasized. Functional Virtual Prototyping can yield a wealth of information to support rapid decision-making. It is critical to insure that this information reflects the actual operating performance of the new product. The validation phase is not overly difficult, but often is not approached with as much rigor as is warranted. The companies with the very best records in making effective use of Functional Virtual Prototyping have invested significant time and resources in building a validation library. This library defines how models need to be constructed so that simulation performance results can be easily compared with test results. The library catalogues past validation work and summarizes modeling assumptions that have been validated. And the library is integrated with an internal Product Data Management (PDM) system so that data and information is readily available.

Good simulation tools and processes can greatly facilitate the validation process. For instance, a simulation software product that provides quick information on design sensitivity to various parameter changes can pinpoint areas of a model to be investigated to improve correlation between experiment and simulation. Also, as stated earlier, it is important to "simulate as you test," meaning that the same testing and instrumentation procedures should be used both in the physical and virtual test process.

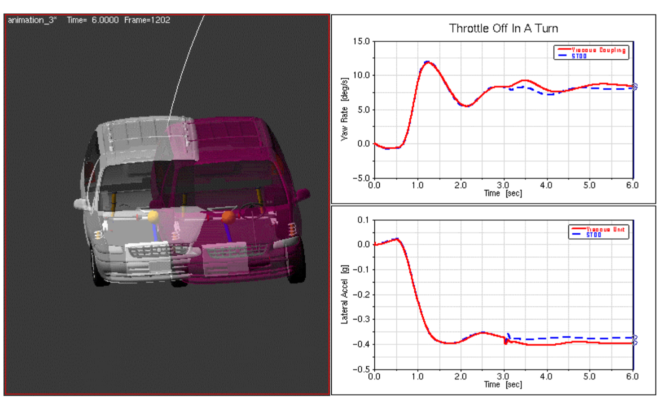

Figure 7. Typical Parameter Study With a Virtual Prototype

In a typical validation process, the physical and virtual models are tested identically and baseline results are derived. The results are compared either manually or in automated computer-based fashion. Discrepancies are noted in specific performance results. Design sensitivity analyses are performed on the virtual model to identify design parameters or model areas that significantly contribute to the performance results that do not correlate. Then, a mixture of manual changes and computerized nonlinear optimization techniques are employed to make changes to the model parameters identified or the test procedures until acceptable correlation is achieved and the model is validated across the different tests.

With experience, modeling assumptions can be correlated and catalogued. This allows for the automated creation of new product virtual prototypes that can be utilized with confidence without the need for the construction and testing of an initial physical prototype. Physical prototypes are still needed downstream in the process to verify the design prior to production.

REFINE

Refining a virtual prototype involves two aspects, refining the fidelity and breadth of the model, and refining the product design itself. Each of these will be discussed separately here.

As the design process progresses, the virtual prototype models will be relied upon to investigate more and more functionality. Initially, it may be enough to understand speed of operation, the space envelope of operation, the total power requirements, etc. This understanding can help drive component topology selection and overall design parameters. Then, as issues of comfort, noise, vibration, and durability need to be addressed; the virtual prototype model will need to be enhanced. It is important that the virtual prototype can access subsystem models of varying complexity and model fidelity. For investigations of more complex phenomenon, it will be important to enhance the model by replacing more and more of the rigid subsystem models with flexible counterparts. Models of the fluid power systems that interact with the mechanical and electrical components will need to be represented. Automatic control systems that alter the operating performance of the product will need to be accurately represented. These are all natural extensions of the initial virtual prototype. Component and subassembly models of varying complexity must be constructed in such a manner so as to be quickly interchangeable. For instance, when investigating engine performance in a vehicle, it may be important to exercise a fairly detailed engine model. However, if vehicle dynamics is the main focus, the engine model can be effectively replaced with a much simpler representation. A template-based design system that allows for quick and easy exchange of various subsystem models is of paramount importance for effective design refinement.

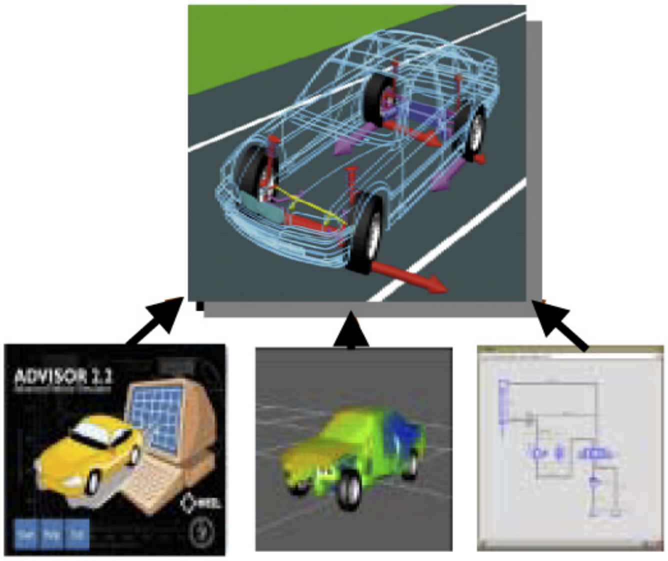

Figure 8. Successive Refinement of a Virtual Prototype

Refining the actual product design is where Functional Virtual Prototyping delivers the real value. Once a validated, system-level virtual prototype has been created with interchangeable subsystem models of varying model fidelity, a very rigorous design refinement process is within reach. First, a complete battery of product functional tests are defined and finalized. These will be the virtual tests used to sign-off on the new product design. Next potential design changes are identified in terms of component parameter changes, system topological changes, and potential manufacturing tolerances. Performing the complete battery of selected tests with all combinations of parameters and tolerances is both impractical and unnecessary. Statistics-based, Design-Of-Experiment (DOE) methods are used to consider the entire universe of combinations of these changes and determine what combinations of these parameters must be simulated in the battery of virtual tests in order to give a statistically relevant prediction of the envelope of operating performance. The identified combinations are then simulated using both the virtual prototype and the battery of virtual tests, and the results are exported to a simple spreadsheet. Curve fitting of these results allows for quick spreadsheet assessment of any potential design changes within the specified range. This approach facilitates rapid, knowledge-based decision making in product design review meetings. Requested changes to system design points or parameters can be immediately assessed for their impact on performance, safety, durability, comfort, and cost. Faster decisions and a better balance of competing functional performances result from this approach.

AUTOMATE (PUBLISH)

The approach outlined above leads to significantly improved products at lower cost. To simultaneously reduce the overall development time, it is necessary to automate the virtual prototyping process. This phase requires close cooperation between designers, development engineers, analysts, and test engineers. Automating the process can be done very effectively in companies that make the same type of products year after year. It is much more difficult in organizations where radically different products are created over time. Once the engineering analysts have worked through a few virtual prototyping cycles and helped create validated models that can be exercised through the parameter changes requested by the development engineers, the virtual prototyping environment can be automated through the use of a template-based design system. It works as follows. The engineering analysts catalogue: (1) parametric topologies that are normally considered for new products, (2) typical parameters that are varied in the design process, (3) the range of validity of various modeling assumptions, and (4) the different levels of subassembly model representations required for various levels of fidelity.

Then an analyst utilizes a template-based design system to create a series of design templates that can be used by the designers and development engineers to evaluate design changes. These templates automate the creation of the subassembly and system models. They allow input only within the range of the validated modeling assumptions. They hide the complexity of the model by only presenting the parameter changes that have traditionally been varied. And they automate the selection of subassembly representations in accordance with the type of test or performance output that is requested. If this is integrated with a PDM, it allows for quick comparisons of new design performance with previous designs or competitive target designs. The analysts publish these design templates internally for use throughout the design process and even later in field troubleshooting.

This makes it possible to have an enterprise-wide virtual prototyping process where any engineer in a vehicle manufacturing organization can access a validated model of any previous vehicle or current new vehicle design. They can replace subsystems, alter vehicle design parameters, add automatic control systems, and run the vehicles through standard test procedures to understand the effects of proposed changes. This is extremely powerful in stimulating creative input and capturing corporate design knowledge.

REALIZATION OF THE "FUNCTIONAL DIGITAL VEHICLE" FOR HEVS

The confluence of technologies such as Digital Mock-up and Functional Virtual Prototyping are enabling the true realization of the **Functional Digital Car** such that we can evaluate and optimize total vehicle performance on a computer. It is now possible to combine accurate mathematical model representations of chassis subsystems, hybrid power plant and driveline subsystems, and body subsystems to create a full virtual vehicle. We can then simulate the performance of this total vehicle in a virtual test lab environment or on a virtual test track and replicate real-world behavior.

This vision is now being realized with the integration of ADVISOR with ADAMS/Car, a product of Mechanical Dynamics Inc. (MDI). ADVISOR (Advanced Vehicle SimulatOR) was created by National Renewable Energy Lab (NREL) in 1994 to support the DOE (Department of Energy) Hybrid Program. ADVISOR, created in the MATLAB/Simulink environment, simulates conventional, electric or hybrid electric vehicles during driving cycles to determine the impact on emissions and fuel economy. ADVISOR is a template driven environment where validated models can be altered to determine the sensitivity of design to changes, a new design analyzed or a design optimized towards specific goals. It has been extensively used by many organizations around the world, with over 1700 copies downloaded from the world-wide-web.

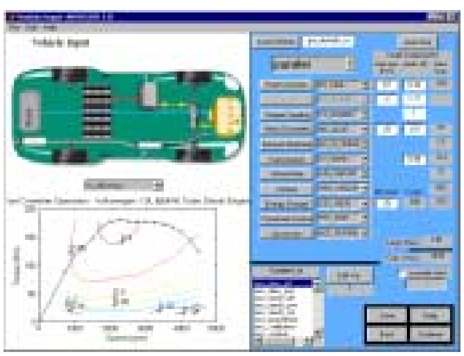

Figure 8. An ADVISOR Template

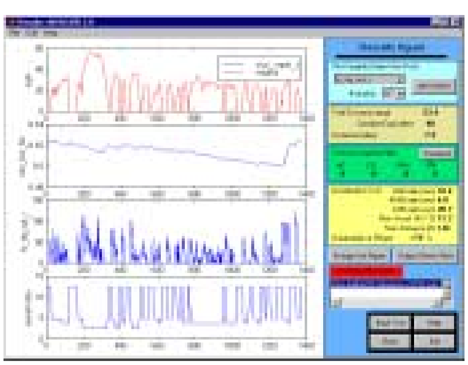

Figure 9. Output Results from ADVISOR

ADAMS/Car is a family of products which includes ADAMS/Pre, ADAMS/Driveline and ADAMS/Engine. The vehicle handling and vehicle dynamics tools are widely used in the automotive industry at companies such as Ford, VW, Audi and Nissan. These tools are used to investigate chassis subsystem performance, total vehicle handling and performance and system/ subsystem loads (static and dynamic). The environment allows the inclusion of chassis subsystems, flexible structures, control systems, drivelines, engine maps and driver models. The system can start from a characteristic based model and work up to a detailed system model including full component flexibility.

Figure 10. ADAMS/Car Application Area

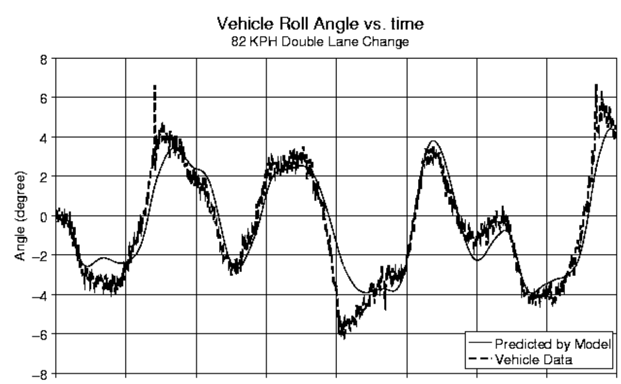

Figure 11. Representative ADAMS Vehicle Handling Output [2]

environment. Each component of a model, including the tests and physical data, is treated as separate template. This allows a user to quickly "swap" one subsystem for another, share models with a colleague or a supplier, run design sensitivity or perform what -if studies. Further, the modular structure eliminates the need to recreate subsystems in new models; a previously created subsystem can easily be retrieved and included. The template-based structure provides the opportunity to shift model building from an art to production, which is a key requirement for Functional Virtual Prototyping to have an impact on the automotive development process.

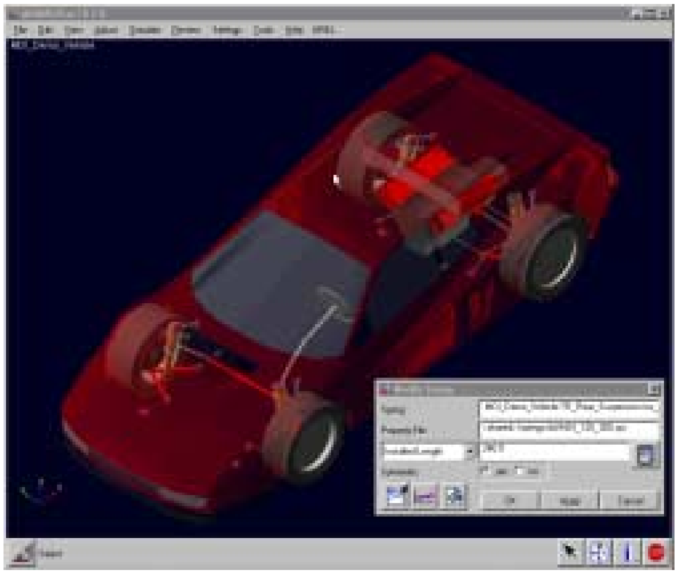

Figure 12: The ADAMS/CAR Application

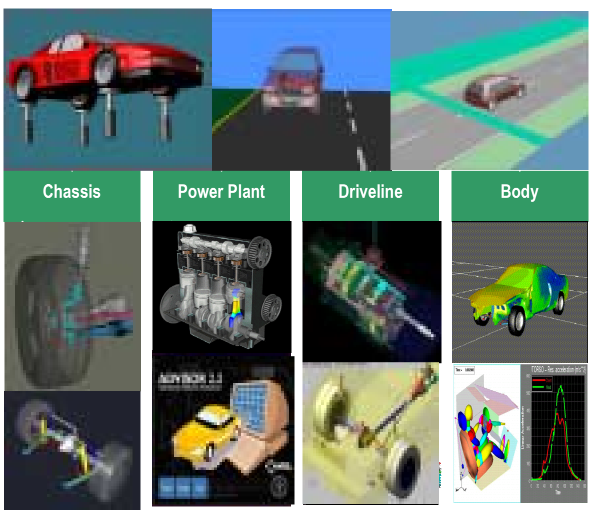

Figure 13: The ADAMS/CAR Modular Template Structure

In a typical design process scenario, ADVISOR can be used to optimized the power plant for fuel economy and emissions. Independently, ADAMS/Car can be used to optimize the chassis design for performance and loading. Then the two models can be combined together to study complete system performance. Combining the models will have two options: Co-simulation and export to ADAMS/Car.

CO-SIMULATION

Co-simulation is accomplished via an interface program called ADAMS/Controls. ADAMS/Controls links the ADVISOR model to the ADAMS/Car model by passing the relevant system states between the two programs during execution at each time step. Within ADAMS/Car a powertrain template will be customized for easy inclusion of an ADVISOR model during a simulation.

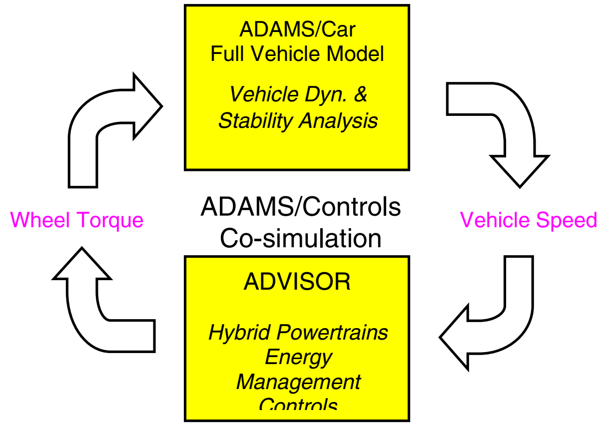

Figure 14: Advisor & ADAMS/Caro-Simulation

With the ADAMS/Car and ADVISOR models coupled, there are various systems, subsystems and attributes that can be more completely modeled and studied:

- 4WD/AWD powertrains (torque split actively controlled by ADVISOR)
- Vehicle handling/dynamics with new mass distribution
- Stability issues related to battery placement
- Determine energy losses during handling and durability events
- Determine accessory load energy impact vs. performance
- Asses impact of vehicle/component mass reduction on dynamic performance

EXPORT TO ADAMS/CAR

In this mode, there is one-way transfer of information from ADVISOR to ADAMS/Car. Since the ADVISOR contains information (mass and inertia) that ADAMS/Car requires, an export utility provides an easy method to populate an ADAMS/Car model, while minimizing the potential for data entry errors.

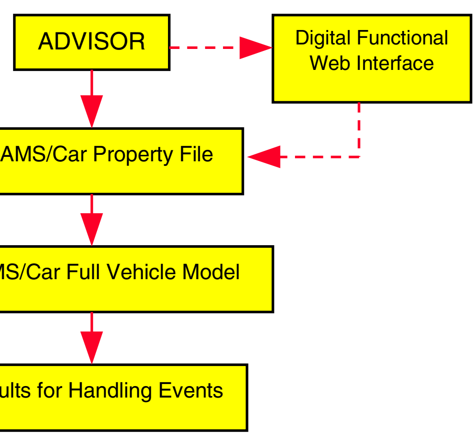

Figure 15: Export to ADAMS Flow

Once data is exported from ADVISOR to ADAMS/Car, it is possible to get a quick determination of the vehicle handling properties of a proposed HEV. For example, battery pack constitute a large percentage of the mass on some HEVs, so battery positioning is a major contributor to vehicle handling performance.

The integration of ADVISOR is currently under development and scheduled to be completed in late 2000. When completed, the complete system can be evaluated across multiple attributes by replicating standard test suites and modifying typical vehicle design parameters throughout their acceptable ranges. Results can be shared globally among design teams over the World Wide Web by means of Design-of-Experiment response surfaces, plotted results, and performance animations.

This, in essence, is the technology that will allow vehicle manufacturers to realize the projected dramatic reductions in cycle times while maintaining and increasing vehicle performance, safety, longevity, fuel economy and emissions. Effective implementation and automation of functional virtual prototyping can provide a significant competitive edge in the market.

MANAGING RISK MORE EFFECTIVELY

The result of Functional Virtual Prototyping is that manufacturers are much better equipped to manage the risks inherent in the product development cycle. Traditionally, the amount of information concerning the actual performance of a new vehicle was fairly low throughout the vehicle development process until the prototype and assembly stage. Then, behavioral information increased, and risk could be reduced through effective design changes. Unfortunately, late cycle changes are very expensive and error prone. With Functional Virtual Prototyping, behavioral performance predictions are obtained much earlier in the design cycle, thereby allowing more effective and cost efficient design changes and reducing overall risk substantially. Reducing risk in this way has multiple benefits. It leads to vastly improved designs, limits warranty and liability issues, reduces late cycle changes and costs, and helps to reduce overall development time.

TECHNOLOGY ENABLERS AND LIMITING FACTORS

An often-asked question is ‘why haven’t technologies such as Digital Mock-Up (DMU) and Functional Virtual Prototyping (FVP) been applied extensively before now?’ To understand this, it is important to look at factors that enable this technology and factors that inhibit it. Key enablers include the fact that three-dimensional solid models and component finite element models are now available for most system components, unlike in the past. Secondly, new technologies have been developed for simplifying the representation of component data so that it can be efficiently processed in large system simulations. Thirdly, fast graphic workstations that can quickly analyze and display system-level models have now become inexpensive and plentiful. Also, Product Data Management systems facilitate system-level design by making vast quantities of data available and current. These four factors make it possible to effectively deploy DMU and FVP today.

A few limiting factors still exist which retard progress in applying these newer technologies. First, very few universities have instituted effective training in these technologies, thus limiting the number of knowledgeable candidates for deployment. Secondly, hardware testing is ingrained in most manufacturing organizations and this newer technology is sometimes viewed as a threat rather than being synergistic. And lastly, effective deployment requires some process change within these large organizations and that requires a significant amount of training and the passage of time for overall adoption.

CONCLUSION

One of the bottlenecks in developing consumer accepted hybrid electric vehicles is the creation, instrumentation, testing, and modification of system-level hardware prototypes. Traditional CAD/CAM/CAE methodologies do not provide a good means to break this bottleneck. New products in the Digital Mock-Up (DMU) area, Functional Virtual Prototyping (FVP) area, and Virtual Factory Simulation (VFS) provide system-level counterparts to traditional component-focused CAD/CAM/CAE solutions and allow for breakthroughs in speed, cost, and quality for new product design. Key enablers are present in the market to make these technologies practical today.

This paper provides a brief overview of Functional Virtual Prototyping and how it can be successfully implemented in HEV programs. Clearly the need for this technology exists. Rapidly increasing product complexity coupled with declining development budgets and time-to-market pressures mandate an alternative to singular reliance on hardware prototype testing. New computer hardware and software have enabled cost-effective implementations of this FVP technology.

Critical success factors for FVP implementation include:

- *A well-defined process*
- *System-level focus*
- *Effective target setting*
- *Rapid simulation turnaround*
- *High quality CAE infrastructure*

Implementation of Functional Virtual Prototyping on an enterprise level requires a significant commitment of time and financial resources. The benefits of making this commitment are enormous in terms of return-on-investment and global competitiveness.

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From NREL's Vehicle System Analysis Team:

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Posters

A Logic-Based, Performance-Driven Electric Vehicle Software Design Tool

David G. Alexander and Donald M. Blackketter, University of Idaho

Co-simulation with ADVISOR and Wave: Advanced Engine Modeling

Trevor Blohm and Clive Hughes, Ricardo Inc.

Analysis of PNGV Inverter Power and Current Requirements Using ADVISOR

Gerald W. Davis, Rockwell Automation

Development and Use of a Regenerative Braking Model in ADVISOR

George Delagrammatikas and Dennis Assanis, University of Michigan

A Systematic Way of Choosing Driveline Configuration and Sizing Components in Hybrid Vehicles

Jonas Hellgren, Chalmers University of Technology

A Logic-Based, Performance-Driven Electric Vehicle Software Design Tool

David G. Alexander and Donald M. Blackketter
University of Idaho

ABSTRACT

The goal of this project was to build a performance-driven steady-state hybrid electric vehicle design tool using novel equation management and solving routines currently under development at the University of Idaho. The uniqueness of this performance-driven model is in its logic and mathematics based design algorithms. These algorithms provide advantages when used with traditional numerical techniques. The design algorithms prevent singularity of sets of equations, thereby reducing the possibility of divergent solutions, while also giving added flexibility to the user in defining the system of equations and variables. The algorithms are also used to determine the most efficient solution path. This reduces the number of equations that must be solved simultaneously. Information is also provided to the user to help identify important component relationships. Based on the success of this project, these logic and numerical techniques could be integrated into ADVISOR's Autosize feature. The result would be a robust and flexible, performance-driven, hybrid electric vehicle component design and simulation software tool.

INTRODUCTION

Vehicle simulation software is an essential part of vehicle design and ultimate development. All vehicle software simulations, however, require that vehicle components be specified prior to executing a simulation. This works well if the goal is to gain insight into a particular design. Unfortunately, when the design has not yet been established, running multiple simulations on proposed vehicles can be time consuming. ADVISOR has a tool that helps the designer scope out different vehicle component sizes based on various performance goals. This feature is known as “Autosize.” While providing valuable and accurate design information, “Autosize” lacks in vehicle details and design flexibility. SmartHEV was therefore developed to overcome these limitations.

SmartHEV is a series hybrid electric vehicle software design tool that calculates vehicle component specifications based on steady-state operation. It is written in VisualBasic version 6.0. The governing equations are based on the road load power equation. Its user-friendly graphical interface provides a platform through which engineers can mix-and-match vehicle components and performance goals. The components that are modeled include the wheels, driveshaft/differential, transmission, electric motor, battery pack, alternator, and APU. The road load power equation includes effects due to aerodynamic drag, rolling resistance, uphill climbing and component efficiencies.

At the heart of SmartHEV are the logic-based, design algorithms. These design algorithms have been under development at the University of Idaho for the past several years [1,2]. They have been successfully implemented in various software applications including, SmartSolve™, a linear and non-linear equation solving software package. The design algorithms are used in SmartHEV to determine a valid set of equations and unknown variables. Once a non-singular set of equations and their appropriate known and unknown variables have been selected, the program notifies the user that a solution is possible. The solution is then determined automatically. Values for all components do not need to be specified in order to determine partial solutions.

The algorithms also provide valuable information to the user. Component specifications and performance parameters are linked to the variables which notify the user how a change in one variable effects other variables. This way a user can focus in on the correct set of variables in order to modify a design for the desired performance.

METHODS

VEHICLE DESIGN EQUATIONS

The road load power equation is used to develop the component relationships. The road load power equation is an accounting of the rate of energy passing through each vehicle component according to the First Law of

Thermodynamics. The power required at the wheels to maintain a vehicle at a prescribed velocity under various driving conditions is calculated using the following equation adapted from DOE[3].

$$P(t) = P_{aero} + P_{rolling} + P_{grade} + P_{acc} + P_{bearing} \qquad (1)$$

Where, P_{aero} is the power demand as a result of aerodynamic drag. $P_{rolling}$ is the load due to the resistance of the road on the wheels. P_{grade} is the power required to climb a hill. P_{acc} is the power necessary for acceleration, and $P_{bearing}$ is the power required in overcoming the resistance of the bearings and the final drive shaft.

The total power, *P(t)*, necessary to meet the velocity is transmitted to the driveshaft. From this, the torque and speed requested at the driveshaft can be determined.

Using the torque and speed at the driveshaft, the demand on the transmission is determined. With the transmission gear ratio, the requested torque and speed from the electric motor are determined. The losses through the inverter are calculated using a constant inverter efficiency coefficient.

The power requested at the BUS is used to determine the total power used for discharging and charging of the battery pack. The total battery power is,

$$P_{bat} = P_{alt} + P_{aux} + P_{bus} \qquad (2)$$

Where, P_{alt} is the power from the alternator used to charge the pack, P_{bus} is the BUS power demand, and P_{aux} is the power required for auxiliary loads. Power that is discharging from the batteries is positive and negative when recharging. Equation 2 balances the power from each component. This configuration enables the user to determine the power demand from each component while holding the power from the remaining components at zero. The result is the steady state power demand from each component necessary for continuous operation.

The power demand from the road is requested of the battery pack and the alternator. The power through the alternator is adjusted using a constant alternator efficiency, and the alternator then requests power from the APU.

The battery pack was modeled with an open circuit battery voltage, internal resistance and load voltage. A voltage loop equation was written for the circuit. The power through the circuit was determined by multiply the voltage loop equation by the current. The current was then found using the positive root of the quadratic equation determined from the loop equation with internal resistance and open circuit voltage held constant.

DESIGN ALGORITHMS

There are three main routines that comprise the design algorithms. They are the Variable Select, Solution Path, and Solution Swap algorithms. The Variable Select algorithm is implemented as soon as SmartHEV is loaded. The Solution Path is used to verify whether the set of known and unknown variables that was selected is sufficient for a solution. It also determines the best strategy for solving the equation(s). The Solution Swap routine is called if a set of equations does not converge to a solution, and the unknown guesses and known variable values are manipulated in order to approach a valid solution.

Once SmartHEV has been loaded, the user has the option of selecting variables as known, unknown, or undecided. Known variables are colored yellow, unknown variables are colored orange and undecided are white. Undecided variables and the equations in which they reside are not used when solving for unknown variables.

The Variable Select algorithm is called whenever a variable is selected as known or unknown. When a variable is selected as known, the number of instances that the known variable is present in other equations is determined and a decision is made as to whether other variables are required to be unknown. For example, if an equation consists of three variables and two of the variables have been specified as known, the remaining variable would have to be unknown.

An unknown variable can be changed to known, but only through a process called swapping. During a swap all known variables that interact with the unknown variable are presented to the user. The user has the option of swapping the unknown variable with any on the swap list or removing, i.e. deselecting, any variable on the list. Swapping simply interchanges the two variables known/unknown status, while removing a known variable causes the unknown variable from no longer being forced as unknown.

After a variable has been selected as known or unknown, the Solution Path algorithm is called. This routine determines whether the known and unknown variables constitute a solvable equation set. If it is determined that an equation set can be solved, the Solution Path determines the best solution strategy. This routine is partially based on work completed by Ramirez and Vestal [4].

The solution strategy makes decisions based upon how many unknown variables exist in each equation. Equations with only one unknown variable are selected as being the first equations to solve. Each equation with only one unknown is sent individually to the numerical solving routine. The numerical solving routine consists of a standard Newton-Raphson implicit method for systems of equations with a Gauss-Jordan decomposition routine. The results from the equations with only one unknown variable are then used in subsequent calculations. When systems do not have equations containing only one unknown variable, the Solution Path routine determines the sequence for solving that minimizes the number of simultaneous equations sent to the numerical solver. This provides a high level of stability and efficiency to the numerical solving routines.

Finally, the Solution Swap algorithm provides an additional layer of solving power to SmartHEV. If a set of equations do not converge to a solution, the Solution Swap algorithm is called. The Solution Swap algorithm first determines what the best solution path is for the set of equations. The best solution path is determined regardless of which variables have been selected as known and unknown. The best solution path consists of a list of known variables that minimizes the number of simultaneous equations that must be solved at one time.

The user selected known variables are then compared with the best known variables. If the Solution Swap routine finds a variable that was selected as unknown by the user but would be better as a known variable, a swap is made. The unknown variable then becomes a known variable, or swapped-known variable. The swapped-known variable is assigned a value, typically one. Since the swapped-known variable was originally an unknown variable, its value is arbitrarily selected. The value of the known variable that was swapped, now the swapped-unknown variable is stored.

The Solution Swap then attempts to solve the modified set of equations. If the modified set of equations converges to a solution, the results are compared. If the solution of the swapped-unknown variable is the same as its stored value, the routine stops because a solution was found. In most cases, the stored value and the solved value will be different because the solved value is based on the swapped-known variable with a value that was arbitrarily selected. The swapped-known variable is adjusted and the set of equations is solved again. These two adjustments and resulting solutions are then used to perform a linear interpolation in order to get a better value for the swapped-known variable. Adjustments are made until the swapped-unknown variable value agrees with the stored value within a specified tolerance.

RESULTS

Figure 1 shows the GUI of SmartHEV. The variable value boxes have adjustments that change the value by 10% for every click of the up or down arrow. Once the variable has been changed, the background color becomes yellow. If a variable is forced to be unknown its background color turns orange. The variable value with the dark background and light numbers in Fig. 1 indicate that the variable has changed value because of a change that was made to a known variable value. This is particularly helpful when changing known values because it indicates which variables are effected by the change.

Table 1 lists the results from four different design iterations based on the input parameters and performance goals listed in Table 2.

Figure 1. SmartHEV GUI

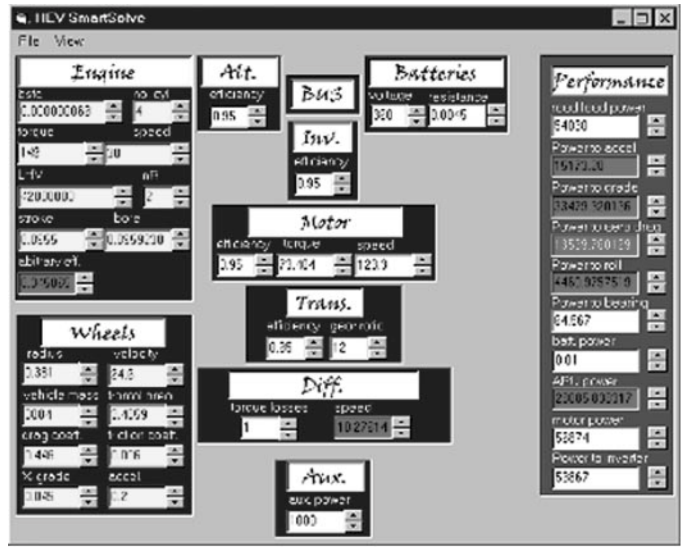

Table 1. Design results from four different scenarios.

	No Batt.	No APU	Hybrid I	Hybrid II	units
Road Load	33,835	33,835	33,835	33,835	watts
Accel. Power	3,478	3,478	3,478	3,478	watts
Grade	20,463	20,463	20,463	20,463	watts
Aero.	5,989	5,989	5,989	5,989	watts
Rolling	3,065	3,065	3,065	3,065	watts
Bearing	838	838	838	838	watts
Motor Power	35,616	35,616	35,616	35,616	watts
Motor Speed	92.7	92.7	92.7	92.7	rev/s
Motor Torque	61.2	61.2	61.2	61.2	Nm
APU Power	51,400	0.0	34,557	30,000	watts
APU Speed	110	0.0	100	80	rev/s
APU Torque	73.9	0.0	55	60	Nm
APU Eff.	0.25	0.0	0.19	0.20	
Batt. Power	0.00	48,830	16,000	20,330	watts
Batt. Current	0.0	245	80	102	amps
Alt. Power	48,830	0.0	32,829	28,500	watts
Alt. Current	244	0.0	164	143	amps
Gear ratio	6.67	6.67	6.67	6.67	

In Table 1, the first column is the results with no power provided by the battery pack. Column two lists the results with no power provided by the APU. The third column, Hybrid I, lists the model results based on a hybrid operation. Neither the APU nor the Battery pack output power was specified. Hybrid II, the fourth column, was designed with a known APU power output of 30 kW. As a result, the APU speed and were adjusted to accommodate the constant APU power output.

Table 2. Design Parameters

Mass	1413	kg
Accel.	0.1	m/s^2
Velocity	24.6	m/s
Grade	0.06	
Drag Coef.	0.335	
Frontal Area	2	m^2
Rolling Coeff.	0.006	
Bearing Loss	9.6	Nm
Wheel Radius	0.282	m
Batt. Voltage	200	volts
Batt. Resistance	0.0045	ohms

The next scenario sizes the vehicle components based upon the following performance goals, constant grade of 6%, maximum speed of 40.2 m/s, and acceleration of 0-26.9 m/s in 12 sec. The Because SmartHEV is a preliminary vehicle design tool and not a vehicle simulation tool, the performance criteria had to be modified slightly. SmartHEV determined the vehicle component sizes for each performance criteria separately. The grade test was performed under constant speed at 24.6 m/s (55 mph). SmartHEV then calculated the component sizes based on the maximum speed at zero grade. The best effort acceleration was determined at zero grade as well. The results were compared and the maximum component size was determined. The same design parameters as Table 2 were input to both SmartHEV and ADVISOR. These results are compared with the results of a similar simulation run in ADVISOR, see Table 3.

Table 3. Component Power Requirements for SmartHEV and ADVISOR

Component	SmartHEV	ADVISOR
APU	46 kW	49 kW
Battery Modules	29 @ 12 V	29 @ 12 V
Alternator	44 kW	56 kW

CONCLUSION

SmartHEV calculates vehicle component sizes similar to those of ADVISOR. However, the two programs have fundamental differences. ADVISOR is an excellent vehicle simulation tool, whereas, SmartHEV excels in vehicle and component design. Since SmartHEV is based on steady state performance its inputs were modified in order to compare it with ADVISOR.

Incorporating SmartHEV into ADVISOR would result in a powerful vehicle design and simulation environment. SmartHEV could be used to investigate preliminary vehicle designs. The flexibility of SmartHEV and its user-friendly GUI provides tremendous insight into component parameter interactions and relationships. A preliminary design can be easily modified and adapted in order to determine the best configuration. The best vehicle design could then be imported into ADVISOR and used to run extensive simulations. SmartHEV could also be used to redesign components since it does not require a complete design to be established before determining results. Individual components can be modified and tested in SmartHEV and then incorporated into an overall vehicle simulation in ADVISOR.

SmartHEV is a performance-driven hybrid electric vehicle model that provides flexibility and power to the design engineer. The unique logic-based algorithms allow many different combinations of performance variables and constraint variables to be selected with the added security of maintaining a solvable set of equations. If a particular arrangement of known and unknown variables is difficult to solve, SmartHEV swaps variables in order to find a solution path that is solvable. Information provided to the user while selecting variables and component parameters is extremely helpful and insightful. Knowing which component is effected by a change in a particular variable guides the user towards a workable design solution. The results are fast, accurate, and easy to follow. Incorporating SmartHEV technology into ADVISOR would result in an invaluable hybrid electric vehicle design and simulation tool.

CONTACT

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Dr. Donald M. Blackketter is an associate professor at the University of Idaho. His expertise is in equation management techniques for systems of linear and nonlinear sets of equations. He has extensive experience in dynamic and kinematic modeling of machine components. Dr. Blackketter's email address is dblack@uidaho.edu.

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Co-simulation with ADVISOR and Wave: Advanced Engine Modeling
by

Trevor Blohm, Clive Hughes
Ricardo, Inc.

Ricardo is currently creating a link between ADVISOR and WAVE, Ricardo's industry-standard engine performance and 1-D gas dynamics software package. WAVE models are based on detailed engine dimensions. The resulting co-simulation will allow prediction of drive cycle performance for engines without performance data. Furthermore, the effect of modifications such as turbocharger size and valve timing can be examined.

Ricardo will present the details of the ADVISOR-WAVE link, including the required modifications to ADVISOR. Fuel consumption of a Class 7/8 truck modeled with and without this link will also be presented.

Analysis of PNGV Inverter Power and Current Requirements Using ADVISOR

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Advanced Technology Labs, Milwaukee, Rockwell Automation

ABSTRACT

The PNGV Program is composed of a number of research projects. The inverter section of the PNGV program is called the “Automotive Integrated Power Module” (AIPM). As part of the AIPM research activity, ADVISOR was used to better understand the power and current requirements of the PNGV vehicle operating under various drive cycles. Since the AIPM manufacturing cost is a key variable for the research project ADVISOR was used to determine an appropriate battery bus voltage, and peak current limits.

INTRODUCTION

AIPM specifications [1, 2, 3] require a peak power of 55 kW for up to 10 seconds. This requirement has a direct impact on the size of the power silicon devices, and the thermal requirements of the AIPM. If the power requirement can be reduced while maintaining the vehicle performance requirements, the AIPM will have reduced size, thermal requirements, and cost. Therefore, it was felt that the AIPM power requirement had to be investigated in detail. Along with the power requirement, the AIPM battery bus voltage and motor current requirements were also investigated.

The objective was to see if it would be possible to refine the requirements for Peak Power, and the Full Performance Voltage Input Range to values that reduce the size and cost of the AIPM. ADVISOR was selected to perform the vehicle configuration and energy balance simulation.

THE PNGV VEHICLE

ADVISOR is an energy balance and efficiency simulation developed at the National Renewable Energy Laboratory (NREL) in Golden, CO [4]. The simulation computes the energy required to perform a vehicle “Drive Cycle” task for a given time duration and flows the energy demand through the vehicle sub-components that must satisfy the demand. If the requested energy demand exceeds the sub-components capability to supply it, the simulation has a backward path that communicates what is possible to the previous sub-component. In this way, ADVISOR through a one-step recursion estimates the actual performance in response to a requested performance. If the actual performance and the requested performance are identical, then the vehicle was able to satisfy the input “Drive Cycle”.

To use ADVISOR, the user interacts with three screens. The first screen inputs a vehicle configuration. Fig. 1 shows an example vehicle input screen. The second screen lets the user specify the Simulation Parameters which determine what “drive cycle” and grade. The third screen is the Results screen which displays how the vehicle performed.

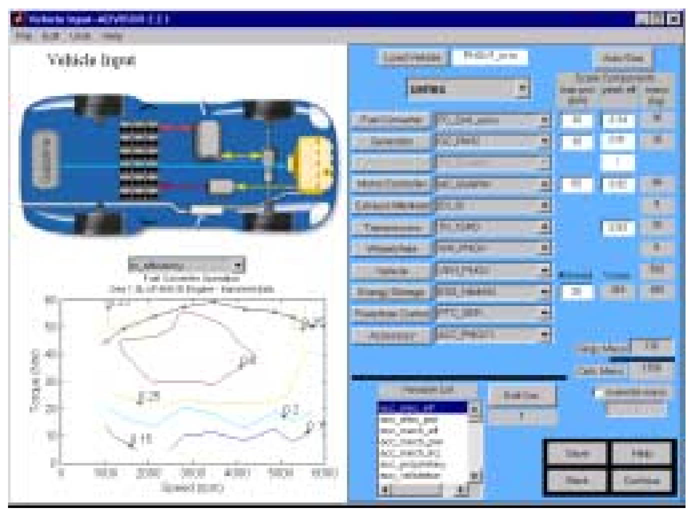

Fig. 1. ADVISOR: Vehicle Input screen of ADVISOR

First, consider the Vehicle Input screen shown in Fig. 1. Each vehicle component, e.g. Fuel Converter (engine, fuel cell, etc.), Motor Controller, Generator, etc., has information about the component’s thermal characteristics, energy conversion efficiency, and weight. To understand the components and the underlying variables of ADVISOR, the best approach is to read reference [4], and to peruse ADVISOR’s HELP files. The vehicle components shown in Fig. 1 are estimates of the component characteristics for a PNGV vehicle. The VEH_PNGV.m file contains these values and was supplied by NREL. The MC_55AIPM was a first cut estimate of the AIPM inverter/motor system and was derived from the MC_PM58.m file.

A key variable to note in Fig. 1 is the total vehicle weight. During an analysis, it is common to adjust the sizes of various components, e.g. the inverter or engine sizes. A change in power size also impacts the weight of the component, so care must be taken to make sure that the vehicle weight doesn't change between simulations.

SELECTION OF PERFORMANCE CRITERION

The second screen in an ADVISOR simulation is the Simulation Parameters screen. This screen specifies the performance test that will be applied to the vehicle determined in the Vehicle Input screen. An example is shown in Fig. 2.

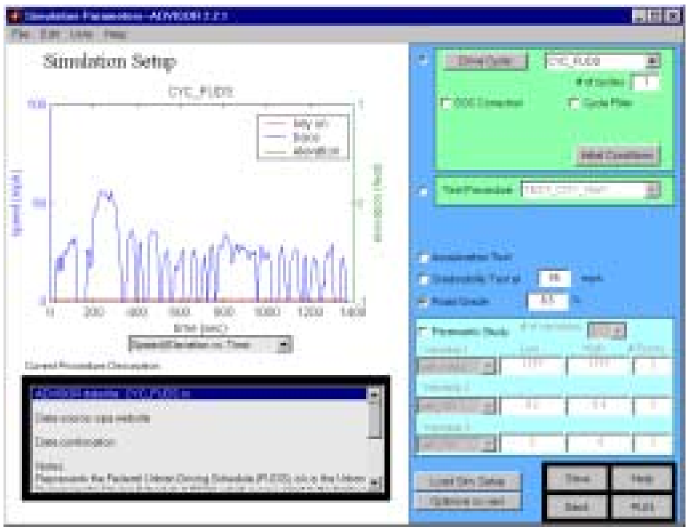

Fig. 2. Simulation Parameters screen of ADVISOR

The green section in the upper right of the screen shown in Fig. 2 selects a drive cycle. A drive cycle is a set of speed commands arrayed over a sampled set of one second time intervals. The example in Fig. 2 shows the FUDS (Federal Urban Driving Schedule) drive cycle.

A road grade of 6.5% has been selected (FUDS@6.5%, as specified in [1]) in the blue, middle section of Fig. 2. The Parametric Study section in the lower right of the screen is not checked, so this option doesn't occur in the simulation. The display window on the left half of the screen allows the user to view various parameter arrays selected by the user.

After completion of the Simulation Parameters screen, the user clicks the RUN button at the bottom right. This action causes ADVISOR's Results screen to appear.

RESULTS FOR VARIOUS SIMULATION SCENARIOS

This section looks at the simulation results for testing the PNGV vehicle with the FUDS and US06 drive cycles. The FUDS drive cycle is the likely certification drive cycle for HEV vehicles. The US06 drive cycle is a higher road speed drive cycle and may be applied to HEVs at some point in the future.

The results screen shows the performance of the user specified vehicle to the user specified drive cycle. Fig. 3 shows an example screen. A large selection of output variables can be displayed in any of the four plot windows on the left. In Fig. 3, the first plot shows the requested speed of the drive cycle was matched by the response of the vehicle, i.e. the energy delivery performance was adequate for the drive cycle. The second plot in Fig. 3 shows the State of Charge (SOC) of the battery. In this example, the battery never discharged to a point where the Internal Combustion Engine (ICE) was required. The third plot shows the RMS current delivered by the battery. The fourth plot shows the RMS Power Bus voltage.

It must be remembered, that ADVISOR only shows RMS, DC energy values for the Motor Controller (MC) part of the simulation. Hence, the VAR current component of a three-phase system is not shown. This means that the actual currents flowing in a three-phase system would have to be estimated by assuming a power factor to the motor.

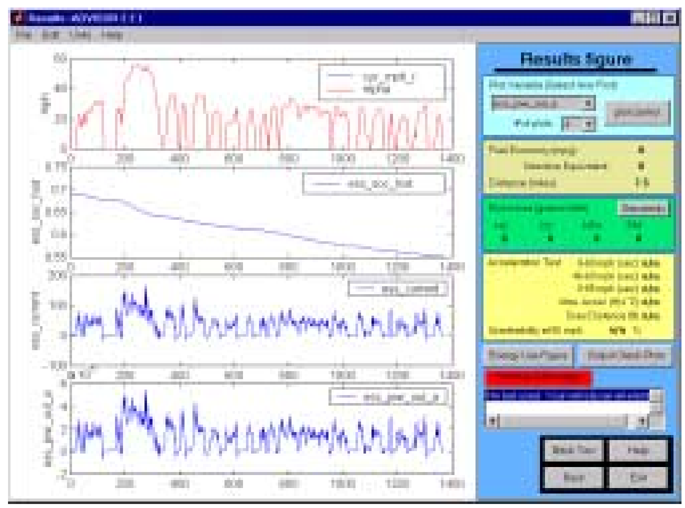

Fig. 3. Results screen from ADVISOR.

The example in Fig. 3 shows that the FUDS drive cycle was satisfied with RMS currents which didn't exceed 200 A. The peak currents occur during periods of maximum acceleration when the power factor is close to a value of 1.0. Hence, a peak current estimate of 300 A provides reasonable margin for demand.

The power requirement is the fourth plot window in Fig. 3 and can also be viewed by plotting the "ess_power" array as shown in

Fig. 4. The plot shows that the peak value required by the FUDS drive cycle was close to 55 kW, but expansion of the plot shows that the peak value represented only a single point

A more informative view of the power requirements is seen in Fig. 5. This is a histogram of the power samples delivered by the motor controller system to satisfy the

FUDS drive cycle. The bin width in the histogram is about 400 W, and the large peak centered at 0 W is due to the zero speed command sections in the drive cycle. Note that the vehicle accessories file was adjusted for this particular simulation to draw zero power. A plot of the histogram of power values without the large peak is shown in Fig. 6.

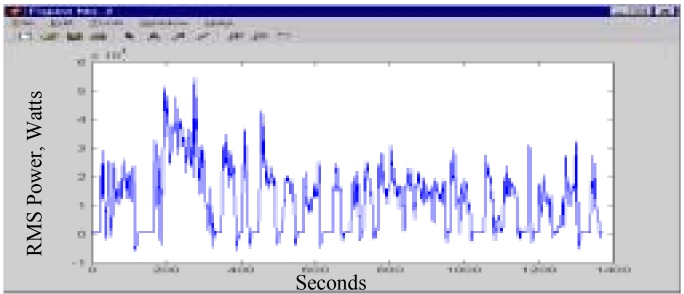

Fig. 4. RMS Power requirement for results shown in Fig. 3.

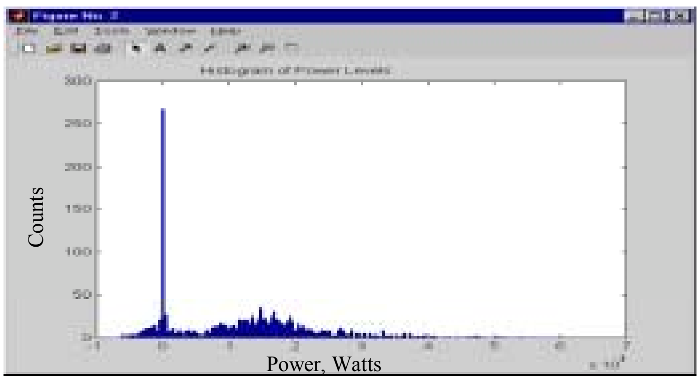

Fig. 5. Histogram of Motor Controller power occurrence density vs power level derived from the FUDS at 6.5% performance data.

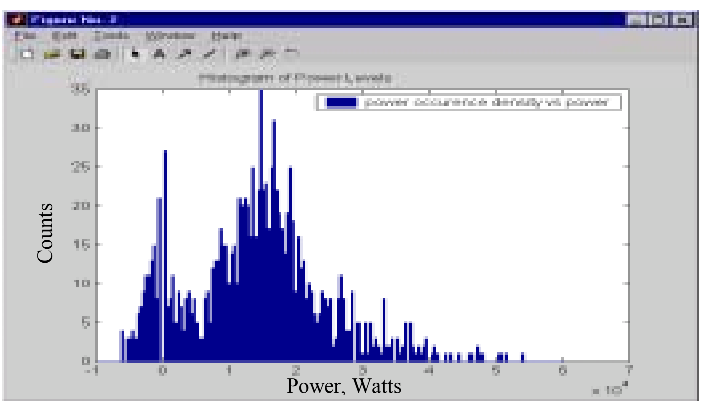

Fig. 6. Histogram of Motor Controller power occurrence density vs power level for densities above the peak shown in Fig. 5.

Fig. 6 shows that the peak values occur at about 55 kW (actual max value is 54.06 kW). Hence, a 55 kW power delivery of power from the battery and motor controller subsystems of the PNGV vehicle configuration satisfies the FUDS drive cycle with a 6.5% grade.

Fig. 7 shows a similar power occurrence histogram, but as applied to the US06 drive cycle with 6.5% grade data. The histogram shows a high density of power level occurrences around 60 kW. The difference between the requested speed command and actual speed command was also significant as shown in Fig. 8. Hence, the 55 kW inverter would not satisfy the US06 drive cycle with the current PNGV vehicle weight.

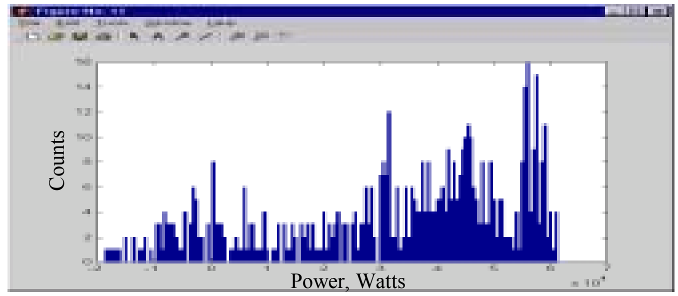

Fig. 7. Histogram of Motor Controller power occurrence density vs power level derived from the US06 at 6.5% performance data.

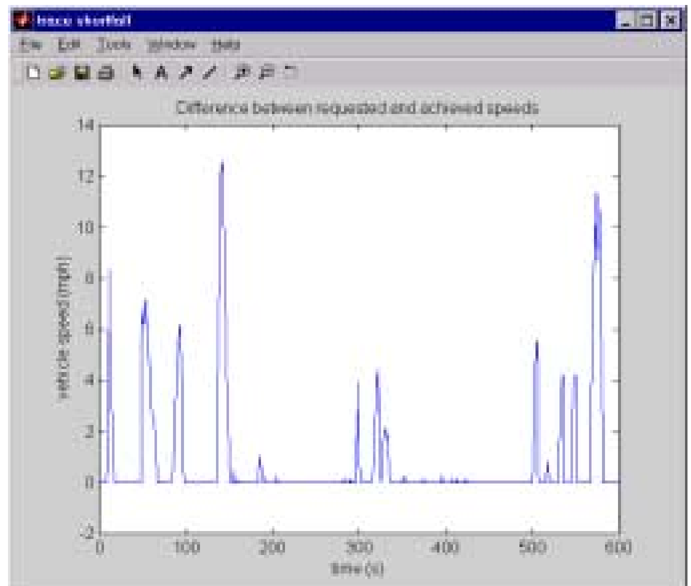

Fig. 8. Difference between Requested Speed and Actual Speed for US06 drive cycle at 6.5% grade.

VARIATION OF BATTERY BUS VOLTAGE

As a battery discharges, the voltage decreases. The battery used for most of the ADVISOR simulations was a 26 cell NIMH battery that produced a nominal voltage of 364 volts. This battery configuration was selected to produce a power bus voltage similar in magnitude to that believed to be used in the Chrysler and General Motors HEV prototypes.

Fig. 9 shows the results of a FUDS@6.5% drive cycle run with the battery initiated to a low State of Charge (SOC). Even under these conditions, the simulation indicates that the drive cycle is satisfied right up to SOC = 0.0 (around t = 740 sec) at which point the simulation ends. Is this an artifact of ADVISOR? Apparently not. NIMH maintain reasonable voltage even at very low SOC. In Fig. 9, we see that the pb_voltage is dropping as the SOC decreases. This amount of voltage drop has been determined from the manufacturer's data sheets (Ovonic, Inc.).

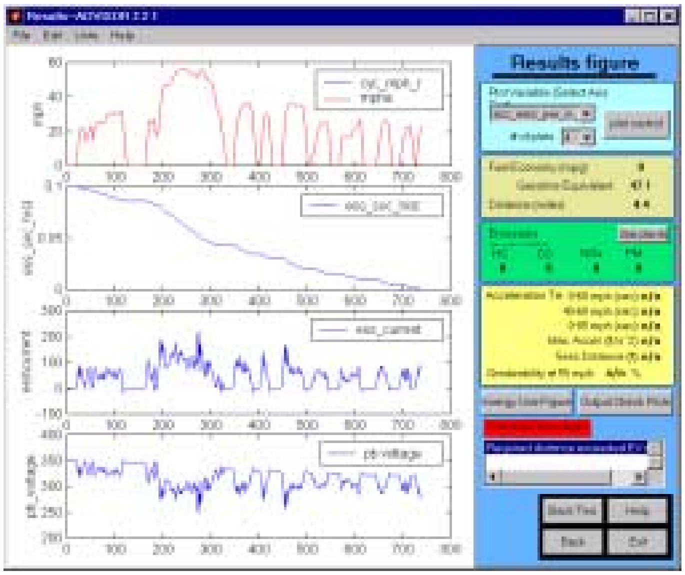

Fig. 9. Battery discharge effect on the power bus.

CONCLUSIONS

The 55 kW design satisfies the FUDS drive cycle almost exactly, but does not satisfy the US06 drive cycle. EPA certification requires that vehicles satisfy the drive cycle speed command within 5%. ADVISOR simulations indicate that, indeed, a 55 kW inverter is about the correct size for the PNGV vehicle weight to satisfy the FUDS@6.5% drive cycle.

ACKNOWLEDGMENTS

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CONTACT

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Development and Use of a Regerative Braking Model in ADVISOR
by

George Delagrammatikas, Dennis Assanis
University of Michigan

The poster details our development of a modular, downloadable regenerative braking control strategy for a parallel HEV. The main objective behind this work was to be able to predict how our new strategy would perform in ADVISOR, then download it to the vehicle controller for on-road use and validation. Comparisons between the two models were then made and conclusions were drawn regarding their differences in various driving cycles and component configurations.

A Systematic Way of Choosing Driveline Configuration and Sizing Components in Hybrid Vehicles

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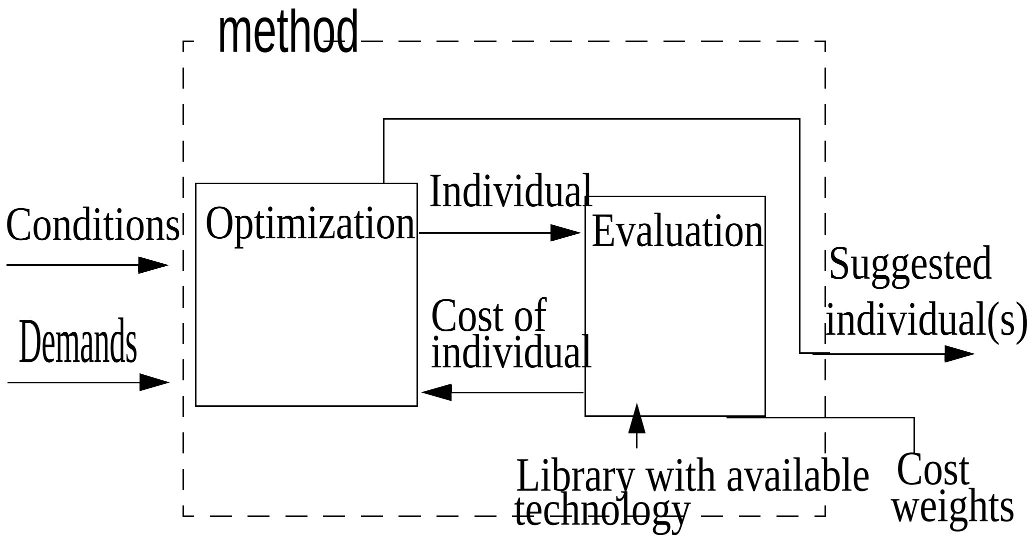
AIM WITH THE METHOD

Transform demands and conditions to suitable drivelines (conventional/hybrid)

Definitions:

- Driveline=vehicle configuration with sized components
- A driveline may either pass or not pass demands. Examples of demands are driving cycle and use of emission free zones.
- Conditions makes a driveline more or less suitable and varyies with time and depends on country. Some conditions are fuel price, tax on pollution and discount rate.
- Name of method = *Driveline Synthesis (DS).*
- DS is of approximative nature, i.e. the result is not a definitive answer of how to design a vehicle, but more an advise.

DESCRIPTION OF METHOD FOR CHOOSING OF PROPULSION SYSTEM



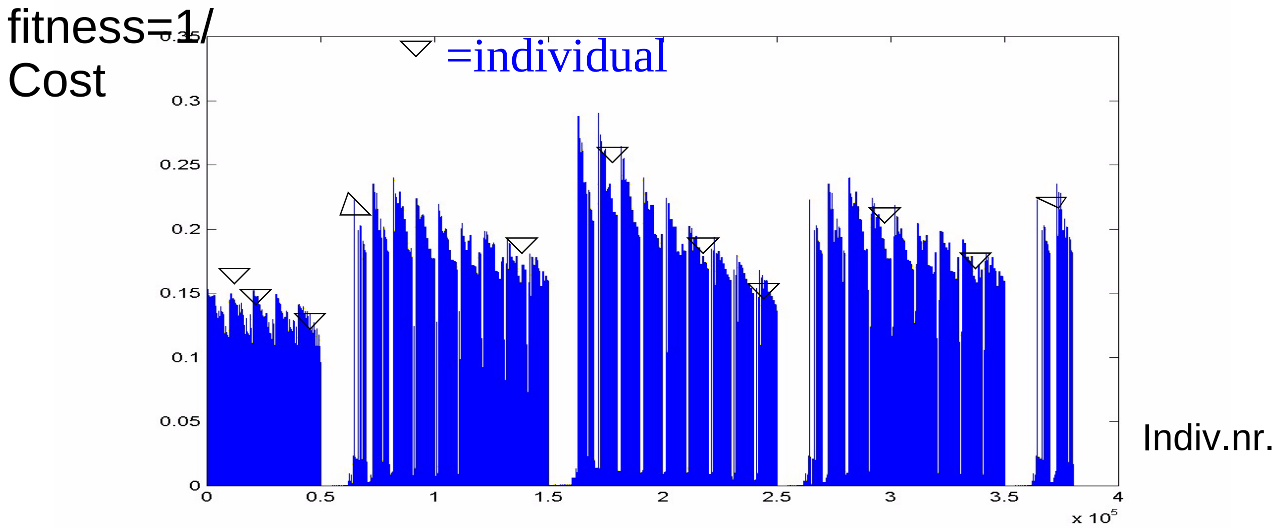
- Many combinations => a simple and fast evaluation is needed.
- Suitable individuals with defined driveline configuration and control strategy are finally presented.

OPTIMIZATION METHOD

The reasons for choosing **genetic algorithms** are:

- A non-gradient based method is needed, because there is a non continuos relation between cost and vehicle properties.
- If some type of driveline configuration is superior this will probably be known early.
- Favorite (good) drivelines can be stored and reused, i.e. compete under different circumstances.
- Genetic algorithms suit very well with parallel (super) computers, which may be needed if more drivelines will be covered.

On a big scale, genetic algorithms work by the principle of evolution: the best-adapted individuals survive and reproduce.



- Several individuals (search agents) evaluate the search space in parallel. The individuals mutate and mate with each other.
- Described by the genes of the individual: type of configuration, mass of PPU, mass of storage, fluctuation of *State Of Charge (SOC)* and type of strategy.

EVALUATION

To evaluate an individual, the following goal function is considered:

$$cost \quad [\text{Euro/km}] = \frac{1}{fitness} =$$

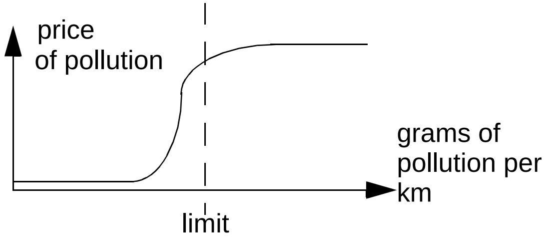
$$(w_c \times comp + w_f \times fuel + w_g \times grid + w_p \times pollution) \quad performance$$

TABLE 1.

comp	Cost of components.
fuel	Fuel cost.
pollution	Cost of pollution.
grid	Cost of grid energy.
w_c, w_f, w_g, w_p	Cost weights.
performance	How well the driving cycle is managed. 1 if the vehicle can follow the desired speed else 0.1 or 0.00017 etc. .

LOAD CASE SIMULATION

- The principle is that one follows the system in the time domain. The driving cycle is divided into *load cases*. A load case can, e.g. be an acceleration from 0 to 80 km/h in 15 s.
- Load case simulation gives much faster computation, approximately 1000 times faster compared to a conventional simulation.
- For each load case following can be determined from a vehicle model: fuel consumption, emissions, wear of storage and change of state of charge.
- Price of pollution:

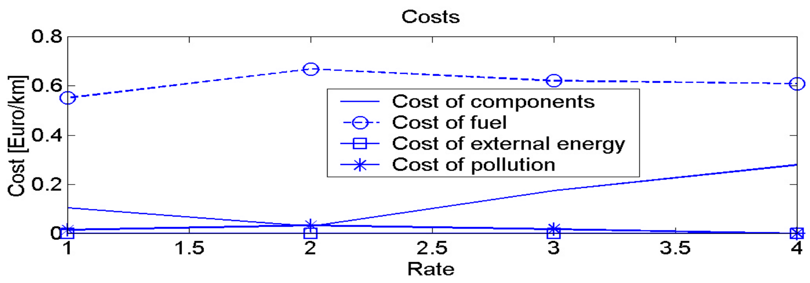


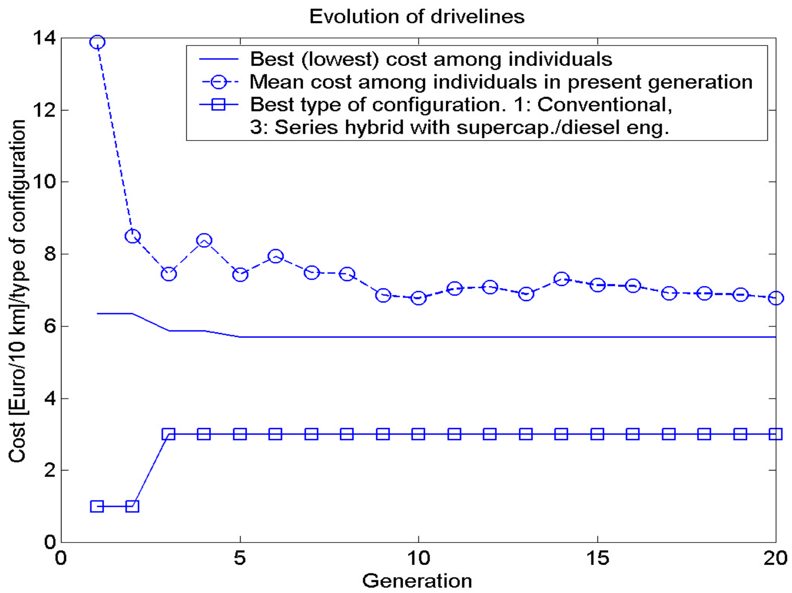
CASE STUDY FOR CHOOSING OF PROPULSION SYSTEM

City bus and Low speed driving cycle with many starts and stops (R = ranking).

R	Driveline configuration	mass PPU [kg]	mass Stor. [kg]	cost [Euro/km]
1	Series HEV: diesel engine+super-capacitor	200 (100 kW)	1250 (1250 kW)	0.67
2	Conventional: diesel eng./automatic tr.	400 (200 kW)	-	0.73
3	Series HEV: diesel engine+NiMH battery	400 (200 kW)	500 (500 kW)	0.82
4	Series HEV: fuel cell+super capacitor	100 (50 kW)	1250 (1250 kW)	0.89

PART COSTS/EVALUATION OF DRIVELINES





Series HEV => lower fuel consumption and higher capital cost.

Conventional vehicle => higher fuel consumption and lower capital cost.

Conclusions/Discussion

- During the application of DS, it has been found that the most appropriate driveline is very dependent on the demands and conditions which are made.
- It is pointless to say that one driveline configuration, in general, is better than another. Eg. very high cost on pollution or a cheap fuel cell will make fuel cell vehicles profitable.
- It is not enough to only consider maximum power request. Case 1=driving cycle contains extremely many starts and stops => super capacitor is profitable . Case 2=fewer starts and stops => NiMH battery is profitable. This is due to less wear in storage.
- A preliminary result is that a cheap battery or super capacitor will make HEV very competitive.

FUTURE WORK

This should be done in the future to improve and evaluate DS further:

- Further validation of DS. ADVISOR is a candidate of doing this.
- Make DS more accurate.
- Add components and driveline configurations. Data from ADVISOR is interesting.
- Collect accurate data on different components used in driveline configurations. Data from ADVISOR is interesting.
- Improve control strategy for each driveline, an adaptive method (learn while driving) is one way.

ASSIGNER/LANGUAGE/PLATFORM

- The work is assigned of Volvo Buses and is specially focusing on heavy vehicles.
- The tool is written in Matlab, by using Matlab:s own programming language.
- At present the tool is not available for the public or for sale.