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Design and Analysis of a Low Production Cost Hybrid Electric High Mobility Multi-Purpose Wheeled Vehicle for Military Use

Craig Blake Rutherford
University of Tennessee - Knoxville

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I am submitting herewith a thesis written by Craig Blake Rutherford entitled "Design and Analysis of a Low Production Cost Hybrid Electric High Mobility Multi-Purpose Wheeled Vehicle for Military Use." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Mechanical Engineering.

William R. Hamel, Major Professor

We have read this thesis and recommend its acceptance:

Jeffrey W. Hodgson, David K. Irick

Accepted for the Council:

Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

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David K. Irick

Acceptance for the Council:

Anne Mayhew

Vice Chancellor and Dean of
Graduate Studies

(Original signatures are on file with official student records)

**DESIGN AND ANALYSIS OF A LOW PRODUCTION
COST HYBRID ELECTRIC HIGH MOBILITY
MULTI-PURPOSE WHEELED VEHICLE FOR
MILITARY USE**

A Thesis Presented for the
Master of Science Degree
The University of Tennessee, Knoxville

Craig Blake Rutherford
August 2004

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Dedication

This thesis is dedicated to Drs. Jeffrey Hodgson and William Hamel without whom I would never have embarked on this endeavor, and my loving wife Kristy without whom I would never have finished.

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Lastly I would like to thank all of my family and friends whose, patience and encouragement made this and all other work not only possible, but bearable.

Abstract

The conceptual design of a low production cost hybrid electric High Mobility Multi-purpose Wheeled Vehicle (HMMWV) is described. The design uses a parallel hybrid configuration incorporating a reduced displacement diesel engine, a permanent magnet electric motor, and lead-acid batteries. The design is termed “low production cost” because it uses commercial off the shelf (COTS) hardware where possible and does not require major alterations to either the chassis or drivetrain of the base vehicle. Computer modeling and simulation of the proposed design indicates that it can meet or exceed Army provided hybrid electric HMMWV performance criteria. The proposed design offers improved fuel efficiency, extended “silent watch” capability, pure electric “stealth” operation, and “limp home” capability in the event of failure of the electrical propulsion system. The design also permits the vehicle to be used as a mobile field generator for mobile headquarters, field hospital, and mobile communication applications.

This thesis will include discussions of design trade-offs associated with the conversion of a HMMWV to hybrid electric operation.

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Nomenclature

η	Efficiency	(dimensionless)
$\eta_{drivetrain}$	Drivetrain efficiency	(dimensionless)
θ	Road gradient	($^{\circ}$)
ρ	Density of air	(kg/m ³)
a	Acceleration	(m/s ²)
A_F	Frontal area	(m ²)
C_D	Drag coefficient	(dimensionless)
C_{rr1}	First coefficient of rolling resistance	(dimensionless)
C_{rr2}	Second coefficient of rolling resistance	(s/m)
C_{rr3}	Third coefficient of rolling resistance	(s ² /m)
E	Energy	(J or kW-h)
F_{accel}	Acceleration force	(N)
F_{aero}	Aerodynamic force	(N)
F_{drive}	Vehicle drive force	(N)
F_{grade}	Gradient climb force	(N)
F_{roll}	Rolling resistance force	(N)
g	Acceleration due to gravity	(m/s ²)
h	Height of CG	(m)
m	Mass	(kg)
m_{eq}	Rotational equivalent mass	(kg)
P	Power	(kW)
P_{wheel}	Vehicle wheel power	(W)
r_{tire}	Tire rolling radius	(m)
T	Torque	(N-m)
t	Time	(s)
V	Vehicle speed	(m/s)
W	Weight	(N)

Abbreviations

AC	Alternating current electricity
ADVISOR	Advanced Vehicle Simulator Software, developed by National Renewable Energy Lab for hybrid and electric vehicle design studies
Ag-Zn	Silver Zinc, a battery technology
A-h	Amp hour, a unit typically used to measure battery capacity
ANL	Argonne National Laboratories
CG	Center of gravity
CI	Compression ignition, an engine type using diesel cycle combustion
CNG	Compressed natural gas, a vehicle fuel
CO	Carbon monoxide, an emission pollutant
CO ₂	Carbon dioxide, a primary product of hydrocarbon fuel combustion
COTS	Commercial-off-the-shelf, a term used to refer to commercial/military dual use equipment that is commonly available rather than military specific
CVT	Continuously variable transmission
DC	Direct current electricity
DOD	Depth of discharge, typically of an energy storage system
F	Farad, a unit of electrical capacitance
FBD	Free-body diagram, a diagram used for visualization of forces on a body
FCEV	Fuel cell electric vehicle, a category of hybrid electric vehicles using a fuel cell as the auxiliary power unit
g/km	Grams per kilometer, a unit of mass emitted per kilometer of travel, typically used to quantify vehicle emissions
GM	General Motors, an American automotive company
HC	Hydrocarbon, as in hydrocarbon fuel or regulated hydrocarbon emissions
HEV	Hybrid electric vehicle
HMMWV	High mobility multi-purpose wheeled vehicle, a light wheeled military vehicle

ICE	Internal combustion engine, typically referring to a spark or compression ignition engine with a variable volume combustion chamber
ICEV	Internal combustion engine vehicle, a vehicle using an ICE as its sole source of propulsive power
IDI	Indirect injection, a fuel injection scheme where fuel is injected into a pre-chamber rather directly into the cylinder
IGBT	Insulated gate bipolar transistor, a transistor technology frequently used in power electronics for hybrid and electric vehicles
km	Kilometer, a unit of length
kph	Kilometers per hour, a unit of speed
kW	KiloWatt, a unit of power
kW-h	KiloWatt hour, a unit of energy
Li	Lithium, an element, or a family of battery technologies based on lithium ion electrolyte lithium metal negative electrodes
Li-Ion	Lithium ion, a battery technology utilizing a lithium salt typically in an organic liquid
Li-P	Lithium polymer, a battery technology similar to Lithium ion using a solid state electrolyte polymer
m	Meter, a unit of length
MOSFET	Metal oxide semiconductor field effect transistor, a transistor technology frequently used in power electronics for hybrid and electric vehicles
m/s	Meter per second, a unit of velocity
MYBRID	Mild hybrid, typically used to describe a parallel hybrid with a very small assist motor, sometimes an oversized starter motor
Na-S	Sodium sulfur, a high temperature battery technology using a solid electrolyte
Na-MCl	Sodium metal chloride, a high temperature battery technology derived from Na-S using a solid electrolyte
Ni-Cd	Nickel cadmium, an alkaline electrolyte battery technology
NiMH	Nickel metal hydride, an alkaline electrolyte battery technology

Ni-Zn	Nickel zinc, an alkaline electrolyte battery technology
NO _x	Oxides of nitrogen, a regulated tailpipe emission
NREL	National Renewable Energy Laboratory
ORNL	Oak Ridge National Laboratory
Pb-A	Lead acid, an acid electrolyte battery technology
PEM	Proton exchange membrane, a fuel cell component/technology
PM	Particulate matter, a solid emission product, typically a concern in compression ignition engines
PMBL	Permanent magnet brushless, a type of high efficiency motor
PNGV	Partnership for a New Generation of Vehicles, a government and industry funded consortium of vehicle and component manufacturers aimed at expediting development of key enabling hybrid vehicle technologies
PSAT	PNGV System Analysis Toolkit, a software package developed by Argonne National Laboratories for control development and system studies for hybrid and electric vehicles
PWM	Pulse-width modulation, a method used for current control in modern high frequency controllers
SI	Spark ignition, an engine type using Otto cycle combustion
SOC	State of charge, typically a measure of the remaining energy available in an ESS normalized to the total available energy at full charge
TDI	Turbocharged, direct injection, a compression ignition engine type utilizing turbocharged inlet air and direct fuel injection
THS	Toyota hybrid system, an epicyclic power-split hybrid system
ULEV	Ultra low emission vehicle, an emission bracket in US emission standards
VFI	Voltage fed inverter, an inverter topology where the energy storage systems is seen by the inverter as a voltage source
VRLA	Valve regulated lead acid battery, an acid electrolyte based, advance lead acid battery technology
ZEV	Zero emission vehicle

1. Introduction

1.1. Research Objectives

The primary objective of this research is to design and analyze a hybrid electric vehicle (HEV) powertrain for military use in the High Mobility Multi-purpose Wheeled Vehicle (HMMWV) similar to the one shown in Figure 1.1. The resulting powertrain should be low cost, provide the same or greater functionality of the current powertrain, and preferably, be capable of retrofit into currently fielded equipment.

In addition to matching normal operational capabilities of currently fielded HMMWVs, it is desirable in a hybrid system to exploit certain features of the increased electric power availability to increase mission capability. Such added features include the capability of an electric only “stealth mode” where reduced noise and thermal signatures allow low-observable low speed operation or extended “silent watch” capability.

A feature inherent in the resulting system which is also seen as highly desirable is the capability to use the vehicle powertrain as a high capacity (up to 100kW continuous) mobile power generator. This feature is particularly useful in some shelter HMMWV

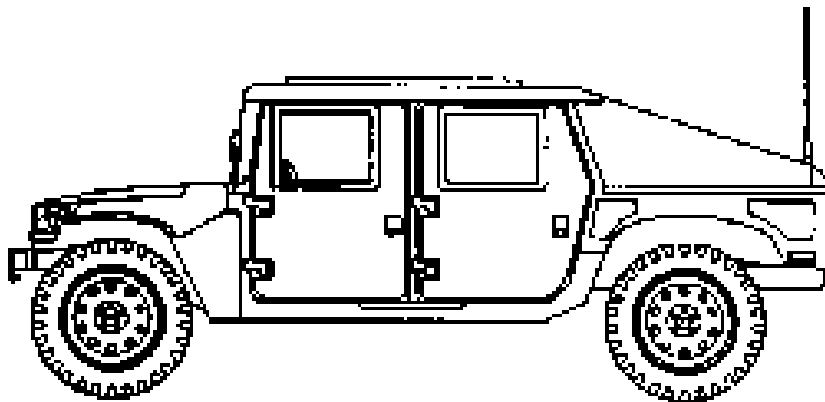


Figure 1.1 M114 HMMWV

applications including mobile field headquarters, hospital shelters, and communication shelters.

1.2. Background of Hybrid and Electric Vehicles

Electric and hybrid vehicles are the ancestors of modern automobiles, and will likely be the descendants of them as well. Advances in technology, along with the desire to improve efficiency and functionality of current vehicles will likely lead to near and long term development of hybrid electric vehicles (HEV).

An electric vehicle (EV) is a vehicle that uses electric motors as its sole propulsive power source. In general the energy to power the motors is contained on-board in a chemical or electrochemical storage device [Husain, 2003]. Some vehicles such as electric trolleys and buses may also have the capability of drawing this motive power directly from the power grid through conductive or inductive means. For the purposes of this study, EVs are assumed to be grid independent during normal operation (portable energy supply), and are recharged during the vehicle's non-operational times.

Electric vehicles offer a simpler system architecture and superior efficiency and reduced point-of-use emissions when compared to typical internal combustion engine vehicles (ICEV) of today [Fenton, 1996; Husain, 2003]. These systems, however, suffer from limited range due to the much lower energy density of current ESS technologies as compared to gasoline, diesel, and other ICEV fuels [Rand, 1998]. For this reason, a "hybrid" powertrain system is of great interest [Jefferson, 2002]. The HEV powertrain uses an electric motor similar to an EV for propulsive power, but is capable of augmenting the ESS capacity and/or propulsive power by use of an internal combustion engine (ICE) and the energy stored chemically in its fuel [Husain, 2003]. This type of system offers a compromise between EV performance and efficiency and ICEV energy density. The various types of HEV will be discussed in greater depth in Section 1.3.

1.2.1. History

Although significant interest has been expressed over the past two to three decades in both EVs and HEVs, the concept is not a new one. Vehicles using either electric energy storage or a combination of electric and chemical energy storage have been in existence

literally since the very beginnings of the automobile. In fact, early EVs greatly outnumbered ICEVs.

It is widely regarded that the first patent application related to HEVs was submitted in 1905 by an American scientist named H. Piper [Wouk, 1995]. A number of earlier patents addressed such items as regenerative braking in electric railcars [Eastwood, 1908], “through the road” parallel hybrid railcars [Schroeder, 1906], turbine engine series hybrid automobile [Meden, 1903], and a series-parallel “dual” hybrid automobile [Lemp, 1903]. The dual hybrid automotive system in Hermann Lemp’s 1900 patent application described:

‘...a gas engine which is geared to an electric generator and connected either directly or indirectly to one member of a differential gear the opposing member of which is acted upon by a dynamo-electric machine the torque of which may be readily controlled, so as to drive the carriage or other vehicle either forward or backward with varying degrees of speed, the engine all the time working at full speed, and therefore under best conditions.’

By any definition this patent definitely addresses what would be considered an advanced hybrid concept by today’s standards. Figure 1.2 shows one of the drawings submitted with Lemp’s patent application. In this figure, an ICE [13] is direct coupled to the dynamo generator [16]. The ICE/dynamo generator set and electric motor [24] are connected to opposite inputs of a differential gearset [5, 6, 7, 8, 9, and 10] through chain drives [11, 14]. In this system, the ICE/dynamo set and the motor are not directly shaft-coupled. The interaction between the two systems occurs solely through the differential gearset. The system also carries a battery pack [17] for electrical energy storage. Functionally, this system is analogous to the first modern production HEV’s powertrain known as the Toyota Hybrid System (THS) (see Section 1.2.2 for details).

It is likely that series hybrid automobile concepts existed prior to Lemp’s patent since there are references to dynamo powered electric vehicles as early as the 1870s [Husain, 2003]. One example of such a dynamo powered series hybrid is the 1900

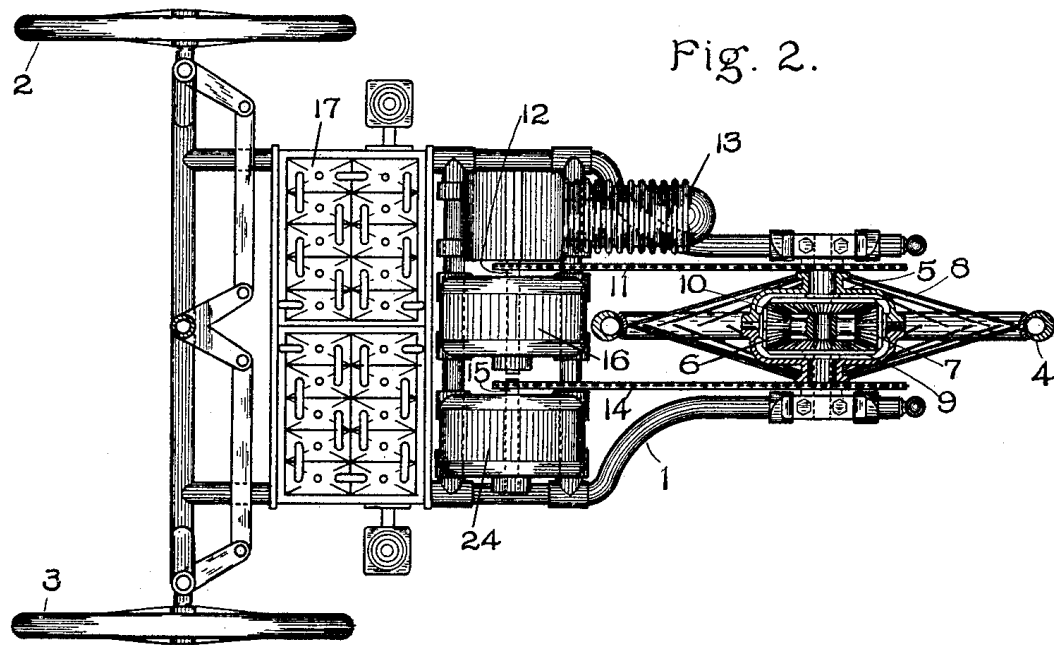


*Figure 1.2 Drawing Figure 2 from Hermann Lemp's US Patent #723,168
Source: US Patent and Trademark Office*

Lohner-Porsche [Porsche, 2000]. This vehicle was developed by a young engineer named Ferdinand Porsche who would later become famous for his design and development of the original Volkswagen and high performance vehicles built by his own company. The original Lohner-Porsche vehicle was an EV with front wheel motors and was the talk of the 1900 Paris Expo. This vehicle was later redesigned into a four wheel drive series HEV in an attempt to reduce battery weight and increase the range of the original vehicle. Figure 1.3 shows a picture of the hybrid version of this vehicle.

Although EVs and HEVs appeared to have a promising future, advances in ICE technology and Henry Ford's mass production techniques brought development of these vehicles to a standstill in the early 1900s. Some interest was rekindled in EV and HEV technology in the 1960s due to concerns related to the environmental hazards associated with ICEVs. Both General Motors (GM) and Ford Motor Company became involved in EV development during this time with GM building several vehicles including the Electrovair and Electrovan. Acceleration performance of the Electrovair was comparable



Figure 1.3 Lohner-Porsche Series Hybrid
Source: Porsche Club of America

to a stock Corvair, but limitations with the Ag-Zn battery technology used in prototypes brought this research to an end.

The fuel crisis of the 1970s once again turned focus to EVs and HEVs. Interest by the government in electric and hybrid vehicles was high enough during this era that the Department of Energy (DOE) developed a standard for EV performance, and Congress passed the *Electric and Hybrid Vehicle Research, Development, and Demonstration Act of 1976* [ERDA, 1977]. Battery technology was greatly advanced during this time with a primary area of research being Ni-Zn battery technology [Rand, 1998]. As before, a lack of high density energy storage was a primary issue, but the existing limits of power electronics also served as a barrier to range due to the relatively low efficiency and high mass of power silicon based controllers. As the fuel crisis began to wane, EV and HEV technology research was once again moved to the background.

In the 1980s and 1990s, a number of advances were made that have once again brought EV and HEV technology to the forefront. Advances in MOSFETs and IGBTs used to control electric motors along with the advent of high efficiency and high power density permanent magnet brushless DC motors (PMBLDC) have brought radical changes in the perceived feasibility of these vehicles. Advances in advanced Lead-Acid

(Pb-A), Nickel Metal Hydride (NiMH), and Lithium based battery technologies also gave promise of onboard energy storage that met or exceeded the original feasibility minimums outlined in the 1970s.

In the 1990s, GM produced a consumer EV called the EV1 that was available for lease in western states. This was the first widely available consumer EV available in the US in the modern era. This vehicle was pulled from the market several years later due to the high maintenance cost of the fleet.

Another key technology which began to come forward during the 1980s and 1990s is the fuel cell. The leading fuel cell technology of this era was the Proton Exchange Membrane (PEM) fuel cell. In this system a hydrogen nucleus is stripped of electrons and the remaining proton is passed through a membrane impermeable to the electron. The electron is then passed through a circuit where work is derived and reunited with the proton on the opposite side of the membrane. In fuel cell electric vehicles (FCEV), the system behaves much like a typical ICE powered series hybrid except that the ICE is replaced with a fuel cell.

1.2.2. Current and Future Research

At the current time, both EVs and HEVs have passed beyond the area of research into the commercial arena. A number of industrial and consumer products are currently available in EV or HEVs. Domestic consumer HEVs include the Honda Insight, Toyota Prius, Honda Civic, and soon the Ford Escape. The Toyota motor company projects that it will sell 300,000 hybrid vehicles per year by 2005 with hybrid options available in every major product by 2012 [Lippert, 2002].

At this time, it is perceived by many that hybrids will eventually move into all markets of automotive technology. An interesting example of an HEV that steps outside the current views of HEV technology is the Toyota concept car “Alessandro Volta” [Toyota, 2004]. The “Volta” is truly an HEV supercar on par with some of the highest performance vehicles in the world. This vehicle has a carbon fiber body designed by the Italian design firm Giugiaro that seats three passengers abreast (see Figure 1.4). The novel and futuristic “drive-by-wire” controls system allows the steering and control pedals to be placed in front of any of the three passengers. Unlike the stereotypical HEV,



*Figure 1.4 Toyota's "Alessandro Volta" Concept Car
Source: Toyota Motor Company*

this vehicle is capable of traveling 435 miles on a 13.7-gallon tank with 0–60 mph acceleration in a mere 4 seconds. A fuel economy of 31.8 mpg for a “super sports car” is a staggering improvement over the 8-15 mpg currently available in similar vehicles using standard ICEV technology.

The primary focus of EV and HEV research in the US is currently in FCEVs and the supporting hardware. This is seen as the “generation-after-next” approach for HEVs. Although this form of vehicle is technically a hybrid utilizing a fuel cell as APU, it is frequently referred to as an electric vehicle. This is because the preferred configuration would utilize an extremely small ESS (potentially ultra-capacitors) to handle transients with the fuel cell meeting the vehicle power demands on a near real-time basis [Husain, 2003]

1.3. Hybrid Electric Vehicle Configurations

An HEV is a vehicle that uses a combination of electric and chemical fuel (typically in the form of hydrocarbons) or mechanical energy storage. The system consists of an electrical energy storage system (ESS), electric motor(s), an auxiliary power unit (APU), and a second non-electrical energy storage system. Typically the second ESS system

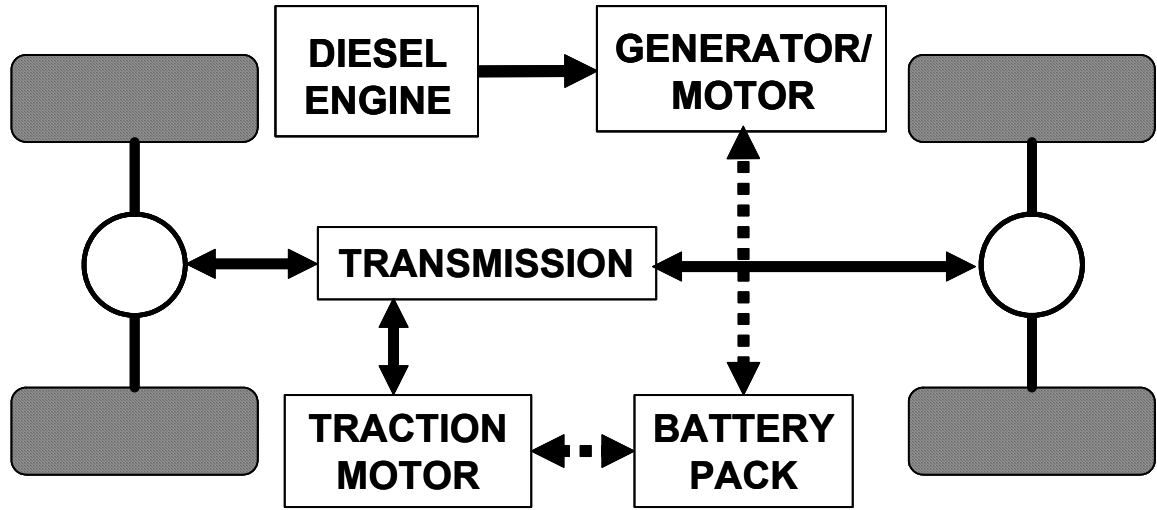


Figure 1.5 Series Hybrid Electric Power-flow Schematic

contains a higher energy capacity than the electrical system. These systems offer improved efficiency over typical ICEVs, and improved range over typical EVs.

In general, there are two major divisions of HEV configuration, with all others being variations or combinations of these two. These two configurations are the Parallel HEV (PHEV) and the Series HEV (SHEV). Other configurations such as Toyota's epicyclic power split HEV and the FCEV can be classified as subsets or combinations of the two primary types.

1.3.1. Series Configuration

The simplest and earliest developed HEV configuration is the SHEV. In the series configuration, tractive power is provided solely by an electric motor. The APU in this system is used to provide power directly to the electric motor and to the electrical ESS. Figure 1.5 shows a block-diagram powerflow schematic of the SHEV system.

Use of the SHEV system completely decouples the APU from the instantaneous vehicle load. As a consequence, the APU can be run at a high efficiency operating point at all times. This also allows relatively simple thermostatic control algorithms to be used for the APU. On the negative side however, lack of tractive power from the APU typically increases the required motor size and thus the power required from the ESS,

complexity of the overall system, and system weight.

There are a number of systems either existing or under development that fit into this category. FCEVs, diesel electric locomotives, and certain nuclear powered ships all fall into the SHEV category. This technology is being pursued for a number of military and commercial applications including over-the-road haulers, transit buses, and postal and urban delivery vehicles.

One characteristic of the series configuration that may be important in military applications is that if the electric drive becomes inoperative the vehicle is rendered immobile. On the other hand, pure electric operation gives the same vehicle performance as hybrid operation -- until the ESS state of charge (SOC) drops to the point where it can no longer deliver the required power to the motor.

1.3.2. Parallel Configuration

In the parallel configuration propulsive power to the drive wheels can be provided by the electric motor, the engine, or both. The power from the engine can typically be used for either propulsive power, ESS charging, or both simultaneously. Figure 1.6 shows a parallel configuration power-flow schematic.

The parallel configuration can implement several operation schemes such as using the engine with the electric motor providing additional power when required (electric assist), or operation relying on the electric motors with the engine providing additional power when required. Since the maximum power requirements of the vehicle can be satisfied by operating both the motor and the engine, the motor can have a lower power rating than in the case of an equivalent series configured HEV. In general, the parallel configuration has better fuel economy than the series configuration under highway (high speed) conditions because the engine can be used to drive the vehicle directly -- thus avoiding some of the energy conversion losses associated with the series configuration.

An advantage of the parallel configuration is that if the electric drive system becomes inoperative the vehicle can continue to function with reduced power through the redundancy of the conventional engine power transmission path ("limp home" capability). This feature is particularly appealing in military applications where access to repair facilities and parts may be unavailable or quite some distance away. In general,

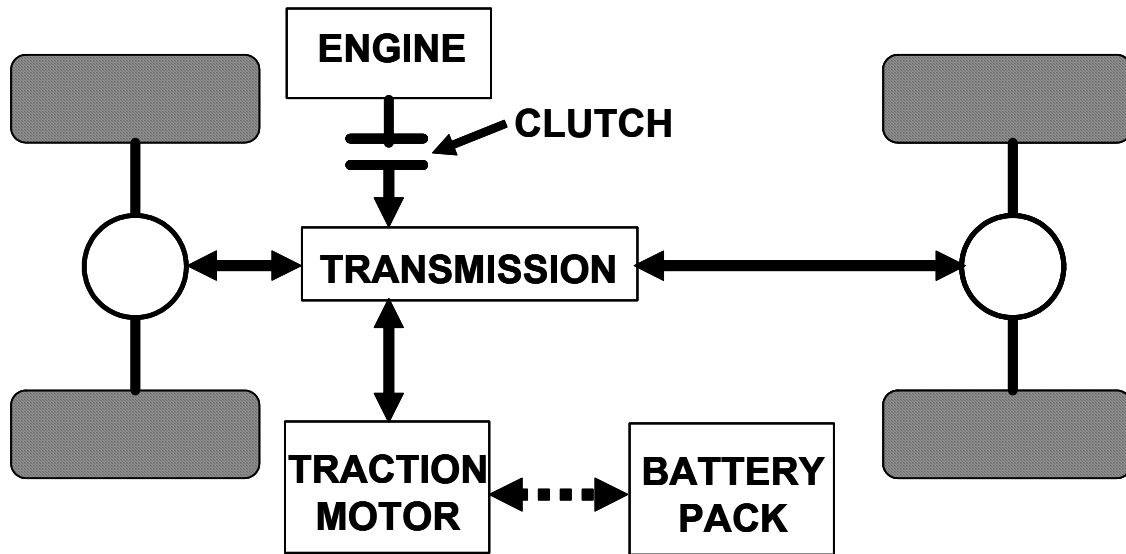


Figure 1.6 Parallel Hybrid Electric Powerflow Schematic

the combat survivability of the PHEV system should be greater than the SHEV due to this system redundancy.

1.3.3. Split-Mode Configuration

The series and parallel configurations have fuel economy advantages and disadvantages relative to each other, which depend on vehicle operating conditions. Ideally, it would be desirable to have a powertrain that could switch between or blend these two configurations as driving conditions change. One system currently in production that allows this a “blended” parallel-series operation is the epicyclic power-split HEV [Toyota, 1997]. This configuration, frequently termed as a split-mode HEV, can operate as either an EV or a parallel-series blended mode. During this blended mode, the engine is on providing both tractive power and regeneration to the ESS. An epicyclic planetary gearset is used to interface the engine, a generator, and an electric motor providing the operational equivalent of a continuously variable transmission (CVT) between the engine and the drive wheels during engine-on operation. The power-flow block diagram of this system is shown in Figure 1.7.

The split mode arrangement results in the greatest power flow flexibility as well as

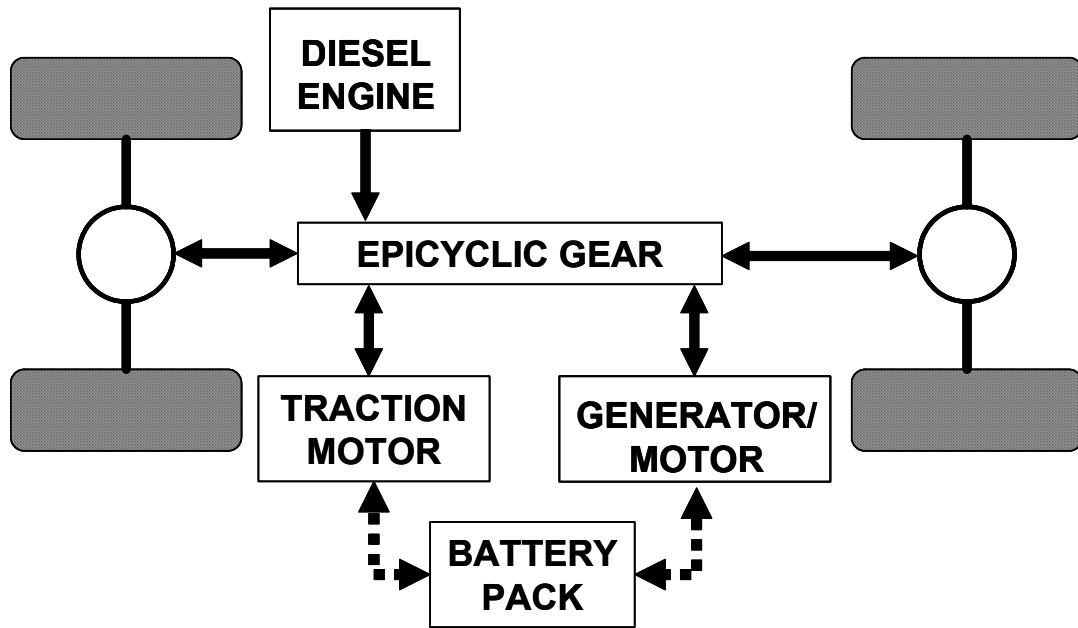


Figure 1.7 Split Mode Hybrid Electric Powerflow Schematic

the greatest control system complexity. Although this approach offers advantages of both the series and parallel systems, it requires additional components to be a truly redundant system, and is likely to be more expensive than the parallel system.

1.3.4. Other Configurations

As stated earlier, all existing hybrid configurations are variations or combinations of the series and parallel HEV configurations. There are several of these that have received enough development to be worth noting.

One type of hybrid that has been studied that would cause a very small impact on existing systems is the mild hybrid or MYBRID (this system is also referred to as the Integrated Starter/Generator (ISG)). This configuration is a PHEV utilizing a small assist motor typically attached directly to the engine. In some cases this motor is little more than an oversized starter/generator. During normal driving, the assist motor is used to boost acceleration torque during launch, and recharges a very small ESS (usually an

oversized or 42VDC accessory battery) during normal driving. Although the fuel and emissions benefit of such a system is typically small (5-10% on fuel economy), it can offer a very inexpensive, driver transparent HEV system that can have a noticeable impact during city driving [German, 2003].

Another version of the PHEV system worth noting is the “through-the-road” hybrid. In the through-the-road hybrid system, the typical arrangement is for the APU (normally an ICE) to drive the front axle of the vehicle as in a normal ICEV, while an electric motor powers the rear axle. This offers a hybrid system with small impact on existing vehicle layouts. One of the primary areas that this type of system has been studied is in over-the-road trucks. The through-the-road hybrid approach offers these vehicles a hybrid option without changing existing tractors. This approach can also offer enhanced braking and traction control if the electric powered axle or axles utilize individual wheel motors.

1.4. Military Requirements

As stated earlier, a hybrid electric HMMWV has the potential to increase fuel efficiency, operate with low noise and low thermal signatures, and to provide auxiliary power generation in the field. At this time, one of the limiting factors for the widespread commercialization of HEVs is related to the lengthy payback time of the specialized components required for these vehicles. In the military this payback time is greatly reduced. The primary reason for this is the fact that fuel delivery is the single largest supply component in a typical military action. Battlefield delivery costs of fuel can easily exceed 50\$/gallon. At this rate an improvement of 10-15% in fuel economy makes HEV technology economically viable so long as performance is not significantly impacted [German, 2003]. It is anticipated that several times this improvement can be achieved with an improvement in performance as well.

The following discussion highlights baseline stock performance requirements, and hardware issues pertaining to the basic hybrid system design and components.

1.4.1. Stock Vehicle Performance

The HMMWV is a fielded equipment item and the military has developed explicit performance requirements for it. The baseline stock vehicle performance as related to

drivetrain parameters follows:

- Maximum Gross Vehicle Weight (GVW): 7700 lbs
- Fording depth: 30 inches
- Grade Operation: At its GVW the vehicle must be able to ascend a 60% grade at 2 mph and to stop and start on this grade. Also at its GVW the vehicle must be able to ascend a 5% grade at 55 mph.
- Acceleration: At its GVW the vehicle must be able to accelerate from 0 to 30 mph in 6 seconds or less and from 0 to 50 mph in 30 seconds or less (both on a level hard surface road).
- Speed: At its GVW in high gear the top speed must be at least 60 mph and in low gear the top speed must be less than 2.5 mph.
- Range: Range must meet or exceed 300-miles.

1.4.2. Electric/Hybrid Vehicle Required/Target Performance

The military is giving greater consideration to the use of industrial grade commercial-off-the-shelf (COTS) components in fielded equipment to reduce costs and enhance maintainability. The role of COTS components in the low cost hybrid HMMWV design is critical. Manufacturers are continually announcing new developments in electric motors, generators, and batteries of all sorts, but at the present time many of these high performance components are in low-volume production, or at the prototype stage of development and are not commercially available. In order to be functionally equivalent to the existing HMMWV powertrain, the hybridized HMMWV must be capable of meeting all performance requirements of the stock vehicle, with the following additional goals:

- Range: As a hybrid the range must meet or exceed the standard 300-mile range. In the pure electric mode, the range must be at least 20 miles at 20 mph or greater vehicle speed.
- While the vehicle must be capable of meeting the baseline vehicle performance requirements as a hybrid, its performance as a pure electric, or in any backup modes, may be appropriately de-rated.

2. Description of Typical Hybrid System Components

At this time there are a wide range of available system components for HEV systems. Many of these options, however, are not commercially available in either sufficient volumes or at acceptable costs for widespread use. A number of the available options for ESS, APU, power transmission, and auxiliary systems are detailed in the following sections.

2.1. Energy Storage System

In general, the ESS of HEVs is one of the most important systems. Power density, energy density, and cost are typically the three most important considerations. In order to perform an effective study of the tradeoffs these three areas must be considered. The ESS design specifications are dictated by the electric motor selection, the vehicle's pure electric range requirement, space and weight constraints, safety, recharging, and cost considerations. Due to the cost limitations of currently available alternatives, the ESS for the proposed HMMWV system is assumed to be a battery pack. Various battery and other ESS technologies are discussed in the following sections.

2.1.1. Pb-Acid Battery

Lead acid (Pb-A) batteries provide one of the oldest and most reliable systems of energy storage use in EVs and HEVs. Recent developments in this battery chemistry have greatly increased both the energy and power density of this battery technology. At this time, the Valve-Regulated-Lead-Acid (VRLA) battery is the state of the art of Pb-A technology. This battery technology offers a marginally sufficient energy and power density for HEV systems, and is typically considered as the baseline technology for ESS systems for hybrids. This is due to the high availability of Pb-A battery systems. Figure 2.1 shows an example of a typical Pb-A battery for hybrid use. This particular battery is a VRLA battery manufactured by Hawker Energy Products for automotive and uninterruptible power supply applications.



Figure 2.1 Hawker Genesis VRLA Battery
Source: Hawker Energy Products

Energy and power density in Pb-A batteries can vary significantly with cell construction, but for typical hybrid and electric applicable VRLA batteries, energy density typically ranges from 35-50 W-h/kg with specific power of approximately 150 W/kg at a C5 discharge rate [Jefferson, 2002; Husain, 2003; Atkin, 1998]

Pb-A battery technology is currently the predominant technology for automotive systems. This is primarily due to the maturity and availability of Pb-A battery systems. For this study, the Pb-A ESS is anticipated to be the likely solution due to the higher cost associated with all other currently available COTS solutions. A number of these more costly ESS systems may be useful for the higher power and energy density systems envisioned for future HEV use.

2.1.2. Ni-MH Battery

The Nickel Metal Hydride (NiMH) battery is one ESS technology that has seen significant development in the past 15 years. This battery technology was the ESS choice for the first two consumer HEVs, the Toyota Prius and the Honda Insight.



Figure 2.2 SAFT High Energy NiMH Battery Module
Source: SAFT Batteries

NiMH batteries are alkaline electrolyte batteries with significantly higher energy density than VRLA batteries [Rand, 1998]. Energy density of approximately 75 W-h/kg and specific power of up to 200 W/kg is possible with this technology [Jefferson, 2002; Atkin, 1998; SAFT, 2004]. This technology also offers cycle life of 1.5 to 2.5 times that of an equivalent VRLA cell. Figure 2.2 shows a currently commercially available NiMH battery available from SAFT. These multiple-cell modules are compatible with the interconnection techniques typically used with VRLA battery systems.

Although the energy and power density of NiMH is substantially superior to VRLA battery technology, there are several disadvantages of this technology. The most significant negative factor for NiMH batteries is cost. Due to the high cost of the nickel electrode material, NiMH batteries are typically 5 to 10 times the cost of equivalent VRLA batteries [Jefferson, 2002; SAFT component quotes]. While this is partially offset by the longer cycle life of this technology, there is still a significant cost disadvantage. Another disadvantage of the NiMH battery is its tendency to self-discharge. A traction application NiMH battery would likely lose 25% charge if left unused for four weeks [Rand, 1998]. This is particularly negative for some military applications where vehicles may be stored for extended times between operational periods. Frequent charging of

batteries in idle vehicles would partially offset advantages gained due to improved fuel economy of a hybrid system. Additionally, this battery technology is very sensitive to high temperatures making an active cooling system mandatory for high power applications.

2.1.3. Ni-Cd Battery

Ni-Cd battery technology is an alkaline electrolyte system and uses a positive nickel electrode similar to the NiMH battery. The negative electrode in the Ni-Cd system however is made of cadmium rather than the metal hydride negative electrode of the NiMH system. The Ni-Cd battery chemistry is superior to VRLA in both energy and power density, with an energy density of approximately 55 W-h/kg and specific power of up to 200 W/kg [Jefferson, 2002; Atkin, 1998; SAFT, 2004]. Additionally, the Ni-Cd battery chemistry is slightly less expensive than equivalent NiMH batteries. This is also a more durable battery technology with life cycles from 1.7 to 3.3 times an equivalent VRLA battery.

Although the cost of Ni-Cd batteries is slightly lower than NiMH with a greater cycle life, the cost is still currently around \$1,000/kW-h [Rand, 1998]. Self discharge is also an issue in Ni-Cd batteries with 30% discharge in 48 hours possible [Jefferson, 2002]. Recent advances have reduced this to 2% discharge in 48 hours for certain cell constructions [Rand, 1998]. Another negative of the Ni-Cd chemistry is the high toxicity of the cadmium electrode. In general, this battery technology is only marginally superior to VRLA systems in performance with a substantial cost premium.

2.1.4. Ni-Zn Battery

Ni-Zn batteries are alkaline electrolyte batteries similar to Ni-MH and Ni-Cd with a nickel positive electrode and a zinc negative electrode. These systems typically have specific energies of approximately 70 W-h/kg and with specific power of approximately 150 W/kg [Rand, 1998; Evercel, 2004]. This is a similar power capability to VRLA batteries with a specific energy of 1.5 to 2 times greater. These batteries also have a low self-discharge rate for nickel based battery technologies and low toxicity of the electrode components [Rand, 1998]. Some companies are currently manufacturing batteries similar



Figure 2.3 Evercel Ni-Zn Batteries
Source: Evercel, Inc.

to the ones shown in Figure 2.3 which are drop-in replacements for existing VRLA or other Pb-A batteries.

There are a number of disadvantages of the Ni-Zn chemistry. The price of this technology is more than double that of current VRLA systems [Evercel, 2004]. This initially appears substantially better than other nickel-based technologies, but the cost advantage is much smaller once cycle life is considered. At this time the cycle life of Ni-Zn batteries is equal to or slightly shorter than equivalent VRLA technologies [Rand, 1998; Husain, 2003; Evercel, 2004]. The shorter battery life is due to plate shape change during the batteries' cycle life [Rand, 1998]. This effect can be reduced by pulse charging [Evercel, 2004], but the technology is not yet mature enough to extend battery life to a level acceptable in most vehicle applications.

2.1.5. Air Electrode Batteries

Air electrode batteries are alkaline batteries that are sometimes referred to as fuel cells or fuel batteries. These types of batteries utilize the oxygen in air as part of the positive electrode. These batteries utilize a porous electrode substrate made of a material made of either nickel or carbon with a platinum or silver catalyst to facilitate the discharge process of oxygen reduction. This concept is attractive because the reduction agent, air, is freely available and does not have to be carried on board. Various batteries

in this category offer energy densities between 4 and 16 times that of VRLA batteries.

One air electrode battery, the Al-Air battery, is regarded by many to be the only direct competitor with ICEV technologies for range and refueling time considerations. The theoretical specific energy of such a battery is more than 16 times the theoretical specific energy of Pb-A chemistry. Batteries of this type have been tested with specific energy in excess of 270 W-h/kg with a specific power of over 160 W/kg.

A substantial disadvantage of the Al-Air design is that the aluminum electrodes cannot be electrodeposited from aqueous solution which prevents recharging of the battery during operation. The intended recharging cycle for this battery is the mechanical replacement of the aluminum electrode after the battery reaches approximately 25-50% depth of discharge (DOD). Replacement at this time prevents degraded specific power seen at higher DOD values. This type of system gives a refuel cycle that could be theoretically superior to that of an ICEV. This system, however, cannot accommodate regenerative braking and is not well suited to military application [Rand, 1998].

2.1.6. Na Batteries

Sodium battery chemistries, including Na-S and Na-MCl systems offer a solid alkaline electrolyte battery technology with very high theoretical specific energy (up to 760 W-h/kg) [Rand, 1998]. Because of the high reactivity of the electrodes, it is impossible to use an aqueous electrolyte, which led to the development of a β -Alumina solid ceramic electrolyte [Husain, 2003].

Although the high specific energy of this battery type seems promising, there are several negative features of this battery. The first, and most important, is the operating temperature of the battery. In order for the β -Alumina electrolyte to effectively transport Na ions, the temperature must be in the range of 200-400°C. This means that the battery temperature must be maintained at a high temperature during operation (and storage to prevent a lag in energy availability during heat-up). An operating temperature of 300°C results in a molten Na electrode that reacts violently with the slightest exposure to moisture. High temperature operation, along with the volatility of the molten Na electrode, makes Na battery technologies unacceptable at this time [Rand, 1998; Jefferson, 2002; Husain, 2003].

2.1.7. Li Batteries

An area of battery research making great advances in recent years are Lithium ion (Li-ion) and Lithium solid polymer (Li-SP) with specific powers of up to 800 W/kg claimed in recent years [Atkin, 1998; Jefferson, 2002]. The low atomic mass of Li (the lightest metal) along with its high electrochemical reduction potential result in an ESS with very good specific energy and power. Both the Li-Ion and Li-SP technologies offer good cycle life. Current costs are somewhat higher than NiMH battery technologies due to the early stage of development for kW-h sized batteries. Future costs are anticipated to be competitive and likely superior to NiMH due to lower material costs [Husain, 2003]. Safety in the Li-Ion battery is on par with Pb-A, with Li-SP being superior due to the immobile solid polymer electrolyte [Juzkow, 1997; Jefferson, 2002].

Li battery technology is seen to hold great promise for the future, but is not currently considered an option due to the early stage of development of high energy, high voltage commercial products. This technology is a likely future replacement for fielded HEV Pb-A and NiMH battery packs.

2.1.8. Ultracapacitors

An interesting choice for energy storage for HEVs is ultracapacitors. This source has a very low specific energy (on the order of 10 W-h/kg), but extremely high specific power of over 500 W/kg. Long term research is anticipated to result in specific energy and power of 15-20 W-h/kg and 4000-5000 W/kg respectively [Husain, 2003; Rand, 1998]. While the specific energy seems too low to consider for primary energy storage, this type of device may work well in conjunction with fuel cells in FCEVs or low power density, high energy density ESS technologies to provide peak power for acceleration and to smooth transients. A primary advantage of ultracapacitors is their relatively low material cost and long cycle life of over 100,000 deep discharge cycles with negligible degradation in capacity [Jefferson, 2002; Husain, 2003; Maxwell, 2004]. An additional advantage is the high charge/discharge rate capabilities of the ultracapacitor. In general, the charge/discharge rate of this device is limited primarily by the resistances of the interfaces between the capacitor and the charging system. Figure 2.4 shows an example of typical packaging for current ultracapacitors.



*Figure 2.4 Maxwell PC10 High Energy Ultracapacitor
Source: Maxwell Technologies*

2.1.9. Flywheel Energy Storage

Mechanical energy storage in a rotating mass has been used for centuries for load leveling and ripple torque reduction. These types of applications are generally low speed and require little stored energy. For use in hybrid and electric systems, a much higher specific energy is required.

The rate of charge/discharge for a flywheel energy storage system, however, is limited primarily by the mechanical limitations of the system and secondarily by the electrical interface. The flywheel energy storage seen in Figure 2.5 has been extensively researched in Europe with Magnet Motor GmbH of Germany being a leader [Jefferson, 2002; Magnet Motor, 2004]. Current flywheel technology concentrates on carbon fiber rotors contained in evacuated housings using magnetic bearings [Magnet Motor, 2004]. Energy is added or subtracted from the spinning rotor through an integrated electric motor/generator. Specific energy is nearly on par with VRLA systems at 55 W-h/kg with specific power of approximately 500 W/kg currently available [Jefferson, 2002]. This technology offers a relatively low cost mechanical energy storage system that is adequate for HEVs with moderate pure electric range. This type of system can be substantially more efficient than battery systems with charge efficiencies in the low 90% range.



*Figure 2.5 Magnet Motor K3 Hybrid Bus Flywheel
Source: Magnet Motor GmbH*

The specific energy of a flywheel ESS is unlikely to be sufficient for primary energy storage in vehicles with a substantial electric range requirement. The flywheel can also be sensitive to shock loading and cause negative vehicle dynamic effects, due to the gyroscopic nature of the system. Countering the gyroscopic issues requires a very comprehensively designed cardanic suspension that can nearly double the system mass. Additionally, this type of system suffers from a rather high rate for loss of capacity due to bearing and aerodynamic drag [Jefferson, 2002]. Perhaps the greatest barrier for fielding this type of energy storage system is the perceived difficulty ruggedizing the system, and the associated risk of catastrophic failure under load. Another issue with the flywheel system is the form factor. In general, flywheel energy storage systems are similar to a cube in volume requirement (see Figure 2.5). Although this is workable in large vehicles such as over-the-road haulers and buses, it is unlikely to be viable in small or medium sized vehicles without substantial development.

2.1.10. Hydraulic Accumulator Energy Storage

A second mechanical solution to energy storage is a hydraulic accumulator system. In this type of system an engine is used to drive a hydraulic compressor which either charges a hydraulic accumulator, or powers a hydraulic motor. This second motor is also capable of acting as a compressor. In this type of system, the ESS is an accumulator

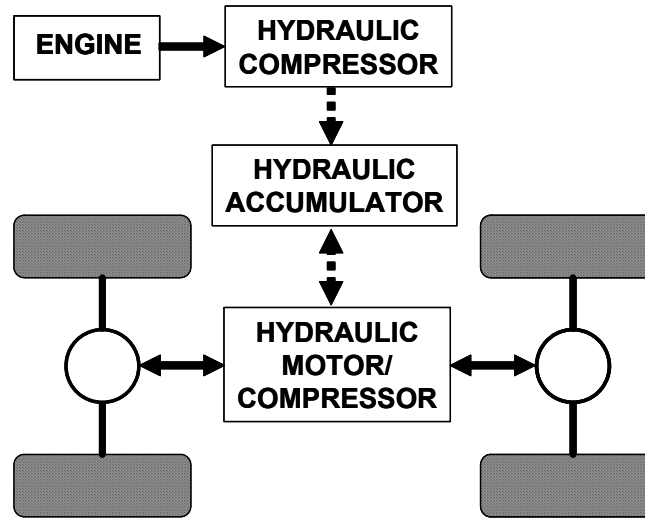


Figure 2.6 Hydraulic Series Hybrid Configuration

filled with a compressible substance such as rubber balls that serve to store energy for use during launch or transient operation situations (see Figure 2.6 for powerflow schematic).

This type of system behaves similar to an SHEV, but has no electric storage capacity. Another option for this type of system is to provide a power-split capability similar to the power-split system described in Section 1.3.3. Either of these options provides some degree of CVT or vehicle speed independent operation with respect to the APU as well as a capability to regenerate energy to the ESS.

A number of hybrid bus powertrains, known as “hydrobuses” have been tested by MAN and Volvo Flygmotor with encouraging results [Hagin, 1985]. This type of storage system has a relatively low specific energy, but was capable of providing a 33% improvement in fuel consumption in primarily city driving cycles [Jefferson, 2002]. This type of system is not suitable for any application which requires a significant engine-off range. In addition to the range issue, this system is quite heavy and takes up a significant volume.

2.2. Auxiliary Power Unit

The selection of an auxiliary power unit (APU) for HEV implementation is typically based on downsizing an existing ICE or operating such an engine at more optimal

speed/torque points. There are, however, a number of other options available to the designer of HEVs with respect to APU. Several APU options are detailed in the following pages.

2.2.1. Spark Ignition Engine

The vast majority of currently available consumer vehicles utilize spark ignition (SI) ICEs as their prime mover. SI engines for vehicle use are typically based on the Otto cycle combustion. This is a four stroke combustion cycle sometimes referred to as the “constant volume” combustion cycle that utilizes an electric spark to detonate the fuel/air charge [Happian-Smith, 2002]. This is a relatively compact, lightweight technology with high power density and quick engine speed acceleration making it useful for mobile applications that see significant transient operation.

At this time, a majority of SI engines are fueled with gasoline, but a number of other fuels including ethanol, methanol, compressed natural gas (CNG), liquid natural gas (LNG), and liquid petroleum gas (LPG) are under study as alternative fuels [Jefferson, 2002].

Recent advances in SI engine technology have been geared toward increasing efficiency, reducing emissions, and increasing power density. A number of approaches have been studied in recent years in this field including cylinder direct fuel injection, turbocharging, supercharging, exhaust gas recirculation, and a number of exhaust aftertreatment options [Fenton, 1996].

SI engine technology is the most mature automotive technology currently available. This is primarily due to the long development time spent on this technology as well as the large amount of funding spent in recent years to improve it. It is unlikely that the gasoline fueled SI engine will be displaced in the near future as the primary engine technology in the US. Diesel CI engines and alternatively fueled SI engines are, however, gaining popularity in Europe as well as other areas of the world.

2.2.2. Compression Ignition Engine

Compression ignition (CI) engines are ICEs based on the Diesel combustion cycle. This, like the Otto cycle, is also a four-cycle combustion but fuel/air detonation is achieved due to compression ignition of the mixture. In order to achieve this, a

significantly higher compression ratio than an SI engine is used in the CI engine. CI engines do not have as high a power density as similar SI engines due to the higher weight for the increased in-cylinder pressures and the lower power yield for a single combustion cycle [Jefferson, 2002]. The vast majority of CI engines worldwide are diesel fueled although a number of alternative fuels, including plant derived oils, are being researched. A significant number of advances in CI technology are geared toward overcoming this power density disadvantage. Such research includes high strength aluminum and magnesium components, turbo- and supercharging, and direct fuel injection [Fenton, 1996].

An advantage of the CI engine over SI engines is the higher cycle efficiency. Peak efficiencies of around 48% can be achieved in some CI applications as compared to 40% in an equivalent SI engine due to the higher volumetric efficiencies afforded by the higher compression ratio [Jefferson, 2002; Happian-Smith, 2002].

Disadvantages of typical diesel fueled engines include the lower level of maturity in CI exhaust aftertreatment, negative consumer perceptions, and increased noise due to the engine knock associated with compression detonation. These issues have been addressed in modern diesel CI engines and are gaining widespread acceptance in Europe where fuel prices are significantly higher. In applications where efficiency is at a premium such as over-the-road and military vehicles, the CI engine has been the primary choice for many years.

Figure 2.7 shows an Alfa Romeo 2.4 L direct injected diesel engine attached to a water brake for testing. This particular engine is widely used in Europe in passenger automobiles. A wide number of manufacturers are developing similar engines for both consumer and commercial applications.

2.2.3. Stirling Cycle Engine

The Stirling cycle engine is a design that has been around for a rather long time [Stirling, 1816]. This engine is of an external combustion design, and uses a hot and cold cylinder section and a system of ports or valves to move a piston to derive work. This type of engine saw widespread use during the mid-19th century and was revived in the 1930s and 40s by the Philips Corporation of Germany for vehicle use [West, 1986].



Figure 2.7 Alfa-Romeo 2.4L JTD Direct-Injected Turbo-Diesel

This version used a hot side and cold side cylinder integrated into the same housing (See Figure 2.8). The primary interest in the Stirling cycle engine is in the high peak theoretical efficiency. In theory, thermodynamic efficiencies of over 50% are achievable.

There are a number of negative features associated with the Stirling engine. One is the obvious delay in power output during hot-side cylinder heat up. This results in a long transient response time for the system. This is unacceptable for a system where the engine provides tractive power directly, but is allowable for the APU of an SHEV. Also, to exceed 50% thermodynamic efficiency a hot-to-cold cylinder temperature differential in excess of 303C is required. Because a large, high temperature heat exchanger is required for this type of operation, Stirling cycle engines typically have relatively low power density (both volumetric and mass based).

A number of manufacturers including GM have considered Stirling engines in the past, but most have stopped work due to the high system weight and volume.

2.2.4. Rankine Cycle Engine

Rankine cycle or vapor-power cycle engines are one option for vehicle application that has not been seriously studied in recent years. Rankine cycle engines include the

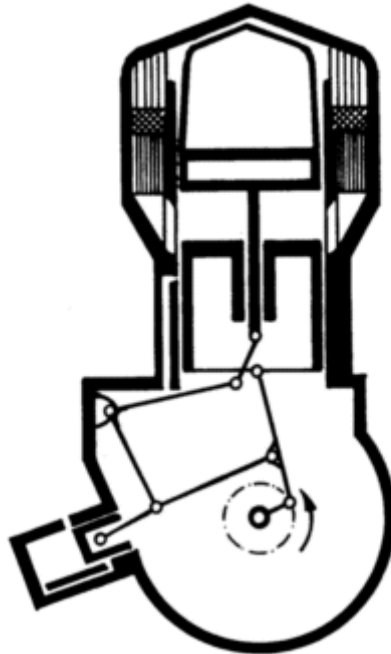


Figure 2.8 Philips Stirling Engine of 1946
Source: NV Philips Gloeilampen-fabrieken

steam engines once used to power large locomotives. These are external combustion engines typically using a flash boiler to evaporate a liquid into vapor to provide work to a power transmission system. Rankine cycle engines provide high low-speed torque and the potential for the elimination of gearboxes. Efficiency in this type of system is typically rather low at approximately 30% peak thermal efficiency.

Rankine cycle steam engines used in locomotive systems were open cycle engines with the water used to create steam a consumable item. In order for a Rankine engine system to be useful for vehicle use today, a closed-loop system would likely be required which would require a large condenser. This would greatly increase the system mass and volume and likely result in an unacceptable power density for automotive applications. One advantage that may make sense for use in developing areas is the Rankine cycle engine's capability to use a wide variety of fuels. In theory this could range from compressed Hydrogen all the way to coal or wood. This inherent flex-fuel capability of

the Rankine and the previously discussed Stirling cycle engines may be useful in areas where a consistent source of fuel may or may not be available.

2.2.5. Gas Turbine Engine

Gas turbine engines are a well developed technology that has been used in aircraft applications for many years. Many features of the gas turbine engine are negative for use in typical automotive applications. High operating speed, poor part-load efficiency, and slow response make gas turbines unacceptable for use as a prime mover in most automotive applications. These negative features of the turbine have no impact on a system utilizing the turbine as the APU for a series HEV.

The high power density of gas turbines makes them a very promising option for mobile applications. An additional advantage of the turbine is that it typically produces a lower level of noxious fumes than reciprocating engines. At this time a number of SHEV light rail vehicles have been tested with gas turbines as small as 50kW [Etemad, 1999].

The most substantial negative feature of gas turbines relates to efficiency. Peak efficiency of a turbine is rarely higher than 30%. In order to increase this efficiency, recuperators must be used, and the compression levels of the combustion process must be greatly increased. These changes also increase temperatures substantially which may make highly toleranced ceramic components necessary to achieve the 40% efficiency possible with SI engines [Jefferson, 2002]. The features of high power density and low maintenance due to few moving parts make the gas turbines promising for the future, but current technology does not allow widespread implementation in the near term.

2.2.6. Proton Exchange Membrane Fuel Cell

While there are a number of potential fuel cell technologies, the one receiving the most attention of late is the Proton Exchange Membrane or PEM fuel cell. In general fuel cells utilize hydrogen and oxygen combined in some process resulting in water and electricity as products. Some systems frequently referred to as fuel cells are very similar to the metal-air batteries discussed in Section 2.1.5. PEM fuel cells operate in a somewhat different manner. In PEM systems, hydrogen enters the system at the anode side of a polymer electrolyte membrane. The membrane allows the flow of protons to the cathode side of the membrane, but not electrons. As a result the electrons must flow

through an alternate path (in this case an electrical circuit) where work is derived [Appleby, 1989].

Conversion efficiency of PEM fuel cells is relatively high with efficiencies as high as 50% possible. There are substantial limitations to current PEM fuel cell systems due to poor transient response, and a start-up delay due to a required minimum operating temperature of around 80C. Another limitation is that a source of hydrogen must be carried onboard. Although hydrogen has very good specific energy on a mass basis, the volumetric energy density is very poor for most storage methods. This means that if significant range is desired, it is likely that the hydrogen for the fuel cell stack must be produced on board. Such a system requires either a reformer to produce hydrogen from gasoline, methanol, or ethanol, or a fuel cell technology that can directly utilize the fuel stock [Appleby, 1989; Jefferson, 2002; Husain, 2003]. Both of these methods result in lower system efficiency and increased weight.

PEM and other fuel cell technologies offer promising future options for EVs and HEVs. At this time, however, the technology is too early in development for substantial commercial use. Significant study of hydrogen based fuel infrastructure is also required to determine whether the most desirable option for future systems is based on direct hydrogen fueling or on board reformation of existing fuel stocks. Based on current military fuel delivery; infrastructure, it is unlikely that any fuel cell option that utilizes any fuel stock other than diesel or gasoline at the organizational supply level will be considered.

2.3. Electric Motor and Controller

An area of advancement in EV and HEV research that is rapidly advancing toward commercial maturity is the area of electric motors and controllers. Recent improvements in power silicon, soft magnetic materials, and rare-earth magnetic materials have resulted in motor/controller combinations with power density and performance suitable for use in current and future EVs and HEVs. The following sections detail a number of motor/controller options currently being pursued for EV and HEV use.

2.3.1. Brushed DC Motor and Controller

One of the earliest options utilized for EV applications is the brushed DC motor. In this type of system, motor rotor commutation is achieved by a series of brushes in contact with the conductors of the rotor. This motor type is relatively inefficient compared to other modern motor technologies due to losses in the commutator and brushes, but is frequently used in very low cost EV conversions. One other significant issue with this motor is that it uses a friction interface for transfer of current which means that there are significant wear and maintenance issues associated with this technology. In this type of motor/controller system, a number of simple control approaches can be taken.

One of the earliest attempts at motor control for brushed DC motors was a variable resistive controller. In this type of system a multi-position switch was attached to several increasing series resistor values, or to a potentiometer with a continuously variable capability. Because the torque of the motor is directly proportional to the current flowing through it, the variable resistor was used to increase or decrease the available voltage to the motor and the corresponding current. This system varies the current to the motor by increasing or decreasing the resistance in the system. While this type of system is very effective (it is still used in older electric golf-cart controllers), it is also very inefficient at part load. No shaft work is derived from the current flowing through the series resistor. As a result, the percent of non-work producing resistive losses increases with resistor value, as the available work decreases due to the drop in current. This system is unacceptable for current EV or HEV powertrain use

The simplest control method for the DC brushed motor system is a simple switch between the battery and motor. In this case, the motor will provide torque based on the difference between its no-load speed at the current battery voltage, and the current motor speed. The no load speed of the motor is based on the motor's torque or voltage constant. This constant is typically expressed in V/rpm or V/rad/s. The higher the value of the voltage constant, the lower the no-load speed for a given battery voltage. In this type of control system, the instantaneous motor torque is determined by the current motor speed, applied battery voltage, and motor ON/OFF state. If the motor is traveling below the no-load speed, the motor will provide a positive tractive torque. If the motor is above the

no-load speed, the motor will actually attempt to generate to the battery pack and will provide a retarding tractive torque. The only control the operator can exert over the motor is based on the ON/OFF state of the switch.

A variation on the ON/OFF switching method of DC brushed motor control uses a solid state power silicon switch in place of the mechanical switch. This switch is capable of turning on and off at a much higher frequency than achievable by a human operator (capable of frequencies in the kHz range). By also altering the amount of time the switch is on, the rms current through the motor can be effectively controlled. This method is known as pulse-width modulation (PWM).

While brushed DC motors offer an extremely low cost and widely available option for EV and HEV applications, efficiency and maintenance issues make them unsuitable for large scale commercial EVs and HEVs and military use.

2.3.2. Permanent Magnet Brushless Motor and Controller

Permanent magnet brushless DC (PMBLDC) motors are currently a fast-growing technology for use in EV and HEV applications. The PMBLDC uses permanent magnets for the rotor field rather than the commutator excited coils of the brushed DC motor. This eliminates a number of losses that are experienced in other motors. This permanent excitation eliminates the resistive copper losses typically seen in the rotors of induction and brushed motors, it also eliminates the brush losses discussed in Section 2.3.1.

The PMBLDC motor requires a different type of controller than the brushed motor discussed earlier. Because there is no mechanical commutator, the motor must be commutated electronically. Switching is typically done using IGBTs or MOSFETs in either a 3-phase WYE or independent H-bridge configuration.

This type of motor also requires some method of position sensing to determine the rotor position relative to the stator in order to properly time the switching for commutation. This is typically done using digital Hall-effect switches to sense whether a North or South pole is in proximity to the corresponding coil. The most frequently used commutation scheme for this type of motor is known as six-step trapezoidal commutation. Figure 2.9 shows an example of the relationship between the Hall-effect signal, back-emf, and phase current for this form of commutation. The current through a

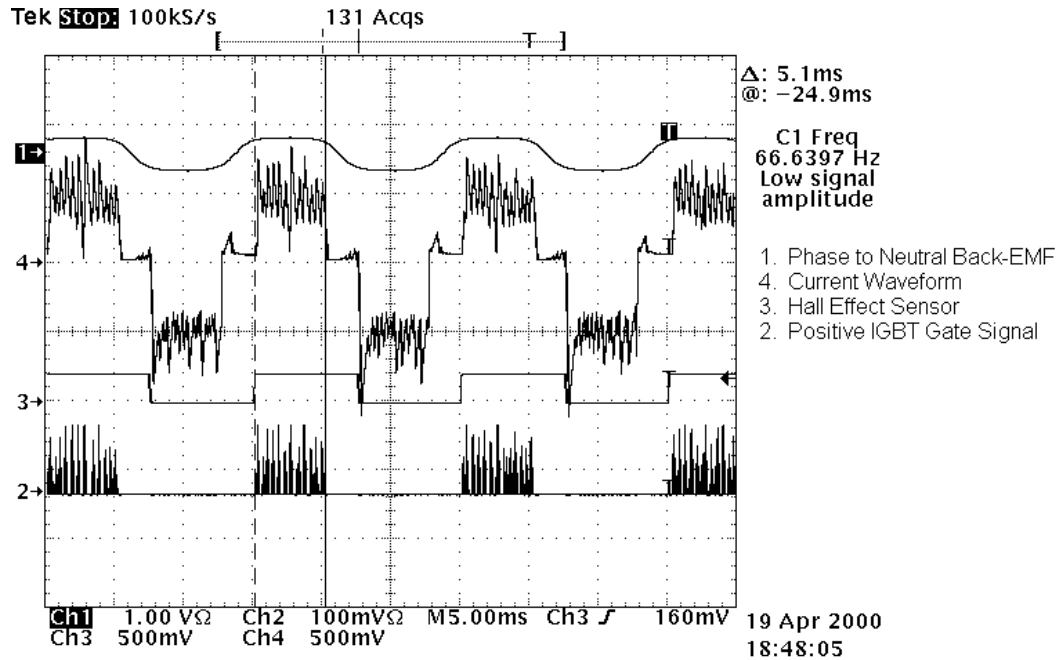


Figure 2.9 Phase Relationship for 6-Step Trap Commutation of PMBLDC Motor

given phase is controlled by the same PWM technique used in the control of brushed motors discussed in Section 2.3.1 [Beaty, 1998].

The PMBLDC motor and controller offer very high power density and efficiency compared to other technologies but have a number of drawbacks. Most drawbacks are related to the magnets used in the rotor. Because these magnets provide a constant flux, it is difficult to field weaken PMBLDC motors. This means that they typically have a limited constant power speed range (CPSR) which is undesirable in motors using a fixed ratio reduction. Magnets are also made of rare-earth elements that are quite costly, and sensitive to high temperatures. This means that PMBLDC motors are currently considered a premium technology.

2.3.3. AC-Induction Motor and Controller

AC-induction motors have been quite popular in modern EVs and HEVs. GM's EV1 was powered by this type of motor. In this type of motor, the rotor rotates at a speed that is different than the synchronous speed of the motor (as in the PMBLDC motor). Torque of the AC-induction motor is determined by the angular difference between the

rotor position and the synchronous position of the rotor. This angle is called the slip angle.

Torque in AC-induction motors can be controlled in one of two ways, by varying stator terminal voltage, or stator frequency. For a given slip angle, the torque increases as voltage increases. In order for an AC-induction motor to provide constant power over a wide speed range, the frequency is also varied to change the rated flux and synchronous speed of the machine. This method of controlling AC-induction motors where both the voltage applied and the input frequency are varied is sometimes referred to as vector control [Husain, 2003, Beaty, 1998].

AC-induction motors are typically capable of a wide CPSR and utilize mature technology. On the negative side, AC-induction motors are typically heavier and less efficient than equivalent PMBLDC motors. This is undesirable if all energy for powering such a device must be carried in an ESS.

2.3.4. Switched Reluctance Motor and Controller

Switched reluctance (SR) motors are synchronous machines similar to the PMBLDC motor. These motors, however, do not have rotor windings or permanent magnets for excitation. Instead, these motors use a positional preference based on a path of least reluctance through the rotor to position it. This means the rotor can be fashioned out of inexpensive steel laminations without windings. The resulting construction is extremely low cost compared to competing technologies, and is capable of very wide CPSR. Because the tractive force is based simply on the path of reluctance, motor currents do not need to be bi-directional. This means that half as many switches can be used as in an analogous PMBLDC controller. There are a number of issues however with this motor configuration.

In the SR configuration, the absence of an excitation on the rotor means that the entire burden for excitation of the machine is on the stator and controller. This means that the stator losses for an SR machine are considerably higher than an analogous PMBLDC machine. Additionally, extremely precise position information must be available to avoid high ripple torque and audible noise during operation. The high ripple torque also results in higher ripple current which drives up the capacitance required in the controller.

Currently, the high ripple torque and noise of the SR motor have made it undesirable for use in most vehicle applications. This is, however, seen as a leading future technology for vehicle traction applications.

2.4. Power Transmission

Hybrid and electric vehicles are heavily dependent on component efficiencies and total system weight to achieve significant improvements in fuel consumption. For this reason, high efficiency, compact gear reductions have been a significant area of research in HEV development. Power transmissions are a necessity in current ICEVs and PHEVs where the APU provides tractive power to the wheels. Simple gear reductions are frequently desirable in SHEVs as well to reduce system weight by eliminating the requirement for sizing electrical components for direct drive torque. The following sections detail several power transmission options under study in modern EVs and HEVs.

2.4.1. Automatic Shift Multiple Ratio Transmission

Automatic shifting multiple ratio transmissions are typically fluid coupled to a prime mover with a hydraulic shift logic unit providing the decision making input for ratio shifts. In most modern automatic transmissions, the hydraulic logic portion of the transmission has been replaced by an electronic controller coupled to a system of solenoids to actuate the hydraulic control circuits. This type of transmission is very popular for its ease of use; it requires extremely little input from the driver. Although this type of transmission is very user friendly, it is quite bulky and heavy due to the hydraulic circuits required. Additionally, because it uses a fluid coupling between the prime mover and the transmission, it has considerably higher losses than a friction clutch based system following launch. Due to the slip in the torque converter being transferred through a fluid rather than a solid, however, there is much lower wear during normal shifting.

The hydraulic automatic shifting transmission is the transmission of choice in current military applications due to the low degree of training required for drivers. The torque multiplication and lower maintenance associated with the fluid coupling rather than a friction clutch system are also appealing for military systems.

2.4.2. Manual Shift Multiple Ratio Transmission

The manual shift multiple ratio transmission is one of the most efficient power transmission means for vehicle use with ICEs. The multi-ratio transmission allows the engine to operate in a fashion that approximates constant power operation without the significant losses associated with the fluid coupling of the automatic shifting multiple ratio hydraulic transmission.

A system currently under development in a number of performance vehicles and HEVs is the automatically shifting manual transmission. This is effectively a standard manual transmission with friction clutch that has had the clutch pedal and shift linkage replaced with a computer controlled system of actuators [Fenton, 1996]. Automatic shifting of a manual transmission results in a system that requires little driver skill, like the automatic shifting hydraulic transmission, but affords the efficiency advantages of the manually shifted transmission. With improved clutch control algorithms and shift actuators, it is likely that the automatically shifted manual transmission will rival the current automatic hydraulically shifted transmissions in high efficiency applications.

2.4.3. Fixed Ratio Transmission

A fixed ratio transmission is simply a single speed gear reduction typically used in electric motor applications. In general this type of transmission is not highly effective when used with an ICE due to the torque curve of SI and CI engines. In order to use a fixed ratio transmission in conjunction with an electric motor, the motor should have a substantial CPSR (typically 4:1 or greater). This is a highly effective option for speed reduction of AC-induction, SR and some PMBLDC motors.

2.4.4. Continuously Variable Ratio Transmission

Continuously variable transmissions or CVTs are a subject of considerable interest for improved vehicle efficiency. The purpose of a CVT is to allow the engine to work at an optimal speed for a given wheel power. True CVTs offer an infinitely variable speed ratio between the prime mover and wheels of a vehicle. This type of transmission is capable of greatly improving the engine efficiency by allowing the speed ratio to be adjusted dynamically to the current vehicle load [Fenton, 1996]. While this seems like a perfect fit for most applications, currently available CVTs are bulky and inefficient

compared to transmissions utilizing a simple gear reduction. Significant research is currently focused on increasing system efficiency.

2.4.5. Split-Mode Epicyclic Transmission

Split-mode epicyclic transmissions are those similar to the type of drive system used in the Toyota Prius [Toyota, 1997]. This type of a system effectively allows the engine to operate at a point independent of vehicle speed similar to the fashion of the CVT. This system however, requires at least one, and typically two electric motors to achieve the “power-split”. In this system, the ICE is attached to the planet carrier of an epicyclic gearset, the sun is connected to a generator, and the ring is typically connected to an output device as well as a drive motor.

This type of configuration offers semi-CVT operation over a wide range of vehicle operating points. Additionally, the ICE can be coupled to the generator and motor as in a SHEV while providing tractive torque directly as in a PHEV.

Substantial research has been performed in this technology, and several versions of this type of transmission are either in production or planning stages. This system has the advantage of being more scalable than most other CVT technologies currently available, but is considerably more difficult to implement due to the complicated control algorithm required.

2.4.6. Multi-Ratio Transfer Case

Multi-ratio transfer cases are used almost exclusively in off-road and military vehicles. A transfer case is used to split power between multiple axles of a vehicle; typically the front and rear axles. A multiple ratio transfer case is used in off-road applications to provide a higher gear ratio than is needed for typical driving in order to increase available torque at the wheel. This type of device is not normally used in vehicles not requiring extremely high tractive torque.

2.4.7. Differential

The differential is a device typically used as a torque splitting device between two wheels on opposite sides of a vehicle, but on the same transverse axis. A differential is normally integrated into the “final drive” of a conventional drivetrain. This type of

gearset allows a differential motion between the two sides of the vehicle which reduces wheel scrub and slip losses and improves vehicle driveability. Vehicles that do not utilize this type of gearset between tires on the same axle experience wheel skip during turning maneuvers due to the two tires trying to track a different turn radius while rotating at the same speed.

In many traditional differentials, the gearset is what is termed as an “open differential”. This means that torque will try to flow to the tire with the least resistance to motion. For example: in a vehicle with an open differential, if one wheel on a driven axle is off the ground and experiences no rolling resistance it will be accelerated rather than the opposite wheel which is on the ground providing tractive torque. In military vehicles, it is desirable to limit the amount of slip that is experienced between two wheels on the same axle. For this reason, military vehicles typically use lockable, limited slip, or torque biased differentials.

The HMMWV uses a differential technology known as the Torsen differential. This type of differential uses a modified crossed-helical gearset to provide a torque-biasing capability. In the Torsen differential, torque is applied at a greater rate to the wheel having a greater capability to provide tractive effort, rather than the wheel having less tractive capability. This effect is caused by friction internal to the gearset and is effectively a limited lockup condition. The biasing ratio of the differential can be controlled by the design of the gearset with higher ratios behaving in a fashion more similar to a locked axle, and lower ratios behaving more like an open differential. While this is a very effective solution for off-road vehicles, the system also experiences higher losses due to the internal friction of the gearset.

2.4.8. Wheel Hub Reducer

Wheel hub reducers offer a compact reduction option that is particularly appealing in large vehicles with high driveshaft torques. Use of wheel hub reducers in heavy vehicles allows the section of driveshafts to be reduced due to the reduction available at the wheel. This reduces the weight and inertia of the driveshafts but requires them to operate at higher speed.

Hub reducers are also a technology being studied for use with in-wheel motors. Hub

reducers could allow a compact high speed motor with a single or double stage epicyclic gear reduction to provide the high torques necessary to drive a vehicle's wheels. A number of companies are pursuing motors of this type.

For military vehicles, wheel hub reducers have the additional benefit of allowing an offset of the entry point of the driveshaft into the wheel hub. This feature can be used to increase ground clearance by offsetting the hub input vertically.

3. Vehicle Modeling

3.1. Description of Required Design Considerations

As stated earlier, a hybrid electric HMMWV has the potential to increase fuel efficiency, operate with low noise and low thermal signatures, and to provide auxiliary power generation in the field.

The following discussion highlights baseline performance requirements, and hardware issues pertaining to the basic hybrid system design and components.

3.1.1. Baseline Performance Requirements

The HMMWV is a fielded equipment item and the military has developed explicit performance requirements for it. The baseline requirements (including appropriate hybrid vehicle considerations) related to drivetrain parameters were discussed earlier in Section 1.4 and are restated here in an integrated form for the HEV option:

- Maximum Gross Vehicle Weight (GVW): 7700 lbs
- Fording depth: 30 inches
- Grade Operation: At its GVW the vehicle must be able to ascend a 60% grade at 2 mph and to stop and start on this grade. Also at its GVW the vehicle must be able to ascend a 5% grade at 55 mph.
- Acceleration: At its GVW the vehicle must be able to accelerate from 0 to 30 mph in 6 seconds or less and from 0 to 50 mph in 30 seconds or less (both on a level hard surface road).
- Speed: At its GVW in high gear the top speed must be at least 60 mph and in low gear the top speed must be less than 2.5 mph.
- Range: As a hybrid, range must meet the standard 300-mile range. In the EV mode, the range must be at least 20 miles at 20 mph. on a hard surfaced road.
- While the vehicle must be capable of meeting the baseline vehicle performance requirements as a hybrid, its performance as a pure electric, or in any backup modes, may be appropriately de-rated.

3.1.2. Hardware Considerations

The military is giving greater consideration to the use of industrial grade COTS components in fielded equipment to reduce costs and enhance maintainability. The role of COTS components in the low cost hybrid HMMWV design is critical. Manufacturers are continually announcing new developments in electric motors, generators, and batteries of all sorts, but at the present time many of these high performance components are in low-volume production, or at the prototype stage of development and are not commercially available. There are wide ranges of price-performance ratios for these components, which must be incorporated into the design optimization process. The following discussion summarizes some of these issues.

3.1.2.1. Engine Considerations

The standard HMMWV comes equipped with a DDC 6.5L Indirect Injection naturally aspirated diesel engine with a rating of 119 kW at 3,400 rpm. The torque curve is fairly flat at 393 ± 40 N-m over the speed range of 1,200 to 3,400 rpm. Any engine chosen for the hybrid version must use diesel fuel and must be able to provide equivalent drive wheel power in conjunction with the electric motor.

3.1.2.2. Electric Motor Considerations

On the surface there appear to be many motors that might be available for use in this application, but closer examination of candidate motors suggests that permanent magnet DC motors have some advantages over other designs. These motors are lightweight, have high efficiency, and have been developed especially for hybrid electric drives.

Motor requirements are based primarily on the performance specifications of the vehicle when operating as a pure electric vehicle. The motor selection is driven by cost and availability considerations as well as suitability for the off-road environment.

3.1.2.3. Battery Pack Considerations

The battery pack design specifications are dictated by the electric motor selection, the vehicle's pure electric range requirement, space and weight constraints, safety, recharging, and cost considerations.

Motor Requirements. The electric motor imposes certain requirements on the battery pack selection -- namely voltage and current capability. The electric motor requires a certain voltage supply range in order to operate satisfactorily and so the battery pack must be made up of a certain number of cells in series to generate the required pack voltage (this is often referred to as a module).

If a particular battery design cannot meet the motor's current requirements with one module, the designer may consider wiring two or more modules in parallel.

Range Requirements. Assuming that the motor's voltage and current requirements can be met, the designer must then examine how much energy storage the battery pack has to provide. This requirement is almost always dictated by the range that the vehicle must achieve under pure electric conditions.

Safety. There are safety considerations associated with battery use and these include exposure of personnel to battery chemicals (acids), fire, and explosion [Rand, 1998]. The designer must work with the battery supplier to make sure that the proper thermal environment is provided for the battery pack (provisions for cooling the battery pack) and that ventilation of the battery pack is provided -- particularly if hydrogen evolution could exist. Because of the high voltage levels required for motor operation, shock isolation and safety interlocking are key issues. The battery pack will be one of the heaviest vehicle components. Its structural design and vehicle mounting must be commensurate with the nominal and off-nominal shock and vibration requirements of the HMMWV.

Recharging. During regenerative braking, the kinetic energy of the moving vehicle is converted into electrical energy by driving the motor as a generator to recuperate energy to the battery pack. While it is likely that a battery pack designed to deliver large currents can also accept large regeneration currents (at least for brief periods of time), the control system of an electric vehicle has to incorporate some means of monitoring battery conditions (state of charge, temperature) to avoid overcharging the battery pack [He, 1997]. In some advanced chemistry options, this charge control also requires active temperature monitoring and control of the pack. This must be considered during the integration of the ESS into the vehicle. Active cooling of the ESS significantly impacts vehicle weight, packaging, and complexity.

3.1.2.4. Transmission

From a systems integration standpoint, it is apparent that the simplest transmission to integrate into the overall system is the existing vehicle transmission. There are several considerations which must be made prior to making a choice of transmission, however. These include:

- Engine and motor input speeds
- Engine and motor input torques
- Required wheel torque at a given vehicle speed
- Transmission efficiency
- Size and weight
- Robustness of the component
- Component should be a COTS available item

If possible the existing stock GM 4L80E electronically controlled 4-speed automatic transmission will be used along with the stock transfer case, Zexel-Gleason Torsen differential, and wheel hub reducers. Replacement of the torque converter is reasonable in a retrofit implementation, but it is likely the existing 2.1:1 converter will be acceptable.

3.1.2.5. Controls and Electronics

HEVs involve the coordinated operation of several power sources during the dynamic operation of the vehicle. Ideally, the mode switching of the system should be completely transparent to the driver such that the vehicle performs like a standard vehicle. These issues are increasingly more complex for the parallel and dual configurations compared to the series configuration. The most effective way to implement the hybrid vehicle control system including driver displays and controls is as a digital control system. There are a large number of established sources of COTS-type microcomputer systems, interface electronics, sensors and real-time operating system software suitable for the hybrid HMMWV.

3.1.3. Cost Considerations

The powertrain design and the cost of the components associated with the configuration selected influence the overall cost of an HEV. The primary cost factors

related to the vehicle design are:

- Type of electric motors
- Number of electric motors
- Type of batteries
- Vehicle integration cost

There are many alternatives regarding electric drive motors. Light-weight and high efficiency motors normally used in HEVs are typically permanent magnet DC motors that incorporate pulse width modulated drive converters. At the power levels required for HEVs, these motors are produced in low quantities and are expensive compared with industrial electric motors of the same capacity. A limited number of production electric vehicles use less expensive (and less efficient) AC synchronous type motors with solid-state vector drives. The series configuration requires one generator and at least one traction motor, the parallel configuration requires at least one traction motor/generator, and the dual configuration requires at least one traction motor and one motor/generator. The designer has the freedom to incorporate multiple electric motors in parallel with any of these configurations, but since the unit cost of motor/converter combinations for this general class of motors is not a strong function of motor size, powertrain costs increase proportional to the number of motors.

There is a wide range of cost variation with battery storage alternatives. Lead acid batteries are manufactured on a large scale with common materials, and are by far the least expensive. Higher energy storage density alternatives such as nickel cadmium, nickel metal hydride and lithium ion are two to four times more expensive in production depending on the particular technology. Design tradeoffs between battery cost and weight are major cost drivers.

The final major cost factor is vehicle integration, which refers to the cost and complexity associated with incorporating the HEV drivetrain into the HMMWV chassis. Ideally, the HEV drivetrain should consist of retrofittable module(s) that can be installed in a standard HMMWV with minimal modifications to the chassis. Vehicle integration costs and military deployment costs can be reduced by giving careful consideration to the electrical and mechanical vehicle modifications required.

3.2. Initial Tradeoff Study and Component Down-Select

A two step design approach was taken for vehicle configuration and component study for the HEV HMMWV. The first step was rough sizing and component technology selection based on paper study and first order approximations. This section of development included a number of hand calculations based on generally accepted automotive and hybrid vehicle design procedures along with research into currently available COTS equipment.

The primary function of this portion of the research was to narrow the scope of the more calculation intensive computer simulation step of the program. In general this step utilized less refined mathematical models and more general assumptions than those utilized in follow-on stages of the project. Focus during this stage was on rough order of magnitude computations to guide the general direction of future research.

The following sections detail the process and findings of this first step. Computer simulation of the options identified during the down-select process will be detailed in Section 3.3 and Chapter 4.

3.2.1 Hand Calculations and Considerations for Component Selection

Prior to computer simulation, a number of hand calculations were performed to assist in determining a design start point. Because the majority of these calculations require knowledge of the vehicle loading under a given set of environmental conditions, a generalized equation was developed to determine this. In general the majority of cases studied require the power or force required to propel the vehicle forward at a given speed. The only consideration studied that did not require forward propulsion force was the side-slope gradeability where the vertical center of gravity is the primary value of interest. In order to determine the power or force required for propulsion a simple mathematical model of vehicle load was developed [Burke, 1992; Gillespie, 1992]. This should be a generalized equation that considers the major load components for all cases to be studied. The simplified vehicle load model is defined by the equation:

$$F_{drive} = F_{aero} + F_{roll} + F_{accel} + F_{grade} \quad (3.1)$$

where:

F_{drive} is Vehicle Propulsive Force

F_{aero} is Aerodynamic Drive Force defined as:

$$F_{aero} = \frac{1}{2} \cdot \rho \cdot C_D \cdot A_F \cdot V^2 \quad (3.2)$$

F_{roll} is Rolling Resistance Force defined as:

$$F_{roll} = m \cdot g \cdot \cos \theta \cdot (C_{rr1} + C_{rr2} \cdot V + C_{rr3} \cdot V^2) \quad (3.3)$$

F_{accel} is Acceleration Force defined as:

$$F_{accel} = (m + m_{eq}) \cdot a \quad (3.4)$$

F_{grade} is Road Gradient Force defined as:

$$F_{grade} = m \cdot g \cdot \sin \theta \quad (3.5)$$

Using the information from Eq. 3.1, the drive power of the vehicle at the wheel can be determined using the equation:

$$P_{wheel} = F_{drive} \cdot \omega_{tire} \cdot r_{tire} \quad (3.6)$$

This information, along with efficiency assumptions and gear ratios of drivetrain components can give the component power at any point in the drivetrain. An Excel spreadsheet and Matlab *.m file were developed to provide quick calculation of power and force requirements (see Appendices B and C for Matlab code and Excel output examples). Values for the variables in Eq. 3.1-3.6 are shown in Table 3.1 [Bradley, 2000].

No published values were available for the C_{rr2} and C_{rr3} variables for the Goodyear radial 37·12.5 R16.5 tires that come as standard equipment on the stock HMMWV. Published values were available for C_{rr1} on both hard surfaced roads as well as unpacked soil. It is anticipated that use of only the C_{rr1} term will have little impact on the overall load calculation. In general, the load contribution by the C_{rr2} and C_{rr3} variables is very minor except at high speed. Because the primary area of interest in the HEV HMMWV simulation is related to low speed operation, lack of this information will have negligible impact on the vehicle simulation results.

Another assumption concerning values shown in Table 3.1 relates to the equivalent mass used to correct for rotational inertia. The table lists a value that is approximately 14% of the vehicle mass. This assumption is based on typical automotive equivalent masses ranging from 8-10% of the vehicle mass. This value was increased in

Table 3.1 Road Load Parameters for M998 HMMWV

Parameter	Value	Units
M	3,500	kg
m_{eq}	490	kg
C_D	0.5	-
A_F	3.58	m ²
r_{tire}	0.456	m
$C_{rr1-paved}$	0.013	-
$C_{rr1-dirt}$	0.045	-
G	9.81	m/s ²
P	1.23	kg/m ³

order to accommodate the higher rotational inertia in the HMMWV due to added rotational inertia due to hybridization as well as the high inertia rims used in the HMMWV run-flat tire system. The value of 14% was confirmed based on calculations of rotational inertia during operation at high engine speed during low vehicle speed. In vehicles with multiple transmission ratios or hydraulic torque converters, this correction factor actually changes dynamically with vehicle and engine operating point. Errors in this assumption only effect acceleration requirement calculations detailed in Section 3.2.1.4. This is due to the fact that all other design hand calculations are performed at steady state with no vehicle acceleration.

3.2.1.1. Gradeability Hand Calculations

There are two significant gradeability issues which must be explored for component sizing. The first is the requirement to provide continuous operation on a hard surface road at 88.5 kph on a 5% grade. In addition to this, the vehicle must be able to negotiate a 60% grade at 3.2 kph and stop and start on the slope. A third gradeability requirement, the side slope gradeability is primarily an issue related to the vehicle's vertical center of

gravity (CG) and will be discussed in Section 3.2.1.1. For the 88.5 kph gradeability requirement, the vehicle is considered to be at steady state. For this reason, the acceleration term of Eq. 3.1 can be assumed to be zero. The revised equation is:

$$F_{drive} = F_{aero} + F_{roll} + F_{grade} \quad (3.7)$$

Substitution of the values in Table 3.1 into Eq. 3.7 indicates that a drive force of approximately 2,830 N is required at the wheel for the 88.5 kph operational point. Using Eq. 3.6, a wheel power of approximately 69.5 kW is necessary for the high speed gradeability requirement. In order to turn this information into meaningful knowledge for component sizing, it is necessary to work backward through the powertrain to the engine to determine the engine operating point for this vehicle state. In order to do this, assumptions related to the component gear reductions and efficiencies must be made.

Table 3.2 gives a table of system gear reductions in the powertrain. For the high speed gradeability requirement, the transmission is assumed to be in 3rd gear with the torque converter locked and the transfer case is in high gear. Efficiency is assumed to be approximately 95% per reduction for the transmission, transfer case, differential, and hub reducers, with the torque converter at 100% due to the locked state. This results in a powertrain mechanical efficiency of approximately 81%. Although this efficiency seems relatively low, it is similar to tested vehicle efficiencies over the FUDDS schedule and is anticipated to be conservative [Bradley, 2001]. Using these assumptions, the engine must provide approximately 299 N-m of torque at a speed of 2,725 rpm if no wheel slip is assumed. Table 3.3 shows the high speed gradeability calculation results.

For the low speed gradeability calculation, Eq. 3.1 was further simplified by eliminating the F_{aero} term due to the low speed of the vehicle at this operating point. The resulting equation is:

$$F_{drive} = F_{roll} + F_{grade} \quad (3.8)$$

The vehicle state for the low speed is assumed to be: transmission in first gear, torque converter slipping, transfer case in low range, and tire constants for loosely packed soil. For the system efficiencies, the same assumptions were made as in the high speed gradeability except that the torque converter is assumed to operate at 70% rather than 100% due to operation at a maximum slip condition. This gives a powertrain mechanical

Table 3.2 Powertrain Gear Ratios

Component	Ratio
Transmission	
Torque Converter	2.10:1
1st Gear	2.48:1
2nd Gear	1.48:1
3rd Gear	1.00:1
4th Gear	0.75:1
Transfer Case	
High Range	1.01:1
Low Range	2.72:1
Differential	2.73:1
Wheel Reducer	1.92:1

Table 3.3 High Speed Gradeability

88.5 kph at 5% Grade	Value	Units
Vehicle Force	2,830	N
Wheel Power	69.5	kW
Wheel Torque	1,289	N-m
Engine Torque	299	N-m
Engine Speed	2,725	RPM

Table 3.4 Low Speed Gradeability

3.2 kph at 60% Grade	Value	Units
Vehicle Force	19,000	N
Wheel Power	17.0	kW
Wheel Torque	8,660	N-m
Engine Torque	205	N-m
Engine Speed	1,800	RPM

efficiency of roughly 57% and a gear reduction of over 74:1. Based on these assumptions, the vehicle force required at the low speed point is approximately 19,000 N. Once again, this assumes no wheel slip which is a poor assumption for this operating point. In general, the system design must locate the CG to distribute weight relatively equally to prevent slip at this operating point. Other than weight distribution, little can be done to impact the slip characteristics of the system as it is currently designed. The required engine/motor combined torque for this operating point is considerably lower at approximately 205 N-m; however, this occurs at a significantly lower speed of 1,400 to 2,000 rpm depending on torque converter slip assumptions. The low speed gradeability results are shown in Table 3.4.

3.2.1.2. Rangeability Hand Calculations

In general, rangeability is a function of the vehicle load requirements and the energy storage capacity of the vehicle. Range is typically defined over a given driving cycle or steady state operation point. For purposes of this study, steady speed operation was assumed as the required cycle. For the vehicle load requirements, Eqs. 3.1-6 were used as described in earlier sections. In order to determine the energy storage requirement over a given drive cycle, an additional mathematical model must be developed to address the energy used. Because load requirements are assumed to be steady state for this model, the vehicle's potential and kinetic energies are neglected, and only losses are considered. A more rigorous study will be discussed in Chapter 4 using a significantly

more comprehensive energy accounting method.

For this study, the rangeability energy requirements will be performed using the assumption that the energy consumed is simply the integral of the power required to drive the vehicle at steady state over a given time period. Because the vehicle is operating at steady state, the acceleration and gradient components of the F_{drive} modeled by Eq 3.1 can be neglected. The drive force calculation at the wheel can be defined by the equation:

$$F_{drive} = F_{aero} + F_{roll} \quad (3.9)$$

To determine the electrical energy storage required for the vehicle, the value obtained using Eq. 3.9 must be modified during the power calculation to reflect the powertrain mechanical efficiency. Using the translational formulation of vehicle power, the equation for energy consumed during a given time span with the vehicle at steady state operation can be simplified to:

$$E_{drive} = \int_{t1}^{t2} V \cdot (F_{aero} + F_{roll}) \cdot dt \quad (3.10)$$

and the efficiency corrected value at the drivetrain input is:

$$E_{tran-in} = \eta_{drivetrain} \cdot \int_{t1}^{t2} V \cdot (F_{aero} + F_{roll}) \cdot dt \quad (3.11)$$

where $\eta_{drivetrain}$ is the drivetrain efficiency and $t1$ and $t2$ are the beginning and end times.

Using Eqs. 3.9-11, the drivetrain efficiency, and tire coefficients discussed in Section 3.2.1.1, the values in Table 3.5 for vehicle power and energy requirements for 32.2 km steady state operation at a variety of speeds were determined. The energy requirement is listed in kW-h which is a convenient unit for evaluation of battery-based energy storage systems. As Table 3.5 shows, there is a substantial difference in the energy requirements based on the surface conditions of the road. For this reason, the off-road rangeability will be less than half the on-road high speed rangeability. This indicates a large ESS with a capacity of approximately 17 kW-h would be required to achieve a 32.2 km off-road EV range.

3.2.1.3. Slip-Tip Hand Calculations

Side gradeability, as discussed earlier, is primarily an issue of vertical CG of the vehicle. As part of the vehicle level design study it is important to place components in

Table 3.5 HMMWV Energy Consumption at Steady State Speeds

Vehicle Speed kph (surface)	Wheel Power kW	Energy kW-h
10 (pavement)	1.3	5.0
25 (pavement)	3.5	5.5
50 (pavement)	9.1	7.3
75 (pavement)	19.3	10.2
10 (unpacked soil)	4.3	17.1
25 (unpacked soil)	11.1	17.6
50 (unpacked soil)	24.4	19.4
75 (unpacked soil)	42.1	22.3

such a manner that side gradeability is not negatively impacted by significant changes in the CG. In order to evaluate the allowable CG height for a 40% side grade, a simplified 2-dimensional Free Body Diagram (FBD) of the HMMWV was constructed (see Figure 3.1).

In Figure 3.1, point *A* is the contact patch of the downhill wheel, *d1* is the height of the CG of the vehicle, and *d2* is the distance to the centerline of the vehicle. In the case of a vehicle tip, the moment exerted on the system about point *A* in Figure 3.1 by the force noted as $W \cdot \sin(\theta)$ exceeds the moment caused by $W \cdot \cos(\theta)$. When this occurs, the normal force at the uphill wheel approaches zero, and the vehicle is approaching a tip condition. For the purposes of this study, the value of interest is the maximum height for *d1* (the CG height) without approaching a tip condition. An impending tip condition is defined by the equation:

$$d1 \cdot W \cdot \sin \theta = d2 \cdot W \cdot \cos \theta \quad (3.12)$$

Solving Ex. 3.12 for *d1* yields:

$$d1 = d2 \cdot \cot \theta \quad (3.13)$$

Substituting a value of 0.91m (one half the track width) for *d2*, and an angular value of 21.8° for θ (the angular equivalent of a 40% grade) into Eq. 3.13 gives a maximum CG height of 1.7 m to reach a tip condition at this grade. This height is approximately one

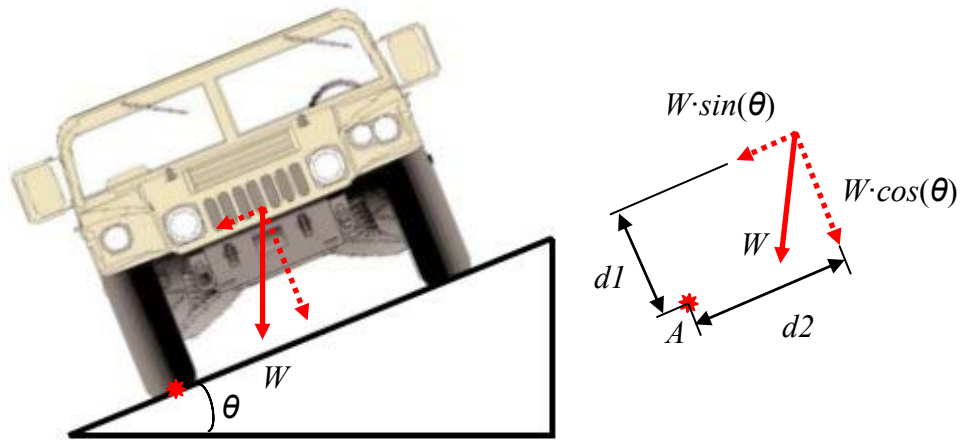


Figure 3.1 Free Body Diagram of HMMWV for Tip Calculation

meter above the stock CG height of 0.73 m. This indicates that a substantial increase in CG height could occur without causing a failure on the 40% grade requirement. If mass added due to hybridization, such as motors and battery packs can be placed at or below the current vehicle's CG, the side gradeability could potentially be improved. Placement of the ESS and other major components will affect the lateral, longitudinal, and vertical CG, but will likely have little impact on the 40% gradeability consideration.

3.2.1.4. Acceleration Power Requirement Calculations

In order to perform acceleration modeling, a generalized engine and motor model was constructed. This model was based on a curve fit of the Volkswagen (VW), 1.9L TDi engine and a 3.4:1 constant power speed range PM motor based on the UQM PowerPhase 100 system (see Appendix A for component spec sheets). A polynomial fit of the engine torque curve with respect to engine speed was performed using Excel, and this model was used for general modeling of various engine sizes for acceleration modeling (see Appendix C for graph of curve fit and sample output).

The generalized electric motor model constructed was a piece-wise model that assumed a constant torque up to base speed of 1300 rpm and constant power from 1300-4400 rpm. These speeds were chosen to match the motor to the engine curve fit. The value for the constant torque is determined by dividing the motor's constant power value

by the motor speed expressed in rad/s to determine the motor rated torque.

Torque values derived from the two models can be scaled to study various motor/engine sizing options. In order to study available engine and motor options, acceleration was studied using the 1.9L TDi curve fit and a scaled value equal to 5/4 the 1.9L TDi curve (roughly equivalent to the Alfa Romeo 2.4L JTD engine).

To model this system, the stock HMMWV drivetrain was assumed for all spreadsheet simulations. In order to determine the available power for acceleration, the engine and motor combined power was found at a given vehicle speed. This was accomplished by finding the max engine speed corresponding to a given vehicle speed based on the HMMWV drivetrain ratios. This value was then placed into the following equation:

$$a = \frac{\frac{P_{wheel}}{V} - \left(\frac{1}{2} \cdot \rho \cdot C_D \cdot A_F \cdot V^2 + m \cdot g \cdot C_{rr1} \right)}{(m + m_{eq})} \quad (3.14)$$

which is Eq. 3.6 expanded and solved for a with the assumption that the grade during the acceleration test is 0%. The value for C_{rr1} used is the on-road coefficient of rolling resistance listed in Table 3.1. The resulting value is the acceleration capability at a given instant in time. This value is then used to determine the time required to achieve the next spreadsheet value for vehicle velocity using the equation:

$$dt = \frac{a}{dv} \quad (3.15)$$

the resulting time increment is then added to the summation of the time up to the current velocity step. This method assumes a constant acceleration capability between velocity points, and is only accurate for relatively small values of dv . The resulting acceleration times for several vehicle configurations are shown in Table 3.6.

3.2.2. System-Level Tradeoff Compromises

There are a number of tradeoffs which must be made during the system design process. As stated earlier, the primary consideration is a reduced cost hybridization approach that allows use of COTS components. For this reason a number of compromises will be required

Table 3.6 Vehicle Acceleration Spreadsheet Results

Vehicle Configuration Engine/Motor	0-48 kph accel s	0-81 kph accel S
1.9L/100kw	6.3	19.0
1.9L/75kw	7.6	23.6
2.4L/100kw	5.6	16.8
2.4L/75kw	6.6	20.3
100kW Electric only	8.5	27.2
2.4L Engine only	11.9	42.6
Stock Vehicle	10.3	29.4

One compromise that will be required based on initial hand calculations relates to engine size. Based on initial calculations, it appears that the steady state power capabilities of the stock 1.9L TDi engine can not support the 5% gradeability at 88.5 kph without modification. For this reason, it is likely that a larger engine displacement or modified version of the 1.9L TDi will be required. This will likely be detrimental to vehicle mass and efficiency.

A second key area of compromise that must be considered is the energy storage system. From a cost and reliability standpoint, the most reasonable solution is a Pb-A battery system. This is a COTS technology that is very mature. A negative feature of this technology is the low specific energy of this battery type (see Table 3.7 for comparison with other technologies). At this time, all competing technologies for electrical energy storage are considerably more expensive, and mechanical options are currently not COTS items for this size vehicle. For this reason, the hybrid HMMWV rangeability will likely be lower than desirable during off-road operation if a Pb-A ESS is used. Another option with higher specific energy is a NiMH ESS option. This is a considerably more expensive technology (projected to be at least two times cost in production, currently 5-10 times), but offers nearly double the specific energy, and superior DOD characteristics to Pb-A.

Table 3.7 Comparison of Specific Energy of Various Energy Storage Systems

Energy Source	Nominal Specific Energy W-h/kg
Gasoline	12,200
Diesel	12,500
Natural Gas	9,350
Methanol	6,050
Hydrogen	33,000
Advanced Lead-Acid Battery	40
NiMH Battery	75
Lithium-Polymer Battery	200
Ultracapacitor	<15
Carbon Fiber Flywheel	200

Another area of compromise relates to the motor selection. At this time, the most desirable COTS options include PMBLDC options. These are considerably more expensive than AC-induction motor options but are far superior from an efficiency and weight standpoint. At this time, it is anticipated that the PMBLDC motor will be the technology of choice in a fielded system.

The final area of compromise which was considered was the system powertrain configuration. There are a number of cost, complexity, and reliability considerations that must be made. Table 3.8 details a number of these options and tradeoffs.

As Table 3.8 shows there is a rather complicated set of options to consider related to the system configuration. For this design analysis, it was determined that the areas of focus should be cost, redundancy, and ease of integration into the vehicle. From a cost and redundancy standpoint, the parallel option is an obvious winner. The third issue, ease of integration, is a more complicated question. From a drivetrain change standpoint, the parallel option is the leading candidate, as it can use all stock vehicle parts with the exception of the engine. At the system level, however, there are some issues with the

Table 3.8 Hybrid System Tradeoffs

Design Factor	Series	Parallel	Dual
Overall Cost	medium	Low	high
Powertrain Complexity	low	medium	high
Control System Complexity	low	medium	high
Motor Size	largest	small	smallest
Generator Size	medium	none	medium
Engine Size	small	medium	medium
Number of Electric Motors/Generators	≥ 2	≥ 1	≥ 2
Battery Pack Power Demand	large	medium	medium
Powertrain Redundancy	no	Yes	possible

parallel system. The primary of these issues is placement of the battery pack. The series option removes a large portion of the drivetrain which provides both a weight and space allowance for the ESS. The parallel and dual options, on the other hand, do not have this advantage. In general, the parallel option appears superior overall, with several distinct advantages related to functionality, but the ESS placement is a key design factor which must be addressed.

3.2.3. Selected System for Analysis

In light of the general design objective of producing a low production cost hybrid HMMWV which retains the performance characteristics of the standard vehicle, the configuration selected for more detailed study is a parallel, electric assist design. The general schematic of this configuration was shown earlier in Figure 1.6.

The features of this configuration that led to its selection as the candidate design are all primarily driven by cost considerations and are as follows:

- Only one electric motor/generator is necessary.
- No generator is used because the motor serves as the generator when required.

- Under the assumption that the conventional vehicle does not demand maximum power for extended periods of operation, the engine and the electric motor will be sized such that together they can provide at least the same drive wheel power as the conventional engine.
- The APU will be a small displacement direct-injected turbo-diesel engine. This will take advantage of recent advances in fuel economy and power density available in modern diesel engines. The engine will be sized to meet the 299 N-m of torque at a speed of 2,725 rpm identified during the gradeability analysis.
- Lead acid batteries will be used in battery pack analysis due to high availability and low cost. It is anticipated that the resulting ESS will be capable of meeting the 10 kW-h anticipated for the 32.2 km EV range on hard ground or pavement, but will be unable to do so on unpacked soil, or other loose media. Additional technologies nearing maturity will be studied as higher cost options for enhanced rangeability.

3.3. Computer Modeling of System Components

Following the initial vehicle architecture and component tradeoffs performed in the first step, a number of computer models were developed and vehicle performance was simulated. This simulation step included modeling and simulation of the baseline vehicle as a check on the simulation validity.

For purposes of this study, the majority of modeling and simulation was performed using the National Renewable Energy Lab's (NREL) Advanced Vehicle Simulator software known as ADVISOR. ADVISOR is a set of model, data, and script text files for use with Matlab and Simulink designed for rapid analysis of the performance and fuel economy of conventional, electric, and hybrid vehicles [NREL, 2002]. Most of the component models used are empirical in nature, and are developed from data provided by national laboratories, automotive manufacturers, and universities.

ADVISOR utilizes a Graphical User Interface (GUI) in the Matlab/Simulink environment to facilitate an interactive data input and results output. The user first selects a vehicle configuration for simulation in the "Vehicle Input" screen, and then

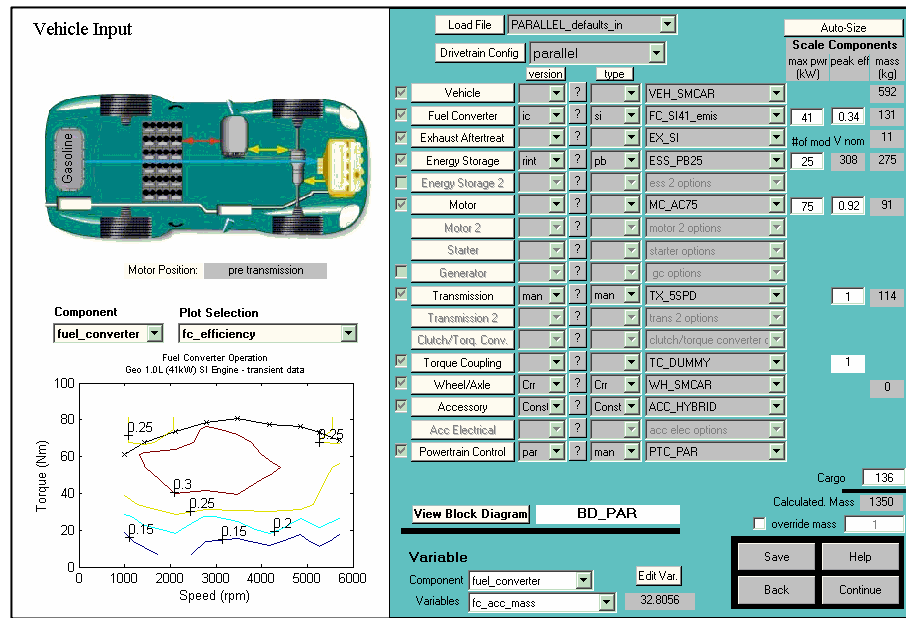


Figure 3.2 Parallel Vehicle Input Screen from ADVISOR

selects various hardware and control options from available component models to complete a test vehicle (See Figure 3.2 for examples of the Vehicle Input screen).

After a vehicle is defined, the selected vehicle is then subjected to a test cycle defined in the “Simulation Parameters” screen shown in Figure 3.3. A number of standard test cycles are included in the program including the Federal Urban Driving Dynamometer Schedule (FUDDS). In addition to the standard test cycles, the user can define a series of several standard cycles, define a new cycle, or perform gradeability and acceleration tests. This portion of the program also has an optimization feature that can be used for component sizing.

Following execution of the defined simulation, outputs are provided to the user in an interactive format shown in Figure 3.4. Output variables can be saved to file as well as displayed in a four window graphic display in the “Results” window (see Figure 3.4). Simulation variables of all components are available in this screen.

Some of the uses for the ADVISOR program include:

- Estimation of the fuel economy of vehicles that have not yet been built

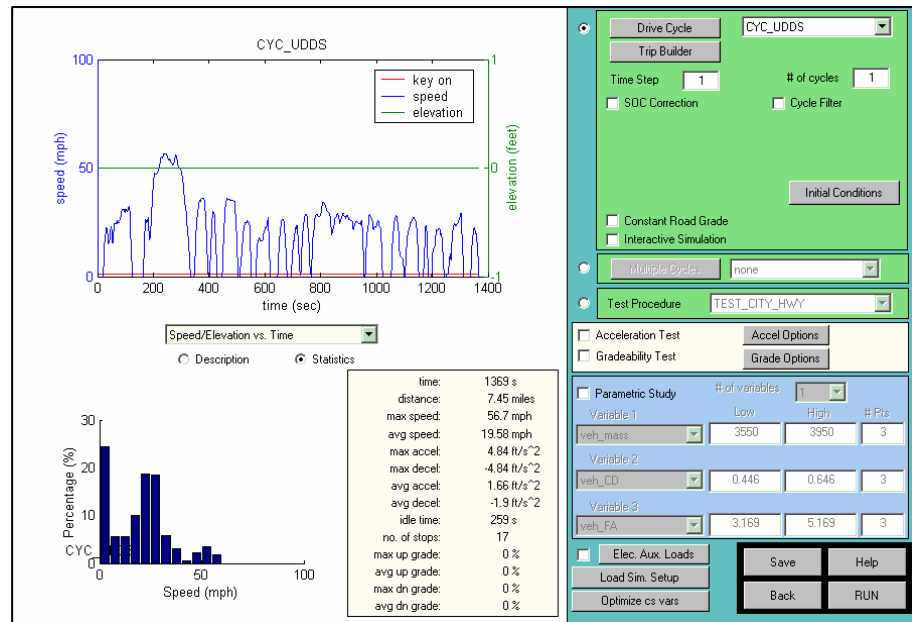


Figure 3.3 Simulation Parameters Screen from ADVISOR

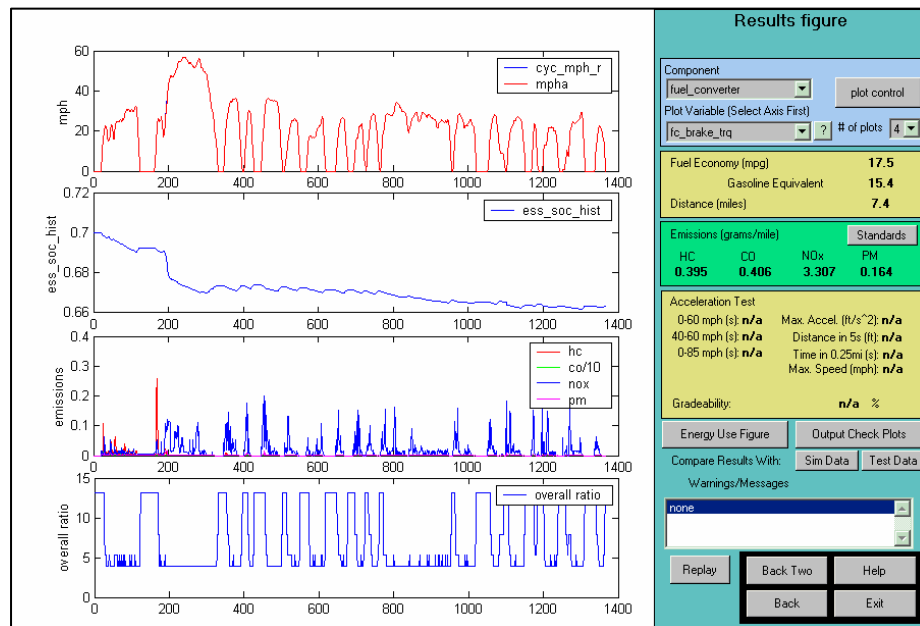


Figure 3.4 Results Screen from ADVISOR

- Insight into how conventional, hybrid, or electric vehicles use (and lose) energy throughout their drivetrains
- Compare relative tailpipe emissions produced on a number of cycles
- Evaluate potential energy management strategies and the impact on ESS and APU energy usage
- Perform tradeoff studies of the gear ratios in potential transmission options to reduce fuel use or improve performance

An additional feature of ADVISOR that is quite useful from a controls and energy management standpoint is the “Energy Use Figure” output screen. This consists of an energy balance accounting screen as shown in Figure 3.5 and two plots showing the energy usage during motoring and regeneration. This gives the user a useful tool for visualizing the energy consumption and the contribution of the various components to the total vehicle energy balance.

3.3.1. Vehicle Model

The first model developed for simulation was the vehicle model. This is a function saved in *.m file format that is called by ADVISOR to determine certain variables related to vehicle characteristics. This file was modified from an existing component file for a rear wheel drive Chevrolet Suburban. Key variables for this model include C_D , F_A , CG height, and wheel base. These values were updated from the original values to reflect the HMMWV vehicle system. The glider mass of the vehicle is also included in this file, but was not modified because an override value is used in the “Vehicle Input” screen. This file also includes local gravity and air density values for purposes of determining vehicle loading. A complete printout of the vehicle model file *VEH_HMMWV.m* is included in Appendix B.1.

3.3.2. Engine Model

For engine modeling, ADVISOR has existing models that were utilized for modeling purposes. The engine model utilized is for a Volkswagen 1.9L TDi engine and includes an emission map. For modeling purposes, the VW engine model was scaled as necessary to simulate other COTS engines. One example studied is the Alfa Romeo 2.4L JTD engine. In this case, the engine power of the model for the VW engine was scaled in the

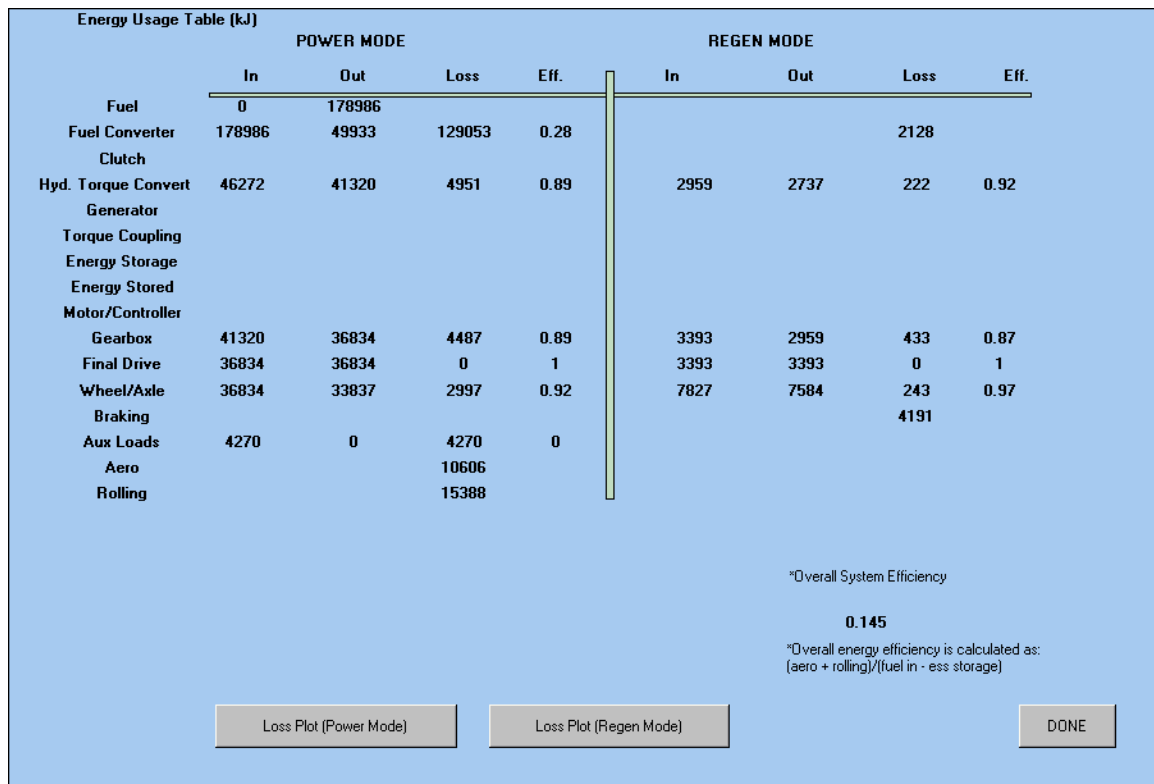


Figure 3.5 ADVISOR Energy Use Figure

“Vehicle Input” screen by a factor of the ratios of the engine displacements (in this case roughly 5/4). Other engine sizes of the same type can be studied in a similar fashion.

Care must be taken not to attempt to perform scaling operations on one engine to model another engine with significantly different operational characteristics. In the case of the Alfa Romeo engine studied, both engines are direct injected turbo-diesel engines for automotive use with similar bore and stroke characteristics. It would be invalid, for instance, to attempt to scale the VW engine model to replicate a 6.5L naturally aspirated engine.

In order to effectively validate the HMMWV model used for simulation, a stock engine was used in a conventional vehicle simulation. The engine studied was a 6.5L direct injected, naturally aspirated engine similar to the HMMWV engine.

No changes were made to either of the engine models used for simulation. Complete printout of both files is available in Appendix B.2.

3.3.3. Motor Model

Like the engine models used, there were existing models within ADVISOR that were similar to the type of PMBLDC intended for use in the hybrid HMMWV simulations. In fact, one of the exact motors (the CaliberEV 100, see Appendix A for specification sheet) is included in the standard model files of ADVISOR. Two other motors, the CaliberEV 75 and CaliberEV53 were also studied using a scaling of the CaliberEV100 motor. These motors are very similar in performance and efficiency, and use of this technique has little effect on the resulting simulation. A complete printout of the file used to simulate the CaliberEV 100 motor is included in Appendix B.3.

3.3.4. Energy Storage System Model

Two energy storage systems were simulated during this study. The first, a 42-A-h Hawker Genesis VRLA battery did not have a corresponding component model in ADVISOR. For simulation purposes, a component model for a similar Hawker Genesis product, the 26-A-h VRLA was modified. The ESS model used for Pb-A batteries in ADVISOR uses look-up tables for A-h capacity, Coulombic efficiency, charge resistance, discharge resistance, and terminal voltage as a function of SOC and temperature (He, 1997). The A-h values were simply changed to 42 to match the higher capacity battery. The coulombic efficiency and the terminal voltage as a function of battery SOC were assumed to be similar for the batteries due to their extremely similar construction and chemistry. Charge and discharge resistances were scaled by the ratio of the open circuit internal resistance of a fully charged battery. This resulted in a 0.9 multiplier for both of these look-up tables.

The second energy storage system studied was an Ovonic 60 A-h NiMH battery with an existing ADVISOR model. Choice of this battery was based on the similarity in weight with the selected VRLA battery for modeling. Study of this system shows the relative rangeability difference for the higher cost NiMH battery technology. This system was used without changes.

Complete outputs of Hawker Genesis and Ovonic battery options studied are shown in Appendix B.4.

3.3.5. Transmission Model

To develop a transmission model, an existing ADVISOR model for a very similar transmission was modified to more closely match the HMMWV's GM 4L80E transmission. The transmission model chosen for modification was a GM 4L60E. This is a lighter duty transmission used for SUVs and a number of other highly loaded vehicles which is functionally similar to the 4L80E. A number of changes were required to this model.

The first change made was to modify the 4L60E gear ratios to match those in the 4L80E transmission. Because the torque converter model used for the 4L60E transmission appears very similar to the 4L80E based on slip and torque multiplier characteristics, no change was made to this portion of the model.

In ADVISOR component models, the final drive of the drivetrain system is included in the transmission model. As a result, it was necessary to model two transmissions to accommodate the difference in post-transmission reductions based on the state of the transfer case. In the "on-road" transmission model, the final drive ratio was equal to the product of the transfer case high range reduction, differential, and wheel hub reductions. For the "off-road" model, the transfer case low reduction was used in place of the transfer case high range reduction.

The major change made to the model relates to the efficiency lookup tables. Because the 4L80E is a more heavily loaded transmission and utilizes a less efficient Torsen differential as a final drive, the efficiency lookup table was modified by adding a 0.95 multiplier to the efficiency lookup tables. This is not a highly accurate method, as the actual impact on efficiency is based on the load condition and torque split of the Torsen differential, however, insufficient information was available to suitably quantify the difference.

The model input files developed for both the on-road and off-road 4L80E transmission are included in Appendix B.5.

3.3.6. Vehicle Control Model

Two vehicle control models were used for simulation in ADVISOR. The first, the conventional vehicle model simply takes the input driving schedule target, compares it to

the current vehicle state, and generates a command to the engine, transmission, and mechanical brake in an attempt to achieve the requested target. In this case all power is supplied by the engine, and the control functionality is very straightforward.

In the PHEV control schemes there are a number of options including a proportional assist, electric launch, and engine efficiency maximizing fuzzy control scheme. For purposes of this modeling and simulation, the ADVISOR fuzzy control scheme was used without modification. There are several advantages and disadvantages to this system. One advantage is that the engine operating torque tends to be at the highest operational point allowed for a given load. As a result the battery pack SOC is maintained at a high level. This is desirable for military operations because it maintains the battery at a level that will allow long periods of EV operation on-demand during most operational states. The negative effect of this is that it can increase fuel consumption somewhat. Because of these operational issues, the fuzzy control scheme is only useful in situations where the IC engine is undersized with comparison to the vehicle's peak loads. Complete printouts of both the conventional and fuzzy model inputs are listed in Appendix B.6.

3.3.7. Accessory Load Model

Accessory load models used in ADVISOR are simple wattage loads and efficiencies applied to either the engine or the ESS. For the hybrid HMMWV, a vehicle accessory load of approximately 2000 Watts was assumed. The full code of the accessory load model developed for the hybrid HMMWV model is shown in Appendix B.7.

3.3.8. Tire Model

ADVISOR uses a two-coefficient version of the rolling resistance equation listed in Eq. 3.3. For purposes of simulation only one coefficient was available for the stock HMMWV tires. The second coefficient in ADVISOR was assumed to be zero. Like the transmission model discussed earlier, two tire models were also necessary to differentiate between the rolling resistance coefficients for the on- and off-road cases.

The tire model input file also contains constants related to the drag torque associated with differential and wheel reducer seals and bearings. Typical values for SUV tire models were multiplied by 2.5 to accommodate the full-time 4WD system of the HMMWV and the drag associated with the wheel reducers.

One area not accurately defined that affects the acceleration capability of the vehicle is the inertia of the wheels and drivetrain components. Existing models were not adequate due to the heavy insert section of the HMMWV wheels required for run-flat capability. An approximation was made based on knowledge of the system, but further clarification is necessary to insure accuracy of this model item. Complete output code from the on- and off-road tire models is shown in Appendix B.8.

3.3.9. Drive Cycle

ADVISOR uses a number of predefined driving cycles to provide information related to vehicle loading for simulation. Driving cycles are typically defined in a **.m* or **.mat* format as a function containing the desired vehicle speed, the time step, road gradient, and the keyswitch position (engine ON/OFF signal). For the purpose of rangeability determination at various steady state vehicle speeds, a number of driving cycles were constructed including 20, 40, 60, and 80 kph steady state drive cycles. The complete output code for these cycles is listed in Appendix B.9.

4. Vehicle Computer Simulation

4.1. Base Vehicle Simulation

Because the stock HMMWV is a substantially tested piece of fielded equipment, a large amount of information is available about the performance of the stock vehicle. The first stage of computer simulation was geared primarily at establishing a benchmark case for comparison with information available from literature on the currently fielded HMMWV.

Because acceleration was known for the stock HMMWV, the model for the conventional HMMWV was run multiple times with the test mass being varied until the simulation acceleration closely matched the tested acceleration of the stock HMMWV. This corrected mass was then used throughout the simulation process to provide an accurate comparison between the hybrid and stock configuration HMMWV. No simulation of rangeability was performed for the stock vehicle, but a fuel economy value was developed for comparison with the stock values.

4.1.1. Acceleration

As stated previously, the first step of simulation was the determination of a corrected mass for use in simulation. The listed stock simulation for the M1097-A2 HMMWV is listed as 10s for 0-48.3 kph acceleration, and 29s for 0-80.5 kph acceleration [Bradley, 2000]. The acceleration test for the stock vehicle was configured in the “Accel Options” screen of the “Simulation Parameters” window. Figure 4.1 shows an example of the “Accel Options” screen with the values used for determination of the corrected vehicle mass. After a number of iterations, it was determined that a corrected vehicle mass of approximately 4,235 kg gave acceleration performance of 10.0s for the 0-48.3 kph acceleration test, and 29.0s for the 0-80.5 kph acceleration test. This close match of the simulation outputs with both of the stock vehicle acceleration values was considered to be an indication that the stock vehicle model was accurately scaled with respect to engine performance relative to the drivetrain loads.

Test Conditions

Basic Parameters

☒ Shift Delay

Units

s

Value

0.2

Enable/Disable Systems

☒ All Systems Enabled
☐ Energy Storage Disabled
☐ Fuel Converter Disabled

☐ Initial SOC

--

0.5

Mass Parameters

☒ Use Current Mass

kg

4235

☐ Override Vehicle Mass

kg

4200

☐ Add to Current Mass

kg

0

Test Results

Parameter

Initial Speed

Final Speed

Units

☒ Accel time #1

0

to

48.3

km/h

☒ Accel time #2

0

to

80.5

km/h

☒ Accel time #3

0

to

137

km/h

Value

Units

☐ Distance in ...

5

s

☐ Time in ...

0.402

km

☐ Max accel rate

☐ Max speed

OK

Cancel

Help

Defaults

Load PNGV

Figure 4.1 Stock HMMWV Acceleration Test Settings

4.1.2. Gradeability

Values for the gradeability of the stock HMMWV were determined using the value for vehicle corrected mass determined in the acceleration portion of the study of the stock vehicle. For purposes of study, both the 88.5 kph gradeability and the max gradeability in low gear were studied. The stock values and the target design values are 5% at 88.5 kph with a max gradeability of 60%. Analysis in ADVISOR at the corrected mass gave 6.3% gradeability at the 88.5 kph speed condition. There were, however, significant difficulties associated with the max gradeability.

Because of the way ADVISOR models wheel slip, the slip for tractive effort is assumed to occur based on a single axle providing tractive torque. In the high load situations, this assumption causes wheel slip to occur at a tractive effort significantly lower than the real world value for a 4WD system which distributes this tractive effort across four tire patches rather than two. An effort was made (with the assistance of NREL) to change this model to accommodate the 4WD case; however, a Simulink model with usable maximum gradeability results was not completed. If the earlier hand calculations for maximum gradeability are referenced, however, it is apparent that the minimum gradeability of 60% at 3.2 kph is not likely to be an issue in either the stock or PHEV configurations.

4.1.3. Fuel Economy

Because no military standard driving cycle is available for simulation or testing purposes, a driving cycle was developed for comparison purposes. For this purpose, a test cycle was constructed using two cycles of the Federal Test Procedure (FTP) as modeled within ADVISOR (see Figure 4.2 for the FTP speed trace from ADVISOR). Although the results of this testing cannot be directly compared with the stock vehicle performance as tested in the field, they can be used as a baseline to quantify relative fuel economy improvements of the hybrid system over the stock configuration.

The FTP driving cycle as modeled in ADVISOR consists of one Federal Urban Dynamometer Driving Schedule (FUDDS) followed immediately by a Highway Fuel Economy Test (HWFET), a 10 minute engine-off hot soak, and a second FUDDS cycle.

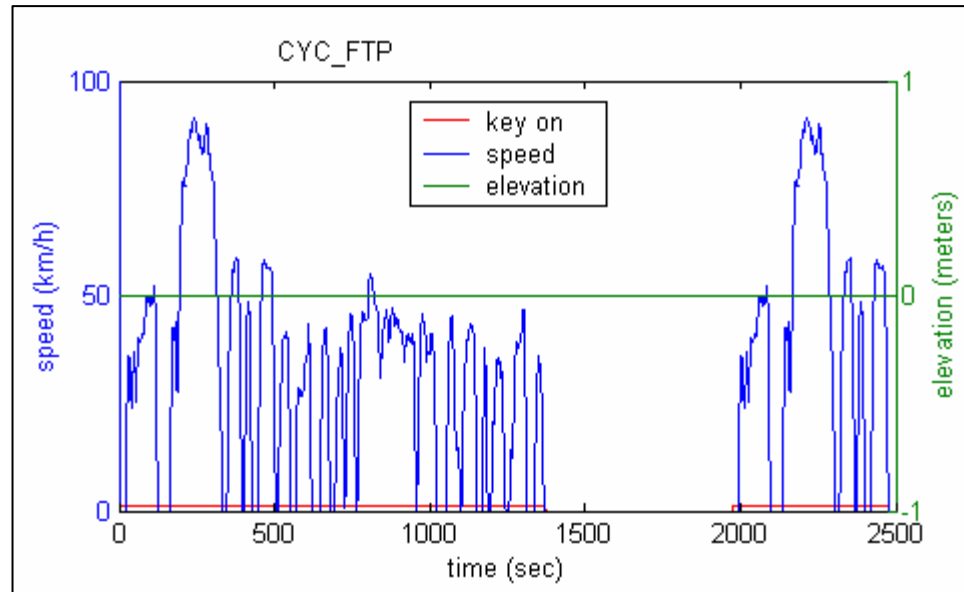


Figure 4.2 FTP Speed Trace in ADVISOR

This schedule is used to determine vehicle emissions compliance with federal emissions standards for consumer vehicles, and was anticipated to give a relatively useful representation of typical on-road HMMWV operation with a mix of relatively low speed start-stop driving and a period of high speed highway/convoy type operation. Use of this cycle gave an on-road fuel economy value of 22.3 L/100km (~10.5 mpg).

One area of interest for comparison to the PHEV simulation is the Energy Use Figure for the stock vehicle. Figure 4.3 shows the Energy Use Figure for this vehicle configuration. One area to note is the energy dissipated by the friction braking. In this case, the energy dissipated during braking was approximately 9,755 kJ. This is equivalent to almost 2.7 kW-h. Recovery of a portion of this energy into the ESS will be key to efficient operation during stop-and-go driving situations in the PHEV system.

4.2. Parallel Hybrid Simulation

During the PHEV simulation of the Hybrid HMMWV, a number of candidate systems were studied for comparison with the stock vehicle. Table 4.1 shows the matrix of potential engine/motor combinations that were studied. All systems were studied with a 42 A-h Hawker Genesis VRLA ESS consisting of 25 battery modules with a nominal

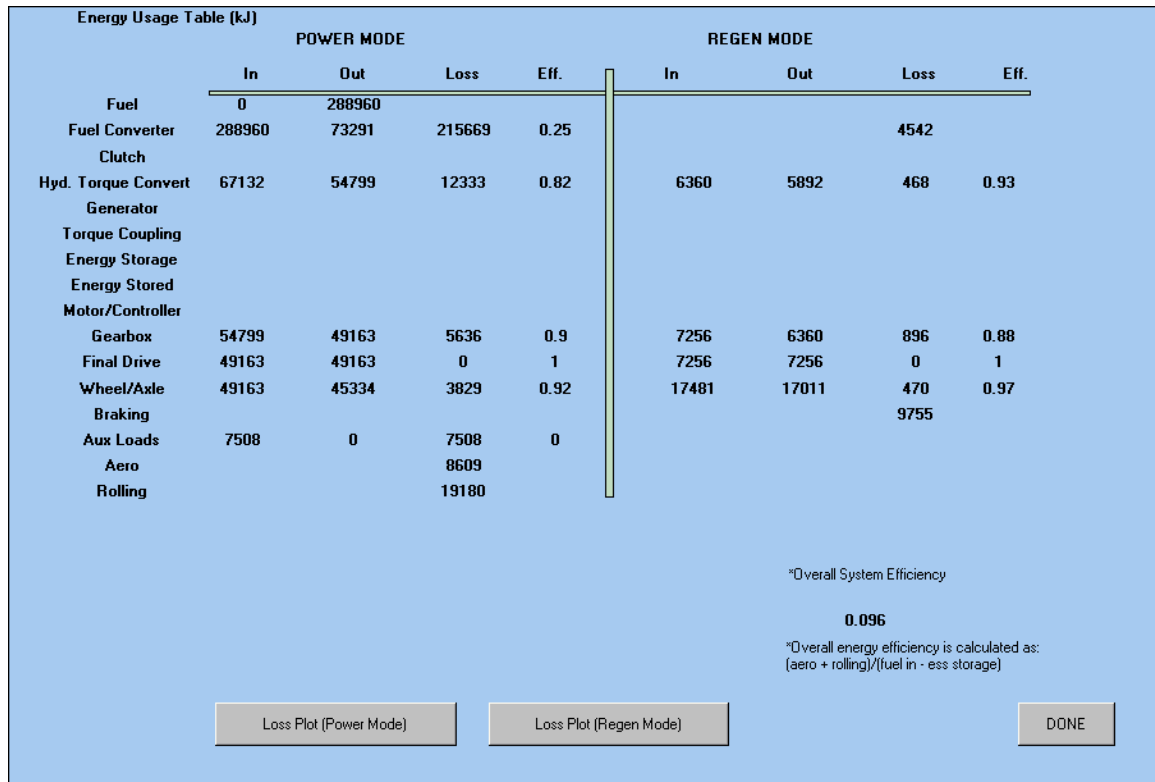


Figure 4.3 Energy Use Figure for Stock HMMWV over 2 FTP Cycles

Table 4.1 Engine and Motor Combinations Studied in PHEV Analysis

Motor	Engine		
	1.9L TDi	2.4L JTD	3.0L TDi
CaliberEV 75	X	X	X
CaliberEV100	X	X	XX*

* Indicates system modeled with both Pb-A and NiMH ESS
All other simulations with Pb-A only

voltage of 308 VDC. In addition to these analyses one engine/motor combination was studied with a NiMH battery option equivalent in mass to the 42 A-h Hawker Genesis VRLA ESS as a basis for comparison with advanced battery technologies.

4.2.1. Acceleration

For acceleration testing, the corrected vehicle mass determined in the stock vehicle modeling was applied as an override mass in the Vehicle Inputs screen. The parallel drivetrain discussed earlier was used with the 42 A-h Pb-A ESS at 65% SOC which was assumed to be an operationally normal situation. Each engine/motor option described in Table 4.1 was tested in full hybrid, engine only, and motor only modes for the 0-48.3 kph and 0-80.5 kph accelerations modeled in the stock vehicle acceleration test.

Tables 4.2 and 4.3 give the acceleration results for the hybrid acceleration simulations. As the results show, the acceleration capability of all hybrid options is superior to that of the stock vehicle. Increasing the motor size from 75 to 100 kW however had little impact on the acceleration results. This is due to the fact that the battery pack nears its discharge limit over the course of the acceleration test during the 75 kW test. Increasing the power density of the pack through a change in chemistry or an increase in the A-h rating could eliminate this issue. As would be expected the pairing of the largest engine displacement studied (3.0L) along with the largest motor rating studied (100 kW) resulted in the best acceleration performance with 6.4s for 0-48.3 kph time, and 16.0s for the 0-80.5 kph time. This performance is substantially superior to the stock vehicle.

Like the hybrid acceleration simulations, the motor and engine component accelerations yielded similarly anticipated results. Table 4.4 shows the 0-48.3 kph and 0-80.5 kph acceleration values for the engine only operational mode. Only the 0-48.3 kph time for the 3.0L engine resulted in what would be considered an acceptable acceleration performance with a time of 9.9s. Both the 1.9L and 2.4L engines were substantially slower and offered unacceptable performance in this mode. None of the three engines offered acceptable performance for the 0-80.5 kph acceleration. The 1.9L engine was unable to meet the target speed of 80.5 kph within 90s.

Table 4.2 Acceleration Results for 0-48.3 kph ESS and Engine Enabled

Motor	Engine		
	1.9L TDi	2.4L JTD	3.0L TDi
CaliberEV 75	7.7s	7.0s	6.5s
CaliberEV100	7.7s	6.9s	6.4s

Table 4.3 Acceleration Results for 0-80.5 kph ESS and Engine Enabled

Motor	Engine		
	1.9L TDi	2.4L JTD	3.0L TDi
CaliberEV 75	19.1s	17.5s	16.2s
CaliberEV100	19.1s	17.4s	16.0s

Table 4.4 Acceleration Results for Engine Only Enabled

Speed	Engine		
	1.9L TDi	2.4L JTD	3.0L TDi
0-48.3 kph	16.0s	12.2s	9.9s
0-80.5 kph	--	58.5s	41.3s

Table 4.5 Acceleration Results for ESS Only Enabled

Speed	Motor	
	CaliberEV 75	CaliberEV100
0-48.3 kph	15.9s	14.1s
0-80.5 kph	39.3s	33.0s

Electrical acceleration capabilities for both the 75 and 100 kW motor options were generally better than the engine-only accelerations with only the 3.0L having superior performance in the 0-48.3 kph time. Table 4.5 shows the relative performance of the 75 and 100 kW motors. The relative difference is not extremely large owing in part to the limitations of the ESS at the 65% SOC used in the model inputs for this simulation.

4.2.2. Gradeability

Due to the difficulties with the maximum gradeability discussed earlier in the stock vehicle simulation, only the high speed gradeability was simulated in ADVISOR. The same values for vehicle corrected mass and engine capabilities were used for gradeability simulation. In order to guarantee that the value for continuous gradeability was truly a continuous value, the ESS was disabled for the high speed gradeability simulation. Due to the high vehicle normal load during the gradeability test, this portion of the simulation was used to determine the minimum engine size.

Simulation of the 1.9L and 2.4L engine options yielded unacceptable gradeability with values of 2.5 and 3.8% respectively. Initial indications are that the 3.0L engine is the smallest commercially available option that can meet the 88.5 kph at 5% gradient requirement. While a smaller engine is capable of meeting the gradeability requirement with assistance from the electric motor, this type of operation would not be considered “continuous”. This is due to the fact that gradeability under the hybrid condition would be limited by the ESS SOC. Table 4.6 shows the high speed gradeability for the engine options simulated.

Table 4.6 Gradeability Results at 88.5 kph Engine Only Enabled

Engine			
1.9L TDi	2.4L JTD	3.0L TDi	6.5L Stock
2.5%	3.8%	5.2%	6.3%

4.2.3. Fuel Economy

Like the earlier stock vehicle simulation, the parallel vehicle fuel economy was determined using the FTP driving cycle as the load criteria. The vehicle mass used was the same as the Vehicle Corrected Mass determined during stock vehicle simulation. In order to simulate electric accessories as well as a more electric vehicle approach, a 2kW electrical accessory load was used for all fuel economy simulations. This was intended to reflect the higher electrical loads necessary to accommodate potential electrical accessories as well as communications and sensor equipment. A similar accessory load was used for the alternator of the stock vehicle simulation.

In order to insure a corrected fuel economy value that included any energy depleted from the ESS, the “SOC Correction” option was chosen for the driving cycle. When this option is selected, the SOC corrected fuel economy value will contain an energy usage correction that is within a user selected percentage of the energy consumed from the ESS during the driving cycle. In addition to this, the user also has the option of correcting the energy consumption to fuel usage ratio to accommodate the method used for off-board ESS energy replenishment. As an example, if an extremely inefficient method of off-board ESS charging is used a lower value of ESS/fuel energy ratio can be used to indicate this off-board inefficiency.

The vehicle control strategy implemented utilizes a fuzzy logic rule set to attempt to maximize engine efficiency. As stated earlier, this typically results in a very aggressive usage of the engine to avoid inefficiencies associated with partial loading. This mode of operation tends to keep the ESS at a high SOC during most types of operation. While

Table 4.7 FTP Fuel Economy Results with SOC Correction

Motor	Engine			
	1.9L TDi	2.4L JTD	3.0L TDi	6.5L Stock
CaliberEV 75	15.6 L/100km	16.3 L/100km	17.7 L/100km	22.3 L/100km
CaliberEV100	15.8 L/100km	16.4 L/100km	17.7 L/100km	

this may not yield the best values for fuel economy, it is likely to be the preferred method of operation to provide the highest military application functionality.

As might be expected, the simulation results indicate that all PHEV options studied resulted in an improvement in fuel economy. The greatest improvement was seen using the 1.9L engine which resulted in a 30% reduction in fuel consumption. Fuel consumption for the 3.0L engine paired with either the 75 or 100 kW motor was approximately 21% lower than the stock vehicle. As stated earlier, this may not be a sufficient level for a typical consumer vehicle to warrant hybridization, but this improvement coupled with increased functionality is sufficient to warrant study for military applications. Table 4.7 details fuel economy findings for all systems simulated.

One issue addressed earlier during the explanation of the stock vehicle fuel economy relates to the recovery of braking and system inertial energy. During two cycles of the FTP, the system as modeled recovered approximately 2 kW-h of energy during braking. This is equivalent to roughly 15% of the energy capacity of the ESS at the 42 A-h capacity. This contributes significantly to fuel consumption reduction during stop-and-go driving.

4.2.4. Rangeability

For rangeability determination four vehicle cases were considered. The first was a PHEV system with 100kW motor and 42 A-h VRLA ESS at the Vehicle Corrected Mass. The ESS was assumed to be at 100% SOC which is likely to be the state of the vehicle ESS in anticipation of a silent-mode operation. This configuration approximated a pre-transmission electric motor with low cost ESS. All vehicles used the same 2 kW hotel or

Table 4.8 Electric Rangeability for Several Operational Speeds

Cycle	Pb-A Pre-Trans km	Pb-A Post Trans km	NiMH Pre-Trans km	NiMH Post Trans km
20 kph	25.0	29.4	37.2	45.0
40 kph	25.6	31.1	40.0	47.8
60 kph	21.7	28.3	36.7	43.3
80 kph	15.6	20.0	31.1	35.6

accessory load used for fuel economy determination discussed in Section 4.2.3. The second vehicle was simulated using an EV system configuration with a single speed gear reducer to replicate the option of a post-transmission electric transfer case approach. The second option was studied to determine the impact of the inefficiencies of the stock transmission on the rangeability. These two vehicle configurations allowed rangeability simulation of the most likely suggested pre- and post-transmission electric motor PHEV configurations.

The third and fourth vehicles simulated were identical to the first and second vehicles respectively, with the exception that each utilized a 60 A-h NiMH ESS that was equivalent in mass to the Pb-A ESS. This allowed rangeability simulation of the most likely suggested vehicle configuration along with a high technology ESS option in the same configuration.

For simulation purposes, four steady-state driving cycles were defined at 20, 40, 60, and 80 kph. For electric rangeability each of the four vehicle configurations was tested at each of these four operation points. Table 4.8 shows the rangeability for each of the 16 cases in the test matrix.

As this matrix indicates, a pre-transmission electric motor with Pb-A ESS PHEV configuration is unlikely to meet the rangeability requirement of 32.2 km at any operational speed. The post-transmission option with the Pb-A is very close to meeting the rangeability target over a significant portion of the speed range studied. This

configuration will likely make the EV range requirement for a relatively wide operational speed range if a lower than anticipated (2 kW) accessory load is seen. One area of note in the range is that the 20 kph speed rangeability is substantially lower than the 40 and 60 kph rangeabilities. At first look this is counter to the normally accepted behavior of the ESS. Typically, the energy capacity of the ESS will be inversely proportional to the vehicle load. This would indicate a lower rangeability as speed increases. In this case, however, the small value for 20 kph EV rangeability is due to the high accessory load which is independent of the vehicle load. In this instance, the energy consumed by the accessory load is the product of the power and time. For the low speed cases, the accessory load energy consumption is roughly equivalent to the rolling losses (the largest loss in the system).

For the NiMH cases, both the pre- and post-transmission electric motor configurations appear to be capable of meeting the range requirements over a broad speed range. An additional advantage of this type of system relates to the battery cycle life. Based on the 80% DOD used in this simulation, the Pb-A battery option is likely to be capable of only 300-400 full discharge cycles prior to replacement. The NiMH option however may be able to yield as many as 1500 cycles at the same DOD [SAFT, 2004]. Although the NiMH option is initially much more expensive, the increased cycle life and EV range may warrant consideration.

Another item of interest related to the NiMH ESS is the much flatter discharge curve. Table 4.9 and Figure 4.4 show the energy usage and battery capacity for each of the vehicles used in simulation over the various load conditions. As the figure shows, the capacity of the NiMH ESS is much less sensitive to the system load than the Pb-A system. This is typical of this battery chemistry.

It is not clear based on only the rangeability whether the pre- or post-transmission option is most reasonable from a system standpoint, but both options have advantages and disadvantages which must be considered.

Table 4.9 A-h Ratings for Several Speeds at Maximum Electric Range

Cycle	Pb-A Pre-Trans A-h	Pb-A Post-Trans A-h	NiMH Pre-Trans A-h	NiMH Post-Trans A-h
20 kph	37.4	36.8	54.7	55.5
40 kph	35.9	37.4	54.5	55.8
60 kph	34.7	37.6	55.7	55.7
80 kph	29.4	32.6	55.0	55.5

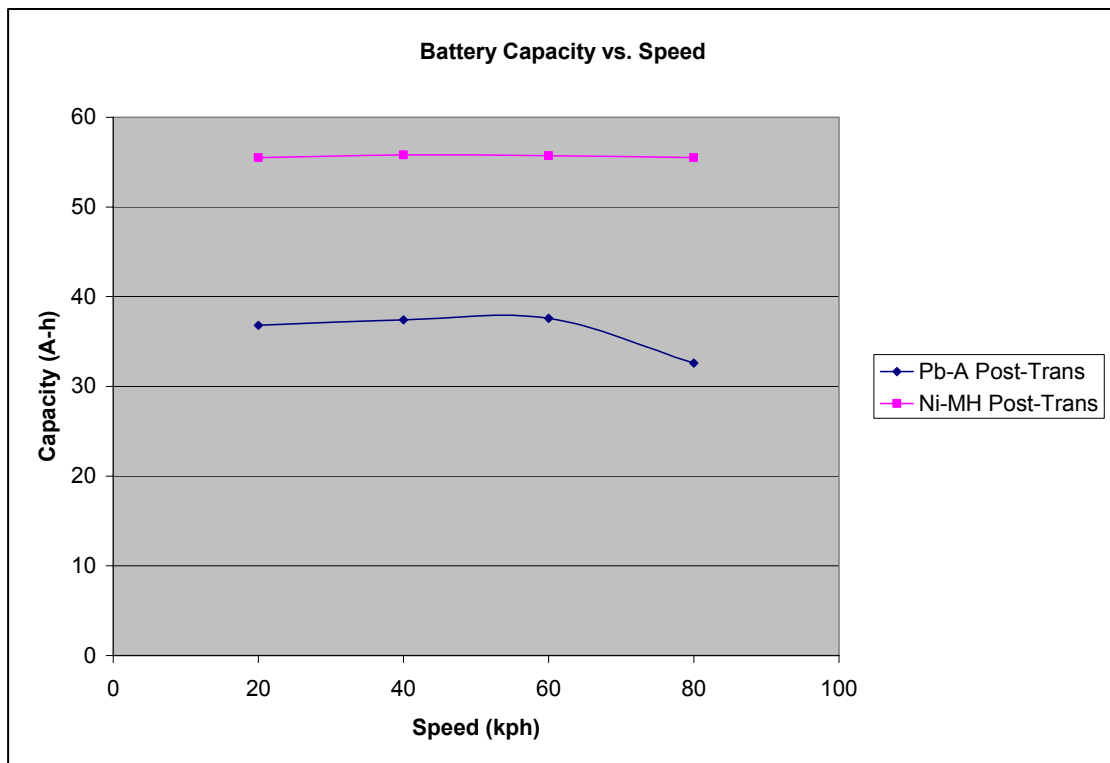


Figure 4.4 A-h Rating vs. Speed for Post Transmission PHEVs

5. Conclusions

5.1. Proposed Configuration

The proposed configuration based on the findings of the design study is based on low-cost, COTS equipment in a PHEV system. There are two potential drivetrain configuration options, each with similar performance characteristics. The first of these options is the pre-transmission electric motor PHEV, and the second is a post-transmission electric motor PHEV. Figures 5.1 and 5.2 show the two potential configurations. The two options have the following characteristics:

Pre-Transmission Option

- Affords the greatest torque multiplication of the electric motor torque by allowing use of stock hydraulic torque converter and multi-ratio transmission
- Placement of motor before transmission allows use of PMBLDC motors without a significant CPSR operational capability
- Can be packaged as engine/motor modular unit that is a bolt-on underhood retrofit. This avoids all changes to any components between the torque converter and wheels
- Requires clutch between engine and electric motor and engine for EV operation
- Has lower EV range due to inefficiencies in transmission and fluid coupling of torque converter. This effect can be reduced by locking torque converter during EV operation, but would require auxiliary electric transmission pump and modified transmission

Post-Transmission Option

- Lower torque multiplication than pre-transmission option due to location downstream from torque converter and transmission
- Can be packaged as engine module that is bolt-on underhood retrofit along with electric transfer case replacement. This requires changes to drivetrain downstream from torque converter

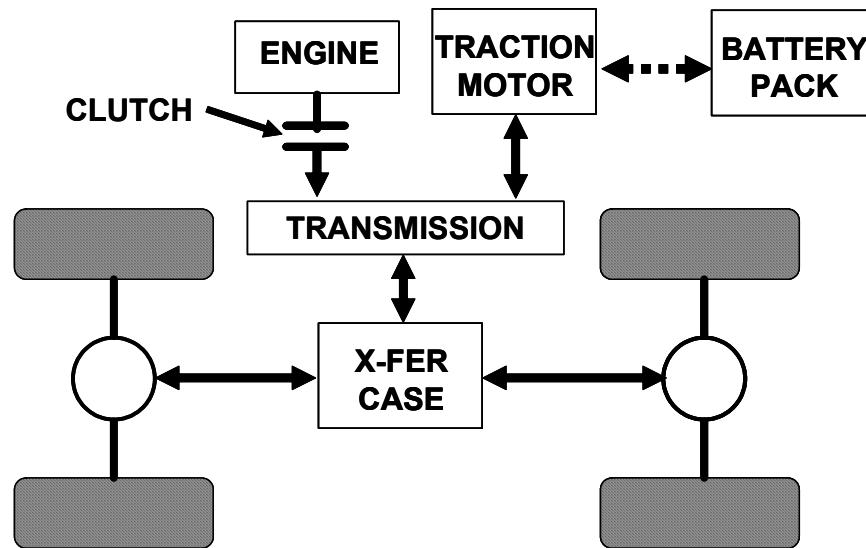


Figure 5.1 Pre-Transmission PHEV Configuration

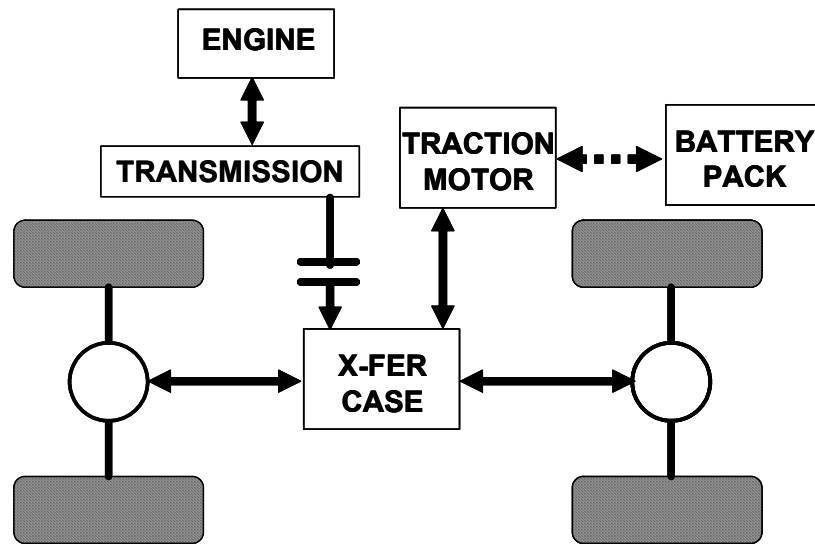


Figure 5.2 Post-Transmission PHEV Configuration

- Can utilize existing transmission neutral gear for EV operation which eliminates requirement for engine/motor clutch
- Has higher EV range due to elimination of transmission and torque converter losses

At this time, the two approaches require further input from potential customers prior to finalization of system configuration. The decision between the two is dependent upon the preferred operational characteristics of the final system. If the highest priority is an extended silent run mode, then the post-transmission option is undoubtedly the preferred option. If ease of implementation is seen as the highest priority, and little importance is placed on EV range, then the pre-transmission option is likely the preferred option.

Regardless of the system ultimately chosen, system simulation indicates that the same motor and engine components would be used.

Engine

The desired engine, based on ADVISOR simulation, is a 3.0L direct-injected turbo-diesel engine. This sizing is based primarily on the required 5% gradeability at 88.5kph.

Motor

Motor sizing in both the pre- and post-transmission options indicates that a PMBLDC motor sized for a minimum of 100kW continuous power is desirable. This results in an acceptable derated performance during EV operation.

Energy Storage System

Like the overall system layout, there are two ESS options that are considered to be viable based on the most desirable characteristics of the vehicle. If an extended EV range is desired, it is likely necessary to utilize an advanced battery technology such as the NiMH batteries modeled during the rangeability study. Based on anticipated cycle life at frequent 80% DOD operation, these batteries could be cost competitive on a life-cycle basis at a cost of four times or potentially more than the competing VRLA ESS option.

If initial cost and low replacement cost is the primary issue, and EV rangeability is considered secondary, then the VRLA ESS option is likely to be considered the most desirable. At this time, it is suggested that any prototype development be performed

using a VRLA ESS system. Further study is required to better understand the life-cycle costs of the NiMH ESS option.

5.2. Projected Performance

The proposed PHEV is capable of meeting or exceeding all operational capabilities of the stock HMMWV in hybrid mode with sufficient ESS SOC. Addition of an EV capability also gives a number of new functional capabilities including silent-running and low noise and thermal signature operation. Projected performance is given in Table 5.1.

5.3. Suggested Future Development

There are a number of areas the warrant further research based on the study performed to date. These include placement of key components such as the ESS, model improvement to accommodate 4WD simulations, further study of alternative control strategies, and development of a system level controller.

5.3.1. Component Placement

As stated previously, there are a number of issues related to component placement that must be addressed. This issue impacts vehicle dynamic stability, CG, and required modifications. Initial studies have been performed to locate the ESS in the vehicle. At this time, it appears that this particular system must be split into two to four smaller systems which are linked by power cables. This is less desirable than a single compartment primarily due to safety and maintenance issues associated with a distributed ESS.

In addition to the ESS, a significant study must be performed on the required modifications to the existing thermal management systems to accommodate the PHEV system. It is likely that the stock heat exchanger will be replaced with a number of smaller heat exchangers to accommodate the smaller ICE, and the addition of power electronics and ESS requiring additional cooling.

5.3.2. Modeling and Simulation

Additional modeling and simulation is required to verify 4WD performance on gradients (particularly 60% gradeability). This will require substantial changes to the

Table 5.1 System Performance Projections

Motor Motor Location ESS Engine Transmission	CaliberEV100 Pre-Trans Pb-A 3.0L TDi 4L80E	CaliberEV100 Post Trans Pb-A 3.0L TDi 4L80E	6.5L Stock 4L80E
0-48.3 kph PHEV Accel	6.4s	6.4s	
0-80.5 kph PHEV Accel	16.0s	16.0s	
0-48.3 kph EV Accel	14.1s	8.7s	
0-80.5 kph EV Accel	33.0s	24.6s	
0-48.3 kph ICE Accel	9.9s	9.9s	10.0s
0-80.5 kph ICE Accel	41.3s	41.3s	29.0s
Gradeability at 88.5kph	5.2%	5.2%	6.3%
Fuel Consumption	17.7 L/100km	17.7 L/100km	22.3 L/100km
20 kph EV Range	25.0km	29.4km	--
40 kph EV Range	25.6km	31.1km	--
60 kph EV Range	21.7km	28.3km	--
80 kph EV Range	15.6km	20.0km	--
20 kph Battery Capacity	37.4A-h	36.8A-h	--
40 kph Battery Capacity	35.9A-h	37.4A-h	--
60 kph Battery Capacity	34.7A-h	37.6A-h	--
80 kph Battery Capacity	29.4A-h	32.6A-h	--

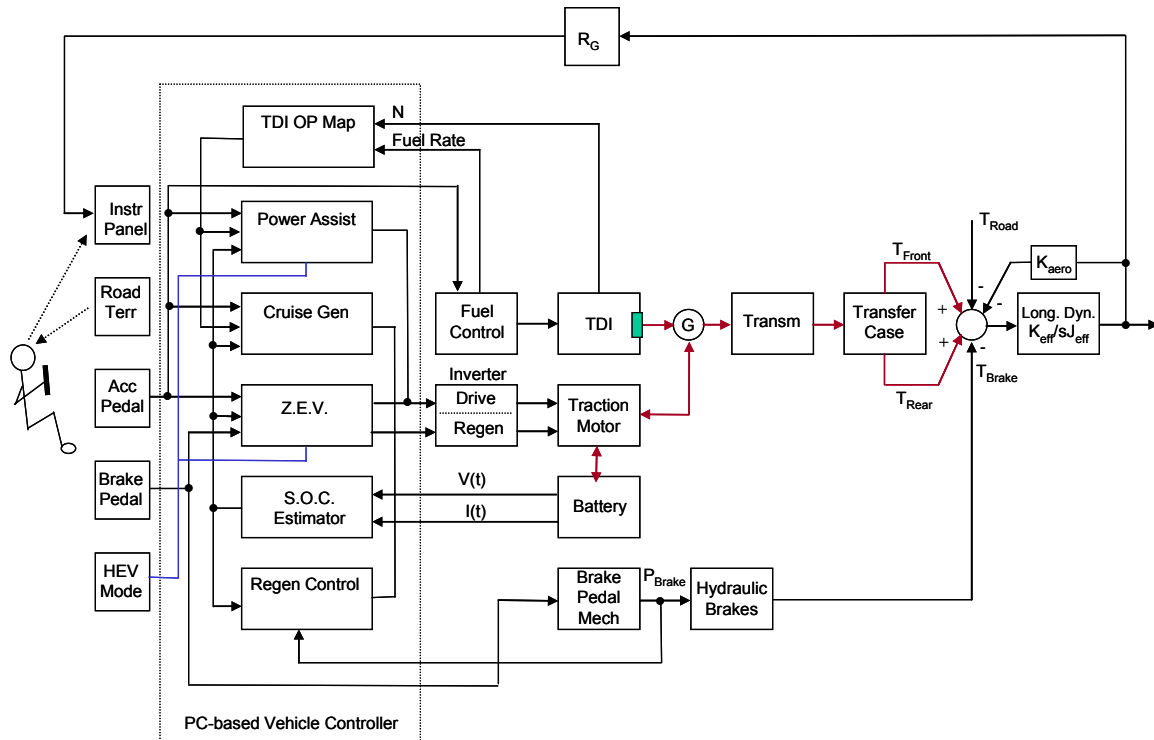


Figure 5.3 System Control Block Diagram For PHEV HMMWV

Simulink *.mdl files for the wheel and axle in ADVISOR. This work was attempted as part of this study, but the resulting model did not yield results that were considered accurate. Additional work must be performed with the assistance of NREL to accomplish this task.

In addition to the issue of accurate modeling of the 4WD system, additional control model development and simulation is required. The initial control schemes are somewhat rudimentary, and a more complex multi-state control strategy is required to accommodate the broad range of operational requirements for military use. An initial control system block diagram was developed but considerable additional development is required.

5.3.3. Development of System Controller Hardware Requirements

As previously stated initial system controls block-diagrams were developed for a system controller (see Figure 5.3), but no detailed hardware list was developed. It is anticipated that a significant effort will be required to develop the required sensors,

computer hardware, and driver interface for the final system. Where possible COTS equipment will be used, but military requirements are anticipated to greatly limit options for this equipment.

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Appendices

Appendix A. Component Specification Sheets

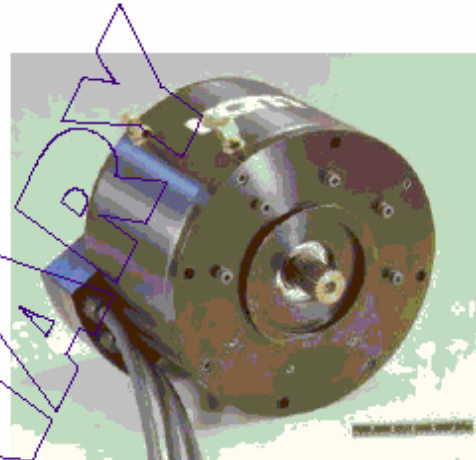
Appendix A.1. UQM CaliberEV 100



Introducing a new traction drive system...

CaliberEV 100

SR286N Motor			
Dimensions	Length	13 in	330 mm
	Diameter	15 in	381 mm
Weight		190 lb	86 kg
Performance			
Peak Power		TBD	
Continuous power		134 hp	100 kW
Max. torque		550 lb-ft	745 N-m
Continuous torque		405 lb-ft	550 N-m
Max. speed		4400 rpm	
Efficiency		90%	
Peak efficiency		92%	
Power density (based on 100 kW)		0.71 hp/lb	1160 W/kg
Max. torque duty cycle		25% (e.g. 1 min/4 min)	
Characteristic curve - Constant torque to base speed & constant power			
CA40-400L Inverter			
Operating Voltage		270 to 336 Vdc	
Nom. battery input range		250 to 400 Vdc (meets rated speed)	
Full performance voltage input range			
Minimum voltage limit		180 V (with derated power output)	
Input current limitation		400 A	
Inverter Type			
Control type - PWM & phase advance		3-phase brushless dc	
Applicable max. current		600 A peak	
Power device		IGBT module half bridge x 3	
Switching frequency		20 kHz	
Standby power consumption		17 W (inverter and microprocessor)	
Cooling System			
Min. inlet coolant flow		7.5 l/min	
Max. inlet T of controller		131 °F	55 °C
Inner diameter of hose		5/8 in	16 mm
Max. inlet pressure		10 psig	
Dimensions			
	Length	16.63 in	423 mm
	Width	22.50 in	572 mm
	Height	4.63 in	118 mm
Weight		50 lb	22.7 kg
Mounting method		4 x 5/16" - 18 screw studs	
EVPH332 Microprocessor (internally packaged)			
Nominal input voltage		12 V	
Input supply voltage range		8 to 18 V	
Input supply current range		0.3 to 0.5 A	



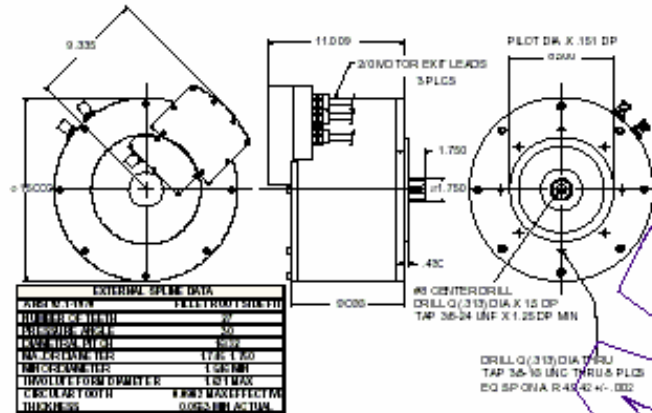
- 100 kW / 745 N-m
- High torque at low RPM
- High efficiency / light weight
- Brushless permanent magnet motor
- Microprocessor-controlled inverter with phase advance
- Traction drive or starter / generator compatible
- Outstanding power control
- Superior performance and energy management
- Minimum maintenance and operating costs

Drive Electronics	
IGBT power switches	Temperature sensing/alarm
Serial communication	Speed sensing
Diagnostic capability	Software controlled forward/reverse
Digital "power-up" control signals	Coolant fan control
Charger port and parking brake interlocks	Liquid cooling
Operation tailorable for battery management	
Features	Your Benefits
Torque based traction control	Smooth vehicle operation
Phase advance control	Eliminates gear change requirements
Regenerative braking (selectable)	Improved braking and extended range
Rugged enclosure	Suitable for automotive applications
Liquid cooling	Enhanced thermal management
Vehicle control software	Customized (optional)

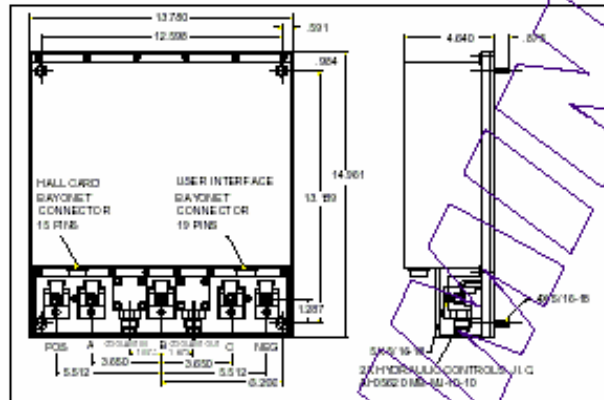
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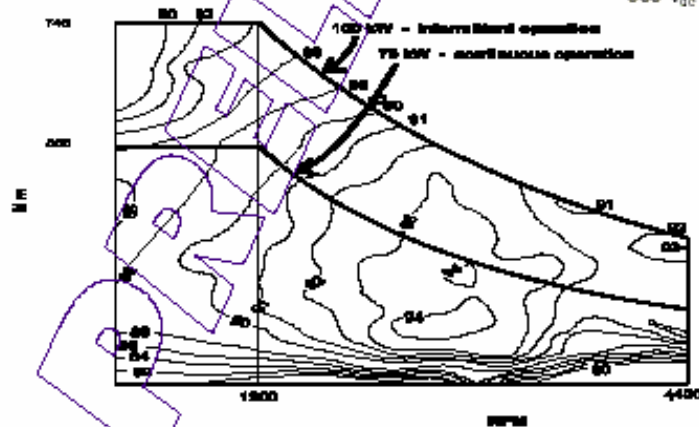
SR286N Motor



CA40-300L Inverter



Efficiency Map (system)
300 V_{dc} Input



Appendix A.2. UQM CaliberEV 75



Introducing a new traction drive system...

CaliberEV 75

SR286N Motor			
Dimensions			
Length	13 in	330 mm	
Diameter	15 in	381 mm	
Weight	190 lb	86 kg	
Performance			
Power	100 hp	75 kW	
Torque	405 lbf-ft	550 Nm	
Max. speed	4400 rpm		
Efficiency	90%		
Peak efficiency	92%		
Power density (based on 100 kW)	0.71 hp/lb	1160 W/kg	
Max. torque duty cycle	25% (e.g. 1 min/4 min)		
Characteristic curve - Constant torque to base speed & constant power			

CA40-400L Inverter			
Operating Voltage			
Nom. battery input range	270 to 336 Vdc		
Full performance voltage input range	250 to 400 Vdc (meets rated specs)		
Minimum voltage limit	180 V (with derated power output)		
Input current limitation	350 A		
Inverter Type			
Control type - PWM & phase advance, 3-phase brushless dc			
Applicable max. current	550 A peak		
Power device	IGBT module half bridge x 3		
Switching frequency	20 kHz		
Standby power consumption	17 W (inverter and microprocessor)		
Cooling System			
Min. inlet coolant flow	7.5 l/min		
Max. inlet T of coolant	131 °F	85 °C	
Inner diameter of hose	5/8 in	16 mm	
Max. inlet pressure	10 psig		
Dimensions			
Length	14.96 in	380 mm	
Width	13.78 in	350 mm	
Height	4.64 in	118 mm	
Weight	28.8 lb	13.1 kg	
Mounting method	4 x 5/16"-18 screw slots		

EVPH332 Microprocessor (internally packaged)	
Nominal input voltage	12 V
Input supply voltage range	8 to 18 V
Input supply current range	0.3 to 0.5 A

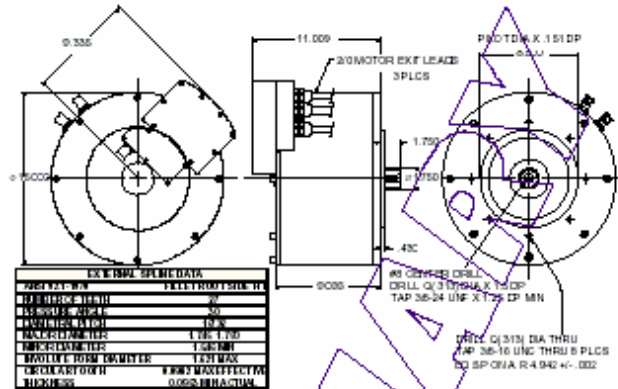
Drive Electronics	
IGBT power switches	Temperature sensing/alarm
Serial communication	Speed sensing
Diagnostic capability	Software controlled forward/reverse
Digital "power-up" control signals	Coolant fan control
Charger port and parking brake interlocks	Liquid cooling
Operation tailorable for battery management	

Features	Your Benefits
Torque based traction control	Smooth vehicle operation
Phase advance control	Eliminates gear change requirements
Regenerative braking (selectable)	Improved braking and extended range
Rugged enclosure	Suitable for automotive applications
Liquid cooling	Enhanced thermal management
Vehicle control software	Customized (optional)

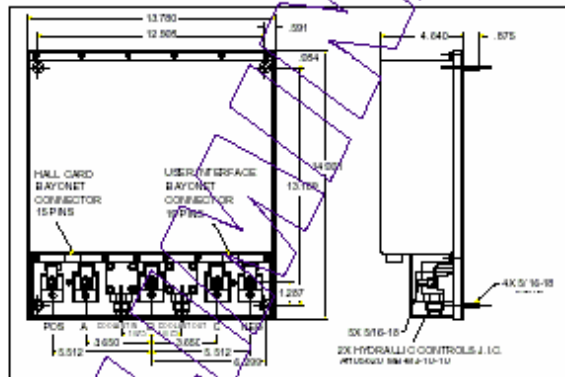
(All data subject to change without notice)

- 75 kW / 745 N-m
- High torque at low RPM
- High efficiency / light weight
- Brushless permanent magnet motor
- Microprocessor-controlled inverter with phase advance
- Traction drive or starter / generator compatible
- Outstanding power control
- Superior performance and energy management
- Minimum maintenance and operating costs

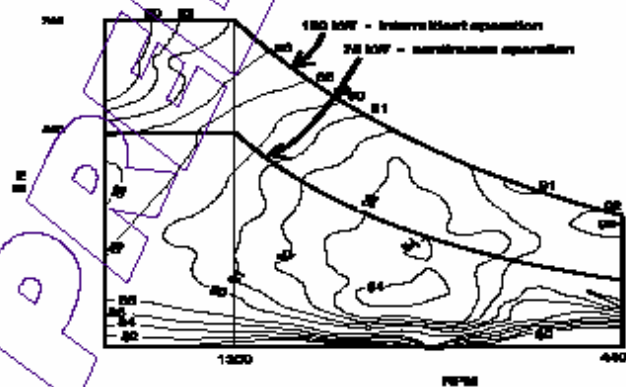
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SR286N Motor



CA40-300L Inverter



Efficiency Map (system)
300 V_{dc} Input

Appendix A.3. Hawker Genesis 42 A-h VRLA Battery

When You're Designing in Performance, Don't Settle For Less Than Pure Lead-Tin.

If you just need a battery, there are many choices. If you need more from your design, however, there is only one choice: pure lead-tin technology. Pure lead-tin overpowers conventional sealed lead products in every category of comparison, and it can only be found in Cyclon® and Genesis® batteries manufactured by Hawker Energy Products Inc. These two design-enhancing battery families provide:

- higher discharge rate
- longer operating life
- wider temperature range (-65°C to +80°C)
- longer shelf life
- faster recharge
- lower internal resistance
- greater design flexibility
- deep discharge capability
- rugged construction
- Department of Transportation nonspillable classification

In other words, our pure lead-tin technology can give your products a competitive edge at a remarkably low cost of ownership to the equipment owner or end user.

HOW DOES THE PURE LEAD-TIN ADVANTAGE WORK?

It all starts with raw materials. Our high purity system allows greater efficiency in the recombination of gas, in turn minimizing vapor loss and preventing dry-out failure. The grid corrosion rate is greatly reduced as a result of using 99.999% pure virgin lead. Our thin-plate design provides the lowest internal resistance in the sealed lead industry and increases plate surface area for the ultimate in power delivery.

CYCLON: THINKING OUTSIDE THE BOX

With the unique cylindrical shape of Cyclon single cells, and the infinite number of possibilities using 2-volt increments which range in capacity from 2.5Ah up to 25Ah, you can think outside the "box". Single cells can be combined in series and/or parallel to meet your specific voltage, ampere-hour and space requirements.



Also available in 4V and 6V monoblocs, the pure lead-tin advantage is yours in whatever shape you need it.

GENESIS: PRISMATIC POWER

Purpose built for high rate power, long float life and high cycle life, the Genesis flat-plate design can best optimize your space and weight limitations.



POWERED BY PURE LEAD-TIN

You'll find Cyclon and Genesis pure lead-tin technology powering a wide variety of applications around the globe, including:

- Telecommunications
- Disc storage back-up
- Electric vehicles
- Lawn and garden equipment
- Emergency lighting
- Aerospace
- Global positioning systems
- Medical equipment
- UPS
- Specialty engine start
- Electronics/instrumentation
- Solar
- Defense
- Fixed-point data networks



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BTR
A member of the BTR Group

CYCLON® 2V SINGLE CELL:

Products (capacity)	Dimensions					Performance				
	Diameter in. (mm)	Height in. (mm)	Height with terminals in. (mm)	Weight oz. (gn)	Tabs in. (mm)	Constant current discharge/amps* (Constant power discharge/watts per cell)*				
						15 min.	60 min.	90 min.	5 hr.	10 hr.
D cell (2.5Ah)	1.35 (34.3)	2.41 (61.2)	2.68 (68.1)	6.28 (178.0)	.187 x .025 (4.75 x 0.64)	5.9 (11.6)	1.9 (3.8)	1.4 (2.7)	.48 (.94)	.26 (.50)
DT cell (4.5Ah)	1.35 (34.3)	3.78 (96.0)	4.05 (102.9)	9.68 (274.4)	.187 x .025 (4.75 x 0.64)	11.2 (21.0)	3.7 (7.1)	2.6 (5.1)	.85 (1.7)	.45 (.90)
X cell (5.0Ah)	1.75 (44.5)	2.87 (72.9)	3.21 (81.5)	12.77 (362.0)	.250 x .025 (6.35 x 0.64)	13.2 (23.9)	3.9 (7.8)	2.8 (5.6)	.96 (1.9)	.50 (1.0)
E cell (8.0Ah)	1.75 (44.5)	3.94 (100.1)	4.28 (108.7)	17.28 (489.9)	.250 x .025 (6.35 x 0.64)	19.0 (35.5)	6.2 (12.4)	4.4 (8.9)	1.6 (3.1)	.81 (1.6)
J cell (12.0Ah)	2.04 (51.8)	4.85 (123.2)	5.34 (135.6)	29.60 (839.2)	0.312 x 0.032 (7.92 x 0.81)	29.4 (53.4)	9.2 (18.3)	6.5 (13.2)	2.3 (4.7)	1.20 (2.3)
BC cell (25Ah)	2.57 (65.3)	6.25 (158.8)	6.82 (173.2)	58.88 (1669.2)	M6 (-) and M8 (+) terminals	54.3 (105.5)	19.3 (36.8)	14.0 (25.6)	4.85 (9.20)	2.55 (4.95)

MONOBLOC 4V & 6V:

Products (capacity)	Dimensions					Performance				
	Length in. (mm)	Width in. (mm)	Height in. (mm)	Weight lb. (kg)	Tabs in. (mm)	Constant current discharge/amps* (Constant power discharge/watts per cell)*				
						15 min.	60 min.	90 min.	5 hr.	10 hr.
4V D (2.5Ah)	3.13 (79.5)	1.81 (46.0)	2.75 (69.9)	.80 (.36)	0.187 x .025 (4.75 x 0.64)	5.9 (11.7)	1.9 (3.8)	1.4 (2.7)	.48 (.93)	.26 (.49)
4V X (5.0Ah)	3.80 (96.5)	2.12 (53.8)	3.02 (76.7)	1.62 (.74)	.250 x .025 (6.35 x 0.64)	13.5 (24.2)	4.0 (7.8)	2.8 (5.6)	1.0 (2.0)	.52 (1.0)
4V E (8.0Ah)	3.81 (96.8)	2.13 (54.1)	4.00 (101.6)	2.11 (.96)	0.250 x .025 (6.35 x 0.64)	19.0 (35.5)	6.2 (12.4)	4.4 (8.9)	1.6 (3.1)	.81 (1.7)
6V D (2.5Ah)	4.48 (113.8)	1.81 (46.0)	2.75 (69.9)	1.15 (.52)	0.187 x .025 (4.75 x 0.64)	5.9 (11.7)	1.9 (3.8)	1.4 (2.7)	.48 (.93)	.26 (.49)
6V X (5.0Ah)	5.48 (139.2)	2.12 (53.8)	3.02 (76.7)	2.16 (.98)	0.250 x .025 (6.35 x 0.64)	13.5 (24.2)	4.0 (7.8)	2.8 (5.6)	1.0 (2.0)	.52 (1.0)
6V E (8.0Ah)	5.48 (139.2)	2.13 (54.1)	4.00 (101.6)	3.15 (1.43)	0.250 x .025 (6.35 x 0.64)	19.0 (35.5)	6.2 (12.4)	4.4 (8.9)	1.6 (3.1)	.81 (1.7)

GENESIS® 12V:

Products (capacity)	Dimensions					Performance				
	Length in. (mm)	Width in. (mm)	Height in. (mm)	Weight lb. (kg)	Brass Terminals (metric)	Constant current discharge/amps* (Constant power discharge/watts per battery)*				
						15 min.	60 min.	90 min.	5 hr.	10 hr.
G13EP (13Ah)	6.910 (175.51)	3.282 (83.36)	5.113 (129.87)	10.8 (4.9)	M6	32.2 (36.1.2)	10.4 (121.2)	7.3 (85.8)	2.5 (29.4)	1.3 (15.6)
G16EP (16Ah)	7.150 (181.61)	3.006 (76.33)	6.805 (172.77)	13.5 (6.1)	M6	40.1 (45.3.6)	12.7 (190.2)	8.9 (105.0)	3.0 (36.0)	1.6 (19.2)
G26EP (26Ah)	6.565 (166.75)	6.920 (175.77)	4.957 (125.91)	22.3 (10.1)	M6	67.4 (75.1)	21.7 (251)	15.1 (175.8)	5.0 (59)	2.6 (31)
G42EP (42Ah)	7.775 (197.49)	6.525 (165.74)	6.715 (170.56)	32.9 (14.9)	M6	104.1 (11.73)	33.8 (394)	23.5 (276)	7.9 (94)	4.2 (51)
G70EP (70Ah)	13.020 (330.71)	6.620 (168.15)	6.930 (176.02)	53.5 (24.3)	M6	173.4 (1940)	57.4 (670)	40.6 (486)	13.4 (161)	7.1 (86)

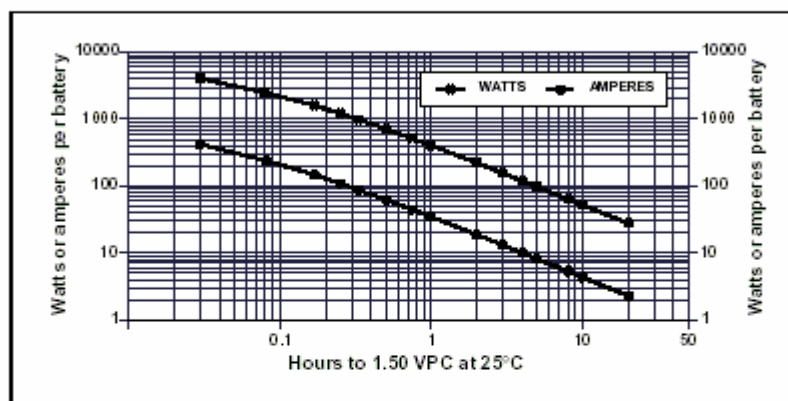
* to 1.67 vpc @ 25°C

UL Recognized Component. Cyclon & Genesis meet UL 1989.

The information in this publication is accurate as of its publication date. Specifications are subject to change without notice.
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Revised 7/98

Figure A-16: Genesis 42Ah discharge to 1.50 VPC at 25°C



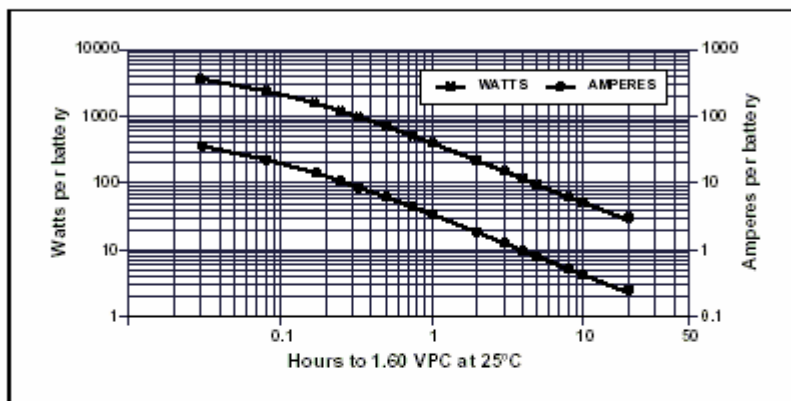
Run time to 1.50 vpc	Energy and power densities							
	Watts	Amps	Capacity (Ah)	Energy (Wh)	Watts per liter	Wh per liter	Watts per kilogram	Wh per kilogram
2 min	4046	417.0	13.90	134.90	723.20	24.10	275.20	9.20
5 min	2498	240.5	20.00	208.15	446.50	37.20	169.90	14.20
10 min	1607	148.3	24.70	267.90	287.30	47.90	109.35	18.20
15 min	1210	109.2	27.30	302.40	216.20	54.05	82.30	20.60
20 min	979	87.2	29.10	326.20	174.90	58.30	66.60	22.20
30 min	716	62.7	31.35	357.90	127.95	64.00	48.70	24.35
45 min	516	44.6	33.45	387.00	92.20	69.20	35.10	26.30
1 hr	406	34.8	34.80	406.20	72.60	72.60	27.60	27.60
2 hr	223	18.8	37.60	446.40	39.90	79.80	15.20	30.40
3 hr	155	13.1	39.30	466.20	27.80	83.30	10.60	31.70
4 hr	119	10.0	40.00	477.60	21.30	85.40	8.10	32.50
5 hr	98	8.2	41.00	489.00	17.50	87.40	6.65	33.30
8 hr	64	5.3	42.40	508.80	11.40	90.95	4.30	34.60
10 hr	52	4.3	43.00	516.00	9.20	92.20	3.50	35.10
20 hr	28	2.3	46.00	564.00	5.00	100.80	1.90	38.40

Table A-16: 42Ah Genesis Performance Data at 25°C

All Figures Based on 12V Module



Figure A-17: Genesis 42Ah discharge to 1.60 VPC at 25°C

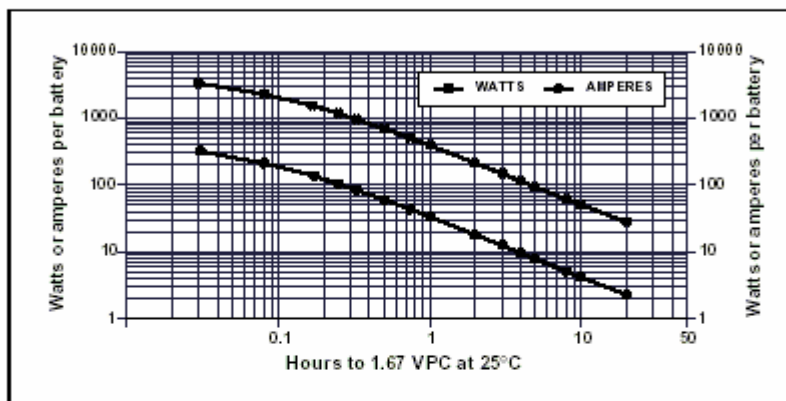


Run time to 1.60 vpc	Energy and power densities							
	Watts	Amps	Capacity (Ah)	Energy (Wh)	Watts per liter	Wh per liter	Watts per kilogram	Wh per kilogram
2 min	3622	361.2	12.00	120.70	647.35	21.60	246.40	8.20
5 min	2404	226.2	18.85	200.35	429.70	35.80	163.55	13.60
10 min	1586	144.3	24.05	264.40	283.60	47.30	107.90	18.00
15 min	1201	107.5	26.90	300.30	214.70	53.70	81.70	20.40
20 min	973	96.1	28.70	324.20	173.85	57.95	66.20	22.05
30 min	710	62.1	31.05	354.90	126.90	63.40	48.30	24.10
45 min	510	44.2	33.15	382.50	91.20	68.40	34.70	26.00
1 hr	400	34.4	34.40	399.60	71.40	71.40	27.20	27.20
2 hr	218	18.5	37.00	435.60	38.90	77.90	14.80	29.60
3 hr	152	12.8	38.40	455.40	27.10	81.40	10.30	31.00
4 hr	117	9.8	39.20	468.00	20.90	83.65	8.00	31.80
5 hr	95	8.0	40.00	477.00	17.05	85.30	6.50	32.45
8 hr	62	5.2	41.60	499.20	11.15	89.20	4.20	34.00
10 hr	52	4.3	43.00	516.00	9.20	92.20	3.50	35.10
20 hr	28	2.3	46.00	564.00	5.00	100.80	1.90	38.40

Table A-17: 42Ah Genesis Performance Data at 25°C

All Figures Based on 12V Module

Figure A-18: Genesis 42Ah discharge to 1.67VPC at 25°C



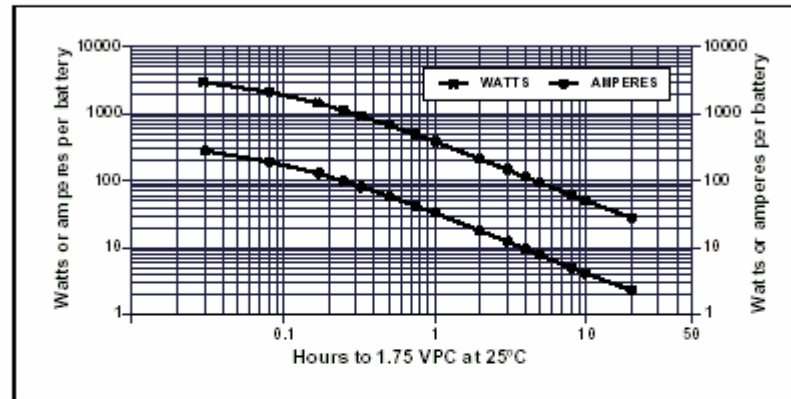
Energy and power densities								
Run time to 1.67 vpc	Watts	Amps	Capacity (Ah)	Energy (Wh)	Watts per liter	Wh per liter	Watts per kilogram	Wh per kilogram
2 min	3317	322.3	10.70	110.60	593.00	19.80	225.70	7.50
5 min	2291	212.0	17.70	190.95	409.60	34.10	155.90	13.00
10 min	1540	138.4	23.10	256.60	275.20	45.90	104.70	17.50
15 min	1173	104.1	26.00	293.25	209.70	52.40	79.80	19.95
20 min	953	83.8	27.90	317.60	170.30	56.80	64.80	21.60
30 min	698	60.8	30.40	348.90	124.70	62.40	47.50	23.70
45 min	502	43.3	32.50	376.65	89.80	67.30	34.20	25.60
1 hr	394	33.8	33.80	393.60	70.35	70.35	26.80	26.80
2 hr	215	18.2	36.40	429.60	38.40	76.80	14.60	29.20
3 hr	149	12.6	37.80	448.20	26.70	80.10	10.20	30.50
4 hr	115	9.7	38.80	460.80	20.60	82.40	7.80	31.35
5 hr	94	7.9	39.50	471.00	16.80	84.20	6.40	32.00
8 hr	62	5.1	40.80	494.40	11.05	88.40	4.20	33.60
10 hr	51	4.2	42.00	510.00	9.10	91.20	3.50	34.70
20 hr	28	2.3	46.00	564.00	5.00	100.80	1.90	38.40

Table A-18: 42Ah Genesis Performance Data at 25°C

All Figures Based on 12V Module



Figure A-19: Genesis 42Ah discharge to 1.75VPC at 25°C



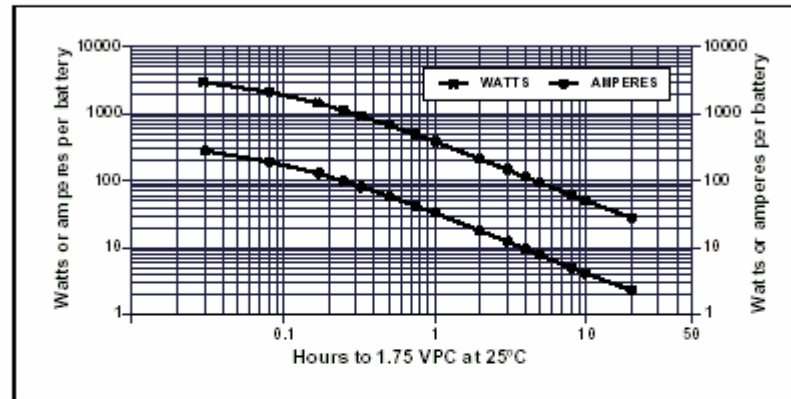
Run time to 1.75 vpc	Energy and power densities							
	Watts	Amps	Capacity (Ah)	Energy (Wh)	Watts per liter	Wh per liter	Watts per kilogram	Wh per kilogram
2 min	2978	279.9	9.30	99.30	532.40	17.75	202.60	6.75
5 min	2130	193.0	16.10	177.50	380.70	31.70	144.90	12.10
10 min	1461	129.4	21.60	243.50	261.15	43.50	99.40	16.60
15 min	1124	98.5	24.60	281.10	201.00	50.25	76.50	19.10
20 min	919	80.0	26.70	306.20	164.20	54.70	62.50	20.80
30 min	678	58.5	29.25	339.00	121.20	60.60	46.10	23.10
45 min	491	42.0	31.50	368.10	87.70	65.80	33.40	25.00
1 hr	386	32.9	32.90	385.80	69.00	69.00	26.20	26.20
2 hr	212	17.9	35.80	423.60	37.90	75.70	14.40	28.80
3 hr	147	12.4	37.20	441.00	26.30	78.80	10.00	30.00
4 hr	113	9.5	38.00	453.60	20.30	81.10	7.70	30.90
5 hr	93	7.7	38.50	465.00	16.60	83.10	6.30	31.60
8 hr	61	5.0	40.00	484.80	10.80	86.70	4.10	33.00
10 hr	50	4.1	41.00	498.00	8.90	89.00	3.40	33.90
20 hr	28	2.3	46.00	562.00	4.90	98.70	1.90	37.55

Table A-19: 42Ah Genesis Performance Data at 25°C

All Figures Based on 12V Module



Figure A-19: Genesis 42Ah discharge to 1.75VPC at 25°C

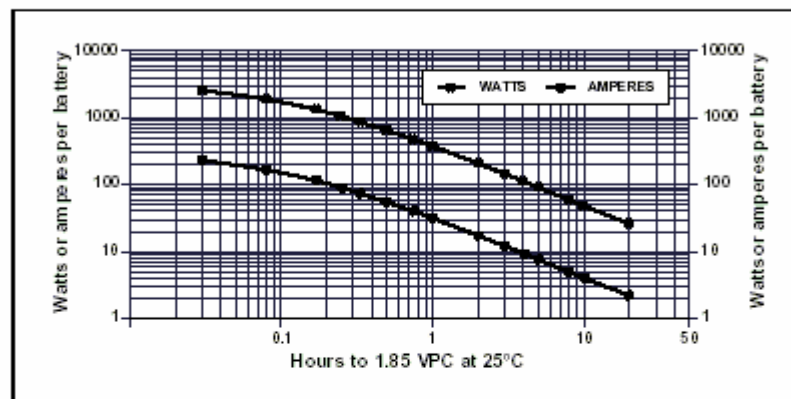


Run time to 1.75 vpc	Energy and power densities							
	Watts	Amps	Capacity (Ah)	Energy (Wh)	Watts per liter	Wh per liter	Watts per kilogram	Wh per kilogram
2 min	2978	279.9	9.30	99.30	532.40	17.75	202.60	6.75
5 min	2130	193.0	16.10	177.50	380.70	31.70	144.90	12.10
10 min	1461	129.4	21.60	243.50	261.15	43.50	99.40	16.60
15 min	1124	98.5	24.60	281.10	201.00	50.25	76.50	19.10
20 min	919	80.0	26.70	306.20	164.20	54.70	62.50	20.80
30 min	678	58.5	29.25	339.00	121.20	60.60	46.10	23.10
45 min	491	42.0	31.50	368.10	87.70	65.80	33.40	25.00
1 hr	386	32.9	32.90	385.80	69.00	69.00	26.20	26.20
2 hr	212	17.9	35.80	423.60	37.90	75.70	14.40	28.80
3 hr	147	12.4	37.20	441.00	26.30	78.80	10.00	30.00
4 hr	113	9.5	38.00	453.60	20.30	81.10	7.70	30.90
5 hr	93	7.7	38.50	465.00	16.60	83.10	6.30	31.60
8 hr	61	5.0	40.00	484.80	10.80	86.70	4.10	33.00
10 hr	50	4.1	41.00	498.00	8.90	89.00	3.40	33.90
20 hr	28	2.3	46.00	562.00	4.90	98.70	1.90	37.55

Table A-19: 42Ah Genesis Performance Data at 25°C

All Figures Based on 12V Module

Figure A-20: Genesis 42Ah discharge to 1.85 VPC at 25°C



Run time to 1.85 vpc	Energy and power densities							
	Watts	Amps	Capacity (Ah)	Energy (Wh)	Watts per liter	Wh per liter	Watts per kilogram	Wh per kilogram
2 min	2581	231.2	7.70	86.00	461.30	15.40	175.55	5.85
5 min	1901	167.4	13.95	158.45	339.90	28.30	129.35	10.80
10 min	1338	116.1	19.35	223.00	239.20	39.90	91.00	15.20
15 min	1046	90.0	22.50	261.45	185.90	46.70	71.10	17.80
20 min	863	73.9	24.60	287.80	154.30	51.40	58.70	19.60
30 min	646	54.9	27.45	323.10	115.50	57.75	44.00	22.00
45 min	473	39.9	29.90	355.05	84.60	63.50	32.20	24.15
1 hr	376	31.5	31.50	375.60	67.10	67.10	25.55	25.55
2 hr	208	17.3	34.60	416.40	37.20	74.40	14.20	28.30
3 hr	145	12.1	36.30	435.60	25.95	77.90	9.90	29.60
4 hr	112	9.3	37.20	448.80	20.10	80.20	7.60	30.50
5 hr	91	7.6	38.00	456.00	16.30	81.50	6.20	31.00
8 hr	59	4.9	39.20	475.20	10.60	84.90	4.00	32.30
10 hr	48	4.0	40.00	480.00	8.60	85.80	3.30	32.65
20 hr	26	2.2	44.00	516.00	4.60	92.20	1.80	35.10

Table A-20: 42Ah Genesis Performance Data at 25°C

All Figures Based on 12V Module

Appendix B. ADVISOR Component Model Files

Appendix B.1. ADVISOR Vehicle Model VEH_HMMWV.m

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% ADVISOR data file: VEH_HMMWV.m
% Data source: TACOM, UW Madison, other publications
% Data confirmation: Input data agrees with sources
% Notes: Defines road load parameters for HMMWV.
%
% Created on: 12/27/03
% Modified by: Craig Rutherford
% Original by: KW of NREL, keith_wipke@nrel.gov
%
% Revision history at end of file.
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% FILE ID INFO
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
veh_description='HMMWV';
veh_version=2002;      % version of ADVISOR for which the file was generated
veh_proprietary=0;     % 0=> non-proprietary, 1=> proprietary, do not distribute
veh_validation=1;      % 0=> no validation, 1=> data agrees with source data,
% 2=> data matches source data and data collection methods have been verified

disp(['Data loaded: VEH_HMMWV - ',veh_description])

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% PHYSICAL CONSTANTS
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

veh_gravity=9.81;      % m/s^2
veh_air_density=1.2;   % kg/m^3

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% VEHICLE PARAMETERS
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Note on vehicle mass:
%      Override value is used in the "Vehicle Inputs" screen. No accurate glider
%      mass calculated for HMMWV

veh_glider_mass=(6200/2.205)-633; % (kg), vehicle mass w/o propulsion system (fuel converter,
%exhaust aftertreatment, drivetrain, motor, ESS, generator)

veh_CD=0.5;            % (--)
veh_FA=3.169;          % (m^2), frontal area

% for the eq'n: rolling_drag=mass*gravity*(veh_1st_rrc+veh_2nd_rrc*v)
```

```

%veh_1st_rrc=0.006;          % (--) source: Matt Merkle @ Goodyear Tech Center
%veh_2nd_rrc=0;             % (s/m)

% fraction of vehicle weight on front axle when standing still
veh_front_wt_frac=1-0.555;   % ave SUV % wgt on front tires (from Consumer Reports)

% height of vehicle center-of-gravity above the road
veh_cg_height=0.7;          % m,

% vehicle wheelbase, from center of front tire patch to center of rear patch
veh_wheelbase=3.3;          % m,

veh_cargo_mass=180;          %kg cargo mass,

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% REVISION HISTORY
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% Created 8/21/98 KW
% Modified 8/31/98 KW; frontal area increased based on new data
% Modified 9/10/98 KW; moved veh_mass definition into comments section since it's only
%                          used as a guideline to the user about what the total vehicle mass should be
% Modified 9/10/98 SB; modified veh_front_wt_frac=0.6; veh_cg_height=0.6; and veh_wheelbase=2.6;
%                          to be ave of three SUVs from Consumer Reports
% Modified 9/11/98 KW; changed CD from 0.53 to 0.44, rolling resistance from 0.009 to 0.012
% Modified 9/11/98 KW; changed frontal area from 2.5 m^2 to 2.66 m^2
% Modified 2/2/99 ss: added veh_cargo_mass.
% Modified For 2000 Suburban
% 3/15/99:ss updated *_version to 2.1 from 2.0
% 07-Oct-1999: automatically updated to version 2.2
% 07-Oct-1999: automatically updated to version 2.2
% 15-Aug-2001: automatically updated to version 3.2
% 04-Apr-2002: mpo moving veh_1st_rrc and veh_2nd_rrc over to the wheel files as wh_1st_rrc and
wh_2nd_rrc

```

Appendix B.2. ADVISOR Engine Models

This appendix includes the model input files for the conventional engine used for baseline modeling (FC_CI119.m) and the model input file for the converted parallel design's engine (FC_CI67_emis.m).

Appendix B.2.1. FC_CI119.m

```
% ADVISOR Data file: FC_CI119.M
%
% Data source: Data interpreted from "Internal Combustion Engine Fundamentals"
% by John B. Heywood, page 859, Figure 15-21.
%
% Data confidence level: no comparison has been performed
%
% Notes:
% Engine performance map for a 6.54 L 8-cylinder air-cooled, naturally aspirated
% DI Diesel engine. Data provided as g/kW-h vs. RPM and Torque.
% Engine Specs.
% Bore - 102 mm
% Stroke - 100 mm
% Compression Ratio - 18
% Max rated power 119kW @ 3200 rpm
% Peak Torque 400 Nm @ 2000 rpm
% Brake fuel conversion efficiency - 38.5%
% Gross indicated fuel conversion efficiency - 48%
%
% Created on: 07/01/98
% By: Tony Markel, National Renewable Energy Laboratory, Tony_Markel@nrel.gov
%
% Revision history at end of file.
%

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% FILE ID INFO
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
fc_description='6.5L (119kW) Diesel Engine'; % one line descriptor identifying the engine
fc_version=2002; % version of ADVISOR for which the file was generated
fc_proprietary=0; % 0=> non-proprietary, 1=> proprietary, do not distribute
fc_validation=0; % 0=> no validation, 1=> data agrees with source data,
% 2=> data matches source data and data collection methods have been verified
fc_fuel_type='Diesel';
fc_disp=6.54; % (L), engine displacement
fc_emis=0; % boolean 0=no emis data; 1=emis data
fc_cold=0; % boolean 0=no cold data; 1=cold data exists
disp(['Data loaded: FC_CI119.m - ',fc_description]);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% SPEED & TORQUE RANGES over which data is defined
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

```

% (rad/s), speed range of the engine
fc_map_spd=[1000:500:3500]*2*pi/60;

% (N*m), torque range of the engine
fc_map_trq=[120 140 180 220 260 300 340 380 420];

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% FUEL USE AND EMISSIONS MAPS
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% (g/s), fuel use map indexed vertically by fc_map_spd and
% horizontally by fc_map_trq
fc_fuel_map_gpkW-h = [
250    242    230    225    224    224    225    225    225
250    243    231    226    222    220    222.5    226    226
254    248    235    228    225    221    222.5    226    226
260    255    241    234    228    226    226    228.5    228.5
270    264    256    245    238    235    236    236    236
280    275    270    263    255    249    247    246    246]; % (g/kW*hr)

% convert map from g/kW-h to g/s
[T,w]=meshgrid(fc_map_trq,fc_map_spd);
fc_map_kW=T.*w/1000;
fc_fuel_map=fc_fuel_map_gpkW-h.*fc_map_kW/3600;

% (g/s), engine out HC emissions indexed vertically by fc_map_spd and
% horizontally by fc_map_trq
fc_hc_map=zeros(size(fc_fuel_map));

% (g/s), engine out HC emissions indexed vertically by fc_map_spd and
% horizontally by fc_map_trq
fc_co_map=zeros(size(fc_fuel_map));

% (g/s), engine out HC emissions indexed vertically by fc_map_spd and
% horizontally by fc_map_trq
fc_nox_map=zeros(size(fc_fuel_map));

% (g/s), engine out PM emissions indexed vertically by fc_map_spd and
% horizontally by fc_map_trq
fc_pm_map=zeros(size(fc_fuel_map));

% (g/s), engine out O2 indexed vertically by fc_map_spd and
% horizontally by fc_map_trq
fc_o2_map=zeros(size(fc_fuel_map));

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Cold Engine Maps
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
fc_cold_tmp=20; %deg C
fc_fuel_map_cold=zeros(size(fc_fuel_map));
fc_hc_map_cold=zeros(size(fc_fuel_map));
fc_co_map_cold=zeros(size(fc_fuel_map));
fc_nox_map_cold=zeros(size(fc_fuel_map));
fc_pm_map_cold=zeros(size(fc_fuel_map));

```

```

%Process Cold Maps to generate Correction Factor Maps
names={'fc_fuel_map','fc_hc_map','fc_co_map','fc_nox_map','fc_pm_map'};
for i=1:length(names)
    %cold to hot ratio, e.g. fc_fuel_map_c2h = fc_fuel_map_cold ./ fc_fuel_map
    eval([names{i},'_c2h=',names{i},'_cold./(' ,names{i},'+eps);'])
end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% LIMITS
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% (N*m), max torque curve of the engine indexed by fc_map_spd
fc_max_trq=[310 380 400 392 368 330];

% (N*m), closed throttle torque of the engine (max torque that can be absorbed)
% indexed by fc_map_spd -- correlation from JDMA
fc_ct_trq=4.448/3.281*(-fc_disp)*61.02/24 * ...
    (9*(fc_map_spd/max(fc_map_spd)).^2 + 14 * (fc_map_spd/max(fc_map_spd)));

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% DEFAULT SCALING
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% (--), used to scale fc_map_spd to simulate a faster or slower running engine
fc_spd_scale=1.0;
% (--), used to scale fc_map_trq to simulate a higher or lower torque engine
fc_trq_scale=1.0;
fc_pwr_scale=fc_spd_scale*fc_trq_scale; % -- scale fc power

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% STUFF THAT SCALES WITH TRQ & SPD SCALES (MASS AND INERTIA)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
fc_inertia=0.1*fc_pwr_scale; % (kg*m^2), rotational inertia of the engine (unknown)
fc_max_pwr=(max(fc_map_spd.*fc_max_trq)/1000)*fc_pwr_scale; % kW peak engine power

fc_base_mass=2.8*fc_max_pwr; % (kg), mass of the engine block and head (base engine)
% assuming a mass penalty of 1.8 kg/kW from S. Sluder
% (ORNL) estimate of 300 lb
fc_acc_mass=0.8*fc_max_pwr; % kg engine accy's, electrics, cntrl's - assumes mass penalty
% of 0.8 kg/kW (from 1994 OTA report, Table 3)
fc_fuel_mass=0.6*fc_max_pwr; % kg mass of fuel and fuel tank (from 1994 OTA report,
% Table 3)
fc_mass=fc_base_mass+fc_acc_mass+fc_fuel_mass; % kg total engine/fuel system mass
fc_ext_sarea=0.3*(fc_max_pwr/100)^0.67; % m^2 exterior surface area of engine

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% OTHER DATA
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% user definable mass scaling function
fc_mass_scale_fun=inline('(x(1)*fc_trq_scale+x(2))*(x(3)*fc_spd_scale+x(4))*(fc_base_mass+fc_acc_ma
ss)+fc_fuel_mass','x','fc_spd_scale','fc_trq_scale','fc_base_mass','fc_acc_mass','fc_fuel_mass');
fc_mass_scale_coef=[1 0 1 0]; % coefficients of mass scaling function

fc_fuel_den=0.85*1000; % (g/l), density of the fuel
fc_fuel_lhv=43.0*1000; % (J/g), lower heating value of the fuel

```

```

%the following was added for the new thermal modeling of the engine 12/17/98 ss and sb
fc_tstat=99;           % C   engine coolant thermostat set temperature (typically 95 +/- 5 C)
fc_cp=500;             % J/kgK ave cp of engine (iron=500, Al or Mg = 1000)
fc_h_cp=500;          % J/kgK ave cp of hood & engine compartment (iron=500, Al or Mg = 1000)
fc_hood_sarea=1.5;    % m^2  surface area of hood/eng compt.
fc_emisv=0.8;         % eff emissivity of engine ext surface to hood int surface
fc_hood_emisv=0.9;;   %      emissivity hood ext
fc_h_air_flow=0.0;    % kg/s  heater air flow rate (140 cfm=0.07)
fc_cl2h_eff=0.7;      % --   ave cabin heater HX eff (based on air side)
fc_c2i_th_cond=500;   % W/K   conductance btwn engine cyl & int
fc_i2x_th_cond=500;   % W/K   conductance btwn engine int & ext
fc_h2x_th_cond=10;    % W/K   conductance btwn engine & engine compartment

% calc "predicted" exh gas flow rate and engine-out (EO) temp
fc_ex_pwr_frac=[0.50 0.40]; % --   frac of waste heat that goes to exhaust as func of engine
                                %      speed
fc_exflow_map=fc_fuel_map*(1+20); % g/s  ex gas flow map: for CI engines, exflow=(fuel use)*
                                %      [1 + (ave A/F ratio)]
fc_waste_pwr_map=fc_fuel_map*fc_fuel_lhv - T.*w;
                                % W   tot FC waste heat = (fuel pwr) - (mech out pwr)

spd=fc_map_spd;
fc_ex_pwr_map=zeros(size(fc_waste_pwr_map)); % W   initialize size of ex pwr map
for i=1:length(spd)
    fc_ex_pwr_map(i,:)=fc_waste_pwr_map(i,:)*interp1([min(spd) max(spd)],fc_ex_pwr_frac,spd(i));
                                % W   trq-spd map of waste heat to exh
end
fc_extmp_map=fc_ex_pwr_map./(fc_exflow_map*1089/1000) + 20;
                                % W   EO ex gas temp = Q/(MF*cp) + Tamb (assumes engine tested ~20 C)

%the following variable is not used directly in modelling and should always be equal to one
%it's used for initialization purposes
fc_eff_scale=1;

% clean up workspace
clear T w fc_waste_pwr_map fc_ex_pwr_map spd fc_map_kW

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% REVISION HISTORY
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% 07/01/98 (tm): file created from a_di65l.m
% 07/03/98 (MC): changed fc_init_coolant_temp to fc_coolant_init_temp for
%                consistency with block diagrams
% 07/16/98 (SS): added variable fc_fuel_type under file id section
% 07/17/98 (tm): file renamed FC_CI119.M
% 08/28/98 (MC): added variable fc_disp under file id section
%                fc_ct_trq computed according to correlation from JDMA, 5/98
% 10/9/98 (vh,sb,ss): added pm and removed init conditions and added new exhaust variables
% 10/13/98 (MC): updated equation for fc_ct_trq (convert from ft-lb to Nm)
% 12/17/98 ss,sb: added 12 new variables for engine thermal modelling.
% 01/14/99 (SB): removed unneeded variables (fc_air_fuel_ratio, fc_ex_pwr_frac)
% 2/4/99: ss,sb changed fc_ext_sarea=0.3*(fc_max_pwr/100)^0.67 it was 0.3*(fc_max_pwr/100)
%                it now takes into account that surface area increases based on mass to the 2/3 power
% 3/15/99:ss updated *_version to 2.1 from 2.0

```



```

% 11/03/99:ss updated version from 2.2 to 2.21
% 01/31/01: vhj added fc_cold=0, added cold map variables, added +eps to avoid dividing by zero
% 02/26/01: vhj added variable definition of fc_o2_map (used in NOx absorber emis.)
%      7/30/01:tm      added      user      definable      mass      scaling      function
mass=f(fc_spd_scale,fc_trq_scale,fc_base_mass,fc_acc_mass,fc_fuel_mass)

```

Appendix B.2.2. FC_CI167.m

```
% ADVISOR Data file: FC_CI167_emis.m
%
% Data source: Scott Sluder of Oak Ridge National Laboratory
%
% Data confidence level: Excellent
%
% Notes from original Excel spreadsheet from ORNL:
% This workbook contains an engine map for a Volkswagen 1.9L TDI engine.
% The data was gathered by Oak Ridge National Laboratory. The engine retained the
% alternator, and so was self-sufficient. The battery was kept charged externally,
% so that the only electrical loads during testing were those necessary to power the
% engine controls and sensors. (The fuel injection is electronically controlled,
% but mechanically actuated, so no high electrical loads are required for fuel injection.)
%
% The tests were conducted with a fully-warmed engine. Measurements were made
% at the following steady-state points:
% idle, with and without commanded EGR (apparently VW turns off EGR during extended idle periods)
% 1000 RPM no absorbed load
% 1200, 1600, 1900, 2400, 2800, 3200, 3600, 4000, and 4000 RPM at 10%, 25%, 40%, 50%, 60%, 75%,
% 90%, and 100% load
% additionally, no load data points were collected at 1200, 1600, and 1900 rpm.
%
% The data collected at these points was used to produce the "regular" matrix
% of data in this workbook. The regular matrix is a requirement for using this
% data with the ADVISOR model. Data at higher-than-attainable torque values at
% each speed are the same as the value for the highest-attainable torque value
% at each speed. Otherwise, the data is linearly interpolated as necessary to fill
% the matrix. The matrix is basically in increments of 200 rpm and 5 foot pounds
% of torque, with a few exceptions. The 1900 rpm sweep has been included as it
% is the speed at which rated torque is produced. 900 rpm has also been included,
% as it is the idle speed. The engine produces its rated power at 4000 rpm,
% while 4400 rpm is the maximum engine speed. All units for emissions, exhaust
% flow, and fuel consumption are grams per brake kilowatt-hour.
% Units for exhaust temperature are degrees Celcius.
%
% Exhaust gas temperature was measured at the inlet to the downpipe (downstream of manifold, EGR split,
% and turbo.
%
% Many additional measurements were made at each data point,
% including particulate size distribution, and non-regulated compounds via FTIR.
%
% Created on: 01/05/99
% By: Keith Wipke, National Renewable Energy Laboratory, keith_wipke@nrel.gov
%
% Revision history at end of file.

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% FILE ID INFO
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
fc_description='Volkswagen 1.9L Turbo Diesel Engine f/ ORNL'; % one line descriptor
                                                                %identifying the engine
fc_version=2002;          % version of ADVISOR for which the file was generated
```

```

fc_proprietary=0;      % 0=> non-proprietary, 1=> proprietary, do not distribute
fc_validation=2;      % 0=> no validation, 1=> data agrees with source data,
                      % 2=> data matches source data and data collection methods have been verified

fc_fuel_type='Diesel';
fc_disp=1.9;          % (L) engine displacement
fc_emis=1;            % boolean 0=no emis data; 1=emis data
fc_cold=1;            % boolean 0=no cold data; 1=cold data exists
disp(['Data loaded: FC_CI67_emis.m - ',fc_description]);

```

```

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% SPEED & TORQUE RANGES over which data is defined
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% (rad/s), speed range of the engine (converted from RPM)
fc_map_spd=[800:100:4400]*pi/30;

```

```

% (N*m), torque range of the engine (converted from ft-lbf)
fc_map_trq=[165:-5:0]*(1/(3.281*0.224809));
fc_map_trq=fliplr(fc_map_trq);

```

```

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% FUEL USE AND EMISSIONS MAPS
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% (g/s) , fuel use map indexed vertically by fc_map_spd and
% horizontally by fc_map_trq

```

fc_fuel_map=	1.59	1.63	1.71	1.81	1.89	1.95	1.99	2.04	2.13	2.25
2.4	2.55	2.71	2.87	3.02	3.15	3.25	3.34	3.44	3.54	3.65
3.76	3.86	3.96	4.05	4.12	4.18	4.24	4.31	4.4	4.49	4.58
4.67	4.75	4.83	4.9	4.93						
1.53	1.58	1.67	1.78	1.88	1.94	1.99	2.04	2.12	2.24	2.38
	2.69	2.85	3	3.14	3.25	3.34	3.44	3.54	3.65	3.76
	3.96	4.05	4.13	4.2	4.27	4.35	4.44	4.52	4.61	4.69
	4.84	4.9	4.93							
1.44	1.5	1.61	1.73	1.84	1.92	1.97	2.02	2.1	2.21	2.35
	2.66	2.82	2.98	3.11	3.23	3.33	3.43	3.54	3.65	3.75
	3.96	4.06	4.15	4.24	4.32	4.41	4.49	4.57	4.65	4.72
	4.86	4.91	4.94							
1.37	1.43	1.54	1.67	1.79	1.87	1.93	1.99	2.07	2.18	2.31
	2.61	2.77	2.93	3.07	3.19	3.3	3.41	3.52	3.64	3.74
	3.96	4.06	4.17	4.27	4.37	4.47	4.55	4.63	4.7	4.76
	4.88	4.92	4.94							
1.32	1.37	1.47	1.59	1.71	1.8	1.87	1.94	2.02	2.13	2.26
	2.55	2.71	2.87	3.01	3.14	3.25	3.37	3.49	3.6	3.72
	3.94	4.06	4.17	4.29	4.4	4.51	4.6	4.68	4.75	4.81
	4.91	4.94	4.95							
1.29	1.33	1.41	1.51	1.61	1.7	1.79	1.87	1.96	2.07	2.19
	2.47	2.63	2.78	2.93	3.06	3.18	3.3	3.43	3.55	3.66
	3.9	4.03	4.15	4.28	4.41	4.53	4.62	4.71	4.78	4.85
	4.93	4.95	4.96							
1.27	1.29	1.35	1.42	1.51	1.6	1.69	1.79	1.89	2	2.12
	2.39	2.53	2.69	2.83	2.96	3.09	3.22	3.34	3.47	3.59
	3.84	3.98	4.12	4.26	4.39	4.51	4.62	4.71	4.8	4.87
	4.94	4.96	4.96							
1.25	1.27	1.3	1.35	1.42	1.51	1.61	1.71	1.82	1.93	2.05
	2.3	2.44	2.58	2.72	2.85	2.98	3.11	3.24	3.36	3.49

	3.76	3.91	4.05	4.2	4.34	4.47	4.59	4.69	4.79	4.86	4.92
	4.94	4.95	4.95								
1.24	1.25	1.27	1.3	1.35	1.43	1.53	1.64	1.75	1.86	1.98	2.1
	2.22	2.35	2.49	2.62	2.75	2.87	3	3.12	3.25	3.38	3.52
	3.66	3.81	3.96	4.11	4.26	4.4	4.52	4.64	4.74	4.83	4.89
	4.91	4.92	4.93								
1.24	1.24	1.25	1.27	1.31	1.37	1.46	1.57	1.68	1.8	1.91	2.03
	2.15	2.28	2.41	2.54	2.66	2.77	2.89	3.01	3.14	3.26	3.4
	3.54	3.68	3.83	3.99	4.14	4.28	4.42	4.55	4.67	4.76	4.82
	4.85	4.86	4.86								
1.23	1.23	1.23	1.24	1.27	1.33	1.41	1.51	1.62	1.74	1.85	1.96
	2.08	2.21	2.34	2.46	2.58	2.69	2.8	2.91	3.03	3.15	3.27
	3.39	3.53	3.67	3.83	3.99	4.14	4.29	4.44	4.56	4.66	4.72
	4.74	4.75	4.74								
1.21	1.21	1.21	1.22	1.24	1.29	1.36	1.46	1.57	1.68	1.79	1.9
	2.01	2.13	2.26	2.38	2.5	2.61	2.72	2.83	2.93	3.03	3.14
	3.24	3.36	3.5	3.66	3.82	3.99	4.15	4.3	4.43	4.53	4.58
	4.6	4.59	4.59								
1.17	1.17	1.17	1.18	1.2	1.25	1.32	1.41	1.51	1.62	1.72	1.82
	1.93	2.05	2.18	2.3	2.41	2.52	2.63	2.74	2.84	2.93	3.01
	3.11	3.21	3.34	3.5	3.66	3.83	3.99	4.15	4.28	4.37	4.42
	4.43	4.42	4.41								
1.13	1.13	1.13	1.14	1.16	1.2	1.27	1.35	1.45	1.55	1.65	1.75
	1.85	1.97	2.08	2.2	2.31	2.42	2.53	2.64	2.73	2.82	2.9
	2.98	3.09	3.22	3.36	3.52	3.68	3.84	3.99	4.11	4.2	4.24
	4.25	4.24	4.23								
1.07	1.07	1.07	1.08	1.1	1.15	1.21	1.29	1.38	1.48	1.58	1.67
	1.77	1.88	1.99	2.1	2.2	2.3	2.41	2.52	2.62	2.7	2.78
	2.87	2.98	3.1	3.25	3.4	3.55	3.69	3.83	3.95	4.03	4.08
	4.09	4.09	4.08								
1.01	1.01	1.01	1.02	1.05	1.09	1.15	1.23	1.32	1.41	1.51	1.6
	1.7	1.8	1.91	2	2.09	2.18	2.28	2.39	2.49	2.59	2.67
	2.77	2.87	2.99	3.13	3.27	3.41	3.54	3.67	3.78	3.87	3.92
	3.95	3.97	3.97								
0.95	0.95	0.96	0.97	0.99	1.03	1.09	1.16	1.25	1.34	1.43	1.53
	1.62	1.72	1.82	1.9	1.99	2.07	2.16	2.26	2.37	2.47	2.56
	2.66	2.76	2.87	3	3.13	3.26	3.39	3.51	3.63	3.72	3.78
	3.83	3.87	3.89								
0.9	0.9	0.91	0.91	0.94	0.97	1.03	1.1	1.18	1.27	1.36	1.45
	1.54	1.63	1.72	1.8	1.88	1.95	2.04	2.14	2.25	2.35	2.45
	2.54	2.64	2.75	2.86	2.98	3.1	3.23	3.35	3.47	3.56	3.64
	3.71	3.77	3.8								
0.85	0.85	0.86	0.87	0.89	0.92	0.98	1.04	1.12	1.2	1.29	1.37
	1.45	1.54	1.62	1.7	1.76	1.83	1.92	2.01	2.12	2.23	2.33
	2.43	2.52	2.62	2.73	2.84	2.95	3.07	3.19	3.31	3.41	3.5
	3.59	3.66	3.7								
0.81	0.81	0.81	0.82	0.84	0.87	0.93	0.99	1.06	1.14	1.22	1.29
	1.37	1.44	1.52	1.59	1.65	1.71	1.79	1.89	2	2.11	2.21
	2.31	2.41	2.51	2.6	2.71	2.81	2.92	3.03	3.14	3.24	3.34
	3.44	3.52	3.57								
0.76	0.76	0.77	0.77	0.79	0.83	0.88	0.94	1.01	1.08	1.15	1.21
	1.28	1.35	1.42	1.48	1.54	1.6	1.68	1.77	1.88	1.99	2.1
	2.2	2.3	2.39	2.49	2.58	2.68	2.78	2.88	2.97	3.07	3.17
	3.27	3.35	3.4								

0.72	0.72	0.72	0.73	0.75	0.78	0.83	0.89	0.95	1.01	1.07	1.13
	1.19	1.26	1.33	1.39	1.44	1.5	1.57	1.66	1.76	1.88	1.99
	2.1	2.19	2.29	2.38	2.46	2.55	2.64	2.73	2.82	2.91	3
	3.1	3.17	3.22								
0.68	0.68	0.68	0.69	0.7	0.73	0.78	0.83	0.89	0.94	1	1.05
	1.11	1.17	1.23	1.29	1.34	1.4	1.47	1.55	1.66	1.77	1.89
	1.99	2.09	2.18	2.26	2.35	2.43	2.51	2.59	2.67	2.75	2.84
	2.93	3	3.04								
0.63	0.63	0.63	0.64	0.66	0.68	0.72	0.77	0.82	0.87	0.91	0.96
	1.01	1.07	1.14	1.2	1.25	1.3	1.37	1.45	1.55	1.67	1.78
	1.89	1.98	2.06	2.14	2.22	2.3	2.38	2.46	2.53	2.61	2.69
	2.77	2.83	2.87								
0.58	0.58	0.58	0.59	0.6	0.63	0.66	0.7	0.74	0.79	0.83	0.88
	0.93	0.99	1.05	1.1	1.16	1.21	1.28	1.36	1.45	1.56	1.66
	1.77	1.86	1.94	2.01	2.09	2.17	2.24	2.32	2.4	2.47	2.55
	2.62	2.68	2.71								
0.51	0.51	0.52	0.53	0.54	0.57	0.6	0.63	0.67	0.72	0.76	0.8
	0.85	0.91	0.96	1.02	1.07	1.13	1.19	1.27	1.35	1.45	1.55
	1.64	1.73	1.8	1.88	1.95	2.03	2.11	2.19	2.26	2.34	2.41
	2.47	2.53	2.56								
0.43	0.44	0.45	0.47	0.48	0.51	0.53	0.57	0.6	0.64	0.69	0.73
	0.78	0.83	0.88	0.93	0.99	1.05	1.12	1.19	1.26	1.34	1.43
	1.51	1.6	1.67	1.74	1.82	1.9	1.98	2.06	2.13	2.2	2.27
	2.33	2.38	2.41								
0.35	0.36	0.38	0.4	0.42	0.45	0.47	0.5	0.53	0.57	0.61	0.65
	0.7	0.75	0.8	0.85	0.9	0.96	1.03	1.1	1.17	1.24	1.32
	1.39	1.47	1.54	1.61	1.69	1.76	1.84	1.92	2	2.06	2.13
	2.19	2.24	2.27								
0.28	0.29	0.32	0.34	0.37	0.39	0.41	0.44	0.47	0.5	0.54	0.58
	0.62	0.67	0.72	0.76	0.82	0.88	0.94	1.01	1.07	1.13	1.2
	1.27	1.34	1.41	1.48	1.56	1.63	1.71	1.79	1.86	1.93	1.99
	2.05	2.09	2.12								
0.22	0.23	0.26	0.29	0.32	0.34	0.36	0.38	0.41	0.44	0.47	0.51
	0.56	0.6	0.65	0.69	0.74	0.79	0.85	0.91	0.97	1.03	1.09
	1.16	1.23	1.3	1.36	1.43	1.51	1.58	1.66	1.73	1.8	1.86
	1.91	1.95	1.97								
0.18	0.2	0.22	0.26	0.28	0.31	0.32	0.35	0.37	0.4	0.43	0.47
	0.51	0.56	0.6	0.64	0.68	0.72	0.78	0.83	0.88	0.94	1
	1.07	1.14	1.2	1.27	1.34	1.41	1.48	1.55	1.62	1.68	1.73
	1.77	1.8	1.82								
0.16	0.17	0.2	0.23	0.25	0.28	0.3	0.32	0.34	0.37	0.4	0.44
	0.49	0.53	0.58	0.61	0.65	0.69	0.73	0.78	0.83	0.88	0.94
	1.01	1.07	1.14	1.2	1.27	1.34	1.41	1.47	1.53	1.58	1.62
	1.66	1.68	1.69								
0.15	0.16	0.18	0.21	0.23	0.26	0.28	0.31	0.33	0.36	0.39	0.43
	0.48	0.53	0.57	0.6	0.63	0.67	0.71	0.75	0.8	0.85	0.91
	0.98	1.04	1.11	1.17	1.24	1.31	1.37	1.43	1.48	1.52	1.55
	1.58	1.59	1.6								
0.15	0.16	0.17	0.2	0.22	0.25	0.27	0.3	0.32	0.35	0.39	0.43
	0.47	0.52	0.57	0.6	0.63	0.66	0.7	0.74	0.79	0.84	0.91
	0.97	1.03	1.1	1.16	1.23	1.3	1.36	1.41	1.46	1.49	1.52
	1.54	1.55	1.56]								

fc_fuel_map=flipr(fc_fuel_map);

% (g/s), engine out HC emissions indexed vertically by fc_map_spd and

% horizontally by fc_map_trq											
fc_hc_map=1e-3*[8.95											
	8.81	6.93	6.16	6.5	7.5	8.56	9.33	9.78	10.02	10.14	10.11
	9.9	9.5	9.02	8.6	8.34	8.26	8.32	8.46	8.73	9.26	10.38
	12.36	15.17	18.29	20.96	22.47						
7.93	8.85	10.48	12.36	14.03	15.09	15.41	14.85	13.4	11.19	8.78	6.91
	6.15	6.51	7.52	8.59	9.37	9.82	10.05	10.15	10.12	9.9	9.5
	9.02	8.61	8.36	8.31	8.4	8.6	8.97	9.62	10.86	12.87	15.62
	18.61	21.14	22.57								
6.44	7.49	9.34	11.49	13.41	14.66	15.09	14.61	13.21	11.05	8.68	6.86
	6.14	6.55	7.59	8.69	9.48	9.92	10.13	10.2	10.14	9.89	9.48
	9.01	8.61	8.4	8.38	8.53	8.86	9.44	10.38	11.86	13.97	16.6
	19.31	21.54	22.78								
5.13	6.21	8.13	10.39	12.44	13.85	14.44	14.1	12.83	10.77	8.51	6.78
	6.15	6.63	7.74	8.89	9.7	10.12	10.28	10.29	10.17	9.88	9.46
	8.99	8.61	8.43	8.45	8.69	9.2	10.1	11.48	13.35	15.61	18.05
	20.34	22.12	23.09								
4.25	5.23	6.98	9.08	11.08	12.58	13.37	13.27	12.22	10.36	8.26	6.68
	6.18	6.78	7.99	9.2	10.02	10.41	10.49	10.41	10.21	9.88	9.43
	8.97	8.61	8.46	8.52	8.84	9.55	10.82	12.7	15.02	17.46	19.7
	21.52	22.79	23.44								
3.73	4.48	5.86	7.6	9.39	10.92	11.95	12.18	11.45	9.85	7.97	6.57
	6.23	6.96	8.28	9.56	10.39	10.73	10.72	10.55	10.27	9.88	9.42
	8.97	8.64	8.5	8.6	8.98	9.87	11.45	13.78	16.49	19.1	21.16
	22.56	23.38	23.75								
3.38	3.87	4.81	6.09	7.6	9.14	10.41	11	10.62	9.32	7.68	6.48
	6.29	7.15	8.57	9.91	10.75	11.04	10.95	10.69	10.34	9.91	9.44
	9	8.69	8.59	8.71	9.14	10.12	11.91	14.5	17.46	20.15	22.08
	23.19	23.71	23.9								
3.13	3.4	3.95	4.82	6.05	7.54	8.97	9.87	9.81	8.81	7.41	6.39
	6.34	7.31	8.8	10.18	11.03	11.3	11.16	10.84	10.44	9.98	9.5
	9.06	8.79	8.71	8.87	9.32	10.34	12.17	14.83	17.83	20.49	22.31
	23.26	23.61	23.71								
2.98	3.09	3.38	3.94	4.91	6.29	7.77	8.85	9.05	8.31	7.13	6.29
	6.35	7.39	8.93	10.35	11.22	11.48	11.34	11	10.58	10.1	9.6
	9.17	8.91	8.88	9.06	9.53	10.51	12.25	14.75	17.55	20.02	21.68
	22.51	22.8	22.86								
2.89	2.93	3.07	3.44	4.2	5.41	6.84	7.99	8.36	7.83	6.84	6.14
	6.29	7.37	8.94	10.37	11.26	11.56	11.44	11.12	10.71	10.22	9.72
	9.29	9.05	9.04	9.26	9.72	10.6	12.1	14.24	16.62	18.72	20.11
	20.8	21.03	21.07								
2.84	2.85	2.92	3.17	3.78	4.82	6.15	7.29	7.76	7.38	6.53	5.92
	6.12	7.2	8.74	10.17	11.07	11.42	11.36	11.11	10.74	10.29	9.8
	9.39	9.16	9.19	9.42	9.86	10.59	11.74	13.35	15.12	16.68	17.7
	18.19	18.33	18.34								
2.78	2.78	2.83	3.01	3.51	4.43	5.65	6.75	7.25	6.95	6.19	5.63
	5.81	6.83	8.29	9.65	10.56	10.96	11	10.85	10.57	10.19	9.77
	9.41	9.24	9.29	9.54	9.93	10.49	11.27	12.3	13.42	14.38	14.98
	15.22	15.24	15.2								
2.71	2.71	2.75	2.9	3.34	4.16	5.27	6.28	6.76	6.49	5.79	5.26
	5.4	6.3	7.61	8.85	9.71	10.16	10.3	10.28	10.13	9.88	9.59
	9.36	9.28	9.39	9.65	9.99	10.39	10.85	11.39	11.95	12.39	12.6
	12.59	12.46	12.35								
2.64	2.64	2.67	2.81	3.2	3.93	4.91	5.8	6.21	5.95	5.32	4.83
	4.93	5.69	6.83	7.92	8.71	9.17	9.39	9.48	9.47	9.4	9.31

	9.27	9.33	9.51	9.78	10.08	10.35	10.6	10.83	11.02	11.11	11.04
	10.82	10.55	10.36								
2.59	2.59	2.62	2.75	3.08	3.69	4.5	5.22	5.53	5.3	4.76	4.36
	4.47	5.13	6.11	7.07	7.77	8.2	8.46	8.63	8.75	8.88	9.02
	9.19	9.41	9.67	9.94	10.18	10.37	10.49	10.55	10.55	10.45	10.22
	9.87	9.5	9.25								
2.55	2.56	2.58	2.68	2.94	3.41	4.01	4.53	4.73	4.54	4.14	3.88
	4.05	4.69	5.58	6.44	7.07	7.47	7.72	7.93	8.17	8.46	8.8
	9.16	9.5	9.81	10.06	10.26	10.38	10.42	10.38	10.28	10.09	9.8
	9.41	9.01	8.76								
2.5	2.51	2.53	2.59	2.77	3.06	3.44	3.75	3.86	3.72	3.48	3.4
	3.68	4.36	5.23	6.05	6.65	7.04	7.32	7.58	7.9	8.3	8.74
	9.18	9.56	9.87	10.11	10.26	10.31	10.26	10.12	9.94	9.7	9.41
	9.06	8.73	8.51								
2.42	2.42	2.43	2.46	2.55	2.69	2.86	3	3.04	2.96	2.88	2.96
	3.36	4.1	4.99	5.82	6.45	6.92	7.31	7.71	8.13	8.54	8.93
	9.28	9.58	9.84	10.04	10.15	10.15	10	9.77	9.49	9.23	8.97
	8.72	8.49	8.35								
2.3	2.3	2.3	2.31	2.32	2.34	2.37	2.38	2.37	2.35	2.38	2.59
	3.09	3.87	4.78	5.65	6.38	7.04	7.73	8.41	8.97	9.33	9.49
	9.55	9.62	9.74	9.89	9.97	9.92	9.71	9.38	9.04	8.76	8.56
	8.42	8.31	8.25								
2.17	2.17	2.17	2.16	2.13	2.08	2.02	1.97	1.93	1.93	2.03	2.31
	2.86	3.65	4.57	5.48	6.37	7.35	8.47	9.58	10.37	10.62	10.41
	10.03	9.74	9.65	9.71	9.77	9.69	9.44	9.07	8.71	8.43	8.28
	8.23	8.22	8.22								
2.06	2.06	2.05	2.03	1.99	1.92	1.83	1.74	1.69	1.7	1.82	2.12
	2.66	3.45	4.36	5.32	6.37	7.7	9.32	10.91	11.94	12.08	11.48
	10.6	9.92	9.6	9.56	9.58	9.5	9.24	8.87	8.5	8.25	8.15
	8.16	8.21	8.25								
1.96	1.96	1.95	1.94	1.9	1.82	1.72	1.63	1.57	1.57	1.68	1.96
	2.49	3.25	4.15	5.13	6.32	7.94	9.97	11.94	13.18	13.23	12.32
	11.06	10.06	9.56	9.44	9.44	9.35	9.1	8.74	8.39	8.17	8.1
	8.15	8.23	8.3								
1.87	1.87	1.87	1.85	1.81	1.74	1.64	1.55	1.48	1.47	1.56	1.82
	2.32	3.06	3.93	4.92	6.19	7.96	10.22	12.39	13.73	13.75	12.68
	11.24	10.09	9.51	9.35	9.34	9.25	9	8.66	8.33	8.12	8.08
	8.15	8.26	8.33								
1.77	1.77	1.76	1.75	1.71	1.64	1.55	1.45	1.38	1.37	1.44	1.68
	2.16	2.86	3.71	4.7	6	7.82	10.11	12.31	13.65	13.67	12.61
	11.17	10.03	9.43	9.27	9.25	9.17	8.94	8.61	8.29	8.1	8.06
	8.14	8.26	8.34								
1.64	1.64	1.63	1.61	1.57	1.51	1.42	1.34	1.27	1.26	1.32	1.55
	2	2.67	3.51	4.51	5.83	7.65	9.89	12.02	13.31	13.35	12.38
	11.03	9.94	9.36	9.19	9.18	9.11	8.9	8.59	8.29	8.1	8.07
	8.14	8.25	8.33								
1.49	1.48	1.47	1.45	1.41	1.35	1.28	1.21	1.16	1.15	1.21	1.43
	1.86	2.5	3.33	4.35	5.72	7.57	9.79	11.83	13.06	13.12	12.23
	10.96	9.89	9.3	9.11	9.11	9.06	8.88	8.6	8.32	8.15	8.1
	8.16	8.24	8.3								
1.36	1.35	1.32	1.29	1.24	1.19	1.14	1.08	1.05	1.04	1.11	1.32
	1.72	2.34	3.15	4.21	5.65	7.58	9.83	11.87	13.09	13.17	12.29
	11.01	9.89	9.23	9.01	9.01	8.99	8.85	8.61	8.37	8.2	8.14
	8.17	8.23	8.27								

1.29	1.26	1.22	1.17	1.12	1.06	1.02	0.97	0.94	0.94	1	1.2
	1.58	2.18	2.98	4.04	5.53	7.55	9.9	12.04	13.33	13.44	12.52
	11.14	9.88	9.13	8.85	8.85	8.87	8.78	8.59	8.39	8.24	8.17
	8.17	8.2	8.22								
1.28	1.25	1.18	1.11	1.04	0.98	0.93	0.89	0.86	0.85	0.9	1.08
	1.45	2.03	2.79	3.82	5.3	7.38	9.88	12.21	13.67	13.85	12.85
	11.3	9.87	8.98	8.64	8.64	8.69	8.66	8.52	8.36	8.23	8.16
	8.14	8.14	8.14								
1.32	1.27	1.19	1.1	1.02	0.95	0.89	0.83	0.79	0.77	0.81	0.98
	1.34	1.89	2.61	3.58	5.02	7.12	9.75	12.31	13.99	14.26	13.2
	11.47	9.84	8.81	8.42	8.41	8.49	8.5	8.42	8.3	8.19	8.12
	8.08	8.06	8.05								
1.36	1.31	1.22	1.12	1.03	0.95	0.87	0.8	0.75	0.71	0.75	0.92
	1.27	1.8	2.48	3.38	4.75	6.84	9.58	12.35	14.24	14.6	13.49
	11.6	9.81	8.66	8.22	8.2	8.31	8.35	8.31	8.23	8.14	8.07
	8.02	7.99	7.98								
1.39	1.34	1.25	1.14	1.05	0.96	0.87	0.79	0.72	0.68	0.71	0.88
	1.23	1.75	2.41	3.26	4.58	6.66	9.46	12.36	14.39	14.82	13.68
	11.69	9.78	8.56	8.08	8.07	8.18	8.25	8.23	8.17	8.09	8.03
	7.98	7.94	7.92								
1.4	1.35	1.26	1.16	1.07	0.97	0.88	0.79	0.71	0.66	0.7	0.86
	1.21	1.73	2.38	3.21	4.5	6.56	9.4	12.36	14.47	14.93	13.77
	11.73	9.77	8.51	8.02	8	8.12	8.19	8.18	8.13	8.06	8
	7.95	7.92	7.89								
1.41	1.36	1.27	1.17	1.08	0.98	0.88	0.79	0.7	0.66	0.69	0.86
	1.21	1.73	2.37	3.19	4.48	6.53	9.38	12.36	14.49	14.97	13.8
	11.75	9.77	8.5	7.99	7.97	8.09	8.17	8.16	8.11	8.05	7.99
	7.94	7.91	7.88];								

fc_hc_map=flipr(fc_hc_map);

% (g/s), engine out CO emissions indexed vertically by fc_map_spd and

fc_co_map=1e-3*[27.01	24.64	20.48	15.66	11.4	8.59	7.27	7.1	7.6	8.51		
	9.61	10.74	11.79	12.77	13.66	14.45	15.17	15.92	16.78	17.69	18.52
	19.14	19.56	19.88	20.21	20.66	21.3	22.23	23.45	24.93	26.55	28.22
	29.93	31.72	33.42	34.81	35.58						
29.94	27.25	22.52	17.02	12.17	8.93	7.38	7.1	7.56	8.44	9.5	10.61
	11.66	12.66	13.57	14.39	15.14	15.91	16.78	17.7	18.52	19.13	19.56
	19.9	20.3	20.87	21.69	22.78	24.1	25.57	27.1	28.66	30.28	31.97
	33.59	34.9	35.63								
34.19	31.09	25.62	19.25	13.56	9.68	7.71	7.19	7.51	8.3	9.3	10.38
	11.42	12.43	13.38	14.24	15.03	15.83	16.72	17.64	18.46	19.07	19.52
	19.9	20.42	21.2	22.3	23.65	25.12	26.61	28.05	29.49	30.97	32.5
	33.95	35.1	35.73								
37.91	34.63	28.82	21.95	15.66	11.13	8.55	7.53	7.52	8.12	9.04	10.07
	11.1	12.12	13.08	13.97	14.78	15.61	16.51	17.42	18.23	18.85	19.33
	19.8	20.47	21.47	22.86	24.49	26.15	27.71	29.15	30.55	31.93	33.28
	34.48	35.4	35.89								
40.37	37.32	31.85	25.2	18.76	13.64	10.2	8.32	7.69	7.96	8.75	9.73
	10.73	11.73	12.68	13.56	14.37	15.2	16.07	16.95	17.74	18.38	18.92
	19.51	20.34	21.57	23.21	25.06	26.9	28.58	30.13	31.59	32.96	34.14
	35.09	35.74	36.07								
41.84	39.41	34.92	29.16	23.03	17.38	12.81	9.69	8.13	7.89	8.47	9.39
	10.35	11.3	12.2	13.04	13.82	14.6	15.41	16.23	16.97	17.62	18.24
	18.96	19.98	21.41	23.24	25.25	27.22	29.04	30.76	32.38	33.79	34.88
	35.61	36.04	36.23								

42.87	41.22	38.03	33.5	27.95	21.89	16.12	11.57	8.86	7.95	8.25	9.06
	9.98	10.87	11.7	12.48	13.19	13.9	14.62	15.35	16.04	16.7	17.38
	18.22	19.38	20.96	22.91	25	27.05	29	30.91	32.72	34.26	35.33
	35.94	36.22	36.32								
43.66	42.73	40.76	37.47	32.64	26.4	19.64	13.75	9.86	8.18	8.11	8.79
	9.64	10.46	11.23	11.93	12.57	13.2	13.84	14.49	15.13	15.78	16.5
	17.4	18.62	20.25	22.21	24.3	26.38	28.45	30.57	32.61	34.32	35.46
	36.05	36.26	36.32								
44.04	43.61	42.52	40.24	36.14	30.04	22.75	15.88	10.96	8.54	8.07	8.59
	9.37	10.14	10.83	11.47	12.05	12.61	13.18	13.78	14.38	15.01	15.73
	16.63	17.82	19.36	21.2	23.19	25.26	27.46	29.83	32.14	34.06	35.3
	35.91	36.11	36.15								
43.57	43.41	42.84	41.26	37.85	32.18	24.84	17.5	11.9	8.91	8.1	8.48
	9.21	9.93	10.57	11.14	11.67	12.18	12.71	13.26	13.84	14.45	15.13
	15.96	17.03	18.39	20.01	21.84	23.89	26.25	28.88	31.47	33.57	34.9
	35.51	35.69	35.71								
41.42	41.37	41.06	39.94	37.16	32.15	25.26	18.06	12.33	9.12	8.15	8.47
	9.16	9.85	10.43	10.96	11.45	11.93	12.43	12.96	13.49	14.06	14.69
	15.42	16.32	17.43	18.8	20.44	22.47	24.98	27.85	30.66	32.89	34.22
	34.79	34.9	34.88								
36.92	36.9	36.72	35.91	33.71	29.54	23.58	17.18	11.97	9.04	8.17	8.52
	9.21	9.87	10.42	10.91	11.36	11.83	12.31	12.8	13.31	13.82	14.37
	14.99	15.71	16.59	17.69	19.15	21.13	23.74	26.78	29.71	31.97	33.26
	33.71	33.71	33.62								
30.01	30.01	29.89	29.33	27.7	24.54	19.92	14.91	10.85	8.64	8.13	8.6
	9.3	9.94	10.46	10.92	11.35	11.79	12.26	12.74	13.21	13.67	14.15
	14.65	15.22	15.9	16.8	18.08	19.97	22.57	25.64	28.6	30.82	32.01
	32.33	32.2	32.02								
21.97	21.97	21.9	21.54	20.47	18.35	15.25	11.92	9.32	8.08	8.04	8.66
	9.39	10.01	10.5	10.93	11.33	11.76	12.21	12.68	13.13	13.56	13.97
	14.38	14.84	15.39	16.13	17.26	19.02	21.52	24.5	27.38	29.51	30.6
	30.82	30.59	30.36								
14.57	14.57	14.53	14.33	13.74	12.56	10.85	9.09	7.86	7.52	7.93	8.7
	9.44	10.03	10.49	10.89	11.26	11.65	12.1	12.56	13.01	13.42	13.79
	14.16	14.55	15.03	15.67	16.69	18.32	20.66	23.47	26.18	28.17	29.18
	29.36	29.12	28.89								
9.28	9.28	9.27	9.18	8.92	8.42	7.71	7.08	6.83	7.14	7.85	8.69
	9.42	9.99	10.41	10.77	11.11	11.47	11.89	12.35	12.81	13.22	13.6
	13.96	14.33	14.78	15.38	16.32	17.83	20	22.6	25.09	26.93	27.88
	28.1	27.97	27.8								
6.31	6.31	6.31	6.3	6.23	6.12	5.99	6	6.3	6.94	7.79	8.65
	9.34	9.87	10.27	10.59	10.89	11.22	11.62	12.07	12.54	12.99	13.41
	13.81	14.2	14.64	15.2	16.07	17.47	19.48	21.85	24.11	25.8	26.75
	27.09	27.13	27.09								
5.08	5.08	5.09	5.1	5.13	5.19	5.33	5.62	6.13	6.88	7.74	8.56
	9.21	9.71	10.09	10.39	10.67	10.97	11.33	11.77	12.27	12.78	13.28
	13.75	14.18	14.61	15.12	15.91	17.18	19.01	21.16	23.22	24.8	25.79
	26.3	26.54	26.64								
4.73	4.73	4.74	4.77	4.84	4.97	5.21	5.59	6.16	6.9	7.69	8.44
	9.05	9.53	9.91	10.22	10.49	10.77	11.1	11.53	12.04	12.62	13.21
	13.77	14.25	14.67	15.13	15.82	16.96	18.6	20.54	22.42	23.93	24.98
	25.66	26.08	26.3								
4.76	4.76	4.77	4.8	4.89	5.06	5.33	5.73	6.28	6.95	7.66	8.33
	8.9	9.39	9.8	10.14	10.42	10.68	10.98	11.38	11.91	12.54	13.22

	13.86	14.38	14.79	15.19	15.8	16.8	18.27	20.03	21.77	23.22	24.31
	25.11	25.66	25.96								
4.95	4.95	4.96	5	5.09	5.27	5.55	5.95	6.46	7.05	7.67	8.27
	8.83	9.35	9.82	10.21	10.52	10.77	11.04	11.4	11.91	12.57	13.3
	13.98	14.52	14.92	15.29	15.82	16.72	18.04	19.65	21.27	22.67	23.77
	24.61	25.21	25.54								
5.25	5.25	5.26	5.3	5.39	5.58	5.87	6.25	6.72	7.24	7.77	8.32
	8.88	9.47	10.05	10.53	10.88	11.13	11.35	11.66	12.12	12.76	13.48
	14.16	14.7	15.08	15.41	15.89	16.71	17.93	19.43	20.94	22.27	23.33
	24.15	24.74	25.07								
5.64	5.64	5.65	5.7	5.8	5.99	6.28	6.65	7.07	7.52	7.98	8.49
	9.09	9.81	10.54	11.16	11.59	11.83	11.99	12.21	12.58	13.14	13.8
	14.45	14.95	15.29	15.58	16.01	16.76	17.91	19.32	20.76	22	23
	23.75	24.3	24.59								
6.15	6.15	6.17	6.22	6.33	6.54	6.84	7.19	7.55	7.91	8.29	8.78
	9.47	10.36	11.31	12.13	12.65	12.88	12.94	13.03	13.27	13.71	14.29
	14.86	15.31	15.6	15.83	16.19	16.87	17.95	19.3	20.68	21.86	22.77
	23.45	23.92	24.17								
6.72	6.73	6.77	6.84	6.98	7.21	7.52	7.86	8.18	8.46	8.77	9.25
	10.04	11.14	12.35	13.37	13.98	14.17	14.1	14.03	14.11	14.42	14.9
	15.4	15.8	16.03	16.18	16.44	17.02	18.04	19.34	20.68	21.8	22.63
	23.22	23.61	23.82								
7.23	7.28	7.36	7.5	7.7	7.99	8.34	8.7	9.01	9.26	9.54	10.05
	10.96	12.27	13.72	14.91	15.57	15.66	15.43	15.15	15.06	15.25	15.65
	16.11	16.46	16.61	16.64	16.76	17.23	18.16	19.42	20.72	21.79	22.56
	23.06	23.38	23.55								
7.5	7.6	7.79	8.06	8.38	8.78	9.24	9.7	10.1	10.4	10.73	11.32
	12.37	13.87	15.51	16.83	17.48	17.45	17.02	16.55	16.31	16.39	16.72
	17.14	17.42	17.46	17.31	17.24	17.53	18.34	19.52	20.79	21.82	22.54
	22.98	23.24	23.38								
7.4	7.6	7.96	8.43	8.95	9.53	10.17	10.83	11.42	11.89	12.34	13.06
	14.27	15.95	17.75	19.15	19.78	19.65	19.06	18.44	18.07	18.06	18.33
	18.65	18.82	18.67	18.28	17.92	17.96	18.59	19.68	20.89	21.9	22.58
	22.99	23.22	23.33								
7.01	7.33	7.91	8.62	9.38	10.18	11.05	11.95	12.78	13.45	14.09	14.97
	16.34	18.18	20.11	21.6	22.26	22.13	21.51	20.84	20.41	20.33	20.49
	20.69	20.67	20.27	19.54	18.83	18.54	18.94	19.9	21.07	22.06	22.73
	23.13	23.35	23.45								
6.53	6.97	7.74	8.69	9.68	10.69	11.76	12.87	13.9	14.77	15.58	16.61
	18.13	20.1	22.15	23.74	24.52	24.49	23.97	23.37	22.96	22.82	22.87
	22.91	22.68	21.99	20.91	19.81	19.19	19.36	20.21	21.32	22.31	23
	23.41	23.65	23.76								
6.15	6.66	7.57	8.68	9.83	10.98	12.17	13.41	14.57	15.57	16.5	17.66
	19.29	21.38	23.52	25.22	26.13	26.28	25.95	25.5	25.15	24.99	24.95
	24.85	24.42	23.49	22.1	20.69	19.81	19.81	20.57	21.66	22.65	23.36
	23.81	24.08	24.22								
5.91	6.45	7.4	8.57	9.8	11.03	12.3	13.59	14.8	15.85	16.86	18.12
	19.85	22	24.21	25.99	27.02	27.34	27.18	26.87	26.6	26.43	26.33
	26.13	25.58	24.48	22.9	21.31	20.28	20.21	20.93	22.02	23.01	23.75
	24.24	24.57	24.74								
5.8	6.31	7.24	8.39	9.63	10.91	12.22	13.54	14.75	15.82	16.87	18.2
	19.99	22.2	24.44	26.27	27.38	27.8	27.75	27.53	27.31	27.15	27.02
	26.78	26.16	24.98	23.31	21.65	20.58	20.5	21.23	22.32	23.32	24.07
	24.61	24.98	25.18								

```

5.75    6.24    7.12    8.25    9.49    10.78   12.11   13.44   14.65   15.73   16.81   18.17
        20      22.23   24.49   26.34   27.47   27.93   27.93   27.75   27.54   27.39   27.25
        26.99   26.35   25.15   23.46   21.77   20.71   20.65   21.4    22.49   23.49   24.26
        24.82   25.21   25.43]';

```

```

fc_co_map=flipr(fc_co_map);

```

% (g/s), engine out NOx emissions indexed vertically by fc_map_spd and

% horizontally by fc_map_trq

```

fc_nox_map=1e-3*[82.72 85.85  91.37  97.76  103.4  107.14  108.94  109.3  108.91  108.25
                  107.97  109.01  112.14  117.35  123.53  129.32  133.94  137.7  141.24  144.87  148.52
                  152.04  155.45  158.62  161.4   163.63  165.48  167.32  169.44  171.7  173.34  173.16
                  170.25  164.7   157.97  152.05  148.67
78.82    82.37  88.62  95.88  102.3  106.57  108.65  109.12  108.73  108.03  107.71  108.72
          111.86  117.13  123.39  129.27  133.98  137.8  141.36  144.99  148.62  152.12  155.51
          158.71  161.59  164.02  166.16  168.23  170.35  172.26  173.31  172.53  169.28  163.74
          157.26  151.64  148.45
73.15    77.22  84.39  92.75  100.2  105.27  107.84  108.55  108.25  107.53  107.15  108.14
          111.31  116.68  123.1   129.16  134.03  137.97  141.59  145.21  148.8  152.26  155.64
          158.88  161.91  164.65  167.23  169.62  171.65  172.88  172.82  170.95  167.11  161.65
          155.72  150.76  147.99
68.16    72.42  79.98  88.88  97      102.79  106.05  107.29  107.27  106.64  106.22  107.18
          110.4   115.92  122.56  128.87  133.99  138.12  141.84  145.48  149.03  152.46  155.83
          159.12  162.3   165.34  168.3   170.94  172.73  173.02  171.51  168.27  163.71  158.47
          153.42  149.45  147.29
64.86    68.77  75.77  84.25  92.37  98.73  102.9   105.03  105.59  105.15  104.71  105.61
          108.86  114.54  121.42  128.04  133.47  137.88  141.78  145.51  149.1  152.57  156.01
          159.41  162.74  166     169.21  171.92  173.32  172.59  169.6  164.98  159.76  154.84
          150.8   147.96  146.5
62.89    65.96  71.6   78.77  86.29  93.04  98.32  101.69  103.06  102.92  102.42  103.16
          106.34  112.07  119.13  126.01  131.78  136.58  140.8  144.78  148.57  152.27  155.97
          159.65  163.22  166.7   170.03  172.67  173.61  171.97  167.73  161.98  156.23  151.62
          148.48  146.65  145.81
61.54    63.59  67.52  72.99  79.52  86.42  92.71  97.33  99.58  99.77  99.2   99.72
          102.69  108.27  115.28  122.24  128.26  133.42  138.05  142.45  146.68  150.92  155.24
          159.52  163.58  167.39  170.85  173.41  173.99  171.69  166.6  160.12  154.03  149.63
          147.1   145.92  145.5
60.54    61.67  64.03  67.84  73.23  79.89  86.71  92.2   95.18  95.72  95.15  95.48
          98.13  103.34  110     116.75  122.76  128.12  133.09  137.94  142.78  147.84  153.12
          158.35  163.21  167.59  171.39  174.08  174.56  172.01  166.55  159.76  153.55  149.3
          147.07  146.24  146.02
59.86    60.38  61.63  64.11  68.33  74.26  80.92  86.65  90      90.82  90.33  90.52
          92.86  97.64  103.81  110.16  115.93  121.21  126.26  131.39  136.77  142.66  148.98
          155.29  161.13  166.34  170.83  174.07  174.98  172.75  167.57  161.03  155.07  151.03
          148.96  148.23  148.06
59.44    59.63  60.23  61.79  64.93  69.83  75.74  81.07  84.29  85.03  84.4   84.34
          86.39  90.86  96.75  102.83  108.39  113.52  118.5  123.68  129.31  135.69  142.69
          149.82  156.54  162.69  168.19  172.48  174.46  173.3  169.21  163.66  158.47  154.86
          152.91  152.11  151.85
58.97    59.02  59.32  60.28  62.52  66.32  71.14  75.54  77.99  77.99  76.64  75.96
          77.62  81.95  87.87  94.06  99.74  104.99  110.06  115.29  120.95  127.38  134.55
          142.01  149.33  156.38  163.09  168.81  172.41  173.01  170.8  167.01  163.13  160.14
          158.17  157.01  156.45
58.04    58.05  58.2   58.77  60.28  62.99  66.51  69.52  70.59  69.18  66.52  64.8
          65.87  70.02  76.08  82.58  88.68  94.4   99.91  105.4  111.11  117.46  124.58

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	132.22	140.08	148.05	156	163.23	168.59	171.26	171.35	169.76	167.47	165.06
	162.75	160.82	159.67								
56.22	56.22	56.28	56.55	57.38	58.94	60.92	62.18	61.54	58.59	54.62	51.88
	52.22	55.89	61.68	68.15	74.47	80.65	86.69	92.6	98.52	104.97	112.3
	120.43	129.12	138.2	147.44	156.03	162.94	167.51	169.83	170.4	169.57	167.52
	164.55	161.49	159.52								
53.31	53.3	53.28	53.27	53.38	53.65	53.85	53.21	50.97	46.99	42.45	39.29
	39.1	42.02	46.96	52.7	58.57	64.59	70.65	76.67	82.77	89.54	97.45
	106.49	116.34	126.66	137.02	146.62	154.66	160.74	164.94	167.37	167.77	165.98
	162.37	158.33	155.64								
49.29	49.28	49.19	48.92	48.34	47.34	45.82	43.51	40.23	36.08	31.98	29.26
	28.94	31.07	34.8	39.25	43.99	49.05	54.36	59.89	65.85	72.82	81.23
	90.99	101.68	112.8	123.75	133.85	142.56	149.79	155.54	159.54	161.1	159.86
	156.3	152.07	149.22								
44.41	44.39	44.26	43.8	42.71	40.76	37.99	34.59	30.91	27.3	24.29	22.54
	22.52	24.16	26.86	30.01	33.36	37	41.02	45.56	50.96	57.72	66.07
	75.77	86.27	97.07	107.58	117.38	126.23	134.23	141.24	146.65	149.51	149.46
	147.07	143.91	141.73								
38.92	38.9	38.76	38.23	36.93	34.59	31.31	27.61	24.11	21.31	19.45	18.7
	19.14	20.61	22.69	24.95	27.21	29.6	32.38	35.89	40.54	46.68	54.28
	62.94	72.11	81.41	90.47	99.16	107.51	115.73	123.48	129.93	134.09	135.75
	135.49	134.44	133.61								
33.18	33.17	33.04	32.55	31.32	29.09	25.98	22.6	19.65	17.63	16.63	16.6
	17.42	18.94	20.79	22.62	24.26	25.87	27.82	30.56	34.53	39.91	46.44
	53.62	60.94	68.19	75.25	82.33	89.67	97.49	105.31	112.23	117.4	120.77
	122.83	124.11	124.77								
27.6	27.59	27.49	27.1	26.1	24.27	21.73	19.01	16.76	15.41	14.97	15.35
	16.38	17.95	19.72	21.38	22.77	24.05	25.61	27.94	31.41	36.09	41.63
	47.47	53.15	58.59	63.9	69.45	75.59	82.55	89.84	96.63	102.25	106.77
	110.49	113.46	115.19								
22.64	22.63	22.55	22.26	21.51	20.14	18.24	16.25	14.67	13.86	13.8	14.4
	15.53	17.08	18.79	20.35	21.63	22.79	24.2	26.31	29.45	33.62	38.43
	43.35	47.95	52.2	56.33	60.77	65.92	72.01	78.58	84.95	90.57	95.5
	99.91	103.55	105.69								
18.58	18.57	18.52	18.31	17.77	16.77	15.41	14.02	13	12.59	12.78	13.5
	14.65	16.14	17.75	19.23	20.43	21.54	22.89	24.89	27.79	31.6	35.92
	40.25	44.22	47.82	51.28	55.07	59.58	65.01	71	76.93	82.31	87.15
	91.48	95.02	97.08								
15.41	15.41	15.37	15.22	14.82	14.1	13.12	12.16	11.51	11.37	11.72	12.48
	13.6	15.02	16.52	17.9	19.03	20.1	21.4	23.32	26.07	29.64	33.64
	37.6	41.17	44.35	47.4	50.79	54.92	59.97	65.62	71.25	76.39	80.96
	84.95	88.12	89.92								
12.88	12.87	12.84	12.73	12.43	11.9	11.18	10.51	10.1	10.12	10.53	11.29
	12.34	13.65	15.03	16.29	17.35	18.36	19.61	21.45	24.09	27.49	31.29
	35.01	38.29	41.15	43.89	46.98	50.84	55.67	61.11	66.55	71.48	75.8
	79.48	82.34	83.94								
10.61	10.6	10.58	10.49	10.27	9.88	9.36	8.9	8.67	8.81	9.26	9.98
	10.94	12.09	13.29	14.41	15.36	16.3	17.49	19.23	21.73	24.99	28.64
	32.19	35.27	37.89	40.36	43.2	46.87	51.53	56.81	62.09	66.84	70.96
	74.45	77.13	78.63								
8.39	8.39	8.37	8.3	8.15	7.88	7.55	7.29	7.25	7.5	8.01	8.7
	9.54	10.5	11.5	12.43	13.28	14.15	15.25	16.85	19.14	22.16	25.61
	29.02	31.96	34.43	36.72	39.39	42.89	47.4	52.5	57.59	62.14	66.08
	69.4	71.97	73.41								

6.23	6.22	6.19	6.13	6.05	5.92	5.78	5.74	5.88	6.27	6.83	7.49
	8.22	8.99	9.77	10.54	11.3	12.14	13.19	14.63	16.65	19.34	22.5
	25.71	28.54	30.91	33.1	35.64	39.01	43.32	48.21	53.05	57.38	61.12
	64.29	66.76	68.15								
4.36	4.33	4.27	4.21	4.18	4.17	4.2	4.35	4.64	5.1	5.68	6.3
	6.92	7.55	8.17	8.83	9.56	10.42	11.45	12.76	14.5	16.8	19.61
	22.55	25.24	27.52	29.63	32.06	35.26	39.35	43.99	48.58	52.68	56.2
	59.19	61.52	62.84								
3.03	2.96	2.85	2.77	2.74	2.8	2.94	3.18	3.53	3.98	4.49	5.03
	5.56	6.09	6.63	7.24	7.96	8.86	9.92	11.15	12.67	14.64	17.1
	19.74	22.23	24.38	26.37	28.65	31.64	35.48	39.85	44.21	48.1	51.42
	54.19	56.35	57.57								
2.31	2.2	2.04	1.9	1.85	1.91	2.07	2.3	2.59	2.94	3.34	3.77
	4.21	4.69	5.2	5.78	6.49	7.39	8.44	9.62	11	12.73	14.88
	17.22	19.47	21.42	23.26	25.35	28.11	31.67	35.8	39.96	43.67	46.76
	49.29	51.19	52.26								
2.06	1.91	1.69	1.49	1.4	1.42	1.53	1.69	1.88	2.1	2.37	2.69
	3.08	3.52	4	4.55	5.22	6.06	7.06	8.18	9.47	11.03	12.94
	15.02	17.02	18.78	20.45	22.35	24.87	28.17	32.04	35.95	39.43	42.27
	44.49	46.11	47								
2.04	1.87	1.61	1.36	1.22	1.2	1.25	1.34	1.44	1.56	1.73	1.98
	2.32	2.75	3.22	3.72	4.31	5.05	5.96	7	8.21	9.66	11.4
	13.27	15.06	16.65	18.18	19.94	22.3	25.37	28.95	32.54	35.68	38.16
	40.02	41.32	42.02								
2.08	1.89	1.61	1.34	1.17	1.12	1.14	1.18	1.22	1.29	1.41	1.63
	1.95	2.36	2.81	3.28	3.8	4.45	5.27	6.24	7.4	8.77	10.4
	12.13	13.79	15.27	16.72	18.43	20.69	23.6	26.89	30.1	32.8	34.85
	36.33	37.33	37.85								
2.1	1.91	1.62	1.34	1.16	1.1	1.1	1.13	1.15	1.2	1.3	1.51
	1.82	2.23	2.67	3.12	3.6	4.18	4.94	5.87	6.99	8.33	9.89
	11.56	13.16	14.59	16.01	17.71	19.96	22.78	25.86	28.72	31.01	32.65
	33.77	34.51	34.89								
2.11	1.92	1.62	1.34	1.16	1.09	1.1	1.12	1.14	1.18	1.28	1.48
	1.8	2.2	2.64	3.08	3.54	4.11	4.84	5.75	6.86	8.18	9.73
	11.37	12.95	14.36	15.78	17.5	19.76	22.54	25.5	28.17	30.21	31.6
	32.51	33.1	33.4]';								

fc_nox_map=flipplr(fc_nox_map);

% (g/s), engine out PM emissions indexed vertically by fc_map_spd and

% horizontally by fc_map_trq

fc_pm_map=1e-3*[	2.28	2.22	2.13	2.02	1.92	1.87	1.89	2.04	2.37	2.88
	3.52	4.28	5.13	6.09	7.05	7.9	8.58	9.14	9.69	10.27
	11.58	12.32	13.13	14.02	15.09	16.47	18.34	20.78	23.59	26.25
	28.64	27.98	26.64	25.34	24.57					
2.34	2.28	2.17	2.04	1.93	1.86	1.87	2.02	2.32	2.81	3.43
	5.01	5.97	6.94	7.81	8.51	9.09	9.65	10.25	10.89	11.58
	13.18	14.21	15.52	17.25	19.43	21.97	24.6	26.87	28.29	28.57
	26.49	25.24	24.52							
2.43	2.36	2.22	2.07	1.92	1.83	1.83	1.95	2.23	2.67	3.25
	4.77	5.72	6.69	7.57	8.29	8.9	9.5	10.13	10.8	11.51
	13.23	14.48	16.19	18.46	21.1	23.78	26.1	27.73	28.47	28.3
	26.15	25.05	24.41							
2.51	2.42	2.27	2.09	1.91	1.79	1.75	1.83	2.07	2.47	3
	4.42	5.32	6.26	7.11	7.83	8.47	9.12	9.8	10.52	11.27

	13.17	14.66	16.8	19.61	22.7	25.49	27.43	28.36	28.38	27.74	26.73
	25.64	24.75	24.26								
2.56	2.47	2.31	2.11	1.91	1.74	1.65	1.68	1.87	2.22	2.7	3.29
	3.98	4.79	5.63	6.42	7.12	7.77	8.44	9.17	9.93	10.74	11.67
	12.85	14.58	17.09	20.33	23.76	26.58	28.18	28.52	27.95	26.97	25.94
	25.05	24.41	24.08								
2.59	2.51	2.37	2.17	1.95	1.74	1.57	1.53	1.65	1.95	2.37	2.89
	3.49	4.18	4.9	5.59	6.23	6.86	7.53	8.25	9.02	9.86	10.85
	12.17	14.11	16.91	20.46	24.07	26.87	28.24	28.21	27.31	26.17	25.2
	24.52	24.11	23.92								
2.62	2.56	2.44	2.27	2.04	1.78	1.55	1.42	1.46	1.68	2.04	2.48
	2.99	3.57	4.16	4.74	5.3	5.88	6.51	7.18	7.92	8.74	9.75
	11.14	13.23	16.2	19.88	23.54	26.28	27.54	27.41	26.49	25.42	24.6
	24.11	23.87	23.78								
2.64	2.6	2.53	2.39	2.17	1.88	1.58	1.36	1.31	1.46	1.74	2.12
	2.54	3.02	3.52	4.01	4.5	5	5.54	6.14	6.79	7.55	8.52
	9.91	12	14.96	18.56	22.09	24.73	26	26.03	25.38	24.6	24.03
	23.72	23.59	23.56								
2.66	2.64	2.59	2.49	2.29	1.99	1.64	1.35	1.22	1.3	1.52	1.84
	2.22	2.62	3.05	3.47	3.87	4.29	4.74	5.24	5.79	6.47	7.35
	8.64	10.57	13.29	16.57	19.78	22.24	23.59	23.96	23.78	23.46	23.21
	23.08	23.03	23.01								
2.66	2.65	2.63	2.55	2.37	2.08	1.71	1.37	1.2	1.23	1.44	1.74
	2.08	2.44	2.8	3.15	3.48	3.81	4.16	4.56	5.01	5.59	6.35
	7.45	9.09	11.39	14.15	16.9	19.12	20.55	21.32	21.68	21.84	21.91
	21.93	21.92	21.91								
2.64	2.64	2.62	2.56	2.4	2.12	1.75	1.41	1.23	1.28	1.51	1.83
	2.16	2.49	2.79	3.08	3.33	3.58	3.84	4.14	4.49	4.94	5.54
	6.4	7.68	9.47	11.66	13.89	15.83	17.32	18.4	19.19	19.73	20.03
	20.13	20.13	20.1								
2.58	2.58	2.57	2.52	2.38	2.12	1.76	1.45	1.3	1.41	1.71	2.08
	2.44	2.75	3.02	3.25	3.44	3.62	3.81	4.02	4.27	4.58	4.98
	5.57	6.47	7.78	9.44	11.2	12.87	14.32	15.56	16.59	17.32	17.73
	17.85	17.82	17.77								
2.46	2.46	2.45	2.41	2.28	2.05	1.74	1.47	1.4	1.59	1.97	2.41
	2.8	3.12	3.38	3.59	3.75	3.89	4.03	4.18	4.34	4.5	4.7
	5.02	5.59	6.5	7.72	9.1	10.49	11.81	13.04	14.09	14.86	15.27
	15.39	15.34	15.28								
2.27	2.27	2.26	2.22	2.12	1.92	1.67	1.48	1.48	1.74	2.18	2.67
	3.09	3.45	3.72	3.95	4.12	4.26	4.4	4.53	4.63	4.66	4.67
	4.76	5.07	5.69	6.6	7.67	8.79	9.91	10.98	11.91	12.61	12.99
	13.12	13.1	13.06								
2.01	2.01	2	1.98	1.89	1.74	1.55	1.43	1.5	1.8	2.25	2.75
	3.2	3.58	3.9	4.16	4.36	4.54	4.71	4.86	4.94	4.89	4.77
	4.69	4.83	5.28	5.99	6.85	7.74	8.61	9.44	10.18	10.74	11.1
	11.28	11.36	11.39								
1.72	1.71	1.71	1.69	1.63	1.52	1.39	1.34	1.44	1.74	2.17	2.63
	3.07	3.47	3.82	4.11	4.36	4.58	4.81	5	5.09	5.02	4.84
	4.69	4.76	5.13	5.75	6.47	7.17	7.82	8.41	8.94	9.38	9.73
	10.01	10.22	10.34								
1.4	1.4	1.4	1.39	1.35	1.28	1.21	1.2	1.32	1.58	1.95	2.36
	2.76	3.15	3.5	3.82	4.09	4.35	4.63	4.88	5.01	4.97	4.8
	4.67	4.75	5.11	5.68	6.32	6.9	7.38	7.79	8.15	8.5	8.86
	9.24	9.58	9.79								

1.1	1.1	1.1	1.1	1.08	1.05	1.02	1.04	1.16	1.38	1.67	2.01
	2.36	2.71	3.06	3.37	3.66	3.95	4.26	4.57	4.76	4.79	4.7
	4.64	4.77	5.14	5.68	6.25	6.74	7.11	7.39	7.65	7.95	8.35
	8.81	9.26	9.53								
0.84	0.84	0.84	0.84	0.84	0.84	0.84	0.89	0.99	1.16	1.39	1.66
	1.95	2.28	2.61	2.92	3.2	3.5	3.85	4.19	4.45	4.56	4.59
	4.62	4.81	5.18	5.68	6.19	6.59	6.87	7.07	7.26	7.55	7.99
	8.52	9.03	9.34								
0.64	0.64	0.64	0.65	0.66	0.67	0.7	0.75	0.84	0.97	1.14	1.35
	1.61	1.92	2.23	2.54	2.82	3.13	3.48	3.86	4.17	4.37	4.49
	4.61	4.84	5.2	5.65	6.09	6.41	6.61	6.73	6.87	7.15	7.6
	8.17	8.7	9.02								
0.52	0.52	0.52	0.52	0.53	0.56	0.59	0.64	0.72	0.82	0.94	1.11
	1.34	1.63	1.95	2.25	2.54	2.85	3.21	3.59	3.95	4.21	4.41
	4.59	4.84	5.19	5.59	5.96	6.21	6.33	6.37	6.46	6.69	7.13
	7.68	8.2	8.51								
0.44	0.44	0.44	0.45	0.46	0.48	0.52	0.56	0.62	0.69	0.78	0.92
	1.13	1.41	1.72	2.02	2.31	2.61	2.97	3.36	3.74	4.05	4.3
	4.53	4.8	5.14	5.51	5.83	6.02	6.07	6.03	6.05	6.23	6.61
	7.11	7.58	7.86								
0.4	0.4	0.4	0.41	0.42	0.43	0.46	0.49	0.54	0.58	0.65	0.77
	0.96	1.21	1.51	1.79	2.06	2.36	2.71	3.11	3.5	3.85	4.15
	4.43	4.73	5.07	5.43	5.72	5.87	5.86	5.76	5.71	5.81	6.11
	6.53	6.94	7.19								
0.37	0.37	0.37	0.37	0.37	0.38	0.4	0.42	0.45	0.49	0.54	0.64
	0.8	1.02	1.28	1.54	1.79	2.07	2.42	2.81	3.21	3.6	3.95
	4.29	4.63	5	5.36	5.65	5.78	5.73	5.58	5.45	5.48	5.69
	6.04	6.38	6.59								
0.33	0.33	0.33	0.34	0.34	0.34	0.34	0.35	0.37	0.4	0.44	0.52
	0.66	0.84	1.06	1.28	1.52	1.79	2.12	2.5	2.9	3.31	3.71
	4.1	4.51	4.92	5.31	5.61	5.75	5.68	5.47	5.28	5.23	5.37
	5.65	5.93	6.11								
0.29	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.31	0.33	0.37	0.43
	0.54	0.69	0.86	1.05	1.27	1.54	1.86	2.22	2.61	3.01	3.44
	3.89	4.35	4.8	5.25	5.59	5.75	5.66	5.42	5.16	5.04	5.12
	5.35	5.6	5.76								
0.25	0.26	0.27	0.27	0.28	0.28	0.27	0.26	0.27	0.28	0.32	0.37
	0.46	0.57	0.71	0.87	1.08	1.33	1.64	1.97	2.32	2.71	3.14
	3.62	4.11	4.62	5.12	5.53	5.73	5.66	5.38	5.08	4.91	4.95
	5.14	5.37	5.52								
0.2	0.21	0.22	0.24	0.25	0.25	0.25	0.24	0.24	0.26	0.28	0.33
	0.39	0.48	0.58	0.72	0.91	1.15	1.43	1.72	2.02	2.37	2.79
	3.26	3.78	4.34	4.91	5.4	5.67	5.64	5.37	5.04	4.85	4.86
	5.03	5.24	5.38								
0.14	0.15	0.18	0.2	0.22	0.23	0.23	0.23	0.23	0.24	0.26	0.3
	0.34	0.41	0.49	0.6	0.75	0.95	1.18	1.42	1.68	1.98	2.36
	2.81	3.34	3.94	4.6	5.2	5.57	5.61	5.37	5.06	4.86	4.85
	5.01	5.21	5.35								
0.09	0.1	0.13	0.16	0.18	0.2	0.21	0.21	0.22	0.23	0.24	0.27
	0.31	0.35	0.41	0.49	0.6	0.75	0.92	1.1	1.31	1.57	1.91
	2.34	2.87	3.51	4.26	4.97	5.45	5.57	5.39	5.11	4.92	4.92
	5.07	5.26	5.39								
0.05	0.06	0.08	0.11	0.14	0.16	0.18	0.19	0.2	0.22	0.23	0.26
	0.28	0.32	0.36	0.41	0.48	0.58	0.69	0.82	0.99	1.21	1.52

	1.93	2.46	3.14	3.96	4.76	5.34	5.53	5.41	5.17	5	5.02
	5.17	5.35	5.48								
0.03	0.04	0.05	0.07	0.1	0.12	0.15	0.17	0.19	0.21	0.23	0.25
	0.27	0.3	0.33	0.37	0.41	0.47	0.54	0.64	0.77	0.98	1.27
	1.66	2.18	2.89	3.76	4.62	5.25	5.49	5.41	5.2	5.08	5.11
	5.27	5.46	5.58								
0.02	0.02	0.03	0.05	0.07	0.1	0.13	0.16	0.19	0.21	0.23	0.24
	0.27	0.29	0.32	0.35	0.38	0.42	0.47	0.54	0.67	0.86	1.14
	1.52	2.05	2.77	3.66	4.54	5.19	5.45	5.4	5.22	5.12	5.18
	5.35	5.54	5.66								
0.01	0.02	0.03	0.04	0.06	0.09	0.12	0.15	0.18	0.21	0.22	0.24
	0.27	0.29	0.32	0.34	0.37	0.4	0.44	0.51	0.63	0.82	1.1
	1.47	2	2.72	3.62	4.51	5.16	5.43	5.38	5.22	5.14	5.21
	5.4	5.59	5.71];								

fc_pm_map=flipplr(fc_pm_map);

% (g/s), engine out O2 emissions indexed vertically by fc_map_spd and

% horizontally by fc_map_trq

fc_o2_map=1e-3*[2379	2541	2827	3158	3450	3651	3779	3905	4098	4382
4715	5041	5318	5547	5734	5887	6012	6125	6245	6381
6723	6932	7144	7327	7456	7534	7585	7631	7683	7745
7906	8010	8117	8206	8256					
2178	2362	2687	3064	3397	3627	3771	3904	4101	4386
	5329	5561	5752	5908	6035	6148	6266	6398	6553
	7150	7333	7464	7548	7604	7654	7708	7769	7840
	8128	8212	8259						
1886	2099	2474	2911	3302	3575	3748	3898	4104	4395
	5357	5600	5802	5969	6102	6216	6328	6452	6596
	7171	7351	7483	7572	7636	7692	7750	7812	7883
	8151	8225	8266						
1631	1856	2255	2726	3157	3475	3691	3874	4103	4408
	5406	5673	5901	6092	6240	6357	6461	6570	6697
	7227	7394	7518	7606	7673	7734	7797	7866	7942
	8185	8244	8276						
1462	1671	2047	2503	2944	3303	3578	3821	4094	4425
	5484	5789	6061	6290	6462	6585	6681	6773	6880
	7342	7484	7588	7661	7720	7779	7846	7923	8006
	8225	8267	8288						
1361	1528	1836	2231	2651	3047	3400	3731	4072	4444
	5591	5948	6277	6556	6759	6893	6983	7061	7150
	7532	7641	7714	7760	7797	7842	7904	7983	8070
	8260	8286	8298						
1291	1404	1623	1933	2315	2740	3178	3612	4038	4466
	5721	6137	6531	6866	7103	7252	7342	7413	7491
	7798	7873	7912	7927	7935	7957	8001	8067	8142
	8291	8306	8312						
1237	1300	1436	1662	1995	2436	2946	3478	3992	4481
	5853	6330	6791	7184	7459	7626	7724	7798	7873
	8118	8167	8184	8175	8159	8154	8171	8207	8253
	8340	8347	8349						
1202	1231	1306	1464	1750	2186	2741	3347	3936	4479
	5944	6479	7007	7458	7776	7971	8090	8180	8262
	8475	8513	8522	8507	8480	8455	8441	8437	8440
	8452	8455	8456						

1190	1201	1241	1352	1596	2011	2581	3228	3864	4433	4934	5417
	5937	6519	7109	7622	7991	8229	8386	8510	8617	8709	8786
	8849	8893	8913	8909	8886	8852	8813	8771	8731	8700	8683
	8679	8682	8686								
1206	1210	1232	1315	1525	1912	2472	3125	3766	4325	4800	5260
	5780	6391	7029	7599	8027	8326	8544	8725	8879	9011	9123
	9217	9291	9339	9358	9351	9320	9267	9199	9130	9076	9050
	9051	9065	9078								
1254	1255	1271	1337	1521	1876	2406	3029	3634	4142	4560	4972
	5468	6083	6745	7354	7836	8203	8498	8757	8985	9189	9373
	9537	9669	9762	9815	9833	9815	9764	9688	9608	9551	9532
	9551	9586	9612								
1341	1341	1354	1410	1573	1892	2372	2935	3472	3908	4257	4611
	5065	5654	6306	6922	7434	7860	8233	8582	8907	9214	9508
	9775	9992	10147	10243	10291	10296	10261	10197	10129	10085	10084
	10124	10180	10220								
1462	1463	1474	1524	1666	1944	2358	2841	3297	3663	3956	4264
	4675	5219	5829	6416	6925	7379	7813	8245	8677	9109	9537
	9932	10253	10478	10620	10700	10733	10727	10691	10650	10628	10643
	10694	10756	10798								
1607	1608	1618	1663	1784	2017	2360	2760	3141	3458	3723	4009
	4388	4882	5434	5968	6444	6894	7359	7860	8394	8958	9529
	10057	10481	10773	10953	11060	11121	11147	11149	11142	11143	11163
	11201	11243	11272								
1756	1757	1767	1806	1907	2097	2375	2703	3028	3318	3580	3866
	4229	4686	5185	5663	6095	6520	6991	7537	8160	8844	9549
	10196	10707	11052	11262	11389	11472	11529	11567	11592	11606	11611
	11611	11609	11607								
1897	1898	1907	1940	2024	2179	2405	2680	2967	3245	3515	3811
	4170	4604	5067	5505	5899	6297	6763	7338	8029	8812	9624
	10363	10939	11322	11554	11698	11800	11882	11947	11992	12006	11983
	11930	11871	11831								
2018	2019	2027	2055	2125	2254	2443	2680	2942	3213	3490	3796
	4157	4583	5029	5445	5817	6198	6660	7253	7992	8844	9731
	10535	11156	11569	11822	11985	12106	12207	12289	12342	12345	12287
	12181	12066	11992								
2111	2112	2119	2144	2203	2313	2477	2688	2931	3197	3477	3789
	4154	4579	5020	5430	5795	6170	6634	7241	8010	8906	9841
	10688	11342	11782	12058	12242	12382	12498	12592	12646	12635	12546
	12399	12247	12151								
2167	2168	2174	2196	2249	2346	2492	2685	2916	3176	3458	3776
	4145	4574	5018	5430	5797	6174	6643	7263	8052	8977	9942
	10818	11497	11960	12259	12465	12623	12754	12857	12911	12890	12784
	12618	12450	12347								
2182	2183	2189	2208	2257	2345	2481	2663	2887	3146	3430	3752
	4128	4562	5012	5429	5800	6183	6660	7294	8102	9050	10038
	10933	11632	12114	12434	12660	12836	12980	13092	13150	13130	13023
	12860	12698	12598								
2158	2158	2164	2182	2228	2312	2441	2619	2842	3102	3391	3719
	4099	4539	4993	5415	5792	6183	6672	7322	8151	9121	10129
	11041	11753	12252	12591	12837	13030	13189	13311	13379	13369	13276
	13130	12985	12897								
2096	2097	2102	2121	2165	2249	2377	2556	2781	3046	3341	3674
	4058	4499	4956	5381	5765	6167	6671	7337	8183	9170	10195

	11125	11857	12377	12739	13008	13221	13396	13530	13611	13618	13547
	13425	13303	13228								
1996	1996	2001	2021	2068	2156	2291	2475	2706	2979	3281	3619
	4005	4444	4898	5326	5722	6143	6664	7340	8187	9175	10212
	11165	11929	12485	12881	13180	13420	13614	13765	13860	13885	13836
	13738	13637	13575								
1861	1859	1863	1883	1938	2038	2186	2383	2624	2904	3212	3552
	3936	4369	4819	5253	5669	6119	6660	7334	8158	9122	10158
	11141	11958	12568	13012	13352	13626	13847	14017	14129	14170	14141
	14063	13979	13925								
1718	1711	1706	1724	1787	1906	2076	2291	2540	2821	3125	3460
	3835	4259	4704	5150	5596	6085	6652	7317	8102	9024	10050
	11067	11945	12620	13121	13507	13821	14075	14272	14403	14462	14449
	14386	14311	14263								
1617	1597	1575	1583	1650	1789	1983	2212	2461	2728	3013	3329
	3687	4098	4538	4994	5472	6004	6603	7267	8018	8901	9918
	10966	11904	12639	13194	13624	13980	14271	14499	14655	14734	14736
	14685	14619	14574								
1596	1557	1509	1497	1563	1716	1928	2161	2392	2626	2873	3155
	3489	3882	4313	4774	5272	5839	6472	7154	7902	8773	9793
	10866	11848	12629	13224	13691	14084	14410	14670	14854	14957	14980
	14944	14888	14849								
1653	1595	1518	1484	1543	1702	1919	2141	2341	2528	2726	2968
	3273	3646	4064	4515	5013	5593	6255	6970	7750	8642	9681
	10777	11787	12596	13220	13715	14136	14492	14781	14993	15122	15170
	15158	15120	15092								
1746	1673	1575	1524	1577	1735	1947	2150	2314	2454	2605	2808
	3085	3440	3842	4273	4752	5324	6002	6756	7584	8518	9587
	10701	11728	12555	13198	13713	14158	14538	14851	15087	15242	15317
	15333	15321	15307								
1828	1748	1641	1583	1633	1789	1992	2177	2312	2417	2534	2707
	2964	3304	3690	4099	4551	5102	5783	6566	7439	8414	9512
	10643	11680	12517	13174	13707	14173	14575	14908	15162	15336	15435
	15479	15493	15496								
1877	1798	1691	1635	1686	1840	2036	2209	2328	2414	2510	2665
	2907	3236	3612	4003	4433	4965	5642	6440	7343	8346	9464
	10605	11649	12492	13159	13708	14192	14613	14963	15230	15415	15531
	15597	15632	15648								
1898	1821	1719	1670	1724	1877	2068	2236	2350	2429	2516	2660
	2892	3215	3584	3966	4384	4903	5575	6379	7295	8312	9440
	10586	11633	12480	13154	13713	14213	14650	15012	15285	15476	15601
	15680	15730	15755								
1904	1829	1732	1686	1743	1895	2086	2251	2365	2443	2526	2664
	2892	3211	3578	3957	4370	4884	5554	6360	7280	8301	9432
	10579	11628	12476	13153	13718	14226	14672	15040	15317	15510	15638
	15723	15780	15810								

];

fc_o2_map=fliplr(fc_o2_map);

% (C), engine exhaust gas temperature indexed vertically by fc_map_spd and

% horizontally by fc_map_trq

```
fc_extmp_map=[437.73 435.82 432.47 428.58 425.15 422.96 422.26 423.22 425.82 430.13
436.1 444.36 455.51 469.56 484.57 498.11 508.77 517.33 525.26 533.24 540.97
547.93 554.54 561.92 572.23 588.06 612.41 647.76 694.41 747.73 795.87 823.03
817.88 781.94 730.3 682.81 655.34
```

440.05	437.86	433.99	429.51	425.53	422.95	422	422.74	425.07	429	434.58	442.54
	453.58	467.7	482.9	496.71	507.65	516.49	524.68	532.87	540.74	547.8	554.65
	562.9	575.76	596.5	627.53	668.62	716.82	765.72	805.19	823.26	812.24	774.75
	724.61	679.49	653.59								
443.39	440.79	436.21	430.85	426.04	422.78	421.32	421.61	423.41	426.7	431.61	439
	449.68	463.68	478.94	492.96	504.29	513.66	522.45	531.2	539.52	546.92	554.31
	564.13	581.11	609.53	650.87	700.58	750.5	791.41	815.93	818.61	798.01	758.73
	712.31	672.38	649.82								
446.26	443.42	438.35	432.32	426.71	422.59	420.3	419.79	420.81	423.29	427.39	433.99
	443.94	457.26	472	485.8	497.36	507.43	517.14	526.82	535.93	544.05	552.42
	564.31	585.85	622.19	673.63	731.27	781.55	812.41	819.46	804.64	773.7	733.85
	693.73	661.71	644.17								
448.12	445.35	440.33	434.13	427.96	422.85	419.28	417.47	417.36	418.87	422.06	427.66
	436.4	448.3	461.68	474.6	486.07	496.81	507.61	518.45	528.63	537.86	547.74
	562.19	588.2	631.2	690.2	752.86	801.56	822.32	813.35	783.1	743.72	704.95
	672.54	649.61	637.77								
449.26	446.92	442.56	436.8	430.41	424.19	418.89	415.2	413.47	413.71	415.81	420.17
	427.28	437.14	448.47	459.91	470.9	482.09	493.83	505.71	516.94	527.53	539.42
	556.98	587.38	635.71	699.53	764.34	810.15	822.46	801.46	760.3	715.59	678.92
	653.75	638.93	632.12								
450.13	448.45	445.14	440.25	433.93	426.61	419.28	413.22	409.38	408	408.79	411.74
	416.98	424.48	433.36	442.93	453.03	464.2	476.37	488.86	500.99	513.12	527.47
	548.63	583.39	636.07	702.69	767.57	810.08	816.44	788.38	741.66	694.97	660.71
	640.8	631.52	628.09								
450.88	449.88	447.69	443.83	437.79	429.57	420.21	411.59	405.39	402.21	401.68	403.28
	406.71	411.81	418.13	425.54	434.25	444.68	456.46	468.89	481.56	495.25	512.25
	537.05	575.73	631.66	699.5	763.21	802.62	805.45	774.65	726.9	681.11	649.42
	632.84	626.58	624.88								
451.3	450.81	449.5	446.55	440.9	432.05	420.99	410.06	401.66	396.96	395.47	396.16
	398.15	401.09	404.88	409.9	416.63	425.41	435.81	447.34	460.01	474.91	494.14
	521.82	563.15	620.66	688.14	749.73	786.33	787.4	756.95	711.51	668.96	640.32
	626.01	621.12	620.06								
450.99	450.8	450.05	447.76	442.5	433.39	421.17	408.6	398.72	393.25	391.59	392.09
	393.16	394.3	395.73	398.23	402.54	408.97	417.15	426.93	438.75	453.83	474
	502.71	544.44	601.17	666.6	725.4	759.75	760.44	732.26	691.08	653.27	628.24
	615.94	611.75	610.82								
449.12	449.06	448.58	446.74	441.9	432.93	420.38	407.22	396.98	391.8	390.85	391.86
	392.6	392.39	391.77	391.93	393.76	397.55	403.08	410.47	420.49	434.37	453.59
	480.97	520.57	574.23	636.19	691.86	724.55	725.82	700.9	664.73	632.11	610.77
	600.21	596.31	595.22								
444.64	444.62	444.29	442.78	438.5	430.24	418.42	406.05	396.79	392.87	393.25	395.14
	395.89	394.74	392.54	390.78	390.48	391.86	394.77	399.53	407.08	418.61	435.35
	459.69	495.48	544.7	602.38	654.73	686.06	688.29	666.67	635.07	606.93	588.58
	579.22	575.29	573.88								
436.48	436.48	436.25	435.1	431.64	424.81	414.95	404.79	397.68	395.64	397.43	400.12
	400.94	399.22	395.99	392.92	391.02	390.41	390.94	393.1	398	406.84	420.75
	441.91	474.04	519.11	572.59	621.45	650.9	653.34	633.89	605.45	580.31	563.84
	555.15	551.09	549.42								
424.67	424.68	424.56	423.84	421.5	416.77	409.9	403.02	398.77	398.65	401.43	404.43
	405.14	403.06	399.33	395.54	392.57	390.37	388.82	388.61	391.12	397.72	409.57
	428.79	458.78	501.13	551.14	596.31	622.82	623.98	604.93	577.91	554.33	539.05
	531.09	527.42	525.94								
410.2	410.22	410.22	409.98	408.95	406.68	403.29	400.1	398.75	400.15	403.24	405.91
	406.23	403.91	400.02	395.95	392.3	388.84	385.49	383.28	383.95	389.14	400.06

	418.78	448.24	489.37	536.8	578.37	601.19	599.78	579.67	552.82	530.09	516.03
	509.49	507.19	506.56								
394.97	395	395.11	395.34	395.58	395.67	395.56	395.72	396.78	399.05	401.79	403.6
	403.25	400.63	396.69	392.52	388.42	384.01	379.29	375.6	375.09	379.67	390.51
	409.53	439.09	479.55	524.89	563.21	582.46	578.33	556.86	530	508.3	496.08
	491.93	491.95	492.79								
380.39	380.43	380.64	381.26	382.54	384.55	387.05	389.76	392.44	394.98	396.94	397.63
	396.42	393.37	389.29	385.01	380.6	375.57	369.96	365.43	364.39	368.94	380.05
	399.38	428.8	468.32	511.7	547.35	563.95	557.97	535.85	509.56	489.45	479.66
	478.44	481.18	483.71								
367.23	367.27	367.55	368.47	370.51	373.87	378.17	382.53	386.1	388.45	389.45	388.96
	386.85	383.28	378.95	374.52	369.92	364.6	358.64	353.86	352.78	357.54	368.89
	388.17	416.93	455.03	496.41	529.95	544.91	538.22	516.45	491.44	473.41	466.27
	467.95	473.26	477.3								
355.41	355.46	355.79	356.91	359.44	363.69	369.12	374.44	378.37	380.27	380.28	378.7
	375.77	371.72	367.18	362.65	358.03	352.78	346.96	342.38	341.55	346.47	357.76
	376.54	404.21	440.67	480.12	511.98	525.99	519.35	498.53	475.19	459.28	454.56
	458.6	465.82	470.93								
344.71	344.77	345.13	346.36	349.2	353.98	360.1	365.94	369.93	371.29	370.38	367.88
	364.3	359.95	355.33	350.87	346.45	341.55	336.25	332.19	331.68	336.56	347.37
	365.22	391.51	426.22	463.82	494.21	507.57	501.25	481.58	459.88	445.86	443.02
	448.68	457.05	462.74								
334.84	334.89	335.26	336.53	339.52	344.59	351.08	357.17	361.03	361.79	360.03	356.74
	352.75	348.38	344	339.89	335.9	331.56	326.94	323.5	323.27	327.91	337.96
	354.62	379.39	412.31	448.14	477.14	489.91	483.91	465.25	444.94	432.32	430.67
	437.15	445.96	451.81								
325.28	325.33	325.69	326.94	329.93	335.07	341.66	347.74	351.33	351.46	348.92	345.02
	340.87	336.82	333.05	329.59	326.18	322.4	318.34	315.38	315.37	319.81	329.24
	344.86	368.24	399.48	433.61	461.29	473.45	467.63	449.71	430.32	418.49	417.34
	423.98	432.73	438.47								
315.3	315.34	315.68	316.89	319.81	324.86	331.35	337.22	340.38	339.87	336.63	332.31
	328.28	324.88	322.05	319.46	316.67	313.24	309.4	306.61	306.73	311.22	320.54
	335.74	358.24	388.2	420.96	447.59	459.26	453.4	435.65	416.41	404.57	403.2
	409.46	417.81	423.3								
303.39	303.5	303.93	305.23	308.2	313.21	319.54	325.15	327.97	327.06	323.51	319.15
	315.5	312.87	310.96	309.14	306.74	303.34	299.33	296.39	296.61	301.49	311.39
	326.93	349.25	378.52	410.55	436.73	448.22	442.05	423.68	403.51	390.68	388.4
	393.91	401.72	406.91								
287.8	288.2	289.14	291.02	294.44	299.66	305.98	311.51	314.3	313.53	310.29	306.41
	303.39	301.49	300.27	298.88	296.56	292.89	288.47	285.21	285.49	290.9	301.7
	318	340.66	369.85	402	428.57	440.39	433.72	413.85	391.58	376.76	372.95
	377.48	384.71	389.63								
266.19	267.44	269.83	273.26	277.85	283.6	290.01	295.63	298.86	298.96	296.85	294.12
	292.09	290.9	290.07	288.77	286.29	282.31	277.56	274.06	274.37	280.17	291.67
	308.58	331.65	361.17	394.2	422.05	434.83	427.65	405.71	380.49	362.94	357.21
	360.66	367.38	372.13								
238	240.83	245.89	252.09	258.6	265.02	271.35	276.97	280.91	282.43	282.14	281.2
	280.6	280.33	279.93	278.71	276.15	272.04	267.19	263.56	263.74	269.4	280.85
	297.69	320.87	351.02	385.71	415.79	430.29	422.98	398.92	370.45	349.83	341.91
	344.16	350.35	354.93								

204.87	209.85	218.48	228.33	237.22	244.25	250.16	255.51	260.18	263.42	265.38	266.69
	267.99	269.01	269.31	268.38	265.97	261.98	257.19	253.4	253.1	257.96	268.46
	284.4	307.31	338.37	375.48	408.78	425.88	419.1	393.31	361.73	337.96	327.68
	328.54	334.07	338.4								
172.07	179.09	191.1	204.36	215.46	222.99	228.43	233.5	238.88	243.78	248.01	251.68
	255.08	257.63	258.87	258.46	256.34	252.5	247.59	243.28	241.97	245.33	254.07
	268.47	290.87	323.15	363.38	400.65	420.96	415.22	388.14	353.79	327.05	314.4
	313.67	318.26	322.15								
144.89	153.07	167.05	182.36	194.9	203.01	208.53	213.83	220.03	226.43	232.64	238.48
	243.85	247.88	250.07	250.17	248.29	244.39	239.02	233.8	231.08	232.62	239.3
	251.95	273.8	307.42	350.85	391.97	415.16	410.17	381.8	345.09	315.97	301.41
	299.28	302.86	306.19								
126.77	134.89	148.83	164.28	177.24	186.11	192.58	198.9	206.13	213.75	221.49	229.08
	236.08	241.33	244.24	244.68	242.83	238.64	232.55	226.22	222.04	221.86	226.68
	237.81	259.19	293.96	339.9	383.69	408.35	402.98	373.01	334.49	304.06	288.57
	285.58	288.3	291.06								

116.85	123.99	136.37	150.51	163.14	172.9	180.93	188.79	197.1	205.67	214.51	223.46
	231.73	237.9	241.28	241.89	239.95	235.41	228.67	221.43	216.16	214.77	218.33
	228.45	249.54	284.99	332.29	377.01	401.34	394.29	362.45	322.8	292.27	276.95
	273.83	276.02	278.31								
112.52	118.41	128.82	141.24	153.25	163.81	173.38	182.7	191.89	201.09	210.66	220.6
	229.78	236.59	240.25	240.93	238.88	234.08	226.91	219.14	213.27	211.24	214.17
	223.78	244.72	280.44	328.1	372.5	395.46	386.28	352.76	312.63	282.74	268.2
	265.37	267.28	269.24								
110.97	116.05	125.17	136.46	148.04	159.07	169.57	179.74	189.42	198.92	208.88	219.36
	229.06	236.21	240.02	240.72	238.62	233.71	226.38	218.4	212.32	210.06	212.78
	222.22	243.11	278.88	326.49	370.34	392.14	381.5	347.01	306.75	277.48	263.6
	261.06	262.87	264.66	]'; % in deg. C							

fc_extmp_map=flipplr(fc_extmp_map);

% (g/s), engine out total exhaust flow indexed vertically by fc_map_spd and

% horizontally by fc_map_trq

fc_exflow_map=	33.41	34.76	37.14	39.89	42.31	44	45.12	46.34	48.3	51.21
	54.71	58.32	61.74	64.97	67.9	70.43	72.5	74.36	76.29	78.39
	82.91	85.27	87.56	89.57	91.13	92.35	93.49	94.79	96.32	97.96
	101.19	102.78	104.25	105.42	106.08					
	31.73	33.26	35.95	39.07	41.83	43.75	44.99	46.25	48.19	51.06
31.73	61.52	64.79	67.78	70.38	72.51	74.41	76.36	78.46	80.68	82.96
	87.62	89.68	91.36	92.76	94.06	95.46	96.97	98.5	100.02	101.51
	104.39	105.5	106.12							
	29.29	31.04	34.13	37.72	40.92	43.17	44.62	45.97	47.92	50.74
	61.1	64.45	67.56	70.28	72.53	74.51	76.5	78.61	80.81	83.07
29.29	87.74	89.88	91.74	93.39	94.96	96.51	98	99.42	100.78	102.12
	104.69	105.67	106.21							
	27.15	28.97	32.22	36.04	39.52	42.08	43.82	45.37	47.42	50.24
	60.56	64	67.26	70.15	72.55	74.65	76.71	78.83	81.01	83.25
	87.9	90.11	92.13	94.03	95.85	97.56	99.09	100.47	101.74	102.96
27.15	105.15	105.92	106.34							
	25.72	27.4	30.4	34.03	37.51	40.3	42.43	44.37	46.67	49.58
	59.92	63.48	66.91	69.98	72.56	74.8	76.93	79.07	81.23	83.45
	88.08	90.33	92.46	94.53	96.52	98.36	99.96	101.39	102.67	103.85
	105.66	106.21	106.49							
25.72	24.87	26.19	28.6	31.67	34.89	37.86	40.48	42.98	45.68	48.77
	59.22	62.91	66.51	69.78	72.53	74.91	77.12	79.29	81.44	83.63

	88.25	90.52	92.72	94.88	96.95	98.85	100.53	102.04	103.41	104.59	105.5
	106.11	106.47	106.63								
24.29	25.17	26.85	29.19	32.01	35.08	38.21	41.34	44.52	47.85	51.28	54.82
	58.46	62.28	66.05	69.51	72.42	74.93	77.2	79.39	81.55	83.76	86.05
	88.39	90.69	92.93	95.12	97.21	99.12	100.83	102.41	103.86	105.07	105.92
	106.41	106.63	106.71								
23.86	24.35	25.36	27.01	29.38	32.45	35.95	39.63	43.27	46.86	50.39	53.96
	57.66	61.62	65.57	69.19	72.23	74.81	77.13	79.36	81.55	83.78	86.11
	88.47	90.8	93.08	95.29	97.37	99.25	100.96	102.57	104.06	105.29	106.11
	106.54	106.7	106.74								
23.58	23.8	24.34	25.45	27.4	30.31	33.96	37.98	41.98	45.8	49.43	53.04
	56.82	60.91	65.02	68.79	71.92	74.54	76.89	79.17	81.42	83.71	86.07
	88.46	90.82	93.13	95.35	97.42	99.29	100.99	102.62	104.12	105.35	106.15
	106.54	106.67	106.7								
23.43	23.51	23.78	24.53	26.11	28.75	32.35	36.5	40.69	44.65	48.31	51.91
	55.73	59.94	64.22	68.15	71.39	74.09	76.51	78.85	81.17	83.52	85.91
	88.32	90.69	93	95.23	97.32	99.22	100.96	102.61	104.12	105.32	106.08
	106.45	106.56	106.58								
23.34	23.37	23.51	24.04	25.33	27.7	31.12	35.21	39.4	43.31	46.85	50.33
	54.11	58.39	62.82	66.92	70.34	73.22	75.81	78.3	80.73	83.14	85.58
	88.01	90.38	92.68	94.92	97.05	99.02	100.84	102.55	104.06	105.22	105.93
	106.26	106.36	106.37								
23.23	23.24	23.34	23.74	24.84	26.97	30.17	34.05	38.04	41.69	44.95	48.17
	51.8	56.06	60.56	64.8	68.43	71.57	74.45	77.19	79.82	82.39	84.96
	87.5	89.93	92.26	94.52	96.68	98.72	100.63	102.38	103.89	105.02	105.69
	105.99	106.07	106.08								
23.06	23.07	23.14	23.49	24.47	26.41	29.35	32.92	36.56	39.84	42.73	45.64
	49.03	53.12	57.53	61.78	65.52	68.91	72.11	75.21	78.18	81.07	83.94
	86.75	89.39	91.84	94.14	96.33	98.4	100.33	102.1	103.6	104.71	105.36
	105.64	105.72	105.73								
22.82	22.82	22.9	23.22	24.12	25.87	28.51	31.71	34.96	37.88	40.47	43.13
	46.27	50.1	54.26	58.31	61.97	65.44	68.87	72.33	75.74	79.12	82.5
	85.79	88.81	91.49	93.88	96.07	98.11	100.01	101.75	103.22	104.31	104.95
	105.25	105.35	105.37								
22.53	22.54	22.61	22.92	23.75	25.31	27.64	30.45	33.35	36.03	38.48	41.01
	43.98	47.52	51.33	55.03	58.43	61.76	65.27	69	72.88	76.86	80.89
	84.76	88.23	91.18	93.69	95.88	97.86	99.69	101.36	102.79	103.85	104.51
	104.84	104.98	105.04								
22.22	22.23	22.31	22.61	23.35	24.74	26.77	29.25	31.87	34.42	36.85	39.37
	42.23	45.55	49.04	52.37	55.42	58.51	61.93	65.83	70.12	74.69	79.35
	83.78	87.65	90.84	93.44	95.64	97.57	99.34	100.95	102.32	103.36	104.02
	104.41	104.62	104.73								
21.92	21.93	22.01	22.28	22.96	24.18	25.97	28.19	30.61	33.08	35.52	38.06
	40.86	44.02	47.27	50.31	53.08	55.92	59.22	63.21	67.82	72.87	78.05
	82.9	87.04	90.37	93.03	95.24	97.16	98.89	100.46	101.79	102.79	103.48
	103.92	104.21	104.37								
21.61	21.62	21.69	21.94	22.55	23.65	25.25	27.27	29.53	31.92	34.33	36.86
	39.61	42.67	45.77	48.65	51.23	53.9	57.11	61.13	65.96	71.35	76.88
	82.01	86.31	89.72	92.41	94.64	96.56	98.29	99.82	101.13	102.12	102.83
	103.33	103.69	103.89								
21.23	21.24	21.31	21.54	22.1	23.11	24.58	26.44	28.57	30.85	33.2	35.67
	38.37	41.35	44.37	47.16	49.65	52.23	55.39	59.44	64.39	69.98	75.72
	81.02	85.43	88.89	91.61	93.86	95.8	97.52	99.03	100.32	101.32	102.06
	102.61	103.02	103.25								

20.76	20.77	20.83	21.05	21.57	22.51	23.89	25.64	27.65	29.83	32.09	34.49
	37.13	40.06	43.04	45.79	48.24	50.77	53.9	57.95	62.96	68.66	74.53
	79.95	84.43	87.94	90.7	92.97	94.91	96.62	98.12	99.4	100.41	101.19
	101.78	102.22	102.47								
20.16	20.17	20.23	20.44	20.93	21.82	23.13	24.8	26.72	28.81	30.98	33.3
	35.89	38.8	41.77	44.5	46.94	49.46	52.57	56.62	61.66	67.43	73.39
	78.88	83.41	86.95	89.73	92.01	93.96	95.67	97.16	98.43	99.46	100.27
	100.9	101.37	101.63								
19.44	19.44	19.5	19.69	20.16	21.01	22.26	23.87	25.72	27.72	29.8	32.06
	34.61	37.5	40.47	43.22	45.66	48.18	51.29	55.36	60.45	66.29	72.33
	77.86	82.42	85.96	88.74	91.04	93	94.71	96.2	97.49	98.54	99.39
	100.06	100.55	100.83								
18.56	18.56	18.61	18.79	19.24	20.05	21.25	22.8	24.58	26.5	28.51	30.71
	33.22	36.09	39.06	41.82	44.29	46.83	49.97	54.06	59.18	65.08	71.17
	76.77	81.35	84.91	87.71	90.03	92.02	93.77	95.29	96.6	97.69	98.57
	99.27	99.79	100.08								
17.45	17.46	17.51	17.69	18.12	18.91	20.07	21.57	23.29	25.17	27.13	29.29
	31.75	34.58	37.52	40.28	42.79	45.39	48.57	52.66	57.73	63.6	69.71
	75.37	80.05	83.68	86.55	88.94	91.02	92.84	94.43	95.79	96.91	97.81
	98.53	99.06	99.36								
16.1	16.1	16.16	16.35	16.8	17.61	18.77	20.25	21.95	23.79	25.74	27.87
	30.28	33.03	35.9	38.65	41.24	43.97	47.22	51.23	56.11	61.77	67.79
	73.52	78.37	82.18	85.2	87.74	89.96	91.91	93.59	95	96.15	97.06
	97.78	98.31	98.6								
14.55	14.56	14.61	14.83	15.34	16.21	17.42	18.91	20.59	22.42	24.34	26.43
	28.76	31.41	34.18	36.94	39.65	42.58	45.94	49.87	54.45	59.75	65.6
	71.36	76.42	80.47	83.7	86.43	88.83	90.94	92.73	94.21	95.38	96.29
	97	97.51	97.8								
13.06	13.05	13.1	13.35	13.92	14.86	16.13	17.63	19.27	21.01	22.83	24.82
	27.06	29.59	32.28	35.04	37.9	41.06	44.58	48.45	52.76	57.71	63.34
	69.11	74.35	78.63	82.08	85	87.59	89.85	91.76	93.32	94.54	95.46
	96.15	96.64	96.91								
11.84	11.82	11.85	12.11	12.72	13.72	15.01	16.46	17.96	19.51	21.14	22.97
	25.07	27.48	30.09	32.84	35.79	39.13	42.83	46.74	50.94	55.69	61.19
	66.96	72.32	76.75	80.37	83.43	86.16	88.55	90.59	92.25	93.54	94.5
	95.2	95.68	95.94								
11.06	11.01	11.01	11.26	11.89	12.89	14.15	15.48	16.78	18.06	19.43	21.04
	23	25.31	27.83	30.5	33.43	36.8	40.59	44.61	48.87	53.63	59.11
	64.89	70.32	74.84	78.56	81.72	84.55	87.04	89.19	90.96	92.34	93.36
	94.09	94.57	94.83								
10.66	10.57	10.53	10.76	11.38	12.37	13.57	14.76	15.84	16.86	17.97	19.39
	21.22	23.44	25.87	28.41	31.18	34.42	38.2	42.32	46.74	51.64	57.2
	63.02	68.48	73.05	76.83	80.05	82.95	85.5	87.72	89.55	91.01	92.08
	92.85	93.35	93.61								
10.49	10.37	10.29	10.48	11.09	12.07	13.23	14.32	15.24	16.07	17.01	18.29
	20.04	22.2	24.55	26.93	29.49	32.52	36.19	40.35	44.92	49.97	55.64
	61.5	66.99	71.58	75.4	78.67	81.62	84.22	86.46	88.29	89.74	90.82
	91.6	92.11	92.38								
10.43	10.27	10.15	10.31	10.9	11.89	13.04	14.1	14.95	15.68	16.53	17.74
	19.45	21.58	23.87	26.14	28.52	31.37	34.92	39.06	43.72	48.87	54.62
	60.52	66.01	70.62	74.47	77.79	80.79	83.42	85.63	87.4	88.77	89.79
	90.54	91.05	91.33								
10.39	10.22	10.06	10.19	10.78	11.78	12.95	14.01	14.85	15.56	16.37	17.56
	19.25	21.37	23.63	25.84	28.12	30.85	34.32	38.44	43.12	48.32	54.1

	60.02	65.52	70.14	74.01	77.38	80.42	83.06	85.24	86.92	88.18	89.12
	89.82	90.31	90.57								
10.37	10.19	10.01	10.12	10.7	11.72	12.9	13.98	14.82	15.53	16.34	17.53
	19.21	21.32	23.58	25.76	28.01	30.69	34.13	38.23	42.93	48.14	53.93
	59.86	65.36	69.98	73.87	77.25	80.32	82.97	85.12	86.75	87.94	88.81
	89.47	89.94	90.19	]'; % in cubic m/s							

fc_exflow_map=flipplr(fc_exflow_map);

% (m^3/s), engine out total volume exhaust flow indexed vertically by fc_map_spd and
% horizontally by fc_map_trq

	fc_exflow_vol_map=[0.066			0.068	0.073	0.078	0.082	0.085	0.088	0.09	0.094
	0.101	0.109	0.117	0.126	0.135	0.144	0.152	0.158	0.164	0.17	0.176
	0.183	0.19	0.197	0.204	0.211	0.219	0.229	0.241	0.258	0.276	0.293
	0.305	0.307	0.301	0.29	0.28	0.274					
0.063	0.065	0.07	0.076	0.081	0.085	0.087	0.09	0.094	0.1	0.108	0.117
	0.125	0.135	0.144	0.152	0.158	0.164	0.17	0.177	0.183	0.19	0.197
	0.204	0.213	0.222	0.234	0.249	0.265	0.282	0.297	0.306	0.306	0.299
	0.289	0.279	0.273								
0.058	0.061	0.067	0.074	0.08	0.084	0.087	0.089	0.093	0.099	0.107	0.115
	0.124	0.133	0.142	0.151	0.158	0.164	0.17	0.177	0.183	0.19	0.197
	0.205	0.215	0.227	0.242	0.26	0.277	0.292	0.302	0.306	0.304	0.296
	0.286	0.277	0.272								
0.054	0.057	0.063	0.07	0.077	0.082	0.085	0.088	0.092	0.098	0.105	0.113
	0.122	0.131	0.141	0.149	0.156	0.163	0.169	0.176	0.183	0.19	0.197
	0.206	0.217	0.231	0.25	0.27	0.288	0.301	0.306	0.305	0.299	0.291
	0.282	0.275	0.271								
0.051	0.054	0.06	0.067	0.073	0.078	0.082	0.086	0.09	0.096	0.103	0.111
	0.119	0.129	0.138	0.147	0.154	0.161	0.168	0.175	0.182	0.189	0.197
	0.206	0.218	0.235	0.256	0.278	0.296	0.305	0.306	0.301	0.293	0.284
	0.277	0.272	0.27								
0.05	0.052	0.057	0.062	0.068	0.073	0.078	0.083	0.088	0.094	0.101	0.108
	0.116	0.126	0.135	0.143	0.151	0.158	0.166	0.173	0.18	0.187	0.195
	0.205	0.218	0.237	0.259	0.282	0.299	0.307	0.305	0.296	0.287	0.279
	0.273	0.27	0.268								
0.049	0.05	0.053	0.058	0.063	0.068	0.073	0.079	0.085	0.091	0.098	0.105
	0.113	0.122	0.131	0.14	0.148	0.155	0.162	0.169	0.177	0.184	0.193
	0.204	0.218	0.238	0.261	0.284	0.3	0.306	0.302	0.292	0.282	0.275
	0.27	0.268	0.267								
0.048	0.049	0.051	0.053	0.058	0.063	0.069	0.075	0.082	0.089	0.095	0.102
	0.11	0.119	0.127	0.136	0.143	0.151	0.158	0.165	0.173	0.18	0.19
	0.201	0.217	0.237	0.261	0.283	0.298	0.303	0.298	0.289	0.279	0.272
	0.268	0.267	0.267								
0.047	0.048	0.049	0.051	0.054	0.059	0.065	0.072	0.079	0.086	0.093	0.1
	0.107	0.115	0.124	0.132	0.139	0.146	0.153	0.16	0.168	0.176	0.185
	0.198	0.214	0.235	0.258	0.28	0.294	0.298	0.294	0.285	0.276	0.27
	0.266	0.265	0.265								
0.047	0.047	0.048	0.049	0.052	0.056	0.062	0.069	0.076	0.083	0.09	0.097
	0.104	0.112	0.121	0.128	0.136	0.142	0.148	0.155	0.162	0.171	0.181
	0.193	0.209	0.229	0.252	0.273	0.287	0.291	0.287	0.279	0.271	0.266
	0.263	0.263	0.262								
0.047	0.047	0.047	0.048	0.05	0.054	0.059	0.066	0.073	0.08	0.087	0.094
	0.101	0.109	0.117	0.125	0.132	0.138	0.144	0.151	0.158	0.166	0.175
	0.187	0.203	0.222	0.244	0.264	0.277	0.281	0.278	0.271	0.265	0.261
	0.259	0.258	0.257								

0.046	0.046	0.046	0.047	0.049	0.052	0.058	0.064	0.071	0.078	0.084	0.09
	0.097	0.105	0.113	0.121	0.127	0.134	0.14	0.146	0.153	0.161	0.17
	0.181	0.196	0.214	0.234	0.253	0.266	0.27	0.268	0.263	0.257	0.254
	0.252	0.251	0.251								
0.045	0.046	0.046	0.046	0.048	0.051	0.056	0.062	0.068	0.074	0.08	0.086
	0.092	0.1	0.108	0.115	0.122	0.128	0.134	0.141	0.148	0.155	0.165
	0.175	0.189	0.206	0.225	0.243	0.255	0.26	0.258	0.254	0.249	0.246
	0.244	0.243	0.243								
0.044	0.044	0.044	0.045	0.047	0.049	0.054	0.06	0.065	0.071	0.076	0.082
	0.088	0.095	0.102	0.109	0.115	0.122	0.128	0.135	0.142	0.15	0.159
	0.171	0.184	0.201	0.219	0.236	0.247	0.251	0.25	0.245	0.241	0.238
	0.237	0.236	0.236								
0.043	0.043	0.043	0.044	0.045	0.048	0.052	0.057	0.063	0.068	0.073	0.078
	0.083	0.09	0.097	0.103	0.109	0.115	0.121	0.127	0.135	0.144	0.154
	0.166	0.181	0.197	0.215	0.231	0.241	0.244	0.242	0.237	0.233	0.231
	0.23	0.229	0.229								
0.041	0.041	0.042	0.042	0.044	0.046	0.05	0.055	0.06	0.065	0.07	0.075
	0.08	0.086	0.092	0.098	0.103	0.108	0.113	0.12	0.128	0.138	0.149
	0.162	0.177	0.194	0.212	0.226	0.235	0.237	0.235	0.23	0.226	0.224
	0.224	0.224	0.225								
0.04	0.04	0.04	0.041	0.042	0.045	0.048	0.052	0.057	0.062	0.067	0.072
	0.077	0.082	0.088	0.093	0.097	0.102	0.107	0.114	0.122	0.133	0.145
	0.159	0.174	0.191	0.207	0.221	0.229	0.231	0.228	0.223	0.22	0.218
	0.219	0.22	0.221								
0.039	0.039	0.039	0.039	0.041	0.043	0.046	0.05	0.055	0.059	0.064	0.068
	0.073	0.079	0.084	0.088	0.093	0.097	0.101	0.108	0.117	0.128	0.14
	0.154	0.17	0.186	0.202	0.215	0.223	0.224	0.221	0.217	0.214	0.213
	0.215	0.217	0.219								
0.037	0.037	0.038	0.038	0.039	0.041	0.044	0.048	0.052	0.057	0.061	0.065
	0.07	0.075	0.08	0.084	0.088	0.092	0.097	0.103	0.112	0.123	0.136
	0.15	0.165	0.181	0.196	0.209	0.216	0.218	0.215	0.211	0.209	0.209
	0.211	0.214	0.216								
0.036	0.036	0.036	0.037	0.038	0.04	0.043	0.046	0.05	0.054	0.058	0.062
	0.066	0.071	0.076	0.08	0.084	0.088	0.092	0.099	0.108	0.119	0.132
	0.146	0.16	0.176	0.19	0.203	0.21	0.211	0.209	0.205	0.203	0.204
	0.207	0.21	0.212								
0.034	0.034	0.035	0.035	0.036	0.038	0.041	0.044	0.048	0.051	0.055	0.059
	0.063	0.068	0.073	0.077	0.081	0.084	0.089	0.095	0.104	0.115	0.128
	0.141	0.155	0.17	0.185	0.196	0.203	0.205	0.202	0.199	0.198	0.199
	0.202	0.205	0.207								
0.033	0.033	0.033	0.033	0.034	0.036	0.039	0.042	0.045	0.049	0.052	0.056
	0.06	0.064	0.069	0.074	0.077	0.081	0.086	0.092	0.101	0.112	0.124
	0.137	0.151	0.165	0.179	0.19	0.197	0.198	0.196	0.193	0.192	0.194
	0.197	0.2	0.202								
0.031	0.031	0.031	0.031	0.032	0.034	0.036	0.039	0.043	0.046	0.049	0.052
	0.056	0.061	0.066	0.07	0.074	0.078	0.082	0.089	0.098	0.108	0.121
	0.134	0.147	0.16	0.174	0.185	0.191	0.193	0.191	0.188	0.187	0.188
	0.192	0.195	0.197								
0.028	0.028	0.029	0.029	0.03	0.031	0.034	0.037	0.04	0.043	0.046	0.049
	0.053	0.057	0.062	0.066	0.07	0.074	0.079	0.085	0.094	0.104	0.117
	0.129	0.143	0.156	0.169	0.18	0.186	0.188	0.186	0.183	0.182	0.183
	0.186	0.189	0.191								
0.026	0.026	0.026	0.026	0.027	0.029	0.031	0.034	0.037	0.04	0.042	0.046
	0.049	0.054	0.058	0.063	0.067	0.07	0.075	0.081	0.089	0.1	0.112

	0.125	0.138	0.151	0.164	0.175	0.182	0.184	0.182	0.178	0.177	0.178
	0.18	0.183	0.185								
0.022	0.022	0.023	0.023	0.024	0.026	0.028	0.031	0.034	0.036	0.039	0.043
	0.046	0.05	0.055	0.059	0.063	0.067	0.072	0.077	0.085	0.095	0.106
	0.119	0.133	0.146	0.16	0.171	0.179	0.18	0.178	0.174	0.172	0.172
	0.174	0.177	0.179								
0.019	0.019	0.02	0.02	0.021	0.023	0.025	0.028	0.03	0.033	0.036	0.039
	0.043	0.047	0.051	0.055	0.059	0.063	0.068	0.074	0.081	0.09	0.101
	0.114	0.127	0.141	0.155	0.167	0.175	0.177	0.174	0.17	0.167	0.166
	0.168	0.171	0.173								
0.016	0.016	0.017	0.017	0.019	0.02	0.022	0.025	0.027	0.03	0.033	0.035
	0.039	0.043	0.047	0.051	0.055	0.059	0.064	0.07	0.077	0.085	0.095
	0.108	0.121	0.135	0.15	0.163	0.172	0.174	0.171	0.165	0.162	0.161
	0.163	0.165	0.166								
0.014	0.014	0.015	0.015	0.017	0.018	0.02	0.022	0.025	0.027	0.029	0.032
	0.035	0.038	0.042	0.046	0.05	0.055	0.06	0.065	0.072	0.08	0.09
	0.101	0.115	0.129	0.144	0.158	0.167	0.17	0.167	0.161	0.157	0.156
	0.157	0.159	0.16								
0.013	0.013	0.013	0.014	0.015	0.017	0.019	0.021	0.022	0.024	0.026	0.028
	0.031	0.035	0.039	0.042	0.046	0.051	0.055	0.061	0.067	0.075	0.084
	0.096	0.108	0.123	0.139	0.153	0.163	0.166	0.162	0.156	0.152	0.15
	0.151	0.153	0.154								
0.012	0.012	0.012	0.013	0.014	0.016	0.018	0.019	0.021	0.022	0.024	0.026
	0.029	0.033	0.036	0.04	0.043	0.047	0.052	0.057	0.063	0.071	0.08
	0.091	0.103	0.118	0.134	0.149	0.159	0.162	0.158	0.152	0.147	0.145
	0.145	0.147	0.148								
0.012	0.012	0.012	0.012	0.014	0.015	0.017	0.019	0.02	0.021	0.023	0.025
	0.028	0.031	0.035	0.038	0.041	0.045	0.049	0.055	0.061	0.068	0.077
	0.087	0.1	0.114	0.131	0.146	0.156	0.158	0.154	0.147	0.142	0.14
	0.141	0.142	0.143								
0.011	0.011	0.012	0.012	0.013	0.015	0.017	0.018	0.02	0.021	0.023	0.025
	0.028	0.031	0.034	0.038	0.041	0.044	0.048	0.053	0.059	0.067	0.075
	0.086	0.098	0.113	0.129	0.144	0.154	0.155	0.151	0.144	0.139	0.137
	0.138	0.139	0.14								
0.011	0.011	0.011	0.012	0.013	0.015	0.016	0.018	0.02	0.021	0.022	0.025
	0.027	0.031	0.034	0.038	0.041	0.044	0.048	0.053	0.059	0.066	0.075
	0.085	0.097	0.112	0.128	0.143	0.153	0.154	0.149	0.142	0.137	0.135
	0.136	0.137	0.138								

];

fc_exflow_vol_map=flipplr(fc_exflow_vol_map);

% adjust ex gas temperature map to estimate temperature drop across manifold & turbo

% assume delta T is equal to 10% of the temp diff between gas temp and 20 C ambient

fc_extmp_map=fc_extmp_map + (fc_extmp_map - 20)*0.1;

% create BS** maps for plotting purposes

[T,w]=meshgrid(fc_map_trq(2:end),fc_map_spd);

fc_map_kW=T.*w/1000;

fc_fuel_map_gpkW-h=fc_fuel_map(:,2:end)./fc_map_kW*3600;

fc_co_map_gpkW-h=fc_co_map(:,2:end)./fc_map_kW*3600;

fc_hc_map_gpkW-h=fc_hc_map(:,2:end)./fc_map_kW*3600;

fc_nox_map_gpkW-h=fc_nox_map(:,2:end)./fc_map_kW*3600;

fc_pm_map_gpkW-h=fc_pm_map(:,2:end)./fc_map_kW*3600;

% replace zero torque column values

```

fc_fuel_map_gpkW-h=[fc_fuel_map_gpkW-h(:,1)*1.1 fc_fuel_map_gpkW-h];
fc_co_map_gpkW-h=[fc_co_map_gpkW-h(:,1)*1.1 fc_co_map_gpkW-h];
fc_nox_map_gpkW-h=[fc_nox_map_gpkW-h(:,1)*1.1 fc_nox_map_gpkW-h];
fc_hc_map_gpkW-h=[fc_hc_map_gpkW-h(:,1)*1.1 fc_hc_map_gpkW-h];
fc_pm_map_gpkW-h=[fc_pm_map_gpkW-h(:,1)*1.1 fc_pm_map_gpkW-h];

```

```

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

```

```

% Cold Engine Maps

```

```

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

```

```

% For cold testing:

```

```

%This spreadsheet contains an engine map for a Volkswagen 1.9 liter turbocharged, direct-injection diesel
%engine. The map was developed through CIDI Benchmarking activities of the Office of Advanced
%Automotive Technology, of the U.S. Department of Energy. The mapping exercise was carried out by
%staff members of the Advanced Propulsion Technology Center at Oak Ridge National Laboratory in
%1999.

```

```

%

```

```

%The mapping was conducted on an engine that was force-cooled but operating normally. The engine was
%equipped with an alternator, but otherwise without accessory loads. An engine map suitable for use with
%the ADVISOR model was subsequently produced from this data and delivered to NREL for inclusion
%with the model.

```

```

%

```

```

%Force-cooling was accomplished by maintaining the engine coolant temperature at ~70 F. Engine intake
%air was also maintained at ~70 F. Ambient temperature during the test was not controlled, but was not
%higher than ~90 F.

```

```

%

```

```

%Exhaust emissions tables are in units of mg/s, fuel consumption is in g/s, exhaust temperature is in
%degrees C. Exhaust flow has been reported both gravimetrically (g/s) and volumetrically (cubic meters
% per second).

```

```

%

```

```

fc_cold_tmp=[21.1]; %deg C

```

```

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

```

```

% COLD FUEL USE AND EMISSIONS MAPS

```

```

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

```

```

% (g/s) , fuel use map indexed vertically by fc_map_spd and

```

```

% horizontally by fc_map_trq

```

```

fc_fuel_map_cold=[

```

1.26	1.33	1.46	1.61	1.74	1.83	1.89	1.94	2.02	2.14	2.28	2.42
	2.53	2.62	2.7	2.78	2.87	3.01	3.19	3.39	3.57	3.71	3.82
	3.89	3.94	3.99	4.03	4.08	4.14	4.2	4.27	4.33	4.38	4.41
	4.43	4.44	4.45								
1.26	1.33	1.46	1.6	1.73	1.82	1.88	1.94	2.02	2.13	2.27	2.4
	2.51	2.61	2.69	2.77	2.87	3.01	3.19	3.39	3.58	3.72	3.82
	3.89	3.95	4	4.05	4.1	4.17	4.23	4.29	4.34	4.38	4.41
	4.43	4.44	4.45								
1.26	1.32	1.44	1.58	1.71	1.8	1.86	1.92	2	2.11	2.24	2.36
	2.47	2.57	2.66	2.75	2.86	3.01	3.19	3.4	3.58	3.72	3.82
	3.89	3.95	4.01	4.08	4.14	4.21	4.27	4.32	4.36	4.39	4.42
	4.43	4.44	4.45								
1.25	1.3	1.41	1.53	1.65	1.75	1.82	1.89	1.97	2.08	2.19	2.31
	2.42	2.52	2.62	2.72	2.84	3	3.19	3.39	3.57	3.71	3.81
	3.88	3.95	4.03	4.1	4.18	4.25	4.31	4.36	4.39	4.41	4.43
	4.44	4.45	4.45								
1.23	1.28	1.36	1.46	1.57	1.67	1.76	1.84	1.93	2.03	2.14	2.25
	2.36	2.46	2.56	2.67	2.8	2.97	3.17	3.37	3.54	3.68	3.78

	3.86	3.94	4.02	4.11	4.2	4.28	4.34	4.38	4.4	4.42	4.43
	4.44	4.45	4.45								
1.22	1.25	1.3	1.38	1.48	1.57	1.67	1.77	1.87	1.97	2.08	2.18
	2.29	2.39	2.49	2.6	2.74	2.92	3.12	3.32	3.49	3.62	3.73
	3.82	3.91	4	4.1	4.2	4.29	4.35	4.39	4.41	4.43	4.44
	4.45	4.45	4.45								
1.2	1.22	1.25	1.31	1.39	1.48	1.58	1.69	1.79	1.9	2	2.11
	2.2	2.3	2.4	2.52	2.66	2.84	3.04	3.24	3.41	3.54	3.65
	3.75	3.85	3.96	4.07	4.18	4.27	4.33	4.38	4.41	4.43	4.44
	4.45	4.45	4.46								
1.19	1.2	1.22	1.25	1.32	1.4	1.5	1.61	1.72	1.82	1.93	2.03
	2.12	2.21	2.31	2.43	2.56	2.74	2.94	3.13	3.3	3.44	3.56
	3.66	3.77	3.88	4	4.11	4.21	4.29	4.35	4.39	4.43	4.44
	4.45	4.46	4.46								
1.18	1.19	1.2	1.22	1.27	1.34	1.44	1.54	1.64	1.75	1.85	1.95
	2.04	2.13	2.23	2.33	2.46	2.63	2.82	3.01	3.18	3.32	3.45
	3.56	3.68	3.79	3.91	4.02	4.12	4.21	4.29	4.36	4.4	4.43
	4.45	4.45	4.45								
1.17	1.17	1.18	1.2	1.24	1.3	1.38	1.48	1.58	1.68	1.79	1.89
	1.98	2.07	2.15	2.25	2.37	2.53	2.71	2.89	3.06	3.2	3.33
	3.46	3.57	3.68	3.79	3.9	4	4.1	4.19	4.28	4.35	4.4
	4.42	4.43	4.43								
1.16	1.16	1.16	1.18	1.21	1.26	1.34	1.42	1.52	1.63	1.73	1.83
	1.92	2	2.09	2.18	2.29	2.44	2.61	2.78	2.95	3.09	3.22
	3.34	3.46	3.56	3.66	3.75	3.84	3.94	4.06	4.17	4.26	4.32
	4.35	4.35	4.36								
1.13	1.13	1.13	1.15	1.18	1.22	1.29	1.38	1.47	1.57	1.67	1.77
	1.85	1.94	2.02	2.11	2.22	2.36	2.52	2.69	2.85	2.99	3.12
	3.23	3.33	3.42	3.51	3.58	3.67	3.77	3.88	4	4.1	4.17
	4.2	4.21	4.21								
1.09	1.09	1.09	1.11	1.13	1.18	1.25	1.33	1.42	1.51	1.61	1.7
	1.78	1.86	1.94	2.03	2.14	2.28	2.44	2.61	2.76	2.9	3.01
	3.11	3.2	3.28	3.35	3.42	3.49	3.58	3.69	3.8	3.89	3.96
	3.99	4	4								
1.05	1.05	1.05	1.06	1.09	1.13	1.19	1.27	1.35	1.44	1.53	1.62
	1.7	1.78	1.86	1.95	2.06	2.19	2.35	2.52	2.67	2.79	2.9
	2.99	3.06	3.13	3.2	3.26	3.32	3.4	3.49	3.59	3.67	3.72
	3.74	3.75	3.75								
1	1	1.01	1.02	1.04	1.08	1.13	1.2	1.29	1.37	1.46	1.54
	1.62	1.7	1.78	1.87	1.97	2.1	2.26	2.42	2.56	2.67	2.77
	2.85	2.92	2.98	3.04	3.1	3.17	3.25	3.33	3.41	3.47	3.51
	3.53	3.53	3.54								
0.96	0.96	0.96	0.97	0.99	1.03	1.08	1.14	1.22	1.31	1.39	1.48
	1.55	1.63	1.71	1.79	1.89	2.01	2.16	2.3	2.44	2.54	2.63
	2.7	2.77	2.83	2.89	2.96	3.03	3.11	3.19	3.26	3.32	3.36
	3.37	3.38	3.38								
0.92	0.92	0.92	0.93	0.95	0.98	1.03	1.09	1.17	1.25	1.33	1.42
	1.49	1.56	1.64	1.71	1.8	1.91	2.05	2.18	2.31	2.41	2.49
	2.57	2.63	2.7	2.76	2.83	2.91	2.99	3.07	3.15	3.21	3.25
	3.26	3.27	3.27								
0.88	0.88	0.88	0.89	0.91	0.94	0.99	1.05	1.12	1.2	1.28	1.36
	1.43	1.5	1.56	1.63	1.71	1.81	1.93	2.05	2.17	2.28	2.37
	2.45	2.52	2.58	2.65	2.72	2.8	2.88	2.96	3.04	3.1	3.14
	3.16	3.17	3.17								

0.84	0.84	0.85	0.86	0.87	0.91	0.95	1.01	1.08	1.15	1.22	1.3
	1.36	1.42	1.49	1.55	1.61	1.7	1.8	1.92	2.04	2.15	2.25
	2.34	2.42	2.49	2.56	2.63	2.7	2.78	2.85	2.92	2.98	3.02
	3.04	3.04	3.04								
0.8	0.8	0.8	0.81	0.83	0.87	0.91	0.97	1.03	1.1	1.17	1.23
	1.29	1.35	1.41	1.47	1.52	1.6	1.69	1.8	1.92	2.04	2.14
	2.24	2.32	2.4	2.48	2.55	2.62	2.68	2.75	2.81	2.86	2.89
	2.91	2.91	2.91								
0.76	0.76	0.76	0.77	0.79	0.82	0.86	0.92	0.98	1.04	1.1	1.16
	1.22	1.28	1.34	1.39	1.44	1.51	1.6	1.7	1.81	1.92	2.03
	2.13	2.23	2.31	2.39	2.47	2.53	2.59	2.65	2.7	2.75	2.78
	2.79	2.79	2.79								
0.71	0.71	0.71	0.72	0.74	0.77	0.81	0.86	0.92	0.98	1.04	1.09
	1.15	1.21	1.27	1.32	1.37	1.43	1.51	1.6	1.71	1.81	1.92
	2.02	2.12	2.21	2.29	2.37	2.44	2.5	2.56	2.62	2.66	2.7
	2.71	2.72	2.72								
0.66	0.66	0.66	0.67	0.68	0.71	0.75	0.8	0.86	0.91	0.96	1.02
	1.07	1.13	1.19	1.25	1.3	1.36	1.43	1.51	1.61	1.7	1.8
	1.9	1.99	2.09	2.18	2.26	2.33	2.4	2.48	2.55	2.61	2.65
	2.67	2.68	2.68								
0.61	0.61	0.61	0.62	0.63	0.66	0.69	0.74	0.79	0.84	0.89	0.94
	0.99	1.05	1.11	1.17	1.22	1.28	1.34	1.42	1.5	1.59	1.68
	1.77	1.86	1.96	2.05	2.13	2.21	2.3	2.39	2.48	2.56	2.62
	2.65	2.66	2.66								
0.55	0.55	0.56	0.56	0.58	0.6	0.64	0.68	0.73	0.77	0.82	0.87
	0.92	0.98	1.04	1.09	1.15	1.2	1.26	1.33	1.4	1.48	1.56
	1.65	1.74	1.83	1.92	2	2.09	2.18	2.29	2.4	2.5	2.57
	2.62	2.64	2.65								
0.49	0.49	0.5	0.51	0.52	0.55	0.58	0.63	0.67	0.71	0.76	0.81
	0.86	0.91	0.97	1.02	1.07	1.12	1.17	1.24	1.31	1.39	1.47
	1.54	1.62	1.71	1.79	1.88	1.97	2.07	2.18	2.3	2.41	2.51
	2.58	2.62	2.64								
0.42	0.43	0.44	0.45	0.47	0.5	0.53	0.57	0.62	0.66	0.71	0.75
	0.8	0.85	0.9	0.95	0.99	1.04	1.09	1.15	1.23	1.3	1.38
	1.46	1.53	1.61	1.69	1.78	1.87	1.96	2.07	2.18	2.3	2.42
	2.52	2.59	2.62								
0.35	0.36	0.38	0.4	0.42	0.45	0.49	0.53	0.57	0.61	0.66	0.7
	0.74	0.79	0.84	0.88	0.92	0.96	1.01	1.07	1.14	1.22	1.3
	1.38	1.45	1.53	1.61	1.7	1.79	1.87	1.96	2.07	2.19	2.32
	2.45	2.55	2.6								
0.29	0.3	0.32	0.35	0.38	0.42	0.45	0.49	0.53	0.57	0.61	0.65
	0.69	0.73	0.77	0.81	0.85	0.89	0.93	0.99	1.06	1.13	1.21
	1.29	1.37	1.45	1.54	1.64	1.73	1.81	1.88	1.97	2.08	2.23
	2.38	2.5	2.57								
0.24	0.26	0.29	0.32	0.35	0.39	0.42	0.45	0.49	0.53	0.57	0.6
	0.64	0.68	0.72	0.76	0.79	0.83	0.87	0.92	0.98	1.05	1.13
	1.21	1.29	1.37	1.47	1.58	1.67	1.75	1.82	1.9	2.01	2.15
	2.31	2.44	2.51								
0.22	0.23	0.26	0.29	0.33	0.36	0.39	0.43	0.46	0.5	0.54	0.57
	0.61	0.65	0.69	0.72	0.76	0.79	0.82	0.87	0.93	0.99	1.06
	1.14	1.21	1.3	1.4	1.5	1.61	1.69	1.76	1.84	1.95	2.08
	2.22	2.34	2.41								
0.2	0.22	0.24	0.27	0.31	0.34	0.38	0.41	0.45	0.48	0.52	0.56
	0.59	0.63	0.67	0.71	0.74	0.77	0.8	0.85	0.9	0.95	1.02

	1.09	1.16	1.24	1.33	1.43	1.53	1.62	1.71	1.8	1.89	2.01
	2.12	2.21	2.27								
0.19	0.21	0.23	0.26	0.29	0.33	0.36	0.4	0.43	0.47	0.51	0.55
	0.59	0.63	0.67	0.7	0.73	0.76	0.8	0.84	0.88	0.94	1
	1.06	1.13	1.2	1.27	1.35	1.45	1.55	1.66	1.75	1.85	1.94
	2.02	2.09	2.12								
0.19	0.2	0.23	0.25	0.28	0.32	0.35	0.39	0.43	0.47	0.51	0.55
	0.59	0.63	0.66	0.7	0.73	0.76	0.79	0.83	0.88	0.93	0.99
	1.05	1.12	1.17	1.23	1.31	1.4	1.51	1.62	1.73	1.82	1.89
	1.96	2	2.03								

];

fc_fuel_map_cold=fliplr(fc_fuel_map_cold);

% (g/s), engine out HC emissions indexed vertically by fc_map_spd and

% horizontally by fc_map_trq

fc_hc_map_cold=1e-3*[

3.82	4.61	6	7.61	9.04	10	10.5	10.72	10.87	11	10.95	10.41
	9.09	7.01	4.99	4.72	8.79	18.94	35.12	54.55	74.39	92.7	109.35
	123.28	132.43	134.22	127.72	113.24	92.35	67.45	42.69	22.35	9.23	2.78
	0.66	0.26	0.28								
3.8	4.57	5.94	7.53	8.95	9.91	10.4	10.56	10.57	10.46	10.17	9.46
	8.15	6.25	4.54	4.67	9.14	19.61	35.94	55.35	75.03	93.18	109.62
	123.06	130.98	130.51	120.92	103.69	81.66	57.9	35.87	18.56	7.64	2.33
	0.59	0.26	0.28								
3.75	4.47	5.76	7.28	8.66	9.63	10.13	10.22	9.98	9.49	8.77	7.79
	6.48	4.91	3.78	4.66	9.91	21.07	37.76	57.17	76.56	94.32	110.23
	122.7	128.53	124.46	110.17	88.82	65.14	43.21	25.4	12.76	5.22	1.65
	0.48	0.26	0.28								
3.64	4.27	5.41	6.77	8.06	9.04	9.59	9.65	9.19	8.28	7.1	5.82
	4.54	3.36	2.96	4.86	11.29	23.55	40.88	60.34	79.17	96.02	110.67
	121.46	124.74	117.07	98.48	73.63	48.83	28.94	15.34	7.21	2.9	1
	0.38	0.27	0.28								
3.48	3.97	4.87	5.99	7.15	8.14	8.77	8.86	8.28	7.07	5.54	4.04
	2.8	2.02	2.35	5.42	13.39	27.35	45.96	65.79	83.69	98.42	110.08
	117.56	117.64	107.19	86.43	60.5	36.21	18.6	8.3	3.4	1.33	0.56
	0.32	0.28	0.29								
3.3	3.63	4.25	5.1	6.07	7.04	7.77	7.96	7.38	6.05	4.37	2.78
	1.62	1.13	2.11	6.44	16.53	33.41	54.92	76.33	93.17	103.81	109.2
	110.18	105.41	92.82	72.43	48.54	27.01	12.25	4.45	1.45	0.55	0.35
	0.29	0.29	0.29								
3.14	3.33	3.7	4.28	5.07	5.99	6.78	7.07	6.57	5.29	3.62	2.07
	0.99	0.71	2.23	8.06	21.45	43.81	71.94	98.27	115.13	119.35	113.56
	102.63	89.43	73.9	55.5	36.17	19.45	8.28	2.65	0.72	0.31	0.29
	0.29	0.29	0.29								
3.04	3.12	3.32	3.7	4.33	5.17	5.97	6.34	5.95	4.78	3.21	1.75
	0.75	0.6	2.72	10.69	29.46	61.37	101.82	138.49	158.02	154.14	131.9
	102.56	75.74	54.63	37.79	23.71	12.55	5.29	1.67	0.48	0.26	0.28
	0.29	0.29	0.29								
2.98	3.01	3.11	3.38	3.89	4.64	5.42	5.83	5.52	4.46	3	1.62
	0.68	0.67	3.69	14.94	41.83	88.03	146.89	199.5	224.74	212.01	169.31
	116.1	70.67	40.46	23.11	13.13	6.79	2.93	1.02	0.39	0.28	0.29
	0.29	0.3	0.3								
2.94	2.95	3.02	3.23	3.68	4.37	5.11	5.53	5.28	4.29	2.89	1.56
	0.66	0.87	5.19	20.85	57.89	121.07	200.93	271.38	303.22	281.82	218.26

	140.41	75.1	34.09	14.18	6.22	2.97	1.39	0.6	0.34	0.29	0.3
	0.3	0.3	0.3								
2.9	2.91	2.96	3.15	3.57	4.23	4.96	5.38	5.16	4.2	2.84	1.54
	0.64	1.13	6.89	27.09	73.83	152.31	249.88	334.41	370.47	341.19	260.68
	163.45	82.64	32.9	10.23	2.85	1.08	0.63	0.41	0.33	0.32	0.32
	0.32	0.32	0.32								
2.84	2.85	2.9	3.09	3.5	4.15	4.88	5.3	5.09	4.15	2.81	1.52
	0.64	1.33	8.07	31.17	83.6	170.27	276.25	366.2	402.2	367.36	278.1
	172.21	85.19	32.31	8.81	1.71	0.46	0.4	0.37	0.36	0.35	0.35
	0.35	0.35	0.35								
2.77	2.78	2.83	3.01	3.42	4.06	4.78	5.21	5.01	4.09	2.77	1.5
	0.63	1.36	8.17	31.3	83.28	168.5	271.64	357.78	390.31	353.83	265.58
	162.75	79.45	29.51	7.74	1.35	0.35	0.37	0.39	0.39	0.4	0.4
	0.4	0.4	0.4								
2.71	2.72	2.77	2.94	3.33	3.95	4.66	5.09	4.91	4.02	2.73	1.48
	0.62	1.22	7.25	27.77	73.94	149.58	240.93	316.73	344.44	310.79	231.85
	140.93	68.13	25	6.49	1.16	0.36	0.39	0.42	0.43	0.44	0.45
	0.46	0.46	0.46								
2.67	2.68	2.73	2.89	3.26	3.86	4.56	4.99	4.83	3.97	2.7	1.48
	0.63	1.03	5.92	22.75	60.94	123.86	200.23	263.79	287.16	258.98	192.86
	116.86	56.25	20.53	5.33	0.99	0.37	0.4	0.44	0.47	0.49	0.5
	0.5	0.51	0.51								
2.67	2.68	2.72	2.87	3.23	3.83	4.52	4.95	4.81	3.99	2.77	1.57
	0.73	0.93	4.75	18.25	49.27	100.85	164.04	217.17	237.35	214.72	160.29
	97.3	46.92	17.17	4.49	0.88	0.36	0.41	0.45	0.48	0.51	0.53
	0.54	0.54	0.54								
2.72	2.72	2.77	2.92	3.29	3.88	4.57	5.03	4.93	4.17	3.03	1.89
	1.04	1.03	3.96	14.88	40.68	84.36	138.77	185.33	203.94	185.4	138.89
	84.49	40.81	14.96	3.94	0.79	0.35	0.4	0.45	0.49	0.52	0.54
	0.55	0.56	0.56								
2.82	2.83	2.88	3.04	3.41	4.01	4.71	5.2	5.17	4.55	3.56	2.52
	1.67	1.4	3.47	12.26	34.25	72.73	122.06	165.4	183.94	168.3	126.51
	77	37.13	13.56	3.57	0.73	0.35	0.39	0.44	0.49	0.53	0.55
	0.56	0.56	0.56								
3	3.01	3.06	3.22	3.59	4.19	4.89	5.41	5.51	5.09	4.33	3.45
	2.6	2.03	3.22	10.06	28.92	63.51	109.59	151.45	170.83	157.73	119.22
	72.71	35.06	12.78	3.36	0.7	0.34	0.39	0.44	0.49	0.53	0.55
	0.56	0.57	0.57								
3.24	3.24	3.29	3.45	3.8	4.37	5.04	5.6	5.83	5.66	5.18	4.49
	3.65	2.78	3.2	8.39	24.55	55.74	98.85	139.38	159.7	149.28	114.02
	70.2	34.18	12.6	3.35	0.71	0.34	0.38	0.44	0.49	0.53	0.55
	0.57	0.57	0.57								
3.53	3.54	3.58	3.72	4.04	4.55	5.17	5.74	6.09	6.14	5.91	5.39
	4.56	3.47	3.33	7.34	21.41	49.71	89.97	129.02	150.11	142.48	110.6
	69.36	34.49	13.05	3.57	0.76	0.33	0.38	0.43	0.49	0.53	0.56
	0.57	0.57	0.57								
3.89	3.9	3.93	4.05	4.32	4.76	5.33	5.88	6.29	6.47	6.39	5.97
	5.14	3.93	3.48	6.8	19.48	45.64	83.56	121.35	143.18	138.19	109.38
	70.25	35.88	14.03	3.96	0.85	0.33	0.38	0.43	0.48	0.53	0.56
	0.57	0.57	0.57								
4.33	4.33	4.36	4.46	4.69	5.08	5.59	6.11	6.52	6.72	6.67	6.25
	5.4	4.13	3.55	6.54	18.43	43.27	79.69	116.72	139.21	136.25	109.62
	71.8	37.47	15.03	4.33	0.92	0.32	0.37	0.42	0.48	0.53	0.55
	0.57	0.57	0.58								

4.86	4.86	4.89	4.98	5.2	5.57	6.06	6.55	6.91	7.05	6.93	6.45
	5.55	4.25	3.65	6.59	18.34	42.95	79.11	116.1	138.88	136.46	110.31
	72.66	38.14	15.39	4.44	0.93	0.3	0.35	0.41	0.47	0.52	0.55
	0.57	0.57	0.58								
5.42	5.44	5.49	5.61	5.87	6.31	6.87	7.41	7.75	7.8	7.54	6.93
	5.96	4.67	4.17	7.5	20.31	46.9	85.67	124.75	148	144.01	115.21
	75.11	39.21	15.95	4.9	1.27	0.49	0.42	0.41	0.45	0.5	0.54
	0.56	0.57	0.57								
5.94	5.99	6.12	6.35	6.79	7.46	8.3	9.08	9.54	9.52	9.08	8.28
	7.23	5.96	5.8	10.41	26.84	60.26	108.31	155.52	181.86	174.12	137.2
	88.55	46.79	20.43	7.9	3.21	1.54	0.84	0.51	0.44	0.47	0.51
	0.54	0.56	0.57								
6.29	6.45	6.78	7.29	8.09	9.24	10.65	11.95	12.71	12.68	12	10.95
	9.78	8.6	9.11	16.32	40.07	87.56	155.3	221.17	257.18	245.48	194.18
	127.88	71.77	36.09	17.91	9.31	4.74	2.14	0.86	0.47	0.43	0.48
	0.52	0.55	0.56								
6.45	6.81	7.49	8.48	9.88	11.78	14.05	16.11	17.33	17.31	16.32	14.92
	13.62	12.56	14.09	25.2	59.97	128.89	227.29	323.88	378.64	365.66	295.6
	202.72	122.29	68.95	39.01	22.24	11.74	5.29	1.96	0.77	0.48	0.47
	0.5	0.53	0.55								
6.46	7.09	8.27	9.92	12.1	14.89	18.13	21.04	22.72	22.66	21.28	19.46
	17.99	17.06	19.73	35.27	82.54	176.06	310.45	445	526.05	517.31	429.73
	307.17	196.45	119.24	72.35	43.64	24.34	11.89	4.96	1.97	0.88	0.56
	0.49	0.51	0.54								
6.43	7.35	9.07	11.42	14.43	18.14	22.31	25.97	28	27.77	25.91	23.6
	21.89	21.05	24.72	44.15	102.46	217.95	385.21	556.11	665	665.36	566.01
	418.08	278.8	177.89	113.78	72.89	44.14	24.32	11.9	5.31	2.18	0.91
	0.53	0.49	0.52								
6.4	7.57	9.75	12.73	16.54	21.11	26.1	30.33	32.49	31.94	29.49	26.61
	24.6	23.74	28.05	50.08	115.74	246.12	436.27	633.99	765.64	776.96	673.3
	509.59	350.4	232.61	156.64	107.6	71.54	44.15	24.36	11.78	4.8	1.64
	0.62	0.45	0.48								
6.4	7.71	10.2	13.69	18.18	23.57	29.32	34	36.14	35.12	31.99	28.49
	26.11	25.13	29.72	53.04	122.38	260.35	462.59	675.42	821.23	841.28	737.88
	567.43	398.75	273.74	194.24	143.44	104.02	70.08	41.74	21.14	8.66	2.72
	0.77	0.4	0.42								
6.4	7.77	10.43	14.26	19.32	25.42	31.82	36.84	38.88	37.38	33.6	29.52
	26.78	25.64	30.29	54.03	124.59	265.2	471.89	690.85	843.2	868.29	766.64
	594.96	424.22	299.13	222.08	174.06	134.47	95.74	59.5	30.85	12.71	3.85
	0.92	0.35	0.37								
6.39	7.78	10.5	14.52	19.91	26.45	33.24	38.47	40.44	38.63	34.43	30
	27.02	25.77	30.4	54.23	125.04	266.21	473.96	694.59	848.96	875.9	775.3
	603.96	433.77	310.6	236.89	192.03	153.3	112.05	70.96	37.17	15.34	4.59
	1.02	0.32	0.33								

];

fc_hc_map_cold=fliplr(fc_hc_map_cold);

% (g/s), engine out CO emissions indexed vertically by fc_map_spd and

fc_co_map_cold=1e-3*[

45.31	40.87	33.07	24.02	16.02	10.67	8.01	7.19	7.2	7.47	7.65	7.44
	6.59	5.12	3.42	2.1	1.78	2.69	4.67	7.09	9.32	10.97	12.01
	12.56	12.71	12.42	11.6	10.22	8.33	6.08	3.85	2.02	0.84	0.27
	0.08	0.05	0.05								
45.4	41.06	33.4	24.48	16.53	11.13	8.31	7.29	7.07	7.1	7.08	6.74
	5.9	4.55	3.04	1.92	1.75	2.75	4.76	7.17	9.38	10.99	12.01

	12.52	12.57	12.08	10.99	9.36	7.36	5.22	3.24	1.68	0.7	0.23
	0.07	0.05	0.05								
45.7	41.62	34.39	25.86	18.07	12.49	9.23	7.66	6.91	6.47	6.07	5.51
	4.67	3.55	2.38	1.61	1.7	2.86	4.91	7.29	9.44	11	11.97
	12.42	12.31	11.51	10.02	8.02	5.88	3.9	2.3	1.16	0.48	0.17
	0.07	0.05	0.05								
46.29	42.74	36.36	28.62	21.15	15.2	11.1	8.5	6.87	5.75	4.88	4.07
	3.25	2.38	1.62	1.26	1.66	2.99	5.08	7.4	9.43	10.89	11.78
	12.14	11.87	10.81	8.95	6.65	4.41	2.62	1.39	0.66	0.28	0.11
	0.06	0.05	0.05								
47.18	44.42	39.33	32.76	25.77	19.3	13.93	9.87	7.05	5.13	3.79	2.78
	1.98	1.35	0.95	0.95	1.63	3.1	5.17	7.38	9.23	10.5	11.22
	11.45	11.05	9.84	7.84	5.47	3.27	1.69	0.76	0.32	0.14	0.07
	0.05	0.05	0.06								
48.19	46.33	42.7	37.5	31.08	24.04	17.25	11.56	7.45	4.75	3.03	1.87
	1.12	0.66	0.51	0.76	1.61	3.14	5.14	7.15	8.73	9.71	10.15
	10.15	9.63	8.42	6.55	4.38	2.44	1.11	0.42	0.15	0.07	0.06
	0.05	0.06	0.06								
49.08	48.02	45.71	41.78	35.96	28.51	20.51	13.35	8.05	4.63	2.6	1.38
	0.66	0.31	0.29	0.65	1.57	3.08	4.96	6.74	7.99	8.57	8.6
	8.27	7.6	6.5	4.97	3.26	1.76	0.76	0.25	0.09	0.05	0.05
	0.06	0.06	0.06								
49.51	48.99	47.61	44.65	39.43	31.88	23.16	14.97	8.73	4.72	2.44	1.17
	0.49	0.19	0.2	0.6	1.49	2.94	4.68	6.24	7.17	7.33	6.9
	6.18	5.34	4.38	3.27	2.12	1.14	0.49	0.17	0.06	0.05	0.05
	0.06	0.06	0.06								
48.98	48.75	47.9	45.6	40.95	33.68	24.81	16.14	9.34	4.9	2.4	1.09
	0.43	0.15	0.18	0.55	1.4	2.76	4.39	5.8	6.5	6.32	5.48
	4.39	3.38	2.53	1.8	1.15	0.62	0.27	0.11	0.06	0.05	0.05
	0.06	0.06	0.06								
46.6	46.48	45.89	44.02	39.95	33.29	24.86	16.38	9.53	4.96	2.38	1.05
	0.41	0.14	0.16	0.51	1.31	2.62	4.19	5.52	6.1	5.72	4.6
	3.26	2.11	1.32	0.82	0.5	0.27	0.13	0.07	0.05	0.05	0.05
	0.06	0.06	0.06								
41.62	41.55	41.09	39.56	36.12	30.37	22.95	15.35	9.07	4.8	2.33	1.03
	0.4	0.14	0.16	0.49	1.28	2.57	4.14	5.47	6.01	5.54	4.27
	2.77	1.52	0.73	0.34	0.17	0.1	0.06	0.05	0.05	0.05	0.05
	0.06	0.06	0.06								
34.05	33.99	33.63	32.43	29.72	25.18	19.28	13.17	8.05	4.45	2.26	1.04
	0.41	0.14	0.16	0.5	1.32	2.65	4.28	5.67	6.23	5.71	4.35
	2.73	1.39	0.56	0.19	0.07	0.04	0.04	0.04	0.05	0.05	0.05
	0.06	0.06	0.06								
25.23	25.18	24.93	24.08	22.18	19	14.89	10.59	6.88	4.11	2.25	1.09
	0.44	0.15	0.17	0.54	1.42	2.86	4.62	6.13	6.75	6.19	4.72
	2.95	1.48	0.57	0.17	0.05	0.03	0.04	0.04	0.05	0.05	0.05
	0.06	0.06	0.06								
17.03	17	16.85	16.35	15.25	13.41	11.02	8.43	6.02	3.97	2.36	1.2
	0.49	0.17	0.19	0.6	1.58	3.19	5.15	6.83	7.53	6.92	5.29
	3.31	1.66	0.65	0.19	0.05	0.03	0.03	0.04	0.05	0.05	0.05
	0.06	0.06	0.06								
10.94	10.93	10.86	10.66	10.21	9.45	8.41	7.13	5.67	4.11	2.61	1.39
	0.6	0.22	0.23	0.69	1.77	3.57	5.77	7.64	8.41	7.72	5.89
	3.68	1.84	0.71	0.2	0.05	0.03	0.04	0.04	0.05	0.05	0.05
	0.05	0.06	0.06								

7.21	7.21	7.21	7.21	7.21	7.19	7.06	6.64	5.8	4.51	3.05	1.74
	0.85	0.39	0.34	0.79	1.94	3.88	6.27	8.3	9.13	8.35	6.34
	3.94	1.96	0.75	0.21	0.05	0.03	0.04	0.04	0.05	0.05	0.05
	0.05	0.05	0.05								
5.35	5.36	5.39	5.51	5.78	6.19	6.6	6.72	6.27	5.2	3.79	2.44
	1.44	0.84	0.63	0.93	2.01	3.97	6.45	8.6	9.47	8.65	6.53
	4.02	1.97	0.74	0.21	0.05	0.03	0.04	0.04	0.05	0.05	0.05
	0.05	0.05	0.05								
4.64	4.65	4.71	4.89	5.3	5.95	6.68	7.14	7.01	6.19	4.95	3.64
	2.54	1.7	1.18	1.16	1.99	3.82	6.28	8.49	9.43	8.64	6.51
	3.98	1.93	0.72	0.2	0.05	0.03	0.04	0.04	0.05	0.05	0.05
	0.05	0.05	0.05								
4.61	4.62	4.69	4.91	5.39	6.17	7.08	7.77	7.93	7.45	6.51	5.35
	4.17	3	2.01	1.52	1.96	3.53	5.9	8.12	9.15	8.45	6.39
	3.9	1.89	0.7	0.19	0.05	0.04	0.04	0.04	0.05	0.05	0.05
	0.05	0.05	0.05								
5.01	5.02	5.09	5.32	5.83	6.65	7.64	8.49	8.93	8.82	8.26	7.33
	6.07	4.54	3.01	1.97	1.99	3.28	5.52	7.74	8.87	8.3	6.35
	3.92	1.92	0.72	0.2	0.05	0.04	0.04	0.04	0.04	0.05	0.05
	0.05	0.05	0.05								
5.71	5.72	5.79	6.01	6.5	7.31	8.33	9.29	9.97	10.23	10.03	9.31
	7.97	6.07	4.02	2.47	2.1	3.16	5.33	7.59	8.85	8.43	6.57
	4.14	2.08	0.8	0.23	0.06	0.04	0.04	0.04	0.04	0.05	0.05
	0.05	0.05	0.05								
6.72	6.73	6.79	7	7.47	8.26	9.29	10.35	11.21	11.72	11.76	11.14
	9.68	7.43	4.92	2.95	2.31	3.27	5.5	7.93	9.38	9.1	7.24
	4.68	2.41	0.96	0.28	0.07	0.03	0.04	0.04	0.04	0.04	0.05
	0.05	0.05	0.05								
8.15	8.16	8.21	8.42	8.89	9.7	10.78	11.91	12.87	13.47	13.57	12.89
	11.23	8.63	5.72	3.4	2.6	3.63	6.11	8.87	10.6	10.4	8.4
	5.52	2.9	1.17	0.34	0.08	0.03	0.04	0.04	0.04	0.04	0.04
	0.04	0.05	0.05								
10.14	10.16	10.23	10.45	10.98	11.88	13.08	14.31	15.3	15.83	15.77	14.85
	12.9	9.97	6.72	4.17	3.35	4.62	7.54	10.77	12.76	12.47	10.04
	6.59	3.45	1.39	0.4	0.09	0.03	0.03	0.04	0.04	0.04	0.04
	0.04	0.04	0.04								
12.67	12.72	12.87	13.21	13.92	15.09	16.58	18.05	19.1	19.45	19.05	17.76
	15.49	12.31	8.92	6.32	5.67	7.38	10.93	14.68	16.76	15.96	12.6
	8.15	4.25	1.75	0.57	0.17	0.07	0.05	0.04	0.04	0.04	0.04
	0.04	0.04	0.04								
15.38	15.58	16	16.73	17.96	19.78	22.04	24.17	25.54	25.76	24.91	23.13
	20.6	17.43	14.24	11.97	11.83	14.28	18.72	23.07	24.96	22.96	17.76
	11.45	6.19	2.89	1.28	0.6	0.3	0.14	0.07	0.04	0.04	0.04
	0.04	0.04	0.04								
17.65	18.23	19.34	20.97	23.31	26.45	30.2	33.66	35.81	36.05	34.68	32.34
	29.67	26.86	24.36	22.92	23.72	27.35	33.09	38.29	39.87	36.06	28
	18.68	11.01	6.08	3.38	1.9	0.98	0.42	0.14	0.05	0.04	0.04
	0.04	0.04	0.04								
19.03	20.28	22.62	25.84	30.01	35.21	41.18	46.62	50	50.4	48.45	45.5
	42.79	40.68	39.34	39.18	41.37	46.6	54.13	60.66	62.21	56.42	44.79
	31.37	20.09	12.43	7.69	4.62	2.47	1.09	0.38	0.12	0.05	0.04
	0.04	0.04	0.04								
19.47	21.65	25.67	31	37.52	45.17	53.62	61.18	65.83	66.36	63.79	60.2
	57.52	56.25	56.25	57.57	61.29	68.31	77.91	86.29	88.48	81.35	66.46

	48.75	33.23	22.03	14.46	9.1	5.14	2.5	1.02	0.38	0.15	0.07
	0.04	0.04	0.04								
19.35	22.49	28.24	35.74	44.6	54.57	65.2	74.47	80.05	80.54	77.33	73.15
	70.49	69.97	71.17	73.79	78.85	87.46	99.02	109.41	112.87	105.43	88.36
	67.19	47.84	33.24	22.88	15.24	9.33	5.13	2.5	1.1	0.42	0.15
	0.06	0.04	0.04								
19.09	22.95	30.04	39.27	50.01	61.77	73.91	84.2	90.13	90.33	86.51	81.83
	79.16	79.13	81.11	84.6	90.56	100.25	113.25	125.37	130.33	123.5	105.63
	82.49	60.64	43.8	31.65	22.54	15.14	9.34	5.14	2.47	0.98	0.31
	0.08	0.04	0.04								
18.85	23.08	30.88	41.14	53.13	66.14	79.27	90.06	95.92	95.69	91.32	86.27
	83.52	83.71	86.09	90.01	96.41	106.67	120.49	133.73	139.87	133.88	116.07
	92.24	69.4	51.84	39.41	30.1	22.03	14.83	8.82	4.45	1.81	0.54
	0.12	0.04	0.04								
18.67	22.96	30.97	41.7	54.4	68.26	82.02	93.02	98.65	97.97	93.16	87.84
	85.01	85.25	87.75	91.81	98.36	108.83	122.98	136.76	143.58	138.23	120.74
	96.95	74.1	56.9	45.21	36.57	28.48	20.27	12.59	6.51	2.67	0.78
	0.16	0.03	0.03								
18.56	22.81	30.8	41.66	54.7	69.01	83.13	94.23	99.71	98.75	93.69	88.22
	85.32	85.56	88.08	92.17	98.75	109.26	123.51	137.47	144.54	139.45	122.16
	98.51	75.91	59.23	48.31	40.37	32.47	23.73	15.02	7.85	3.23	0.94
	0.18	0.03	0.03								

];

fc_co_map_cold=fliplr(fc_co_map_cold);

% (g/s), engine out NOx emissions indexed vertically by fc_map_spd and

% horizontally by fc_map_trq

fc_nox_map_cold=1e-3*[

61	66.72	76.8	88.49	98.83	105.72	109.09	109.94	109.53	108.11	104.81	97.32
	83.66	63.86	42.1	24.66	17.72	23.16	38.76	58.4	76.17	88.27	94.62
	96.71	95.95	92.48	85.83	75.43	61.38	44.83	28.38	14.86	6.14	1.86
	0.45	0.19	0.21								
60.87	66.48	76.38	87.9	98.16	105.06	108.35	108.64	106.86	103.31	97.74	88.75
	75.1	56.81	37.42	22.35	17.15	23.59	39.54	59.12	76.65	88.51	94.66
	96.43	94.89	89.96	81.29	69.08	54.28	38.49	23.84	12.34	5.09	1.56
	0.41	0.2	0.21								
60.49	65.76	75.1	86.1	96.13	103.15	106.49	106.01	102	94.79	85.25	73.65
	60.01	44.41	29.21	18.34	16.27	24.5	41.07	60.54	77.57	88.9	94.58
	95.77	92.99	85.82	74.1	59.18	43.3	28.72	16.89	8.49	3.48	1.11
	0.34	0.2	0.21								
59.72	64.31	72.53	82.5	92.07	99.35	103.14	102.23	95.98	84.74	70.7	56.12
	42.52	30.05	19.75	13.86	15.56	26.03	43.35	62.56	78.71	89.06	93.83
	94.1	89.95	80.66	66.26	49.08	32.46	19.24	10.2	4.8	1.94	0.68
	0.27	0.21	0.22								
58.57	62.13	68.68	77.07	85.91	93.61	98.35	97.7	89.99	75.51	57.67	40.55
	27.04	17.39	11.48	10.1	15.31	27.91	45.89	64.58	79.37	88.03	91.1
	89.85	84.31	73.71	58.13	40.33	24.07	12.37	5.52	2.27	0.9	0.39
	0.24	0.21	0.22								
57.27	59.66	64.29	70.83	78.75	86.83	92.74	92.98	84.9	68.7	48.61	29.99
	16.65	8.94	6.04	7.83	15.59	29.75	48.05	65.84	78.65	84.71	84.99
	81.38	74.37	63.45	48.64	32.35	17.96	8.14	2.97	0.98	0.39	0.26
	0.22	0.22	0.22								
56.12	57.48	60.37	65.16	72.04	80.21	87.03	88.27	80.63	64.14	43.39	24.36
	11.31	4.69	3.35	6.77	15.82	30.66	48.73	65.24	75.63	78.37	75.01

	68.34	59.79	49.41	37.01	24.07	12.93	5.51	1.77	0.5	0.22	0.22
	0.22	0.22	0.22								
55.33	55.98	57.65	61.07	66.91	74.68	81.73	83.61	76.69	60.8	40.52	21.9
	9.3	3.19	2.4	6.27	15.49	30.1	47.39	62.38	70.35	69.78	62.75
	53	43.11	33.75	24.49	15.68	8.34	3.52	1.12	0.34	0.2	0.21
	0.22	0.22	0.23								
54.85	55.13	56.08	58.57	63.42	70.37	77	78.98	72.65	57.69	38.39	20.6
	8.56	2.78	2.06	5.71	14.36	28.04	44.15	57.69	63.79	60.8	51.04
	38.99	28.2	19.93	13.57	8.47	4.51	1.95	0.69	0.28	0.21	0.22
	0.22	0.23	0.23								
54.42	54.56	55.18	57.09	61.1	67.09	72.94	74.62	68.66	54.58	36.38	19.54
	8.13	2.62	1.85	5.08	12.9	25.42	40.27	52.62	57.6	53.38	42.3
	29.14	18.05	10.65	6.29	3.67	1.97	0.92	0.41	0.24	0.22	0.23
	0.23	0.23	0.23								
53.75	53.84	54.31	55.86	59.22	64.32	69.31	70.52	64.72	51.41	34.27	18.41
	7.66	2.45	1.65	4.5	11.57	23	36.7	48.11	52.51	47.98	36.74
	23.54	12.67	5.91	2.63	1.28	0.71	0.42	0.28	0.24	0.24	0.24
	0.24	0.24	0.24								
52.59	52.66	53.06	54.33	57.13	61.35	65.37	65.92	60.15	47.63	31.69	17.01
	7.08	2.25	1.49	4.07	10.5	20.96	33.54	44.01	47.95	43.53	32.85
	20.37	10.21	4.07	1.34	0.49	0.3	0.27	0.26	0.26	0.26	0.27
	0.27	0.27	0.27								
50.78	50.83	51.13	52.1	54.19	57.28	59.99	59.63	53.84	42.35	28.08	15.04
	6.25	1.98	1.31	3.6	9.34	18.68	29.92	39.23	42.65	38.56	28.88
	17.68	8.66	3.28	0.97	0.31	0.23	0.25	0.27	0.29	0.3	0.31
	0.31	0.31	0.31								
48.28	48.31	48.49	49.04	50.2	51.78	52.74	51.15	45.35	35.25	23.21	12.39
	5.14	1.63	1.09	3.02	7.88	15.81	25.36	33.26	36.1	32.53	24.25
	14.74	7.16	2.7	0.81	0.29	0.23	0.26	0.29	0.32	0.34	0.35
	0.36	0.36	0.36								
45.23	45.24	45.28	45.37	45.49	45.4	44.46	41.56	35.81	27.33	17.82	9.49
	3.95	1.28	0.87	2.4	6.28	12.65	20.36	26.75	29.07	26.18	19.48
	11.81	5.72	2.15	0.66	0.26	0.23	0.27	0.31	0.34	0.37	0.39
	0.4	0.4	0.4								
42.03	42.02	41.94	41.62	40.85	39.34	36.78	32.81	27.22	20.29	13.13	7.09
	3.1	1.14	0.81	1.93	4.9	9.85	15.89	20.94	22.81	20.59	15.35
	9.33	4.53	1.72	0.54	0.22	0.21	0.26	0.31	0.35	0.39	0.41
	0.42	0.42	0.42								
39.01	38.98	38.82	38.24	36.88	34.45	30.92	26.4	21.16	15.57	10.28	5.97
	3.08	1.52	1.07	1.74	3.91	7.75	12.56	16.63	18.2	16.49	12.34
	7.52	3.66	1.39	0.44	0.19	0.19	0.24	0.29	0.34	0.38	0.41
	0.42	0.42	0.42								
36.33	36.3	36.08	35.37	33.73	30.89	26.99	22.45	17.79	13.37	9.51	6.4
	4.15	2.63	1.8	1.87	3.31	6.32	10.32	13.82	15.26	13.9	10.43
	6.36	3.09	1.17	0.37	0.16	0.16	0.21	0.26	0.31	0.36	0.38
	0.4	0.4	0.4								
33.81	33.77	33.54	32.78	31.06	28.18	24.36	20.2	16.32	13.02	10.35	8.12
	6.19	4.42	2.97	2.28	3.01	5.38	8.91	12.17	13.65	12.57	9.49
	5.8	2.82	1.07	0.33	0.14	0.14	0.18	0.23	0.28	0.32	0.35
	0.36	0.36	0.36								
31.2	31.16	30.93	30.19	28.54	25.82	22.34	18.74	15.71	13.47	11.83	10.33
	8.57	6.43	4.29	2.85	2.93	4.84	8.12	11.35	12.98	12.13	9.28
	5.74	2.82	1.08	0.33	0.13	0.12	0.16	0.2	0.24	0.28	0.31
	0.32	0.32	0.32								

28.32	28.29	28.08	27.42	25.95	23.53	20.5	17.52	15.26	13.91	13.11	12.17
	10.54	8.09	5.39	3.36	2.98	4.6	7.77	11.06	12.88	12.26	9.55
	6.03	3.03	1.18	0.36	0.13	0.11	0.14	0.18	0.22	0.25	0.27
	0.28	0.28	0.28								
25.15	25.12	24.96	24.41	23.19	21.18	18.65	16.25	14.6	13.85	13.6	13.04
	11.52	8.94	5.97	3.63	3.01	4.47	7.58	10.93	12.91	12.49	9.92
	6.41	3.3	1.32	0.41	0.13	0.1	0.13	0.16	0.2	0.23	0.25
	0.26	0.26	0.26								
21.77	21.75	21.63	21.22	20.26	18.67	16.67	14.79	13.6	13.23	13.26	12.91
	11.51	8.98	6	3.63	2.93	4.3	7.31	10.61	12.66	12.41	10.01
	6.57	3.45	1.4	0.43	0.13	0.09	0.12	0.15	0.18	0.21	0.23
	0.24	0.25	0.25								
18.26	18.24	18.16	17.86	17.16	15.98	14.47	13.09	12.27	12.16	12.36	12.13
	10.87	8.5	5.69	3.44	2.76	4.02	6.83	9.94	11.91	11.74	9.52
	6.31	3.34	1.37	0.42	0.12	0.08	0.11	0.14	0.17	0.21	0.23
	0.24	0.24	0.24								
14.76	14.75	14.68	14.47	13.97	13.14	12.1	11.19	10.75	10.88	11.21	11.1
	10.01	7.87	5.3	3.24	2.6	3.71	6.22	8.99	10.73	10.53	8.52
	5.63	2.99	1.24	0.4	0.13	0.08	0.1	0.13	0.16	0.19	0.22
	0.23	0.24	0.24								
11.48	11.45	11.36	11.18	10.84	10.3	9.67	9.19	9.1	9.46	9.93	9.95
	9.05	7.2	4.95	3.13	2.56	3.51	5.65	7.98	9.37	9.09	7.3
	4.83	2.64	1.2	0.49	0.22	0.13	0.11	0.12	0.15	0.18	0.2
	0.22	0.23	0.24								
8.75	8.67	8.52	8.3	8	7.65	7.33	7.18	7.37	7.88	8.44	8.58
	7.93	6.46	4.64	3.17	2.72	3.5	5.24	7.09	8.12	7.8	6.32
	4.38	2.7	1.57	0.92	0.54	0.31	0.17	0.12	0.13	0.15	0.18
	0.21	0.22	0.23								
6.83	6.66	6.37	6.02	5.67	5.38	5.22	5.26	5.57	6.11	6.68	6.92
	6.56	5.58	4.34	3.34	3.08	3.71	5.03	6.39	7.14	6.91	5.91
	4.64	3.52	2.64	1.9	1.25	0.7	0.34	0.17	0.12	0.13	0.16
	0.19	0.21	0.23								
5.79	5.52	5.03	4.46	3.95	3.61	3.47	3.55	3.86	4.34	4.85	5.16
	5.1	4.66	4.04	3.56	3.52	4.03	4.96	5.92	6.51	6.54	6.2
	5.7	5.17	4.47	3.52	2.42	1.42	0.71	0.33	0.17	0.14	0.15
	0.18	0.2	0.22								
5.4	5.01	4.32	3.52	2.81	2.35	2.16	2.2	2.45	2.84	3.27	3.63
	3.83	3.85	3.79	3.76	3.92	4.33	4.96	5.63	6.19	6.6	6.96
	7.25	7.27	6.74	5.58	4.04	2.55	1.42	0.72	0.35	0.19	0.15
	0.16	0.19	0.2								
5.35	4.86	3.99	3	2.12	1.54	1.29	1.3	1.5	1.82	2.21	2.61
	2.98	3.31	3.62	3.9	4.19	4.54	4.98	5.5	6.11	6.88	7.85
	8.79	9.3	8.98	7.77	5.98	4.12	2.55	1.42	0.71	0.33	0.18
	0.15	0.17	0.18								
5.37	4.81	3.84	2.72	1.74	1.09	0.8	0.8	0.98	1.29	1.67	2.09
	2.55	3.04	3.53	3.96	4.33	4.65	5	5.46	6.14	7.17	8.52
	9.9	10.8	10.77	9.75	8.01	5.98	4.04	2.42	1.25	0.54	0.23
	0.14	0.14	0.15								
5.38	4.79	3.77	2.59	1.55	0.88	0.58	0.58	0.77	1.08	1.46	1.91
	2.4	2.95	3.5	3.99	4.37	4.69	5.01	5.46	6.2	7.35	8.9
	10.51	11.68	11.96	11.26	9.74	7.72	5.51	3.43	1.8	0.77	0.28
	0.12	0.11	0.11								
5.37	4.78	3.74	2.54	1.49	0.8	0.5	0.51	0.7	1.02	1.41	1.86
	2.37	2.93	3.5	3.99	4.38	4.69	5.02	5.47	6.22	7.42	9.03

	10.74	12.05	12.53	12.08	10.77	8.8	6.44	4.09	2.16	0.91	0.31
	0.12	0.09	0.09								

];
fc_nox_map_cold=flipr(fc_nox_map_cold);

% (g/s), engine out PM emissions indexed vertically by fc_map_spd and
% horizontally by fc_map_trq
fc_pm_map_cold=1e-3*[

1.29	1.27	1.27	1.31	1.44	1.66	1.96	2.3	2.67	3.09	3.58	4.23
	5.09	6.18	7.32	8.31	8.96	9.28	9.4	9.49	9.74	10.24	11.01
	11.97	13.01	14.15	15.5	17.27	19.55	22.25	25.03	27.59	29.74	31.52
	32.97	34.06	34.65								
1.43	1.4	1.36	1.35	1.41	1.57	1.79	2.08	2.42	2.83	3.33	3.99
	4.87	5.99	7.17	8.18	8.85	9.19	9.33	9.44	9.71	10.22	11.02
	12.02	13.19	14.55	16.23	18.29	20.72	23.33	25.89	28.18	30.11	31.74
	33.1	34.13	34.69								
1.68	1.62	1.52	1.43	1.39	1.43	1.56	1.76	2.04	2.42	2.91	3.57
	4.47	5.61	6.81	7.86	8.55	8.93	9.1	9.27	9.58	10.15	10.99
	12.07	13.44	15.17	17.35	19.88	22.53	25.05	27.27	29.17	30.79	32.2
	33.39	34.29	34.77								
1.97	1.87	1.71	1.53	1.39	1.33	1.36	1.48	1.7	2.03	2.47	3.09
	3.96	5.07	6.25	7.27	7.98	8.37	8.6	8.84	9.25	9.89	10.82
	12.03	13.63	15.75	18.44	21.42	24.32	26.78	28.75	30.34	31.68	32.84
	33.8	34.52	34.9								
2.23	2.11	1.89	1.64	1.43	1.29	1.26	1.32	1.48	1.74	2.11	2.66
	3.43	4.43	5.5	6.44	7.1	7.5	7.77	8.09	8.59	9.35	10.4
	11.76	13.6	16.06	19.15	22.49	25.58	28.05	29.93	31.38	32.57	33.53
	34.27	34.78	35.03								
2.41	2.28	2.04	1.76	1.51	1.33	1.24	1.25	1.36	1.57	1.87	2.32
	2.97	3.8	4.69	5.47	6.03	6.4	6.69	7.05	7.63	8.49	9.66
	11.19	13.25	15.97	19.33	22.88	26.11	28.67	30.61	32.1	33.27	34.12
	34.69	35.01	35.16								
2.52	2.39	2.17	1.89	1.63	1.41	1.27	1.23	1.3	1.47	1.73	2.1
	2.6	3.25	3.93	4.53	4.96	5.26	5.53	5.9	6.51	7.43	8.7
	10.36	12.55	15.42	18.88	22.51	25.83	28.53	30.67	32.36	33.64	34.48
	34.95	35.16	35.24								
2.58	2.48	2.29	2.05	1.78	1.52	1.32	1.22	1.24	1.39	1.63	1.95
	2.35	2.82	3.31	3.74	4.05	4.27	4.49	4.82	5.42	6.36	7.67
	9.37	11.58	14.41	17.78	21.32	24.65	27.54	30.02	32.07	33.63	34.59
	35.07	35.24	35.28								
2.62	2.55	2.41	2.21	1.94	1.64	1.36	1.19	1.17	1.32	1.56	1.87
	2.19	2.54	2.88	3.18	3.38	3.53	3.68	3.97	4.53	5.44	6.72
	8.36	10.44	13.03	16.07	19.33	22.55	25.64	28.57	31.16	33.15	34.38
	34.96	35.15	35.18								
2.65	2.61	2.52	2.35	2.08	1.73	1.39	1.15	1.11	1.27	1.55	1.86
	2.16	2.43	2.66	2.86	2.98	3.06	3.15	3.38	3.87	4.72	5.92
	7.42	9.24	11.43	13.95	16.71	19.67	22.87	26.25	29.45	32	33.6
	34.35	34.59	34.63								
2.67	2.65	2.58	2.44	2.17	1.8	1.41	1.13	1.09	1.28	1.61	1.97
	2.27	2.5	2.68	2.81	2.88	2.9	2.93	3.08	3.48	4.22	5.28
	6.58	8.07	9.77	11.66	13.78	16.31	19.42	23.07	26.75	29.77	31.7
	32.62	32.92	32.97								
2.65	2.64	2.59	2.47	2.22	1.85	1.45	1.17	1.14	1.38	1.77	2.18
	2.51	2.76	2.92	3.03	3.07	3.06	3.03	3.1	3.4	4	4.86

	5.9	7.02	8.18	9.42	10.87	12.84	15.63	19.21	22.99	26.19	28.26
	29.27	29.59	29.66								
2.56	2.56	2.52	2.42	2.21	1.87	1.51	1.25	1.25	1.52	1.96	2.43
	2.82	3.11	3.32	3.46	3.51	3.49	3.43	3.44	3.64	4.08	4.72
	5.45	6.17	6.84	7.5	8.34	9.74	12	15.12	18.52	21.45	23.37
	24.31	24.62	24.69								
2.39	2.38	2.36	2.28	2.11	1.85	1.54	1.34	1.37	1.66	2.12	2.62
	3.05	3.41	3.7	3.91	4.02	4.03	3.99	3.99	4.12	4.41	4.82
	5.26	5.63	5.9	6.14	6.54	7.43	9.1	11.5	14.17	16.48	18.01
	18.75	19	19.05								
2.12	2.11	2.1	2.05	1.93	1.74	1.53	1.4	1.46	1.74	2.18	2.67
	3.13	3.55	3.91	4.2	4.39	4.48	4.51	4.55	4.65	4.83	5.05
	5.26	5.4	5.45	5.48	5.66	6.22	7.34	8.99	10.8	12.37	13.39
	13.89	14.05	14.08								
1.8	1.8	1.79	1.76	1.7	1.59	1.47	1.42	1.51	1.77	2.15	2.59
	3.02	3.45	3.85	4.19	4.44	4.62	4.76	4.9	5.04	5.18	5.29
	5.37	5.41	5.43	5.47	5.63	6.03	6.76	7.79	8.89	9.81	10.4
	10.68	10.77	10.79								
1.49	1.49	1.49	1.48	1.46	1.43	1.4	1.42	1.53	1.76	2.06	2.41
	2.78	3.16	3.54	3.87	4.16	4.42	4.69	4.95	5.18	5.34	5.43
	5.5	5.58	5.7	5.89	6.15	6.52	7.03	7.64	8.24	8.72	9.02
	9.16	9.2	9.21								
1.22	1.22	1.22	1.24	1.26	1.29	1.34	1.43	1.56	1.73	1.95	2.19
	2.47	2.77	3.07	3.37	3.65	3.97	4.34	4.73	5.07	5.31	5.46
	5.59	5.78	6.07	6.45	6.87	7.29	7.68	8.05	8.36	8.59	8.73
	8.79	8.81	8.81								
1	1	1.01	1.04	1.09	1.19	1.31	1.44	1.57	1.7	1.82	1.96
	2.14	2.35	2.58	2.82	3.09	3.43	3.86	4.34	4.78	5.11	5.37
	5.61	5.94	6.4	6.96	7.53	8.01	8.35	8.59	8.74	8.84	8.9
	8.92	8.93	8.93								
0.83	0.83	0.84	0.88	0.96	1.1	1.27	1.45	1.57	1.65	1.69	1.74
	1.83	1.98	2.15	2.35	2.59	2.92	3.36	3.88	4.38	4.8	5.17
	5.54	6	6.6	7.29	7.95	8.48	8.82	9	9.09	9.14	9.17
	9.18	9.19	9.19								
0.7	0.7	0.72	0.76	0.86	1.03	1.23	1.43	1.55	1.58	1.55	1.53
	1.57	1.67	1.81	1.97	2.18	2.49	2.91	3.41	3.93	4.42	4.89
	5.38	5.95	6.63	7.37	8.08	8.62	8.98	9.17	9.28	9.35	9.39
	9.41	9.42	9.42								
0.63	0.63	0.65	0.69	0.79	0.95	1.16	1.36	1.46	1.47	1.41	1.35
	1.35	1.41	1.52	1.66	1.85	2.12	2.51	2.99	3.5	4.03	4.56
	5.14	5.78	6.49	7.24	7.92	8.46	8.84	9.09	9.28	9.41	9.51
	9.55	9.57	9.57								
0.59	0.59	0.6	0.64	0.72	0.86	1.05	1.21	1.31	1.3	1.24	1.17
	1.14	1.18	1.26	1.36	1.53	1.78	2.15	2.61	3.12	3.66	4.24
	4.86	5.54	6.26	6.97	7.62	8.16	8.57	8.9	9.18	9.4	9.54
	9.62	9.64	9.65								
0.55	0.55	0.56	0.58	0.64	0.74	0.88	1.01	1.08	1.09	1.04	0.99
	0.96	0.96	0.99	1.06	1.19	1.44	1.8	2.26	2.78	3.34	3.95
	4.6	5.29	6	6.72	7.38	7.93	8.39	8.77	9.1	9.37	9.55
	9.64	9.67	9.67								
0.48	0.48	0.49	0.5	0.54	0.61	0.7	0.79	0.86	0.88	0.87	0.84
	0.8	0.77	0.76	0.78	0.89	1.12	1.49	1.97	2.51	3.09	3.71
	4.37	5.06	5.8	6.56	7.29	7.92	8.42	8.83	9.15	9.4	9.57
	9.65	9.67	9.68								

0.39	0.39	0.4	0.41	0.45	0.5	0.58	0.67	0.74	0.78	0.79	0.78
	0.74	0.68	0.62	0.6	0.67	0.88	1.25	1.72	2.28	2.89	3.52
	4.18	4.87	5.64	6.5	7.35	8.09	8.64	9.03	9.29	9.48	9.6
	9.66	9.68	9.68								
0.28	0.29	0.32	0.36	0.41	0.49	0.6	0.71	0.8	0.86	0.87	0.84
	0.79	0.7	0.62	0.57	0.61	0.79	1.1	1.54	2.08	2.69	3.32
	3.96	4.66	5.48	6.44	7.43	8.29	8.9	9.27	9.46	9.58	9.64
	9.67	9.68	9.68								
0.2	0.23	0.29	0.37	0.48	0.62	0.78	0.95	1.07	1.12	1.1	1.03
	0.95	0.85	0.75	0.69	0.71	0.82	1.05	1.4	1.87	2.42	3.03
	3.65	4.35	5.22	6.28	7.41	8.39	9.06	9.43	9.58	9.65	9.67
	9.68	9.68	9.68								
0.15	0.21	0.32	0.46	0.64	0.85	1.1	1.32	1.46	1.48	1.41	1.29
	1.16	1.05	0.96	0.89	0.88	0.93	1.06	1.28	1.63	2.08	2.62
	3.21	3.91	4.82	5.97	7.21	8.3	9.05	9.45	9.62	9.67	9.69
	9.69	9.68	9.68								
0.14	0.23	0.39	0.61	0.86	1.16	1.48	1.75	1.89	1.87	1.73	1.54
	1.37	1.24	1.15	1.09	1.05	1.04	1.07	1.17	1.38	1.72	2.17
	2.71	3.39	4.31	5.49	6.79	7.96	8.8	9.3	9.54	9.65	9.68
	9.69	9.69	9.68								
0.15	0.26	0.48	0.76	1.1	1.48	1.87	2.18	2.32	2.24	2.01	1.74
	1.52	1.38	1.29	1.23	1.17	1.12	1.08	1.08	1.18	1.41	1.78
	2.25	2.88	3.74	4.86	6.12	7.33	8.29	8.95	9.36	9.57	9.66
	9.69	9.69	9.69								
0.16	0.3	0.55	0.89	1.31	1.77	2.23	2.58	2.7	2.56	2.24	1.89
	1.62	1.45	1.35	1.29	1.23	1.16	1.08	1.03	1.06	1.22	1.52
	1.93	2.48	3.21	4.17	5.29	6.47	7.55	8.44	9.07	9.45	9.63
	9.69	9.7	9.69								
0.17	0.32	0.6	0.99	1.46	2	2.53	2.92	3.03	2.83	2.42	1.99
	1.67	1.48	1.38	1.32	1.25	1.18	1.08	1	1	1.13	1.39
	1.75	2.21	2.79	3.54	4.49	5.61	6.8	7.91	8.78	9.33	9.6
	9.69	9.7	9.7								
0.17	0.33	0.62	1.03	1.55	2.14	2.71	3.12	3.22	2.98	2.53	2.05
	1.7	1.49	1.38	1.32	1.26	1.18	1.08	1	0.99	1.1	1.34
	1.68	2.09	2.56	3.17	3.99	5.06	6.32	7.56	8.59	9.25	9.58
	9.68	9.7	9.7								

];

fc_pm_map_cold=flipr(fc_pm_map_cold);

% (C), engine exhaust gas temperature indexed vertically by fc_map_spd and

% horizontally by fc_map_trq

fc_extmp_map_cold=

455.58	455.57	455.52	455.32	454.73	453.33	450.57	445.96	439.34	431.11	422.25	414.01
	407.52	403.49	402.16	403.34	406.6	411.25	416.5	421.59	426.04	429.88	433.68
	438.35	444.7	453	462.78	472.94	482.2	489.66	495.15	499.21	502.83	506.95
	512.09	518.14	524.52	530.45	535.36	539.13	542.05	544.66	547.37	550.33	553.4
	556.28	558.78	560.97	563.21	565.97	569.64	574.29	579.59	584.95	589.82	593.99
	597.73	601.68	606.55	612.65	619.69	626.73	632.47	635.71			
455.58	455.57	455.52	455.32	454.75	453.38	450.67	446.11	439.54	431.34	422.46	414.14
	407.51	403.31	401.75	402.67	405.61	409.92	414.83	419.63	423.87	427.6	431.38
	436.11	442.53	450.91	460.73	470.88	480.09	487.49	492.93	497.01	500.71	504.97
	510.27	516.51	523.04	529.1	534.1	537.93	540.92	543.6	546.41	549.48	552.65
	555.63	558.23	560.52	562.87	565.77	569.6	574.38	579.77	585.17	590.04	594.19
	597.94	601.94	606.88	613.05	620.12	627.15	632.86	636.07			

455.58	455.57	455.52	455.34	454.79	453.48	450.86	446.42	439.95	431.8	422.86	414.36
	407.45	402.88	400.89	401.3	403.65	407.33	411.62	415.88	419.72	423.23	426.96
	431.73	438.25	446.69	456.49	466.54	475.58	482.81	488.16	492.25	496.1	500.62
	506.27	512.85	519.7	525.99	531.16	535.13	538.25	541.1	544.11	547.41	550.82
	554.02	556.82	559.32	561.91	565.09	569.22	574.29	579.89	585.4	590.3	594.46
	598.25	602.36	607.45	613.76	620.9	627.93	633.58	636.74			
455.57	455.56	455.52	455.36	454.85	453.63	451.14	446.87	440.55	432.44	423.38	414.58
	407.22	402.09	399.46	399.16	400.74	403.59	407.06	410.61	413.92	417.11	420.69
	425.43	431.93	440.28	449.88	459.61	468.29	475.19	480.35	484.43	488.48	493.38
	499.5	506.58	513.85	520.47	525.88	530.03	533.36	536.48	539.83	543.51	547.31
	550.86	553.99	556.81	559.77	563.39	568	573.54	579.5	585.25	590.27	594.52
	598.43	602.74	608.07	614.6	621.88	628.92	634.51	637.61			
455.54	455.54	455.5	455.35	454.91	453.79	451.47	447.4	441.25	433.17	423.92	414.68
	406.68	400.79	397.35	396.2	396.89	398.83	401.41	404.16	406.86	409.63	412.96
	417.51	423.78	431.77	440.85	449.95	457.99	464.38	469.22	473.26	477.53	482.85
	489.52	497.16	504.93	511.91	517.59	521.98	525.6	529.09	532.93	537.16	541.51
	545.57	549.14	552.41	555.86	560.05	565.31	571.48	577.98	584.12	589.39	593.84
	597.98	602.61	608.32	615.21	622.73	629.87	635.45	638.51			
455.43	455.42	455.39	455.27	454.88	453.88	451.75	447.9	441.9	433.81	424.28	414.46
	405.65	398.84	394.46	392.4	392.19	393.23	394.95	396.94	399.02	401.32	404.28
	408.44	414.21	421.5	429.7	437.82	444.94	450.59	454.99	458.92	463.38	469.12
	476.32	484.49	492.7	500.03	505.96	510.61	514.57	518.55	523.01	527.94	532.98
	537.67	541.79	545.58	549.6	554.45	560.44	567.34	574.49	581.11	586.75	591.5
	596.01	601.12	607.41	614.89	622.89	630.32	636.04	639.14			
455.09	455.09	455.06	454.96	454.63	453.75	451.79	448.14	442.28	434.13	424.23	413.74
	404	396.16	390.79	387.82	386.8	387.09	388.11	389.47	391.01	392.85	395.35
	398.96	403.95	410.22	417.19	424.03	429.98	434.73	438.57	442.3	446.84	452.88
	460.47	469.03	477.56	485.11	491.24	496.12	500.44	504.96	510.11	515.82	521.63
	527	531.72	536.04	540.59	546.04	552.66	560.19	567.87	574.9	580.87	585.98
	591	596.83	604.04	612.51	621.43	629.59	635.77	639.08			
454.27	454.26	454.25	454.17	453.88	453.1	451.29	447.81	442.05	433.8	423.53	412.33
	401.67	392.83	386.51	382.77	381.11	380.89	381.47	382.44	383.63	385.1	387.13
	390.06	394.08	399.08	404.57	409.91	414.52	418.25	421.44	424.86	429.35	435.48
	443.21	451.9	460.51	468.11	474.29	479.33	483.97	488.98	494.78	501.23	507.76
	513.77	518.99	523.71	528.59	534.32	541.18	548.86	556.6	563.66	569.7	575.09
	580.73	587.62	596.28	606.45	617.05	626.65	633.84	637.68			
452.58	452.57	452.56	452.49	452.25	451.54	449.86	446.52	440.84	432.52	421.94	410.17
	398.73	389.07	382.02	377.72	375.71	375.29	375.77	376.67	377.75	379.01	380.63
	382.85	385.8	389.4	393.3	397.03	400.25	402.91	405.4	408.4	412.66	418.62
	426.19	434.68	443.07	450.48	456.55	461.61	466.42	471.77	478.04	485.01	492.04
	498.46	503.96	508.77	513.55	518.94	525.23	532.15	539.05	545.36	550.94	556.38
	562.75	571.14	582.02	594.88	608.28	620.34	629.35	634.13			
449.57	449.57	449.56	449.5	449.28	448.63	447.06	443.85	438.3	430.03	419.34	407.29
	395.44	385.31	377.88	373.35	371.31	371.02	371.72	372.85	374.07	375.3	376.62
	378.18	380.09	382.3	384.62	386.8	388.66	390.28	392.05	394.55	398.4	403.94
	411.04	419	426.88	433.86	439.62	444.51	449.28	454.7	461.09	468.22	475.38
	481.84	487.23	491.68	495.71	499.88	504.47	509.36	514.18	518.67	523.06	528.22
	535.43	545.85	559.86	576.58	594.04	609.75	621.47	627.69			
444.84	444.84	444.84	444.79	444.59	444	442.53	439.49	434.18	426.19	415.76	403.91
	392.17	382.09	374.71	370.32	368.54	368.62	369.76	371.32	372.86	374.19	375.31
	376.31	377.28	378.24	379.14	379.91	380.56	381.25	382.33	384.29	387.61	392.54
	398.91	406.09	413.21	419.54	424.8	429.33	433.82	438.99	445.12	451.96	458.8
	464.88	469.72	473.27	475.84	477.83	479.54	481.09	482.56	484.19	486.68	491.25
	499.39	512.34	530.28	551.9	574.51	594.86	610.03	618.08			

438.21	438.2	438.2	438.16	437.98	437.45	436.12	433.35	428.47	421.08	411.37	400.29
	389.28	379.83	372.97	369.03	367.69	368.24	369.86	371.85	373.71	375.17	376.16
	376.71	376.91	376.85	376.58	376.2	375.85	375.76	376.23	377.67	380.41	384.63
	390.13	396.37	402.57	408.11	412.74	416.75	420.78	425.43	430.96	437.13	443.26
	448.59	452.51	454.75	455.34	454.47	452.5	449.86	447.17	445.31	445.5	449.33
	458.51	474.26	496.53	523.48	551.67	577	595.86	605.85			
429.73	429.73	429.72	429.69	429.54	429.09	427.94	425.55	421.31	414.86	406.37	396.64
	386.96	378.66	372.71	369.44	368.58	369.51	371.45	373.69	375.71	377.2	378.04
	378.23	377.85	377.01	375.88	374.66	373.57	372.89	372.89	373.86	376.04	379.52
	384.13	389.37	394.62	399.31	403.26	406.69	410.15	414.15	418.91	424.21	429.44
	433.83	436.67	437.48	436	432.24	426.59	419.82	413.09	407.89	405.94	409.14
	419.36	437.78	464.08	495.89	529.06	558.77	580.84	592.5			
419.77	419.77	419.77	419.74	419.63	419.27	418.35	416.43	413.02	407.8	400.9	392.97
	385.07	378.31	373.5	370.97	370.52	371.6	373.55	375.73	377.64	378.98	379.6
	379.48	378.68	377.34	375.64	373.87	372.31	371.24	370.89	371.48	373.16	375.96
	379.72	384.03	388.36	392.26	395.55	398.43	401.35	404.72	408.74	413.2	417.54
	421.03	422.92	422.56	419.47	413.56	405.24	395.51	385.95	378.45	375.09	378.03
	389.18	409.66	438.91	474.12	510.66	543.23	567.32	580.02			
408.82	408.82	408.82	408.81	408.73	408.47	407.81	406.42	403.92	400.08	394.97	389.07
	383.17	378.11	374.54	372.71	372.49	373.45	375.08	376.85	378.36	379.35	379.68
	379.28	378.2	376.55	374.54	372.47	370.65	369.36	368.79	369.09	370.35	372.57
	375.59	379.08	382.61	385.81	388.55	390.98	393.46	396.36	399.81	403.61	407.26
	410.1	411.38	410.41	406.67	399.98	390.77	380.12	369.73	361.65	358.07	361.21
	373.04	394.58	425.11	461.64	499.3	532.69	557.28	570.21			
397.28	397.29	397.31	397.33	397.31	397.17	396.77	395.89	394.29	391.81	388.47	384.58
	380.66	377.27	374.86	373.61	373.44	374.06	375.09	376.19	377.09	377.58	377.54
	376.89	375.62	373.81	371.66	369.47	367.54	366.15	365.45	365.55	366.48	368.22
	370.64	373.45	376.32	378.96	381.26	383.36	385.58	388.19	391.3	394.71	397.97
	400.47	401.58	400.71	397.41	391.55	383.51	374.26	365.31	358.52	355.97	359.8
	371.93	393.39	423.43	459.1	495.67	527.94	551.61	564.01			
385.27	385.33	385.43	385.55	385.63	385.64	385.49	385.08	384.28	383	381.23	379.13
	376.97	375.06	373.65	372.84	372.58	372.7	372.99	373.29	373.44	373.36	372.92
	372.04	370.64	368.77	366.6	364.39	362.46	361.04	360.28	360.23	360.91	362.27
	364.2	366.48	368.83	371.03	373.01	374.9	376.99	379.5	382.49	385.77	388.9
	391.38	392.74	392.59	390.68	387	381.86	375.95	370.32	366.39	365.87	370.71
	382.79	403.19	431.31	464.48	498.34	528.13	549.93	561.34			
372.47	372.67	373	373.38	373.72	373.97	374.1	374.1	373.96	373.64	373.15	372.5
	371.77	371.06	370.44	369.93	369.5	369.07	368.59	368.04	367.44	366.77	365.95
	364.86	363.39	361.52	359.4	357.26	355.38	353.99	353.2	353.05	353.53	354.59
	356.13	357.97	359.9	361.74	363.48	365.24	367.28	369.82	372.88	376.23	379.47
	382.2	384.1	385.06	385.13	384.45	383.22	381.77	380.55	380.36	382.41	388.42
	400.21	418.98	444.42	474.27	504.72	531.49	551.08	561.33			
358.11	358.62	359.5	360.49	361.39	362.08	362.58	362.96	363.33	363.75	364.2	364.64
	364.99	365.18	365.15	364.82	364.18	363.21	361.99	360.66	359.34	358.12	356.95
	355.7	354.2	352.41	350.4	348.39	346.63	345.31	344.54	344.32	344.64	345.44
	346.63	348.08	349.63	351.16	352.67	354.33	356.39	359.04	362.28	365.87	369.41
	372.56	375.18	377.44	379.67	382.17	385.08	388.31	391.7	395.39	400.09	407.25
	418.67	435.72	458.44	485.02	512.16	536.08	553.63	562.84			
341.16	342.29	344.2	346.36	348.31	349.79	350.84	351.64	352.42	353.34	354.45	355.64
	356.74	357.57	357.93	357.71	356.85	355.4	353.53	351.49	349.54	347.84	346.37
	345.01	343.55	341.9	340.09	338.29	336.71	335.53	334.81	334.56	334.74	335.3
	336.16	337.23	338.39	339.59	340.87	342.42	344.5	347.31	350.82	354.77	358.76
	362.47	365.91	369.46	373.7	379.11	385.75	393.17	400.66	407.78	414.81	422.98
	434.11	449.73	470.21	494.14	518.67	540.39	556.39	564.81			

320.75	322.86	326.44	330.49	334.12	336.87	338.73	340.02	341.15	342.42	343.93	345.6
	347.19	348.43	349.05	348.87	347.82	345.97	343.56	340.95	338.47	336.36	334.68
	333.26	331.91	330.49	328.96	327.46	326.14	325.14	324.52	324.26	324.32	324.65
	325.18	325.86	326.62	327.46	328.48	329.9	332.01	335.01	338.87	343.29	347.85
	352.22	356.49	361.2	367.14	374.9	384.48	395.17	405.82	415.57	424.37	433.33
	444.28	458.94	477.93	500.14	523.02	543.39	558.47	566.42			
296.62	300.08	305.94	312.58	318.54	323.02	325.98	327.88	329.35	330.86	332.62	334.57
	336.46	337.95	338.73	338.57	337.38	335.24	332.44	329.39	326.52	324.13	322.3
	320.91	319.74	318.61	317.44	316.3	315.3	314.53	314.03	313.78	313.73	313.83
	314.04	314.32	314.66	315.13	315.88	317.18	319.34	322.58	326.87	331.87	337.1
	342.2	347.27	352.94	360.13	369.53	381.11	393.96	406.7	418.14	428.08	437.54
	448.42	462.59	480.84	502.28	524.5	544.43	559.26	567.11			
269.49	274.52	283.04	292.72	301.42	307.96	312.23	314.86	316.7	318.42	320.36	322.5
	324.58	326.24	327.14	327.02	325.78	323.49	320.48	317.18	314.09	311.55	309.68
	308.38	307.42	306.61	305.82	305.06	304.38	303.84	303.47	303.24	303.09	302.98
	302.87	302.76	302.7	302.81	303.3	304.52	306.8	310.38	315.2	320.88	326.85
	332.69	338.46	344.82	352.77	363.07	375.69	389.66	403.44	415.72	426.2	435.9
	446.76	460.79	478.91	500.38	522.84	543.15	558.37	566.48			
241.02	247.57	258.69	271.36	282.83	291.5	297.18	300.62	302.89	304.86	307	309.32
	311.59	313.43	314.47	314.44	313.24	310.98	307.95	304.62	301.51	298.97	297.16
	295.99	295.24	294.71	294.25	293.81	293.4	293.06	292.79	292.57	292.33	292.03
	291.63	291.16	290.73	290.51	290.81	292.01	294.49	298.51	303.96	310.4	317.13
	323.64	329.93	336.67	344.89	355.41	368.25	382.47	396.5	409	419.61	429.34
	440.2	454.28	472.68	494.74	518.1	539.47	555.66	564.33			
213.21	220.95	234.14	249.28	263.09	273.68	280.71	285.01	287.8	290.11	292.51	295.08
	297.6	299.66	300.91	301.06	300.04	297.94	295.1	291.96	289.01	286.63	284.95
	283.92	283.35	283.01	282.76	282.52	282.29	282.07	281.86	281.62	281.3	280.82
	280.16	279.38	278.62	278.14	278.3	279.55	282.31	286.82	292.93	300.08	307.47
	314.49	321.07	327.86	335.93	346.18	358.72	372.69	386.57	399.01	409.61	419.32
	430.17	444.37	463.19	486.1	510.75	533.62	551.15	560.63			
187.82	196.22	210.62	227.31	242.77	254.85	263.08	268.24	271.62	274.35	277.09	280
	282.84	285.21	286.73	287.15	286.4	284.63	282.13	279.34	276.72	274.6	273.12
	272.23	271.76	271.5	271.32	271.15	270.96	270.77	270.57	270.3	269.88	269.25
	268.38	267.34	266.31	265.61	265.67	266.99	270.01	274.95	281.57	289.22	297.01
	304.24	310.81	317.38	325.07	334.84	346.96	360.65	374.47	387.01	397.77	407.58
	418.47	432.74	451.89	475.59	501.53	526	545.01	555.37			
165.85	174.34	189.01	206.25	222.55	235.64	244.86	250.85	254.84	258.03	261.16	264.44
	267.64	270.35	272.21	272.96	272.57	271.21	269.18	266.87	264.69	262.91	261.67
	260.9	260.46	260.19	259.97	259.74	259.51	259.27	259.02	258.7	258.21	257.45
	256.4	255.14	253.89	253.01	252.98	254.31	257.45	262.55	269.34	277.07	284.8
	291.84	298.09	304.24	311.49	320.91	332.89	346.75	361.04	374.23	385.6	395.82
	406.83	421.06	440.25	464.37	491.24	517	537.29	548.45			
147.59	155.68	169.82	186.76	203.19	216.82	226.79	233.5	238.08	241.72	245.21	248.82
	252.36	255.42	257.61	258.72	258.75	257.88	256.4	254.67	253.02	251.66	250.68
	250.04	249.62	249.28	248.95	248.6	248.26	247.94	247.63	247.24	246.68	245.82
	244.63	243.2	241.77	240.72	240.55	241.77	244.76	249.64	256.06	263.28	270.4
	276.77	282.39	288.02	294.94	304.34	316.72	331.45	347	361.6	374.23	385.27
	396.55	410.59	429.41	453.33	480.38	506.73	527.74	539.4			
132.87	140.25	153.34	169.36	185.37	199.11	209.55	216.84	221.91	225.91	229.69	233.55
	237.36	240.7	243.2	244.68	245.16	244.86	244.05	243.02	242	241.15	240.51
	240.03	239.63	239.22	238.77	238.29	237.83	237.42	237.04	236.6	235.98	235.04
	233.74	232.18	230.6	229.4	229.03	229.95	232.49	236.69	242.2	248.32	254.28
	259.57	264.31	269.37	276.11	285.84	299.14	315.41	332.95	349.69	364.2	376.49
	388.2	401.92	419.9	442.81	469.05	494.93	515.79	527.45			

121.39	127.92	139.69	154.44	169.63	183.13	193.73	201.37	206.79	211.05	215.01	219.04
	223	226.54	229.3	231.13	232.13	232.5	232.5	232.32	232.1	231.88	231.66
	231.4	231.07	230.62	230.08	229.5	228.94	228.45	228.01	227.53	226.86	225.86
	224.49	222.83	221.14	219.77	219.14	219.64	221.49	224.66	228.83	233.43	237.86
	241.81	245.54	250.01	256.66	266.89	281.39	299.54	319.49	338.8	355.58	369.44
	381.74	395.01	411.68	432.77	457.07	481.27	500.94	511.99			
112.85	118.54	128.94	142.28	156.41	169.35	179.83	187.59	193.19	197.61	201.68	205.78
	209.81	213.46	216.41	218.6	220.14	221.29	222.23	223.06	223.77	224.3	224.6
	224.64	224.42	223.98	223.38	222.73	222.11	221.56	221.08	220.57	219.87	218.83
	217.41	215.68	213.89	212.37	211.47	211.49	212.54	214.56	217.25	220.2	223.01
	225.58	228.29	232.18	238.72	249.42	265.02	284.97	307.26	329.16	348.3	363.84
	376.79	389.51	404.53	423.14	444.56	466.01	483.54	493.42			
106.93	111.87	121.02	133.02	146.03	158.26	168.42	176.12	181.78	186.28	190.39	194.5
	198.54	202.23	205.33	207.83	209.92	211.86	213.79	215.68	217.38	218.71	219.56
	219.91	219.84	219.43	218.82	218.13	217.46	216.89	216.39	215.85	215.13	214.07
	212.62	210.84	208.98	207.34	206.2	205.77	206.09	207.05	208.41	209.89	211.29
	212.65	214.48	217.82	224.2	235.15	251.54	272.86	297.07	321.16	342.39	359.47
	373.01	385.18	398.44	414.31	432.42	450.58	465.47	473.89			
103.26	107.64	115.85	126.77	138.84	150.4	160.2	167.75	173.41	177.93	182.06	186.15
	190.18	193.87	197.06	199.81	202.35	204.96	207.74	210.54	213.09	215.11	216.43
	217.07	217.13	216.77	216.16	215.45	214.76	214.17	213.66	213.11	212.38	211.31
	209.83	208.03	206.13	204.4	203.08	202.33	202.11	202.3	202.68	203.1	203.47
	203.97	205.15	208.07	214.25	225.26	242.06	264.22	289.7	315.34	338.12	356.35
	370.35	382.04	393.8	407.27	422.45	437.63	450.09	457.14			
101.53	105.61	113.3	123.62	135.15	146.3	155.86	163.31	168.94	173.46	177.59	181.68
	185.68	189.37	192.61	195.49	198.3	201.3	204.56	207.9	210.95	213.37	214.98
	215.78	215.92	215.59	214.98	214.27	213.57	212.97	212.45	211.9	211.17	210.09
	208.61	206.8	204.87	203.09	201.69	200.77	200.27	200.05	199.93	199.79	199.64
	199.7	200.54	203.23	209.26	220.25	237.2	259.74	285.83	312.26	335.84	354.7
	368.95	380.35	391.24	403.31	416.74	430.15	441.15	447.38			

]; % in deg. C

```
fc_extmp_map_cold=flipr(fc_extmp_map_cold);
```

```
ex_spd=(850:50:4000)*pi/30;
```

```
fc_extmp_map_old=fc_extmp_map_cold;
```

```
fc_extmp_map_cold=zeros(size(fc_fuel_map_cold));
```

```
[a,b]=size(fc_extmp_map_cold);
```

```
for i=1:b
```

```
    fc_extmp_map_cold(:,i)=interp1(ex_spd,fc_extmp_map_old(:,i),fc_map_spd)';
```

```
end
```

% (g/s), engine out total exhaust flow indexed vertically by fc_map_spd and

% horizontally by fc_map_trq

```
fc_exflow_map_cold=[
```

25.9	28.2	32.26	36.97	41.14	43.98	45.66	46.99	48.8	51.41	54.55	57.86
	61.08	64.21	67.12	69.68	71.86	73.95	76.21	78.68	81.25	83.77	86.26
	88.61	90.65	92.21	93.43	94.55	95.83	97.3	98.8	100.15	101.21	102.02
	102.64	103.08	103.32								
25.85	28.11	32.09	36.73	40.87	43.73	45.48	46.87	48.7	51.3	54.41	57.7
	60.91	64.07	67.03	69.65	71.89	74.02	76.3	78.77	81.32	83.82	86.31
	88.67	90.76	92.44	93.83	95.11	96.47	97.89	99.25	100.44	101.38	102.12
	102.69	103.11	103.34								
25.69	27.81	31.58	36.01	40.05	42.99	44.93	46.51	48.46	51.07	54.14	57.38
	60.6	63.82	66.88	69.61	71.96	74.16	76.48	78.95	81.47	83.94	86.41
	88.78	90.95	92.81	94.46	95.98	97.45	98.8	99.97	100.93	101.7	102.31
	102.81	103.17	103.37								

25.38	27.23	30.54	34.55	38.41	41.49	43.8	45.79	47.99	50.69	53.74	56.95
	60.19	63.49	66.67	69.56	72.05	74.37	76.75	79.21	81.69	84.13	86.57
	88.94	91.17	93.19	95.08	96.84	98.42	99.72	100.72	101.48	102.09	102.58
	102.98	103.26	103.42								
24.92	26.35	28.99	32.36	35.91	39.19	42.04	44.64	47.26	50.14	53.21	56.42
	59.7	63.1	66.43	69.49	72.16	74.61	77.04	79.5	81.93	84.33	86.73
	89.1	91.37	93.49	95.54	97.45	99.11	100.39	101.31	101.96	102.47	102.87
	103.17	103.37	103.47								
24.39	25.36	27.22	29.85	33.02	36.47	39.9	43.17	46.29	49.41	52.54	55.78
	59.12	62.64	66.15	69.41	72.25	74.83	77.32	79.77	82.15	84.49	86.87
	89.22	91.5	93.67	95.79	97.77	99.47	100.74	101.65	102.29	102.76	103.11
	103.33	103.46	103.52								
23.93	24.48	25.64	27.56	30.33	33.84	37.71	41.55	45.12	48.49	51.73	55.02
	58.45	62.13	65.83	69.28	72.27	74.96	77.48	79.92	82.27	84.59	86.94
	89.28	91.54	93.72	95.83	97.8	99.48	100.78	101.73	102.42	102.93	103.26
	103.44	103.52	103.55								
23.62	23.88	24.55	25.94	28.32	31.73	35.78	39.95	43.85	47.44	50.81	54.19
	57.74	61.59	65.48	69.11	72.22	74.96	77.49	79.93	82.28	84.61	86.96
	89.28	91.5	93.62	95.66	97.56	99.21	100.53	101.57	102.37	102.95	103.31
	103.49	103.55	103.57								
23.45	23.56	23.95	24.99	27.04	30.23	34.23	38.51	42.58	46.34	49.82	53.29
	56.97	60.99	65.06	68.84	72.03	74.78	77.31	79.77	82.17	84.55	86.92
	89.24	91.41	93.43	95.35	97.13	98.71	100.07	101.21	102.16	102.86	103.29
	103.49	103.55	103.57								
23.35	23.41	23.68	24.52	26.32	29.27	33.1	37.31	41.4	45.18	48.69	52.19
	55.95	60.12	64.37	68.29	71.56	74.35	76.92	79.44	81.92	84.39	86.83
	89.16	91.3	93.25	95.03	96.67	98.17	99.53	100.77	101.85	102.68	103.19
	103.43	103.5	103.52								
23.24	23.28	23.51	24.25	25.89	28.64	32.27	36.31	40.25	43.89	47.26	50.67
	54.42	58.67	63.06	67.1	70.48	73.38	76.09	78.78	81.45	84.07	86.62
	89.04	91.22	93.14	94.85	96.38	97.78	99.1	100.37	101.52	102.43	103
	103.27	103.36	103.37								
23.09	23.12	23.33	24.02	25.54	28.11	31.52	35.31	38.97	42.31	45.38	48.56
	52.19	56.43	60.87	65	68.5	71.59	74.55	77.55	80.52	83.4	86.17
	88.75	91.07	93.08	94.81	96.31	97.64	98.89	100.1	101.23	102.13	102.7
	102.98	103.07	103.09								
22.88	22.91	23.1	23.72	25.11	27.46	30.58	34.04	37.36	40.35	43.09	46
	49.43	53.53	57.89	62.01	65.6	68.9	72.2	75.6	78.96	82.19	85.27
	88.14	90.7	92.88	94.73	96.29	97.63	98.82	99.94	100.96	101.78	102.3
	102.55	102.64	102.65								
22.63	22.66	22.82	23.35	24.55	26.59	29.34	32.42	35.41	38.13	40.65	43.36
	46.59	50.48	54.65	58.64	62.25	65.73	69.33	73.08	76.81	80.42	83.88
	87.1	89.95	92.35	94.35	96.02	97.43	98.63	99.71	100.66	101.4	101.86
	102.08	102.15	102.16								
22.38	22.4	22.53	22.95	23.93	25.64	27.98	30.68	33.4	35.97	38.42	41.05
	44.13	47.8	51.72	55.54	59.09	62.64	66.41	70.39	74.41	78.36	82.19
	85.75	88.86	91.43	93.53	95.28	96.78	98.09	99.25	100.24	100.99	101.44
	101.65	101.71	101.72								
22.15	22.16	22.26	22.6	23.39	24.8	26.78	29.15	31.66	34.16	36.63	39.26
	42.26	45.74	49.44	53.06	56.5	60.01	63.81	67.89	72.09	76.34	80.52
	84.4	87.69	90.31	92.4	94.15	95.72	97.17	98.52	99.69	100.57	101.09
	101.33	101.4	101.42								
21.93	21.94	22.02	22.32	23	24.21	25.93	28.05	30.39	32.83	35.3	37.92
	40.85	44.19	47.69	51.11	54.37	57.76	61.49	65.62	70.03	74.61	79.16

	83.33	86.75	89.36	91.35	93.02	94.58	96.14	97.69	99.08	100.15	100.8
	101.1	101.2	101.21								
21.72	21.73	21.81	22.09	22.72	23.83	25.39	27.32	29.5	31.84	34.25	36.83
	39.69	42.89	46.22	49.44	52.49	55.68	59.31	63.5	68.16	73.13	78.09
	82.57	86.16	88.78	90.71	92.29	93.81	95.39	97.04	98.58	99.8	100.56
	100.91	101.02	101.05								
21.49	21.5	21.59	21.86	22.47	23.51	24.96	26.75	28.78	30.99	33.31	35.8
	38.57	41.66	44.85	47.88	50.72	53.72	57.25	61.49	66.4	71.73	77.1
	81.93	85.77	88.53	90.53	92.12	93.61	95.15	96.77	98.31	99.55	100.34
	100.71	100.83	100.86								
21.2	21.21	21.29	21.55	22.13	23.1	24.45	26.12	28.03	30.12	32.34	34.76
	37.45	40.46	43.54	46.44	49.12	51.96	55.39	59.64	64.66	70.23	75.92
	81.1	85.28	88.34	90.55	92.27	93.79	95.29	96.81	98.25	99.41	100.16
	100.52	100.63	100.65								
20.81	20.82	20.89	21.13	21.65	22.54	23.8	25.37	27.18	29.19	31.33	33.67
	36.3	39.26	42.3	45.13	47.72	50.46	53.79	57.95	62.93	68.53	74.38
	79.86	84.44	87.89	90.42	92.34	93.95	95.44	96.89	98.23	99.32	100.01
	100.35	100.46	100.48								
20.28	20.29	20.34	20.54	21.01	21.82	22.99	24.49	26.23	28.17	30.24	32.52
	35.11	38.05	41.07	43.88	46.44	49.12	52.35	56.35	61.15	66.61	72.5
	78.22	83.19	87.05	89.9	92.01	93.71	95.23	96.7	98.07	99.17	99.88
	100.22	100.34	100.36								
19.58	19.58	19.63	19.81	20.22	20.97	22.09	23.53	25.22	27.1	29.09	31.3
	33.83	36.75	39.77	42.57	45.12	47.76	50.92	54.76	59.36	64.65	70.51
	76.39	81.66	85.82	88.88	91.09	92.86	94.46	96.06	97.6	98.87	99.7
	100.11	100.26	100.29								
18.66	18.67	18.72	18.88	19.28	20.02	21.11	22.53	24.18	25.99	27.91	30.04
	32.52	35.39	38.37	41.14	43.66	46.27	49.39	53.17	57.69	62.92	68.77
	74.73	80.1	84.33	87.41	89.62	91.39	93.09	94.9	96.72	98.28	99.35
	99.92	100.16	100.23								
17.57	17.57	17.62	17.79	18.21	18.96	20.08	21.49	23.11	24.88	26.76	28.84
	31.25	34.05	36.95	39.66	42.13	44.72	47.84	51.67	56.29	61.64	67.57
	73.5	78.73	82.78	85.66	87.73	89.46	91.23	93.23	95.34	97.23	98.63
	99.49	99.93	100.12								
16.39	16.38	16.41	16.56	16.99	17.77	18.92	20.36	21.99	23.76	25.63	27.68
	30.04	32.75	35.56	38.19	40.6	43.16	46.32	50.31	55.19	60.83	66.91
	72.76	77.69	81.35	83.9	85.75	87.38	89.13	91.18	93.43	95.59	97.38
	98.68	99.5	99.89								
15.34	15.29	15.25	15.35	15.72	16.48	17.63	19.09	20.76	22.55	24.42	26.47
	28.8	31.45	34.19	36.76	39.12	41.67	44.87	49.01	54.16	60.11	66.37
	72.17	76.82	80.11	82.35	84	85.48	87.09	88.98	91.15	93.46	95.65
	97.51	98.85	99.55								
14.59	14.48	14.32	14.27	14.5	15.16	16.25	17.71	19.38	21.19	23.07	25.11
	27.43	30.07	32.79	35.33	37.68	40.21	43.41	47.61	52.89	59.03	65.43
	71.26	75.82	78.97	81.08	82.65	84.03	85.41	86.99	88.9	91.2	93.74
	96.16	98.07	99.11								
14.21	14.01	13.69	13.43	13.46	13.95	14.95	16.35	18.02	19.82	21.69	23.72
	26.04	28.69	31.43	34	36.35	38.85	42	46.12	51.31	57.39	63.83
	69.76	74.48	77.77	80	81.63	82.98	84.17	85.42	87.03	89.23	91.98
	94.82	97.16	98.47								
14.09	13.8	13.32	12.85	12.67	13	13.88	15.24	16.88	18.66	20.51	22.53
	24.85	27.52	30.3	32.89	35.25	37.74	40.8	44.72	49.65	55.48	61.84
	67.91	72.91	76.49	78.96	80.72	82.11	83.24	84.31	85.71	87.76	90.49
	93.45	95.94	97.34								

14.09	13.72	13.1	12.48	12.15	12.37	13.2	14.52	16.14	17.9	19.73	21.74
	24.06	26.75	29.56	32.17	34.54	37	39.97	43.68	48.29	53.81	60.03
	66.18	71.44	75.27	77.89	79.74	81.18	82.35	83.44	84.76	86.64	89.14
	91.84	94.13	95.43								
14.1	13.69	12.98	12.26	11.87	12.06	12.88	14.19	15.79	17.53	19.34	21.34
	23.66	26.37	29.18	31.81	34.19	36.63	39.53	43.08	47.45	52.72	58.82
	64.99	70.37	74.28	76.88	78.66	80.1	81.4	82.64	84	85.69	87.75
	89.91	91.72	92.75								
14.1	13.66	12.91	12.15	11.75	11.97	12.8	14.12	15.7	17.42	19.22	21.21
	23.53	26.24	29.06	31.69	34.07	36.5	39.37	42.84	47.08	52.21	58.22
	64.38	69.76	73.6	76.05	77.67	79.07	80.48	81.91	83.35	84.85	86.44
	87.99	89.26	89.97								
14.09	13.64	12.87	12.11	11.73	11.96	12.82	14.14	15.71	17.41	19.19	21.18
	23.51	26.21	29.03	31.66	34.04	36.47	39.33	42.77	46.97	52.05	58.03
	64.17	69.51	73.27	75.58	77.07	78.42	79.9	81.46	82.96	84.33	85.61
	86.76	87.67	88.17								

```

];
fc_exflow_map_cold=flipr(fc_exflow_map_cold);
% End of cold maps
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

```

```

%Process Cold Maps to generate Correction Factor Maps
names={'fc_fuel_map','fc_hc_map','fc_co_map','fc_nox_map','fc_pm_map'};
for i=1:length(names)
    %cold to hot raio, e.g. fc_fuel_map_c2h = fc_fuel_map_cold ./ fc_fuel_map
    eval([names{i},'_c2h=',names{i},'_cold./',names{i},';'])
end

```

```

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% LIMITS
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% (N*m), max torque curve of the engine indexed by fc_map_spd (from Sluder printout 12/14/98) (Note
4400 was used rather than 4381, because that is the value in the table)
temp_max_speed=[0 899 1194 1593 1892 2389 2788 3186 3584 3982 4400]*pi/30; %note, max torque at
idle (900 RPM) was taken as a % of torque at 1200 RPM (last real value)
temp_max_torque=[0 0.8*112.3 112.3 148.1 160.3 152.3 146.4 138.2 130.2 119.1
76.1]*(1/(3.281*0.224809));
fc_max_trq=interp1(temp_max_speed,temp_max_torque,fc_map_spd,'linear');%N*m
clear temp_max_speed temp_max_torque

% (N*m), closed throttle torque of the engine (max torque that can be absorbed)
% indexed by fc_map_spd -- correlation from JDMA
fc_ct_trq=4.448/3.281*(-fc_disp)*61.02/24 * ...
(9*(fc_map_spd/max(fc_map_spd)).^2 + 14 * (fc_map_spd/max(fc_map_spd)));

```

```

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% DEFAULT SCALING
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% (--), used to scale fc_map_spd to simulate a faster or slower running engine
fc_spd_scale=1.0;
% (--), used to scale fc_map_trq to simulate a higher or lower torque engine

```

```

fc_trq_scale=1.0;
fc_pwr_scale=fc_spd_scale*fc_trq_scale; % -- scale fc power

% user definable mass scaling function
fc_mass_scale_fun=inline('(x(1)*fc_trq_scale+x(2))*(x(3)*fc_spd_scale+x(4))*(fc_base_mass+fc_acc_ma
ss)+fc_fuel_mass','x','fc_spd_scale','fc_trq_scale','fc_base_mass','fc_acc_mass','fc_fuel_mass');
fc_mass_scale_coef=[1 0 1 0]; % coefficients of mass scaling function

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% STUFF THAT SCALES WITH TRQ & SPD SCALES (MASS AND INERTIA)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
fc_inertia=(1.9/(0.224809*12*3.28))*fc_pwr_scale; % (kg*m^2), =0.2147, rotational inertia of the engine
% (estimate from ORNL)
fc_max_pwr=(max(fc_map_spd.*fc_max_trq)/1000)*fc_pwr_scale; % kW peak engine power

fc_base_mass=1.8*fc_max_pwr; % (kg), mass of the engine block and head (base engine)
% assuming a mass penalty of 1.8 kg/kW from S. Sluder
% (ORNL) estimate of 300 lb
fc_acc_mass=0.8*fc_max_pwr;; % kg engine accy's, electrics, cntrl's - assumes mass penalty of 0.8
% kg/kW (from 1994 OTA report, Table 3)
fc_fuel_mass=0.6*fc_max_pwr; % kg mass of fuel and fuel tank (from 1994 OTA report, Table 3)
fc_mass=fc_base_mass+fc_acc_mass+fc_fuel_mass; % kg total engine/fuel system mass
fc_ext_sarea=0.3*(fc_max_pwr/100)^0.67; % m^2 exterior surface area of engine

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% OTHER DATA
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
fc_fuel_den=843; % (g/l), density of the fuel from Scott Sluder (ORNL, 1/19/99)
% fc_fuel_den=835; % (g/l), density of the fuel (from original TDI map from publication)
% fc_fuel_den=850; % (g/l), density of fuel from handbook
fc_fuel_lhv=18456*2.205/0.9478; % (J/g), =42937, lower heating value of the fuel from Scott Sluder
% (ORNL, 1/19/99)
% fc_fuel_lhv=43000; % (J/g), lower heating value of the fuel from handbook

%the following was added for the new thermal modeling of the engine 12/17/98 ss and sb
fc_tstat=99; % C engine coolant thermostat set temperature (typically 95 +/- 5 C)
fc_cp=500; % J/kgK ave cp of engine (iron=500, Al or Mg = 1000)
fc_h_cp=500; % J/kgK ave cp of hood & engine compartment
% (iron=500, Al or Mg = 1000)
fc_hood_sarea=1.5; % m^2 surface area of hood/eng compt.
fc_emisv=0.8; % eff emissivity of engine ext surface to hood int surface
fc_hood_emisv=0.9; % emissivity hood ext
fc_h_air_flow=0.0; % kg/s heater air flow rate (140 cfm=0.07)
fc_cl2h_eff=0.7; % -- ave cabin heater HX eff (based on air side)
fc_c2i_th_cond=500; % W/K conductance btwn engine cyl & int
fc_i2x_th_cond=500; % W/K conductance btwn engine int & ext
fc_h2x_th_cond=10; % W/K conductance btwn engine & engine compartment

%the following variable is not used directly in modelling and should always be equal to one
%it's used for initialization purposes
fc_eff_scale=1;

```



```

% clean up workspace
clear fc_exflow_map_gpkW-h fc_co2_map_gpkW-h fc_map_kW T w

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% REVISION HISTORY
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% 05/19/98 (tm): file created from data in a_vw191.m
% 07/03/98 (MC): changed fc_init_coolant_temp to fc_coolant_init_temp
% 07/06/98 (MC): corrected max power computation in mass calc.
% 07/07/98 (MC): cosmetic change
% 07/16/98 (SS): added variable fc_fuel_type under file id section
% 07/17/98 (tm): renamed FC_CI66.M for consistency
% 08/28/98 (MC): added variable fc_disp under file id section
%          fc_ct_trq computed according to correlation from JDMA, 5/98
% 10/07/98 (MC): reduced extrapolated torques in fc_max_trq
% 10/9/98 (vh,sb,ss): added pm and removed init conditions and added new exhaust variables
% 10/13/98 (MC): updated equation for fc_ct_trq (convert from ft-lb to Nm)
% 12/17/98 ss,sb: added 12 new variables for engine thermal modelling.
% 01/25/99 (SB): modified thermal section to work with new BD, revised FC mass calc's
% 01/05/99 (KW): used FC_CI66 as base file in which to replace data
%          with ORNL data
% 01/14/99 (SB): removed unneeded variables (fc_air_fuel_ratio, fc_ex_pwr_frac)
% 2/4/99: (ss,sb) changed fc_ext_sarea=0.3*(fc_max_pwr/100)^0.67 it was 0.3*(fc_max_pwr/100)
%          it now takes into account that surface area increases based on mass to the 2/3 power
% 3/15/99:ss updated *_version to 2.1 from 2.0
% 6/4/99: (KW): source data obtained in g/s data, rather than g/kW-h
% 6/7/99: (KW): updated fuel map (g/s) obtained from ORNL
% 7/7/99: (KW): updated comments and removed previous g/kW-h conversion comments
% 7/7/99:tm added conversions to g/kW-h for plotting purposes
% 11/03/99:ss updated version from 2.2 to 2.21
% 12/30/99:ss interp1 was INTERP1 (changed to work in unix)
% 01/17/010: vhj added variables fc_o2_map, fc_exflow_vol_map (to be used in emissions modeling)
% 01/31/01: vhj added cold maps and correction factor map calculations
%          (new variables e.g. fc_fuel_map_c2h)
%          added boolean fc_cold, 0=no cold data; 1=cold data exists
% 02/26/01: vhj updated O2 map (was missing a column)
% 7/30/01:tm added user definable mass scaling function
%          mass=f(fc_spd_scale,fc_trq_scale,fc_base_mass,fc_acc_mass,fc_fuel_mass)

```

Appendix B.3. ADVISOR Motor Model MC_PM100_UQM.m

```
% ADVISOR Data file: MC_PM100_UQM.m
%
% Data source:
% PowerPhase 100 Data sheet. Unique Mobility website: www.uqm.com
%
% Data confidence level: Good-data from manufacturer spec sheet
%
% Notes: This motor/controller is designed for large EV/HEV applications
%
% Created on: 6/1/00
% By: tony_markel@nrel.gov
%
% Revision history at end of file.

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% FILE ID INFO
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
mc_description='Unique Mobility 100kW (peak) PM motor/inverter';
mc_version=2002; % version of ADVISOR for which the file was generated
mc_proprietary=0; % 0=> non-proprietary, 1=> proprietary, do not distribute
mc_validation=1; % 0=> no validation, 1=> data agrees with source data,
% 2=> data matches source data and data collection methods have been verified
disp(['Data loaded: MC_PM100 - ',mc_description]);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% SPEED & TORQUE RANGES over which data is defined
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% (rad/s), speed range of the motor
mc_map_spd=[0 100 200 300 400 500 600 700 800 900 1000 1100 1200 1300 1400 1500 1600 1700 1800
1900 2000 2100 2200 2300 2400 2500 2600 2700 2800 2900 3000 3100 3200 3300 3400 3500 3600 3700
3800 3900 4000 4100 4200 4300 4400]*(2*pi/60);

% (N*m), torque range of the motor
mc_map_trq=[0 50 100 150 200 250 300 350 400 450 500 550 600];
mc_map_trq=[-fliplr(mc_map_trq(2:end)) mc_map_trq];

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% EFFICIENCY AND INPUT POWER MAPS
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% (--), efficiency map indexed vertically by mc_map_spd and
% horizontally by mc_map_trq
mc_eff_map=[...
78 79 80 81 81 81.3 81.7 81.9 82.1 82.4 82.6 83 83.7 85.2 86.2 86.4 87.1 87.2 88.5 88.4 89.5 87.5 85.4 84
84.5 84.4 83 83.7 83.3 83.6 83.2 82.8 82.9 83.8 82.7 83.3 82.2 82.3 82.3 82 82.3 81.8 81.8 81.6 81.6;
78 79 80 81 81 81.3 81.7 81.9 82.1 82.4 82.6 83 83.7 85.2 86.2 86.4 87.1 87.2 88.5 88.4 89.5 87.5 85.4 84
84.5 84.4 83 83.7 83.3 83.6 83.2 82.8 82.9 83.8 82.7 83.3 82.2 82.3 82.3 82 82.3 81.8 81.8 81.6 81.6;
78 79 80 81 81.7 83.5 83.8 84.1 85.9 86.2 87.6 89.1 90 90.3 91.4 91.8 91.7 92.1 91.9 93 93.1 93 90.6 89.8
89.9 90.2 89.8 90.8 90.1 93 92.5 91.3 92.5 92.2 88.4 88.4 87.1 86.2 88.4 87.5 87.1 85.8 86.6 85.8 85.8;
78 79 80 81.2 82.4 83.7 85.1 85.5 87.2 88.4 89.4 90.4 91 92 93 93 93.4 93.5 93.4 93.6 93.6 93 93 92.2 91.5
92.8 93 92.9 92.7 93 93 93 93 91.7 93 91.9 91.3 91.8 91.7 90.9 90.5 90 89 89;
```

```

78 79 80 81.2 82.6 84 85.9 86.9 87.6 89.1 90 90 91.9 93 93 93 93.5 94 94 94 93.8 93 93 93 93 93 93 93
93 93 93 93 93 93 93 93 93 92.8 93 92.4 90.3 90 90 90;
78 79 80 81.3 82.7 84 86 87 87.3 88.9 90 90 91.7 93 93 93 93.5 93.7 93.9 93.8 93.5 93 93 93 92.2 91.9
91.5 92.1 92.5 93 92.7 92.8 92.6 92.6 92.6 92.7 92.8 92.8 92.7 92.7 91.6 90 88.3 88.3 88.3;
78 79 80 81.3 82.9 84 84.7 86 87.1 87.8 89.7 90 91.1 92.3 92.8 92.8 93.1 93.3 93.5 93.3 93.1 93 93 91.7
90.8 90.5 90 90.9 91.4 91.9 92 91.9 91.9 92 92 92.1 92.2 92.3 92.3 92.2 90.8 90 90 90 90;
78 79 80 81.1 82.7 84 83.9 84.3 85.6 86.7 88.2 89.4 90 91.1 91.9 92.1 92.6 93 93.2 92.8 92.2 91.4 90.5 90
90 90 90 90 90.4 90.8 91.1 91.1 91.2 91.4 91.4 91.5 91.7 91.7 91.8 91.8 90 90 90 90 90;
78 79 80 81.1 82.3 83.3 83.1 83.7 84 86 87 88.5 89.3 90 91.1 91.7 92.1 92.6 92.3 91.9 91.1 90 90 90 90 90
90 90 90 90 90 90.2 90.5 90.8 90.8 91 91.1 91.2 91.3 91.3 90 90 90 90 90;
78 79 80 81.1 81.7 82.4 82.5 83.4 84 85.5 86.6 88.1 88.8 89.8 90.6 91.2 91.9 91.6 91.3 91.1 90.4 90 90 90
90 90 90 90 90 90 90 90 90 90.2 90.4 90.6 90.7 90.9 90.5 90.5 90.5 90.5 90.5;
78 79 80 81.1 81.1 81.7 82.2 83.1 83.9 84.8 86.4 87.5 88.6 89.7 90.4 91.1 90.9 90.6 90.3 90.1 90 90 90 90
90 90 90 90 90 90 90 90 90 90 90.1 90.2 90.4 90 90 90 90 90 90;
78 79 80 81.1 81.1 81.7 82 82.8 83.7 84.6 86.3 87.5 88.5 89.6 90.4 90.2 90 90 90 90 90 90 90 90 90 90
90 90 90 90 90 90 90 90 90 90 90 90 90 90 90 90 90;
78 79 80 81.1 81.1 81.7 82 82.8 83.7 84.5 86.2 87.6 88.7 89.7 90 90 90 90 90 90 90 90 90 90 90 90 90
90 90 90 90 90 90 90 90 90 90 90 90 90 90 90 90 90]/100;

```

```
mc_eff_map=[fliplr(mc_eff_map(:,2:end)) mc_eff_map];
```

```
%% find indices of well-defined efficiencies (where speed and torque > 0)
```

```
pos_trqs=find(mc_map_trq>0);
```

```
pos_spds=find(mc_map_spd>0);
```

```
%% compute losses in well-defined efficiency area
```

```
[T1,w1]=meshgrid(mc_map_trq(pos_trqs),mc_map_spd(pos_spds));
```

```
mc_outpwr1_map=T1.*w1;
```

```
mc_losspwr_map=(1./mc_eff_map(pos_spds,pos_trqs)-1).*mc_outpwr1_map;
```

```
%% to compute losses in entire operating range
```

```
%% ASSUME that losses are symmetric about zero-torque axis, and
```

```
%% ASSUME that losses at zero torque are the same as those at the lowest
```

```
%% positive torque, and
```

```
%% ASSUME that losses at zero speed are the same as those at the lowest
```

```
%% positive speed
```

```
spin_losses=interp1([0 5000]*pi/30,[0 4300],pos_spds); % (W) % estimated
```

```
mc_losspwr_map=[fliplr(mc_losspwr_map) spin_losses' mc_losspwr_map];
```

```
mc_losspwr_map=[mc_losspwr_map(1,:);mc_losspwr_map];
```

```
%% compute input power (power req'd at electrical side of motor/inverter set)
```

```
[T,w]=meshgrid(mc_map_trq,mc_map_spd);
```

```
mc_outpwr_map=T.*w;
```

```
mc_inpwr_map=mc_outpwr_map+mc_losspwr_map;
```

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

```
% LIMITS
```

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

```
% max torque curve of the motor indexed by mc_map_spd
```

```
mc_max_trq=[550.6 550.6 550.6 550.6 550.6 550.6 550.6 550.6 550.6 550.6 550.6 550.6 550.6 550.6 549.4 549.8
550.6 542.6 529.4 512.4 497.1 481.9 457.5 439.1 421.4 403.9 385.3 364.1 344.1 326.3 308.9 294.7 285.8
275.7 265.1 254.3 243.3 236.2 230.9 225.4 220 211.9 203.2 201.4 194.1 190]; % (N*m)
```

```
mc_max_cont_trq=[300.1 300.1 299.8 302.2 302.2 302.2 290.5 275 259.1 248.4 237.3 232 226.7 221.6
216.7 211.8 206.7 201.6 197.5 193 187.2 181.7 176.4 172.3 169.4 166.8 164.6 162.9 162.7 162.7 160
156.8 155.1 153 149.8 147.7 145 141.6 137.4 133.3 129.4 126.2 123.2 115 110];
```

```
% maximum overtorque capability (not continuous, because the motor would overheat)
mc_overtrq_factor=mean(mc_max_trq./mc_max_cont_trq); % (--), estimated
mc_max_trq=mc_max_trq/mc_overtrq_factor;
% tm:6/1/00 the two lines above have been included since ADVISOR at this time is unable to use
% a max and a continuous curve of different shape
```

```
mc_max_gen_trq=-mc_max_trq; % (Nm), estimate
```

```
mc_max_currnt=400; % (A), maximum current allowed by the controller and motor
mc_min_volts=180; % (V), minimum voltage allowed by the controller and motor
```

```
%%%%%%%%%%
% DEFAULT SCALING
%%%%%%%%%
% (--), used to scale mc_map_spd to simulate a faster or slower running motor
mc_spd_scale=1.0;
```

```
% (--), used to scale mc_map_trq to simulate a higher or lower torque motor
mc_trq_scale=1.0;
```

```
%%%%%%%%%%
% OTHER DATA
%%%%%%%%%
mc_inertia=0; % (kg*m^2), rotor inertia; unknown
mc_mass=86+15.9; % (kg), mass of motor and controller
```

```
% motor/controller thermal model
mc_th_calc=1; % -- 0=no mc thermal calculations, 1=do calc's
mc_cp=430; % J/kgK ave heat capacity of motor/controller (estimate: ave of SS & Cu)
mc_tstat=45; % C thermostat temp of motor/controller when cooling pump comes on
mc_area_scale=(mc_mass/91)^0.7; % -- if motor dimensions are unknown, assume rectang
% shape and scale vs AC75
mc_sarea=0.4*mc_area_scale; % m^2 total module surface area exposed to cooling fluid
% (typ rectang module)
```

```
%the following variable is not used directly in modelling and should always be equal to one
%it's used for initialization purposes
mc_eff_scale=1;
```

```
%%%%%%%%%%
% CLEAN UP
%%%%%%%%%
clear T w mc_outpwrl_map mc_losspwr_map T1 w1 pos_spds pos_trqs
```

```
%%%%%%%%%%
% REVISION HISTORY
```

```

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% 6/1/00:tm file created
% 11/1/00:tm added max gen trq placeholder data
% Begin added by ADVISOR 3.2 converter: 30-Jul-2001
mc_mass_scale_coef=[1 0 1 0];

mc_mass_scale_fun=inline('(x(1)*mc_trq_scale+x(2))*(x(3)*mc_spd_scale+x(4))*mc_mass','x','mc_spd_s
cale','mc_trq_scale','mc_mass');

% End added by ADVISOR 3.2 converter: 30-Jul-2001

```

Appendix B.4. ADVISOR Energy Storage System Models

This section of the appendices contains the ESS ADVISOR input models for the 42 A-h VRLA Hawker Genesis batteries (ESS_PB42.m) and the 60 A-h NiMH Ovonic batteries (ESS_NIMH60_OVONICS.m).

Appendix B.4.1. ESS_PB42.m

```
% ADVISOR data file: ESS_PB42.m
%
% Data source:
% Modified from testing done by Virginia Tech
%
% Data confirmation:
%
% Notes:
% These parameters describe the Hawker Genesis 12V42A-h10EP sealed
% valve-regulated lead-acid (VRLA) battery.
%
% Created on: 27 Dec 2003
% By: Craig Rutherford
% From: ESS_PB25.m
%
% Revision history at end of file.
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% FILE ID INFO
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
ess_description='Hawker Genesis 12V42A-h10EP VRLA battery';
ess_version=2002;          % version of ADVISOR for which the file was generated
ess_proprietary=0;         % 0=> non-proprietary, 1=> proprietary, do not distribute
ess_validation=0;         % 0=> no validation, 1=> data agrees with source data,
                          % 2=> data matches source data and data collection methods have been verified
disp(['Data loaded: ESS_PB42 - ',ess_description])

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% SOC RANGE over which data is defined
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
ess_soc=[0:1:1];          % (--)

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Temperature range over which data is defined
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
ess_tmp=[0 22 40];        % (C)

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% LOSS AND EFFICIENCY parameters
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Parameters vary by SOC horizontally, and temperature vertically
ess_max_A-h_cap=[
```

```

42
42
42]; % (A*h), max. capacity at C/5 rate, indexed by ess_tmp
% average coulombic (a.k.a. amp-hour) efficiency below, indexed by ess_tmp
ess_coulombic_eff=[
.9
.9
.9]; % (--);

% module's resistance to being discharged, indexed by ess_soc and ess_tmp
% values are scaled based on ratio of 26 A-h to 42 A-h resistance
% 26A-h=5mOhm, 42A-h=4.5mOhm
ess_r_dis=0.9*[
40.7 37.0 33.8 26.9 19.3 15.1 13.1 12.3 11.7 11.8 12.2
40.7 37.0 33.8 26.9 19.3 15.1 13.1 12.3 11.7 11.8 12.2
40.7 37.0 33.8 26.9 19.3 15.1 13.1 12.3 11.7 11.8 12.2]/1000; % (ohm)

% module's resistance to being charged, indexed by ess_soc and ess_tmp
ess_r_chg=0.9*[
31.6 29.8 29.5 28.7 28.0 26.9 23.1 25.0 26.1 28.8 47.2
31.6 29.8 29.5 28.7 28.0 26.9 23.1 25.0 26.1 28.8 47.2
31.6 29.8 29.5 28.7 28.0 26.9 23.1 25.0 26.1 28.8 47.2]/1000; % (ohm)

% module's open-circuit (a.k.a. no-load) voltage, indexed by ess_soc and ess_tmp
ess_voc=[
11.70 11.85 11.96 12.11 12.26 12.37 12.48 12.59 12.67 12.78 12.89
11.70 11.85 11.96 12.11 12.26 12.37 12.48 12.59 12.67 12.78 12.89
11.70 11.85 11.96 12.11 12.26 12.37 12.48 12.59 12.67 12.78 12.89
]; % (V)

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% LIMITS
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
ess_min_volts=9.5; %VDC
ess_max_volts=16.5; %VDC

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% OTHER DATA
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
ess_module_mass=11; % (kg), mass of a single ~12 V module

% user definable mass scaling relationship
ess_mass_scale_fun=inline('(x(1)*ess_module_num+x(2))*(x(3)*ess_cap_scale+x(4))*(ess_module_mass)
','x','ess_module_num','ess_cap_scale','ess_module_mass');
ess_mass_scale_coef=[1 0 1 0]; % coefficients in ess_mass_scale_fun

% user definable resistance scaling relationship
ess_res_scale_fun=inline('(x(1)*ess_module_num+x(2))/(x(3)*ess_cap_scale+x(4))','x','ess_module_num','
ess_cap_scale');
ess_res_scale_coef=[1 0 1 0]; % coefficients in ess_res_scale_fun

ess_module_num=25; % a default value for number of modules
ess_cap_scale=1; % scale factor for module max A-h capacity

```

```

% battery thermal model
ess_th_calc=1;           % -- 0=no ess thermal calculations, 1=do calc's
ess_mod_cp=660;          % J/kgK ave heat capacity of module
ess_set_tmp=35;          % C thermostat temp of module when cooling fan comes on
ess_mod_sarea=0.2;       % m^2 total module surface area exposed to cooling air
ess_mod_airflow=0.07/5;  % kg/s cooling air mass flow rate across module (140 cfm=0.07 kg/s
at 20 C)
ess_mod_flow_area=0.0025; % m^2 cross-sec flow area for cooling air per module (10-mm gap
% btwn mods)
ess_mod_case_thk=2/1000; % m thickness of module case
ess_mod_case_th_cond=0.20; % W/mK thermal conductivity of module case material
ess_air_vel=ess_mod_airflow/(1.16*ess_mod_flow_area); % m/s ave velocity of cooling air
ess_air_htcoef=30*(ess_air_vel/5)^0.8; % W/m^2K cooling air heat transfer coef.
ess_th_res_on=((1/ess_air_htcoef)+(ess_mod_case_thk/ess_mod_case_th_cond))/ess_mod_sarea;
% K/W tot thermal res key on
ess_th_res_off=((1/4)+(ess_mod_case_thk/ess_mod_case_th_cond))/ess_mod_sarea;
% K/W tot thermal res key off (cold soak)

% set bounds on flow rate and thermal resistance
ess_mod_airflow=max(ess_mod_airflow,0.001);
ess_th_res_on=min(ess_th_res_on,ess_th_res_off);
clear ess_mod_sarea ess_mod_flow_area ess_mod_case_thk ess_mod_case_th_cond ess_air_vel
ess_air_htcoef

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% REVISION HISTORY
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% 6/30/98 (MC): converted from E_HAWKER.M
% 10/13/98:mc recomputed ess_max_A-h_cap and renamed file (from ESS_PB20)
% for consistency with other files
% 02/09/99 (SDB): added thermal model inputs
% 2/4/99 ss: added ess_module_num=25;
% 3/15/99:ss updated * version to 2.1 from 2.0
% 8/5/99:ss deleted all peukert coefficient and data(no longer needed in advisor model)
% added limits 'ess_max_volt' and 'ess_min_volt'
%9/9/99: vhj changed variables to include thermal modeling (matrices, not vector), added ess_tmp
% 11/03/99:ss updated version from 2.2 to 2.21
% 7/30/01:tm added user defineable scaling functions for
% mass=f(ess_module_num,ess_cap_scale,ess_module_mass)
% and resistance=f(ess_module_num,ess_cap_scale)*base_resistance
% 12/27/04: CR modified for 42A-h modules, need to check ess_r_dis
% 05-Jul-2004: automatically updated to version 2002

```

Appendix B.4.2. ESS_NIMH60_OVONICS.m

```

% ADVISOR data file: ESS_NIMH60_OVONIC.m
%
% Data source:

```



```

% Ovonic sales data via UC Davis.
%
% Data confirmation:
%
% Notes: These are designed to be a high power, intermediate energy battery.
% Cell type = M108
% Nominal Voltage = 12V
% Nominal Capacity (C/3) = 60A-h
% Dimensions (L * W * H) = 385mm X 102mm X 119mm
% Weight = 11.6kg
% Volume (modules only) = 5L
% Nominal Energy (C/3) = 750 Wh
% Peak Power (10s pulse @ 50%DOD @ 35 deg. C) = 4.9kW
%
% Created on: 3/24/00
% By: TM, NREL, tony_markel@nrel.gov
%
% Revision history at end of file.
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% FILE ID INFO
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
ess_description='Ovonic 60A-h NiMH HEV battery';
ess_version=2002;          % version of ADVISOR for which the file was generated
ess_proprietary=0;         % 0=> non-proprietary, 1=> proprietary, do not distribute
ess_validation=0;          % 0=> no validation, 1=> data agrees with source data,
                           % 2=> data matches source data and data collection methods have been verified
disp(['Data loaded: ESS_NIMH60_OVONIC - ',ess_description])

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% SOC RANGE over which data is defined
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
ess_soc=[0:1:1];          % (--)

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Temperature range over which data is defined
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
ess_tmp=[0 22 40];        % (C)

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% LOSS AND EFFICIENCY parameters
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Parameters vary by SOC horizontally, and temperature vertically

ess_max_A-h_cap=[
    60
    60
    60];                  % (A*h), max. capacity at C/5 rate, indexed by ess_tmp

% average coulombic (a.k.a. amp-hour) efficiency below, indexed by ess_tmp
ess_coulombic_eff=[
    1
    1

```

```

1]*0.975;                % (--); unknown

% module's resistance to being discharged, indexed by ess_soc and ess_tmp
ess_r_dis=[1.167 0.905    0.851    0.792    0.775    0.760    0.750    0.768    0.823    0.881    0.839
           1.167 0.905    0.851    0.792    0.775    0.760    0.750    0.768    0.823    0.881    0.881
           0.839
           1.167 0.905    0.851    0.792    0.775    0.760    0.750    0.768    0.823    0.881    0.839
]*10/1000;                % (ohm)

% module's resistance to being charged, indexed by ess_soc and ess_tmp
ess_r_chg=ess_r_dis;      % (ohm), no other data available

% module's open-circuit (a.k.a. no-load) voltage, indexed by ess_soc and ess_tmp
%ess_voc=[11.9 12.3 12.6 12.8 12.9 12.9 13 13.1 13.2 13.4 13.7;
% 11.9 12.3 12.6 12.8 12.9 12.9 13 13.1 13.2 13.4 13.7;
% 11.9 12.3 12.6 12.8 12.9 12.9 13 13.1 13.2 13.4 13.7];
%      (V), Source: Ovonic Charge-decreasing
ess_voc=[12.5 12.8 13.1 13.3 13.4 13.4 13.5 13.6 13.7 13.9 14.2;
12.5 12.8 13.1 13.3 13.4 13.4 13.5 13.6 13.7 13.9 14.2;
12.5 12.8 13.1 13.3 13.4 13.4 13.5 13.6 13.7 13.9 14.2];
%      (V), Source: Ovonic Charge-sustaining
%ess_voc=[12.8 13.2 13.5 13.7 13.8 13.8 13.9 14 14.1 14.3 14.6;
% 12.8 13.2 13.5 13.7 13.8 13.8 13.9 14 14.1 14.3 14.6;
% 12.8 13.2 13.5 13.7 13.8 13.8 13.9 14 14.1 14.3 14.6];
%      (V), Source: Ovonic Charge-increasing

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% LIMITS
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
ess_min_volts=0.87*1.05*10; % (V), 0.87*105      % safety factor volts time 10 cells
ess_max_volts=1.65*0.95*10;% (V), 1.65*95        % safety factor volts times 10 cells

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% OTHER DATA
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
ess_module_mass=11.6;      % (kg), mass of a single ~12 V module
ess_module_volume=0.385*0.102*0.119; % (m^3), length X width X height
ess_module_num=25;        % a default value for number of modules

ess_cap_scale=1;          % scale factor for module max A-h capacity

% user definable mass scaling relationship
ess_mass_scale_fun=inline('(x(1)*ess_module_num+x(2))*(x(3)*ess_cap_scale+x(4))*(ess_module_mass)
','x','ess_module_num','ess_cap_scale','ess_module_mass');
ess_mass_scale_coef=[1 0 1 0]; % coefficients in ess_mass_scale_fun

% user definable resistance scaling relationship
ess_res_scale_fun=inline('(x(1)*ess_module_num+x(2))/(x(3)*ess_cap_scale+x(4))','x','ess_module_num','
ess_cap_scale');
ess_res_scale_coef=[1 0 1 0]; % coefficients in ess_res_scale_fun

% battery thermal model

```

```

ess_th_calc=1; % -- 0=no ess thermal calculations, 1=do calc's
ess_mod_cp=830; % J/kgK ave heat capacity of module (estimated for NiMH)
ess_set_tmp=35; % C thermostat temp of module when cooling fan comes on
ess_area_scale=1.6*(ess_module_mass/11)^0.7; % -- if module dimensions are unknown, assume
% rectang shape and scale vs PB25
%tm:3/24/00 ess_mod_sarea=0.2*ess_area_scale; % m^2 total module surface area exposed to
%cooling air (typ rectang module)
ess_mod_sarea=2*(0.385*0.119+0.102*0.119); % m^2 total module surface area exposed to cooling
% air (typ rectang module)
ess_mod_airflow=0.01; % kg/s cooling air mass flow rate across module (20
% cfm=0.01 kg/s at 20 C)
%tm:3/24/00 ess_mod_flow_area=0.005*ess_area_scale; % m^2 cross-sec flow area for cooling air per
% module (assumes 10-mm gap btwn mods)
ess_mod_flow_area=0.005*2*(0.385+0.102); % m^2 cross-sec flow area for cooling air per
% module (assumes 10-mm gap btwn mods)
ess_mod_case_thk=2/1000; % m thickness of module case (typ from Optima)
ess_mod_case_th_cond=0.20; % W/mK thermal conductivity of module case
% material (typ polyprop plastic - Optima)
ess_air_vel=ess_mod_airflow/(1.16*ess_mod_flow_area); % m/s ave velocity of cooling air
ess_air_htcoef=30*(ess_air_vel/5)^0.8; % W/m^2K cooling air heat transfer coef.
ess_th_res_on=((1/ess_air_htcoef)+(ess_mod_case_thk/ess_mod_case_th_cond))/ess_mod_sarea;
% K/W tot thermal res key on
ess_th_res_off=((1/4)+(ess_mod_case_thk/ess_mod_case_th_cond))/ess_mod_sarea;
% K/W tot thermal res key off (cold soak)

% set bounds on flow rate and thermal resistance
ess_mod_airflow=max(ess_mod_airflow,0.001);
ess_th_res_on=min(ess_th_res_on,ess_th_res_off);
clear ess_mod_sarea ess_mod_flow_area ess_mod_case_thk ess_mod_case_th_cond ess_air_vel
ess_air_htcoef ess_area_scale

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% REVISION HISTORY
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% 3/24/00:tm file created
% 9/7/00:tm updated OCV data and removed fliplr from charge resistance definition
% 7/30/01:tm added user defineable scaling functions for
% mass=f(ess_module_num,ess_cap_scale,ess_module_mass)
% and resistance=f(ess_module_num,ess_cap_scale)*base_resistance

```

Appendix B.5. ADVISOR Transmission Models

Appendix B.5.1. TX_AUTO4_4L80E.m

```
% ADVISOR data file: TX_AUTO4_4L80E.m
%
%
% Data confirmation:
%
% Notes:
%   Model of GM 4L80E Automatic Transmission + Final Drive
% Created on: 27 Dec 2003
% By:   Craig Rutherford, UTK
%
% Revision history at end of file.
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%Description of type of transmission(important in determining what block diagram
%
%           to run in gui_run_simulation)
%added 12/22/98 types will be: 'manual 1 speed', 'manual 5 speed','cvt','auto 4 speed'
tx_type='auto 4 speed';
tx_version=2002;

tx_description='Model of GM 4L80E Automatic Transmission + Final Drive';
tx_version=2002; % version of ADVISOR for which the file was generated
tx_proprietary=0; % 0=> non-proprietary, 1=> proprietary, do not distribute
tx_validation=0; % 1=> no validation, 1=> data agrees with source data,
% 2=> data matches source data and data collection methods have been verified
disp(['Data loaded: TX_AUTO4_4L80E - ',tx_description]);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% HYDRAULIC TORQUE CONVERTER
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% LOSS/SR/TR PARAMETERS
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% speed ratio index, SR=wout/win
htc_sr=[0:0.01:0.1 0.15:0.05:1]; % (--)
% torque ratio, indexed by SR, TR=Tout/Tin
htc_tr=[2 1.99 1.98 1.96 1.95 1.94 1.93 1.92 1.91 1.89 1.88 1.83 1.77 1.72 1.66 1.60 ,...
1.55 1.49 1.43 1.38 1.32 1.26 1.21 1.15 1.10 1.04 1 1 1]; % (--)
% Note: temp files used for processing and not in the model. temp variables are deleted at end of file
% k factor,  $K=wi/(Ti)^{.5}$ 
temp_input_spd=[1444 1443 1446 1448 1450 1453 1456 1459 1461 1464 1466 1480 1494 1509 1525 1549
....
1574 1604 1637 1678 1722 1775 1833 1899 1973 2107 2272 3044 3045]*pi/30;
temp_trq=100;
htc_k=temp_input_spd./(temp_trq)^.5; % (rad/s/(Nm)^.5)
```

```

% New K factor,  $K_{adv} = w_{out} / (T_{out})^{0.5} = K * SR / (TR^{0.5})$ 
htc_k_adv = htc_k.*htc_sr./(htc_tr).^0.5;

%Coasting behavior
%htc_sr_coast=1./[1:-.025:.9 .85:-.05:.7 .6:-.1:.1 .05]; % tm 8/29/00 replaced with lines below
temp_output_spd=[4000 3750 3370 3000 2670 2280 2130 1990 1890 1780 1710 1660 1640 1635 1630
1626]*pi/30;
%temp_input_spd=temp_output_spd./htc_sr_coast; % tm 8/29/00 replaced with lines below
%htc_tr_coast=1/0.987*ones(size(htc_sr_coast)); % tm 8/29/00 replaced with lines below
temp_trq=-80;
%htc_k_coast=temp_input_spd./(abs(temp_trq))^.5; % (rad/s/(Nm)^.5) % tm 8/29/00 replaced with lines
below

%%%%%%%% ADDED tm:8/29/00 to produce lower SR's during coast
htc_pwr_out_temp=temp_output_spd.*temp_trq;
htc_sr_coast=-2./(htc_pwr_out_temp/745.7+eps)+ 1; % torque converter characteristics taken from JDM &
Associates'
% "Drive_line," dated May 1998.
htc_tr_coast=1/0.987*ones(size(htc_sr_coast));
temp_input_spd=temp_output_spd./htc_sr_coast;
htc_k_coast=temp_input_spd./(abs(temp_trq))^.5; % (rad/s/(Nm)^.5)
%%%%%%%% END ADDED tm:8/29/00

% New K factor,  $K_{adv} = w_{out} / (T_{out})^{0.5} = K * SR / (TR^{0.5})$ 
htc_k_adv_coast=htc_k_coast.*htc_sr_coast./(htc_tr_coast).^0.5;

%%%%%%%%%
% LIMITS
%%%%%%%%%
htc_max_coast_tr=1; % (--), maximum torque ratio while coasting
htc_min_coast_tr=-0.035; % (--), minimum torque ratio while coasting

%%%%%%%%%
% LOSSES
%%%%%%%%%
%Turbine inertia plus 1/2 fluid inertia = htc inertia
htc_inertia=0.056; %Nm-s^2
%Impeller inertia plus 1/2 fluid inertia is added to engine inertia
if exist('fc_inertia')
    fc_inertia=fc_inertia+.109; %Nm-s^2
end

%Note: htc_lockup found in PTC

%%%%%%%%%
% INITIALIZE
%%%%%%%%%
% The tested transmission had four gears, with the gear ratios listed
% as the first four entries in 'gb_ratio,' below.

gb_ratio=[2.48 1.48 1.00 .75]; %updated values for 4L80E
gb_gears_num=4;

```

%TX_VW % FILE ID, LOSSES

```

% 04/12/04-CR updated 4L60E to reflect 5% loss in transfer case
load tx_4L80Eauto; % load in tx_eff_map, tx_map_spd, tx_map_trq
gb_inertia=0;

gb_mass=84.5; % (kg), mass of the gearbox - 1990 Taurus, OTA Report

%the following variable is not used directly in modelling and should always be equal to one
%it's used for initialization purposes
gb_eff_scale=1;

%final drive variables
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% LOSSES AND EFFICIENCIES
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
fd_loss=0; % (Nm), constant torque loss in final drive, measured at input

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% OTHER DATA
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

fd_ratio=5.29; % (--), =(final drive input speed)/(f.d. output speed), 12/27-CR updated ratio for HMMWV
fd_inertia=0; % (kg*m^2), rotational inertia of final drive, measured at input
fd_mass=0; % (kg),
tx_mass=gb_mass+fd_mass;% (kg), mass of the gearbox + final drive=(transmission)

% Begin added by ADVISOR 3.2 converter: 17-Aug-2001
gb_spd_scale=1;

gb_trq_scale=1;

tx_mass_scale_coef=[1 0 1 0];

tx_mass_scale_fun=inline('(x(1)*gb_trq_scale+x(2))*(x(3)*gb_spd_scale+x(4))*(fd_mass+gb_mass)','x','g
b_spd_scale','gb_trq_scale','fd_mass','gb_mass');
% End added by ADVISOR 3.2 converter: 17-Aug-2001

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% REVISION HISTORY
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%Created 4L60E model 1/1/2001 Stephen Gurski (sgurski@vt.edu)
%17-Aug-2001 mpo: modified for use in ADVISOR 3.2--htc information copied from TX_AUTO4.m,
%......nex transmission effcincy map generated using
%......data from TX_VW.m using the function tx_eff_mapper.m
%Created 4L80E model 12/27/2003 Craig Rutherford
%27-Dec-2003 CR: updated fd_ratio, and gb_ratio to reflect HMMWV transmission values
% 05-Jul-2004: automatically updated to version 2002

```

Appendix B.5.2. TX_AUTO4_4L80E_low.m

```

% ADVISOR data file: TX_AUTO4_4L80E_low.m
%
%
% Data confirmation:

```

```

%
% Notes:
% Model of GM 4L80E Automatic Transmission + Final Drive + Low range X-fer case
% Created on: 27 Dec 2003
% By: Craig Rutherford, UTK
%
% Revision history at end of file.
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%Description of type of transmission(important in determining what block diagram
%
%           to run in gui_run_simulation)
%added 12/22/98 types will be: 'manual 1 speed', 'manual 5 speed','cvt','auto 4 speed'
tx_type='auto 4 speed';
tx_version=2002;

tx_description='Model of GM 4L80E Automatic Transmission+Final Drive+Low Range';
tx_version=2002; % version of ADVISOR for which the file was generated
tx_proprietary=0; % 0=> non-proprietary, 1=> proprietary, do not distribute
tx_validation=0; % 1=> no validation, 1=> data agrees with source data,
% 2=> data matches source data and data collection methods have been verified
disp(['Data loaded: TX_AUTO4_4L80E_low - ',tx_description]);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% HYDRAULIC TORQUE CONVERTER
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% LOSS/SR/TR PARAMETERS
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% speed ratio index, SR=wout/win
htc_sr=[0:0.01:0.1 0.15:0.05:1]; % (--)
% torque ratio, indexed by SR, TR=Tout/Tin
htc_tr=[2 1.99 1.98 1.96 1.95 1.94 1.93 1.92 1.91 1.89 1.88 1.83 1.77 1.72 1.66 1.60 ,...
1.55 1.49 1.43 1.38 1.32 1.26 1.21 1.15 1.10 1.04 1 1 1]; % (--)
% Note: temp files used for processing and not in the model. temp variables are deleted at end of file
% k factor, K=wi/(Ti)^.5
temp_input_spd=[1444 1443 1446 1448 1450 1453 1456 1459 1461 1464 1466 1480 1494 1509 1525 1549
....
1574 1604 1637 1678 1722 1775 1833 1899 1973 2107 2272 3044 3045]*pi/30;
temp_trq=100;
htc_k=temp_input_spd./(temp_trq)^.5; % (rad/s/(Nm)^.5)
% New K factor, K_adv=wout/(Tout)^.5=K*SR/(TR^0.5)
htc_k_adv=htc_k.*htc_sr./(htc_tr).^0.5;

%Coasting behavior
%htc_sr_coast=1./[1:-.025:.9 .85:-.05:.7 .6:-.1:.1 .05]; % tm 8/29/00 replaced with lines below
temp_output_spd=[4000 3750 3370 3000 2670 2280 2130 1990 1890 1780 1710 1660 1640 1635 1630
1626]*pi/30;
%temp_input_spd=temp_output_spd./htc_sr_coast; % tm 8/29/00 replaced with lines below
%htc_tr_coast=1/0.987*ones(size(htc_sr_coast)); % tm 8/29/00 replaced with lines below

```

```

temp_trq=-80;
%htc_k_coast=temp_input_spd./(abs(temp_trq))^.5; % (rad/s/(Nm)^.5) % tm 8/29/00 replaced with lines
below

%%%%%%%% ADDED tm:8/29/00 to produce lower SR's during coast
htc_pwr_out_temp=temp_output_spd.*temp_trq;
htc_sr_coast=-2./(htc_pwr_out_temp/745.7+eps)+ 1; % torque converter characteristics taken from JDM &
Associates'
%
% "Drive_line," dated May 1998.
htc_tr_coast=1/0.987*ones(size(htc_sr_coast));
temp_input_spd=temp_output_spd./htc_sr_coast;
htc_k_coast=temp_input_spd./(abs(temp_trq))^.5; % (rad/s/(Nm)^.5)
%%%%%%%% END ADDED tm:8/29/00

% New K factor, K_adv=wout/(Tout)^.5=K*SR/(TR^0.5)
htc_k_adv_coast=htc_k_coast.*htc_sr_coast./(htc_tr_coast).^0.5;

%%%%%%%%%
% LIMITS
%%%%%%%%%
htc_max_coast_tr=1; % (--), maximum torque ratio while coasting
htc_min_coast_tr=-0.035; % (--), minimum torque ratio while coasting

%%%%%%%%%
% LOSSES
%%%%%%%%%
%Turbine inertia plus 1/2 fluid inertia = htc inertia
htc_inertia=0.056; %Nm-s^2
%Impeller inertia plus 1/2 fluid inertia is added to engine inertia
if exist('fc_inertia')
    fc_inertia=fc_inertia+.109; %Nm-s^2
end

%Note: htc_lockup found in PTC

%%%%%%%%%
% INITIALIZE
%%%%%%%%%
% The tested transmission had four gears, with the gear ratios listed
% as the first four entries in 'gb_ratio,' below.

gb_ratio=[2.48 1.48 1.00 .75]; %updated values for 4L80E
gb_gears_num=4;

%TX_VW % FILE ID, LOSSES
% 04/12/04-CR updated 4L60E to reflect 5% loss in transfer case
load tx_4L80Eauto; % load in tx_eff_map, tx_map_spd, tx_map_trq
gb_inertia=0;

gb_mass=84.5; % (kg), mass of the gearbox - 1990 Taurus, OTA Report

%the following variable is not used directly in modelling and should always be equal to one
%it's used for initialization purposes
gb_eff_scale=1;

```



```

%final drive variables
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% LOSSES AND EFFICIENCIES
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
fd_loss=0; % (Nm), constant torque loss in final drive, measured at input

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% OTHER DATA
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

fd_ratio=14.25; % (--), =(final drive input speed)/(f.d. output speed), 12/27-CR updated ratio for
HMMWV
fd_inertia=0; % (kg*m^2), rotational inertia of final drive, measured at input
fd_mass=0; % (kg),
tx_mass=gb_mass+fd_mass;% (kg), mass of the gearbox + final drive=(transmission)

% Begin added by ADVISOR 3.2 converter: 17-Aug-2001
gb_spd_scale=1;

gb_trq_scale=1;

tx_mass_scale_coef=[1 0 1 0];

tx_mass_scale_fun=inline('(x(1)*gb_trq_scale+x(2))*(x(3)*gb_spd_scale+x(4))*(fd_mass+gb_mass)','x','g
b_spd_scale','gb_trq_scale','fd_mass','gb_mass');
% End added by ADVISOR 3.2 converter: 17-Aug-2001

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% REVISION HISTORY
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%Created 4L60E model 1/1/2001 Stephen Gurski (sgurski@vt.edu)
%17-Aug-2001 mpo: modified for use in ADVISOR 3.2--htc information copied from TX_AUTO4.m,
%.-----nex transmission efficacy map generated using
%.-----data from TX_VW.m using the function tx_eff_mapper.m
%Created 4L80E model 12/27/2003 Craig Rutherford
%27-Dec-2003 CR: updated fd_ratio, and gb_ratio to reflect HMMWV transmission values
% 05-Jul-2004: automatically updated to version 2002

```

Appendix B.6. ADVISOR Accessory Model ACC_HMMWV_hybrid.m

```
% ADVISOR data file: ACC_HMMWV_hybrid.m
%
% Data source:
%
% Data confirmation:
%
% Notes:
% Defines hybrid accessory load data for use with an advanced parallel-
% drivetrain HMMWV in ADVISOR.
%
% Created on: 27-Dec-2003
% By: Craig Rutherford, UTK
%
%
% Revision history at end of file.
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% FILE ID INFO
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
acc_description='2000-W constant electrical load';
acc_version=2002; % version of ADVISOR for which the file was generated
acc_proprietary=0; % 0=> non-proprietary, 1=> proprietary, do not distribute
acc_validation=0; % 0=> no validation, 1=> data agrees with source data,
% 2=> data matches source data and data collection methods have been verified
disp(['Data loaded: ACC_HMMWV_HYBRID - ',acc_description])

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% LOSS parameters
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
acc_mech_pwr=0; % (W), mechanical accessory load, drawn from the engine
acc_elec_pwr=2000; % (W), electrical acc. load, drawn from the voltage/power bus
acc_mech_eff=1; %efficiency of accessory
acc_elec_eff=1; %
acc_mech_trq=0; % (Nm), constant torque load on engine

vinf.AuxLoads=load('Default_aux.mat');
vinf.AuxLoadsOn=0;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% REVISION HISTORY
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%
% Begin added by ADVISOR 2002 converter: 05-Jul-2004
acc_description='700-W constant mechanical load';
```

```

acc_elec_eff=1;

acc_elec_pwr=0;

acc_mech_eff=1;

acc_mech_pwr=700;

acc_mech_trq=0;

acc_proprietary=0;

acc_validation=0;

acc_version=2002;


vinf.AuxLoads=load('Default_aux.mat');vinf.AuxLoadsOn=0;

% End added by ADVISOR 2002 converter: 05-Jul-2004
% Begin added by ADVISOR 2002 converter: 05-Jul-2004
acc_description='700-W constant mechanical load';

acc_elec_eff=1;

acc_elec_pwr=0;

acc_mech_eff=1;

acc_mech_pwr=700;

acc_mech_trq=0;

acc_proprietary=0;

acc_validation=0;

acc_version=2002;


vinf.AuxLoads=load('Default_aux.mat');vinf.AuxLoadsOn=0;

% End added by ADVISOR 2002 converter: 05-Jul-2004
% Begin added by ADVISOR 2002 converter: 05-Jul-2004
acc_description='700-W constant mechanical load';

acc_elec_eff=1;

acc_elec_pwr=0;

acc_mech_eff=1;

acc_mech_pwr=700;

acc_mech_trq=0;

```

```
acc_proprietary=0;  
acc_validation=0;  
acc_version=2002;  
  
vinf.AuxLoads=load('Default_aux.mat');vinf.AuxLoadsOn=0;  
% End added by ADVISOR 2002 converter: 05-Jul-2004
```

Appendix B.7. ADVISOR Tire Models

Appendix B.7.1. WH_HMMWV_Onroad.m

```
% ADVISOR data file: WH_HMMWV_Onroad.m
%
% Data source: Technology Roadmap for the 21st Century Truck
%           Pub #: 21CT-001 (December 2000)
%
% Data confirmation:
%
% Notes:
% Defines tire, wheel, and axle assembly parameters for use with ADVISOR 2, for
% an HMMWV in high range transfer case ratio on paved surface.
%
% Created on: 27-Dec-2003
% By: Craig Rutherford
%
% Revision history at end of file.
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% FILE ID INFO
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
wh_description='Wheel/axle assembly for HMMWV_onroad';
wh_version=2002; % version of ADVISOR for which the file was generated
wh_proprietary=0; % 0=> non-proprietary, 1=> proprietary, do not distribute
wh_validation=0; % 0=> no validation, 1=> data agrees with source data,
% 2=> data matches source data and data collection methods have been verified
disp(['Data loaded: WH_HMMWV_Onroad - ',wh_description])

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% FORCE AND MASS RANGES over which data is defined
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% vehicle test mass vector used in tandem with "wh_axle_loss_trq" to estimate
% wheel and axle bearing and brake drag
wh_axle_loss_mass=[0 2000]; % (kg)
% (tractive force on the front tires)/(weight on front axle), used in tandem
% with "wh_slip" to estimate tire slip at any time
wh_slip_force_coeff=[0 0.3913 0.6715 0.8540 0.9616 1.0212]; % (--)

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% LOSS parameters
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% drag torque applied at the front (drive) axle, used with "wh_axle_loss_mass"
% Values are 2.5 times that of SUV to accomodate 4WD and Torsen Diff
wh_axle_loss_trq=[10 60]*.4; % (Nm)
% slip=(omega * r)/v -1; used with "wh_slip_force_coeff"
%
wh_slip=[0.0 0.025 0.050 0.075 0.10 0.125]; % (--)
```

```

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% OTHER DATA
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
wh_radius=0.456; % (m), rolling radius of Goodyear radial 37-12.5 R16.5
% rotational inertia of all wheels, tires, and axles
% Estimate...
% solid cylinders of radius wh_radius, rotating at wheel speed in this vehicle
% run-flat rims are not considered in this calculation
wh_inertia=360/2.205*wh_radius^2/2; % (kg*m^2)
% fraction of braking done by driveline, indexed by wh_fa_dl_brake_mph
wh_fa_dl_brake_frac=[0 0 0.5 0.8 0.8]; % (--)
% (--), fraction of braking done by front friction brakes,
% indexed by wh_fa_fric_brake_mph
wh_fa_fric_brake_frac=[0.8 0.8 0.4 0.1 0.1]; % (--)
wh_fa_dl_brake_mph=[-1 0 10 60 1000]; % (mph)
wh_fa_fric_brake_mph=wh_fa_dl_brake_mph; % (mph)

wh_1st_rrc=0.013 ; % (--), rolling resistance coefficient, Value is for flat pavement
wh_2nd_rrc=0; % (s/m)

wh_mass=0;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Error checking
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% dl+fa_fric must add up to <= 1 for all speeds. Give user warning if in error
temp_total_braking=wh_fa_dl_brake_frac+wh_fa_fric_brake_frac;
if any(temp_total_braking>1)
    disp('Warning: Driveline and Front Friction Braking need to add to less than or equal to 1 for')
    disp('    all speeds. Please edit either wh_fa_dl_brake_frac or wh_fa_fric_brake_frac');
    disp('    in WH_*.m. See Chapter 3.2.4, Braking of the documentation for more info.');
```

end

```

clear temp_total_braking

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% REVISION HISTORY
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%9/17/98:ss added wh_mass=0;
%01/21/99:mc updated wh_slip and wh_slip_force_coeff per DB's suggestion
% 3/15/99:ss updated *_version to 2.1 from 2.0
% 11/03/99:ss updated version from 2.2 to 2.21
%01/10/01: vhj added error checking (warning to user about incorrect braking numbers)
% 4/4/02: mpo added rolling resistance coefficient data to this file (from vehicle wh_1st_rrc wh_2nd_rrc)

```

Appendix B.7.2. WH_HMMWV_Offroad.m

```
% ADVISOR data file: WH_HMMWV_Offroad.m
%
% Data source: Technology Roadmap for the 21st Century Truck
%           Pub #: 21CT-001 (December 2000)
%
% Data confirmation:
%
% Notes:
% Defines tire, wheel, and axle assembly parameters for use with ADVISOR 2, for
% an HMMWV in low range transfer case ratio on unpacked earth.
%
% Created on: 27-Dec-2003
% By: Craig Rutherford
%
% Revision history at end of file.
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% FILE ID INFO
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
wh_description='Wheel/axle assembly for HMMWV_offroad';
wh_version=2002; % version of ADVISOR for which the file was generated
wh_proprietary=0; % 0=> non-proprietary, 1=> proprietary, do not distribute
wh_validation=0; % 0=> no validation, 1=> data agrees with source data,
% 2=> data matches source data and data collection methods have been verified
disp(['Data loaded: WH_HMMWV_Offroad - ',wh_description])

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% FORCE AND MASS RANGES over which data is defined
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% vehicle test mass vector used in tandem with "wh_axle_loss_trq" to estimate
% wheel and axle bearing and brake drag
wh_axle_loss_mass=[0 2000]; % (kg)
% (tractive force on the front tires)/(weight on front axle), used in tandem
% with "wh_slip" to estimate tire slip at any time
wh_slip_force_coeff=[0 0.3913 0.6715 0.8540 0.9616 1.0212]; % (--)

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% LOSS parameters
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% drag torque applied at the front (drive) axle, used with "wh_axle_loss_mass"
%   Values are double that of SUV to accomodate 4WD and Torsen Diff
wh_axle_loss_trq=[8 48]*.4; % (Nm)
% slip=(omega * r)/v -1; used with "wh_slip_force_coeff"
%   wh_slip not compensated for unpacked soil. Values should be higher
wh_slip=[0.0 0.025 0.050 0.075 0.10 0.125]; % (--)
```

```

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% OTHER DATA
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
wh_radius=0.456; % (m), rolling radius of Goodyear radial 37-12.5 R16.5
% rotational inertia of all wheels, tires, and axles
% Estimate...
wh_inertia=360/2.205*wh_radius^2/2; % (kg*m^2)
% fraction of braking done by driveline, indexed by wh_fa_dl_brake_mph
wh_fa_dl_brake_frac=[0 0 0.5 0.8 0.8]; % (--)
% (--), fraction of braking done by front friction brakes,
% indexed by wh_fa_fric_brake_mph
wh_fa_fric_brake_frac=[0.8 0.8 0.4 0.1 0.1]; % (--)
wh_fa_dl_brake_mph=[-1 0 10 60 1000]; % (mph)
wh_fa_fric_brake_mph=wh_fa_dl_brake_mph; % (mph)

wh_1st_rrc=0.045 ; % (--), rolling resistance coefficient, Value is for unpacked earth
wh_2nd_rrc=0; % (s/m)

wh_mass=0;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Error checking
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% dl+fa_fric must add up to <= 1 for all speeds. Give user warning if in error
temp_total_braking=wh_fa_dl_brake_frac+wh_fa_fric_brake_frac;
if any(temp_total_braking>1)
    disp('Warning: Driveline and Front Friction Braking need to add to less than or equal to 1 for')
    disp('    all speeds. Please edit either wh_fa_dl_brake_frac or wh_fa_fric_brake_frac');
    disp('    in WH_*.m. See Chapter 3.2.4, Braking of the documentation for more info.');
```

```
end
```

```
clear temp_total_braking
```

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

```
% REVISION HISTORY
```

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

```
%9/17/98:ss added wh_mass=0;
```

```
%01/21/99:mc updated wh_slip and wh_slip_force_coeff per DB's suggestion
```

```
% 3/15/99:ss updated *_version to 2.1 from 2.0
```

```
% 11/03/99:ss updated version from 2.2 to 2.21
```

```
%01/10/01: vhj added error checking (warning to user about incorrect braking numbers)
```

```
% 4/4/02: mpo added rolling resistance coefficient data to this file (from vehicle wh_1st_rrc wh_2nd_rrc)
```


Appendix B.8. ADVISOR Control Model PTC_FUZZY_EFF_MODE.m

```
% ADVISOR data file: PTC_FUZZY_EFF_MODE.m
%
% Data source:
%
% Data confirmation:
%
% Notes:
% Defines all powertrain control parameters, including gearbox, clutch, hybrid
% and engine controls, for a parallel hybrid using a multi-spd gearbox.
%
% Created on: 21-July-2001
% By: AR, NREL, arun_rajagopalan@nrel.gov
%
% Revision history at end of file.
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

if ~exist('update_cs_flag')

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% FILE ID INFO
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
ptc_description='Fuzzy Logic controller - Efficiency mode operation';
ptc_version=2002; % version of ADVISOR for which the file was generated
ptc_proprietary=0; % 0=> non-proprietary, 1=> proprietary, do not distribute
ptc_validation=0; % 1=> no validation, 1=> data agrees with source data,
% 2=> data matches source data and data collection methods have been verified
disp(['Data loaded: PTC_FUZZY_EFF_MODE - ',ptc_description])

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% CLUTCH & ENGINE CONTROL
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% engine idle speed
vc_idle_spd=73.3; % (rad/s)
% 1=> idling allowed; 0=> engine shuts down rather than
vc_idle_bool=0; % (--)
% 1=> disengaged clutch when req'd engine torque <=0; 0=> clutch remains engaged
vc_clutch_bool=0; % (--)
% speed at which engine spins while clutch slips during launch
vc_launch_spd=max(fc_map_spd)/6; % (rad/s)
% fraction of engine thermostat temperature below which the engine will stay on once it is on
vc_fc_warm_tmp_frac=0.85; % (--)

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% GEARBOX CONTROL
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% fractional engine load {(torque)/(max torque at speed)} above which a
% downshift is called for, indexed by gb_gearN_dnshift_spd
gb_gear1_dnshift_load=[0 0.6 0.9 1]; % (--)
```

```

gb_gear2_dnshift_load=gb_gear1_dnshift_load; % (--)
gb_gear3_dnshift_load=gb_gear1_dnshift_load; % (--)
gb_gear4_dnshift_load=gb_gear1_dnshift_load; % (--)
gb_gear5_dnshift_load=gb_gear1_dnshift_load; % (--)
% fractional engine load {(torque)/(max torque at speed)} below which an
% upshift is called for, indexed by gb_gearN_upshift_spd
gb_gear1_upshift_load=[0 0.3 1]; % (--)
gb_gear2_upshift_load=gb_gear1_upshift_load; % (--)
gb_gear3_upshift_load=gb_gear1_upshift_load; % (--)
gb_gear4_upshift_load=gb_gear1_upshift_load; % (--)
gb_gear5_upshift_load=gb_gear1_upshift_load; % (--)
gb_gear1_dnshift_spd=[0.1399 0.14 0.3 0.3001]*max(fc_map_spd)*fc_spd_scale; % (rad/s)
gb_gear2_dnshift_spd=gb_gear1_dnshift_spd; % (rad/s)
gb_gear3_dnshift_spd=gb_gear1_dnshift_spd; % (rad/s)
gb_gear4_dnshift_spd=gb_gear1_dnshift_spd; % (rad/s)
gb_gear5_dnshift_spd=gb_gear1_dnshift_spd; % (rad/s)
gb_gear1_upshift_spd=[0.2631 0.2632 0.98]*max(fc_map_spd)*fc_spd_scale; % (rad/s)
% 0.98 rather than 1 because engine may not be able to reach the max speed
% under certain conditions due to speed estimation method
% this setting allows the vehicle to shift before it gets to the max engine speed (tm:11/11/99)
gb_gear2_upshift_spd=gb_gear1_upshift_spd; % (rad/s)
gb_gear3_upshift_spd=gb_gear1_upshift_spd; % (rad/s)
gb_gear4_upshift_spd=gb_gear1_upshift_spd; % (rad/s)
gb_gear5_upshift_spd=gb_gear1_upshift_spd; % (rad/s)

% convert old shift commands to new shift commands
gb_upshift_spd={gb_gear1_upshift_spd; ...
    gb_gear2_upshift_spd;...
    gb_gear3_upshift_spd;...
    gb_gear4_upshift_spd;...
    gb_gear5_upshift_spd}; % (rad/s)

gb_upshift_load={gb_gear1_upshift_load; ...
    gb_gear2_upshift_load;...
    gb_gear3_upshift_load;...
    gb_gear4_upshift_load;...
    gb_gear5_upshift_load}; % (--)

gb_dnshift_spd={gb_gear1_dnshift_spd; ...
    gb_gear2_dnshift_spd;...
    gb_gear3_dnshift_spd;...
    gb_gear4_dnshift_spd;...
    gb_gear5_dnshift_spd}; % (rad/s)

gb_dnshift_load={gb_gear1_dnshift_load; ...
    gb_gear2_dnshift_load;...
    gb_gear3_dnshift_load;...
    gb_gear4_dnshift_load;...
    gb_gear5_dnshift_load}; % (--)

clear gb_gear*shift* % remove unnecessary data

% fixes the difference between number of shift vectors and gears in gearbox
if length(gb_upshift_spd)<length(gb_ratio)
    start_pt=length(gb_upshift_spd);

```

```

for x=1:length(gb_ratio)-length(gb_upshift_spd)
    gb_upshift_spd{x+start_pt}=gb_upshift_spd{1};
    gb_upshift_load{x+start_pt}=gb_upshift_load{1};
    gb_dnshift_spd{x+start_pt}=gb_dnshift_spd{1};
    gb_dnshift_load{x+start_pt}=gb_dnshift_load{1};
end
end

% duration of shift during which no torque can be transmitted
gb_shift_delay=0; % (s)

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% HYBRID CONTROL STRATEGY
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% EFFICIENCY MODE
% Set the mode to operate near peak efficiency of the IC Engine
% 1=> FUEL LIMITING MODE; 0=> PEAK EFFICIENCY MODE
cs_fuzzy_fuel_mode=0; % (--)

% highest desired battery state of charge
cs_hi_soc=0.7; % (--)
% lowest desired battery state of charge
cs_lo_soc=0.6; % (--)
% vehicle speed below which vehicle operates as ZEV
% at low SOC
cs_electric_launch_spd_lo=0; % (m/s)
% at and above high SOC
cs_electric_launch_spd_hi=0; % (m/s)
% req'd torque as a fraction of max trq (at speed)
% below which engine shuts off, when SOC > cs_lo_soc
cs_off_trq_frac=0;
% torque as a fraction of max trq (at speed) that engine
% puts out when req'd is below this value, when SOC < cs_lo_soc
cs_min_trq_frac=0.4;
% accessory-like torque load on engine that
% goes to recharging the batteries whenever the engine is
% on cs_charge_trq*(mean(cs_lo_soc cs_hi_soc)-SOC)/(cs_hi_soc-cs_lo_soc)=additional torque
cs_charge_trq=0.25*min(fc_max_trq);
% charge depleting hybrid strategy flag, 1=> use charge
% deplete strategy, 0=> use charge sustaining strategy
cs_charge_deplete_bool=0; % boolean
% speed above which no engine shut down occurs due to low torque requests
cs_electric_decel_spd=0; % (m/s)

% If used for an automatic transmission
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% HYDRAULIC TORQUE CONVERTER CONTROL
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
htc_lockup=[0 0 0 1]; % (--), htc_lockup(i)=='when in gear i, lock up HTC'

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% START OF SPEED DEPENDENT SHIFTING INFORMATION
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% Data specific for SPEED DEPENDENT SHIFTING in the (PRE_TX) GEARBOX CONTROL

```

```

% BLOCK in VEHICLE CONTROLS <vc>
% --implemented for all powertrains except CVT versions and Toyota Prius (JPN)
%
tx_spd_dep=0; % Value for the switch in the gearbox control
%
% If tx_spd_dep=1, the speed dependent gearbox is chosen
% If tx_spd_dep=0, the engine load dependent gearbox is chosen
%
% Vehicle speed (m/s) where the gearbox has to shift
%tx_1_2_spd=24/3.6; % converting from km/hr to m/s
%tx_2_3_spd=40/3.6;
%tx_3_4_spd=64/3.6;
%tx_4_5_spd=75/3.6;
%tx_5_4_spd=75/3.6;
%tx_4_3_spd=64/3.6;
%tx_3_2_spd=40/3.6;
%tx_2_1_spd=tx_1_2_spd;

% first column is speed in m/s, second column is gear number
% note: lookup data should be specified as a step function
% ..... this can be done by repeating values of x (first column, speed)
% ..... for differing values of y (second column, )
% note: division by 3.6 to change from km/hr to m/s

% speeds to use for upshift transition (shifting while accelerating)
tx_spd_dep_upshift = [
    0/3.6, 1
    24/3.6, 1
    24/3.6, 2
    40/3.6, 2
    40/3.6, 3
    64/3.6, 3
    64/3.6, 4
    75/3.6, 4
    75/3.6, 5
    1000/3.6, 5];

% speeds to use for downshift transition (shifting while decelerating)
tx_spd_dep_dnshift = [
    0/3.6, 1
    24/3.6, 1
    24/3.6, 2
    40/3.6, 2
    40/3.6, 3
    64/3.6, 3
    64/3.6, 4
    75/3.6, 4
    75/3.6, 5
    1000/3.6, 5];
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% END OF SPEED DEPENDENT SHIFTING %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% REVISION HISTORY
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%8/12/98,vh, cs_charge_trq,initialy =0, set to 20

```

%8/17/98,vh, changed behavior of cs_charge_trq in block diagram: only adds this
 % additional torque when SOC < cs_lo_soc
 %8/26/98,vh changed behavior of cs_charge_trq in block diagram: now, cscharge_trq*(cs_lo_soc-
 SOC)=additional torque
 %09/15/98:MC set gb_shift_delay=0 for reasonable trace following
 % 3/15/99:ss updated *_version to 2.1 from 2.0
 % 10/7/99:tm added *fc_spd_scale to shift speed definitions
 %10/25/99:mc updated cs_electric_launch_spd and cs_off_trq_frac to improve FE and reduce engine
 cycling
 % 11/03/99:ss updated version from 2.2 to 2.21
 % 1/12/00:tm introduced cs_charge_deplete_bool
 % 8/9/00:tm updated default value of cs_charge_trq due to block diagram revision
 % 8/16/00:tm removed cs_offset_soc - no longer used in block diagram
 % 8/16/00:tm introduced cs_electric_launch_spd_lo and _hi to replace cs_electric_launch_spd
 % 8/16/00:tm introduced vc_fc_warm_tmp_frac to control engine on state based on coolant temperature
 % 11/1/00:tm introduced cs_electric_decel_spd to prevent engine shutdown at high speeds
 % 07/21/01:ar Adapted from PTC_PAR.m - Changes to Accomodate the Fuzzy Logic Control
 % 7/31/01:mpo added variables for speed dependent shifting

Appendix B.9. ADVISOR Drive Cycle Models

Appendix B.9.1. CYC_CONSTANT_20kph.m

```
% ADVISOR data file: CYC_CONSTANT_20kph.m
%
% Data source: Craig Rutherford, UTK
%
% Data confirmation:
%
% Notes: Requests a constant 20 kph speed of the vehicle for 50s.
%
% Created on: 18-Nov-1998
% Modified By: Craig Rutherford
% From CYC_CONST_45.m By: VHJ of NREL
%
% Revision history at end of file.
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% FILE ID INFO
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
cyc_description='Constant speed cycle';
cyc_version=2002; % version of ADVISOR for which the file was generated
cyc_proprietary=0; % 0=> non-proprietary, 1=> proprietary, do not distribute
cyc_validation=0; % 0=> no validation, 1=> data agrees with source data,
% 2=> data matches source data and data collection methods have been verified
disp(['Data loaded: CYC_CONSTANT_20kph - ',cyc_description])

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% SPEED AND KEY POSITION vs. time
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
if ~exist('vel')
    vel=12.427; %speed in mph
end

cyc_mph=[0 vel
    5-eps vel
    5 vel
    50 vel];

% keep key in 'on' position throughout cycle ('1' in the 2nd column => 'on')
vc_key_on=[cyc_mph(:,1) ones(size(cyc_mph,1),1)];

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% OTHER DATA
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% Size of 'window' used to filter the trace with centered-in-time averaging;
% higher numbers mean more smoothing and less rigorous following of the trace.
% Used when cyc_filter_bool=1
```

```

cyc_avg_time=1; % (s)
cyc_filter_bool=0; % 0=> no filtering, follow trace exactly; 1=> smooth trace
cyc_grade=0; %no grade associated with this cycle
cyc_elevation_init=0; %the initial elevation in meters.

if size(cyc_grade,1)<2
    % convert cyc_grade to a two column matrix, grade vs. dist
    cyc_grade=[0 cyc_grade; 1 cyc_grade]; % use this for a constant roadway grade
end

clear vel

% A constant zero delta in cargo-mass:
% First column is distance (m) second column is mass (kg)
cyc_cargo_mass=[0 0
    1 0];

if size(cyc_cargo_mass,1)<2
    % convert cyc_grade to a two column matrix, grade vs. dist
    cyc_cargo_mass=[0 cyc_cargo_mass; 1 cyc_cargo_mass]; % use this for a constant roadway grade
end

if exist('cyc_coast_gb_shift_delay')
    gb_shift_delay=cyc_coast_gb_shift_delay; % restore the original gb_shift_delay which may have been
    changed by cyc_coast
end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% REVISION HISTORY
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% 3/15/99:ss updated *_version to 2.1 from 2.0
% 11/3/99:ss updated version to 2.21
% 1/18/00:tm created based on cyc_constant
% 8/20/01: mpo added special case code to reset gb_shift_delay if changed by cyc_coast

```

Appendix B.9.2. CYC_CONSTANT_40kph.m

```
% ADVISOR data file: CYC_CONSTANT_40kph.m
%
% Data source: Craig Rutherford, UTK
%
% Data confirmation:
%
% Notes: Requests a constant 40 kph speed of the vehicle for 50s.
%
% Created on: 18-Nov-1998
% Modified By: Craig Rutherford
% From CYC_CONST_45.m By: VHJ of NREL
%
% Revision history at end of file.
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% FILE ID INFO
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
cyc_description='Constant speed cycle';
cyc_version=2002; % version of ADVISOR for which the file was generated
cyc_proprietary=0; % 0=> non-proprietary, 1=> proprietary, do not distribute
cyc_validation=0; % 0=> no validation, 1=> data agrees with source data,
% 2=> data matches source data and data collection methods have been verified
disp(['Data loaded: CYC_CONSTANT_40kph - ',cyc_description])

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% SPEED AND KEY POSITION vs. time
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
if ~exist('vel')
    vel=24.855; %speed in mph
end

cyc_mph=[0 vel
5-eps vel
5 vel
50 vel];

% keep key in 'on' position throughout cycle ('1' in the 2nd column => 'on')
vc_key_on=[cyc_mph(:,1) ones(size(cyc_mph,1),1)];

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% OTHER DATA
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% Size of 'window' used to filter the trace with centered-in-time averaging;
% higher numbers mean more smoothing and less rigorous following of the trace.
% Used when cyc_filter_bool=1
cyc_avg_time=1; % (s)
cyc_filter_bool=0; % 0=> no filtering, follow trace exactly; 1=> smooth trace
```



```

cyc_grade=0; %no grade associated with this cycle
cyc_elevation_init=0; %the initial elevation in meters.

if size(cyc_grade,1)<2
    % convert cyc_grade to a two column matrix, grade vs. dist
    cyc_grade=[0 cyc_grade; 1 cyc_grade]; % use this for a constant roadway grade
end

clear vel

% A constant zero delta in cargo-mass:
% First column is distance (m) second column is mass (kg)
cyc_cargo_mass=[0 0
    1 0];

if size(cyc_cargo_mass,1)<2
    % convert cyc_grade to a two column matrix, grade vs. dist
    cyc_cargo_mass=[0 cyc_cargo_mass; 1 cyc_cargo_mass]; % use this for a constant roadway grade
end

if exist('cyc_coast_gb_shift_delay')
    gb_shift_delay=cyc_coast_gb_shift_delay; % restore the original gb_shift_delay which may have been
    changed by cyc_coast
end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% REVISION HISTORY
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% 3/15/99:ss updated *_version to 2.1 from 2.0
% 11/3/99:ss updated version to 2.21
% 1/18/00:tm created based on cyc_constant
% 8/20/01: mpo added special case code to reset gb_shift_delay if changed by cyc_coast

```

Appendix B.9.3. CYC_CONSTANT_60kph.m

```
% ADVISOR data file: CYC_CONSTANT_60kph.m
%
% Data source: Craig Rutherford, UTK
%
% Data confirmation:
%
% Notes: Requests a constant 60 kph speed of the vehicle for 50s.
%
% Created on: 18-Nov-1998
% Modified By: Craig Rutherford
% From CYC_CONST_45.m By: VHJ of NREL
%
% Revision history at end of file.
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% FILE ID INFO
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
cyc_description='Constant speed cycle';
cyc_version=2002; % version of ADVISOR for which the file was generated
cyc_proprietary=0; % 0=> non-proprietary, 1=> proprietary, do not distribute
cyc_validation=0; % 0=> no validation, 1=> data agrees with source data,
% 2=> data matches source data and data collection methods have been verified
disp(['Data loaded: CYC_CONSTANT_60kph - ',cyc_description])

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% SPEED AND KEY POSITION vs. time
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
if ~exist('vel')
    vel=37.282; %speed in mph
end

cyc_mph=[0 vel
5-eps vel
5 vel
50 vel];

% keep key in 'on' position throughout cycle ('1' in the 2nd column => 'on')
vc_key_on=[cyc_mph(:,1) ones(size(cyc_mph,1),1)];

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% OTHER DATA
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% Size of 'window' used to filter the trace with centered-in-time averaging;
% higher numbers mean more smoothing and less rigorous following of the trace.
% Used when cyc_filter_bool=1
cyc_avg_time=1; % (s)
```

```

cyc_filter_bool=0;          % 0=> no filtering, follow trace exactly; 1=> smooth trace
cyc_grade=0;               %no grade associated with this cycle
cyc_elevation_init=0;      %the initial elevation in meters.

if size(cyc_grade,1)<2
    % convert cyc_grade to a two column matrix, grade vs. dist
    cyc_grade=[0 cyc_grade; 1 cyc_grade]; % use this for a constant roadway grade
end

clear vel

% A constant zero delta in cargo-mass:
% First column is distance (m) second column is mass (kg)
cyc_cargo_mass=[0 0
    1 0];

if size(cyc_cargo_mass,1)<2
    % convert cyc_grade to a two column matrix, grade vs. dist
    cyc_cargo_mass=[0 cyc_cargo_mass; 1 cyc_cargo_mass]; % use this for a constant roadway grade
end

if exist('cyc_coast_gb_shift_delay')
    gb_shift_delay=cyc_coast_gb_shift_delay; % restore the original gb_shift_delay which may have been
    changed by cyc_coast
end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% REVISION HISTORY
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% 3/15/99:ss updated *_version to 2.1 from 2.0
% 11/3/99:ss updated version to 2.21
% 1/18/00:tm created based on cyc_constant
% 8/20/01: mpo added special case code to reset gb_shift_delay if changed by cyc_coast

```

Appendix B.9.4. CYC_CONSTANT_80kph.m

```

% ADVISOR data file: CYC_CONSTANT_80kph.m
%
% Data source: Craig Rutherford, UTK
%
% Data confirmation:
%
% Notes: Requests a constant 80 kph speed of the vehicle for 50s.
%
% Created on: 18-Nov-1998
% Modified By: Craig Rutherford
% From CYC_CONST_45.m By: VHJ of NREL
%
% Revision history at end of file.
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

```

```

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% FILE ID INFO
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
cyc_description='Constant speed cycle';
cyc_version=2002; % version of ADVISOR for which the file was generated
cyc_proprietary=0; % 0=> non-proprietary, 1=> proprietary, do not distribute
cyc_validation=0; % 0=> no validation, 1=> data agrees with source data,
% 2=> data matches source data and data collection methods have been verified
disp(['Data loaded: CYC_CONSTANT_80kph - ',cyc_description])

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% SPEED AND KEY POSITION vs. time
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
if ~exist('vel')
    vel=49.710; %speed in mph
end

cyc_mph=[0 vel
    5-eps vel
    5 vel
    50 vel];

% keep key in 'on' position throughout cycle ('1' in the 2nd column => 'on')
vc_key_on=[cyc_mph(:,1) ones(size(cyc_mph,1),1)];

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% OTHER DATA
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% Size of 'window' used to filter the trace with centered-in-time averaging;
% higher numbers mean more smoothing and less rigorous following of the trace.
% Used when cyc_filter_bool=1
cyc_avg_time=1; % (s)
cyc_filter_bool=0; % 0=> no filtering, follow trace exactly; 1=> smooth trace
cyc_grade=0; %no grade associated with this cycle
cyc_elevation_init=0; %the initial elevation in meters.

if size(cyc_grade,1)<2
    % convert cyc_grade to a two column matrix, grade vs. dist
    cyc_grade=[0 cyc_grade; 1 cyc_grade]; % use this for a constant roadway grade
end

clear vel

% A constant zero delta in cargo-mass:
% First column is distance (m) second column is mass (kg)
cyc_cargo_mass=[0 0
    1 0];

if size(cyc_cargo_mass,1)<2
    % convert cyc_grade to a two column matrix, grade vs. dist
    cyc_cargo_mass=[0 cyc_cargo_mass; 1 cyc_cargo_mass]; % use this for a constant roadway grade
end

```

```

if exist('cyc_coast_gb_shift_delay')
    gb_shift_delay=cyc_coast_gb_shift_delay; % restore the original gb_shift_delay which may have been
    changed by cyc_coast
end

```

```

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

```

```

% REVISION HISTORY

```

```

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

```

```

% 3/15/99:ss updated * _version to 2.1 from 2.0

```

```

% 11/3/99:ss updated version to 2.21

```

```

% 1/18/00:tm created based on cyc_constant

```

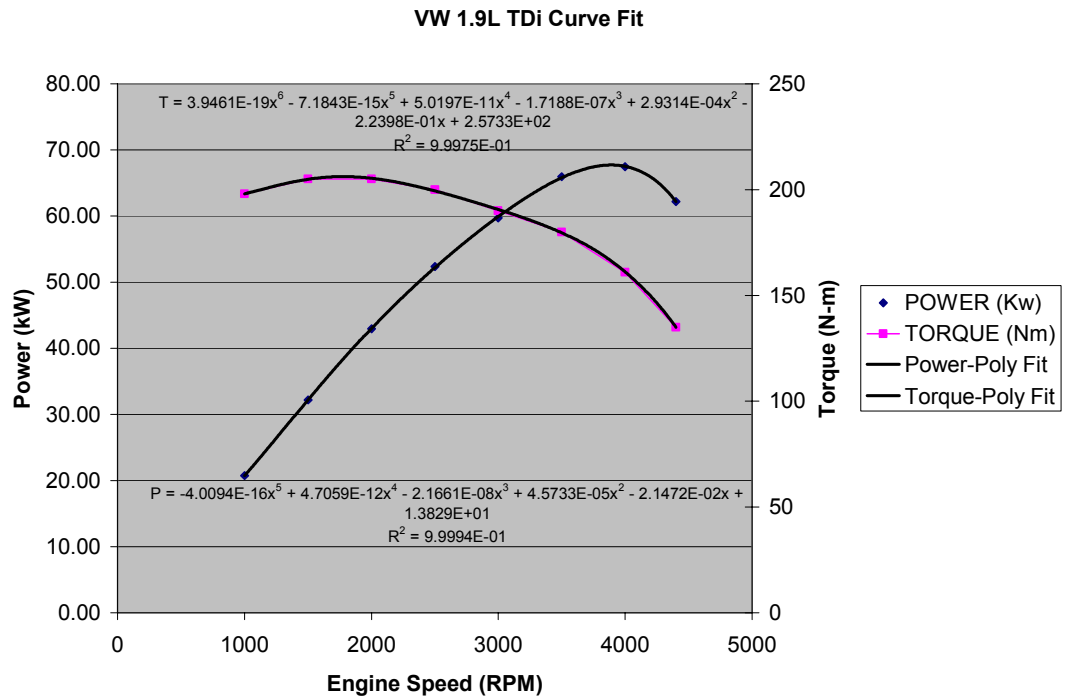
```

% 8/20/01: mpo added special case code to reset gb_shift_delay if changed by cyc_coast

```

Appendix C. Sample Hand Calculation Outputs

Appendix C.1. Engine Power Curve Fits



Appendix C.2. Sample Gradeability Output

Gradeability			Inputs	Calculated	
Parameter	Value	Units	Gradient %	Faero (N)	
m	3,500	kg	5	665.29	
m_{eq}	490	kg	Gradient Angle (rad)	Froll (N) (onroad)	
C_D	0.5	-	0.04996	445.80	
A_F	3.58	m ²	Gradient Angle (deg)	Froll (N) (offroad)	
r_{tire}	0.456	m	2.86	1543.15	
$C_{roll-paved}$	0.013	-	Acceleration (m/s ²)	Faccel (N)	
$C_{roll-dirt}$	0.045	-	0	0	
g	9.81	m/s ²	Velocity (kph)	Fgrade (N)	
ρ	1.23	kg/m ³	88.5	1714.61	
			Velocity (m/s)		
			24.58	Ftotal (onroad) (N)	
Component	Ratio			2825.69	
Transmission				Ftotal (offroad) (N)	
Torque Converter	2.10:1			3923.04	
1st Gear	2.48:1				
2nd Gear	1.48:1			Wheel Torque	Wheel Power
3rd Gear	1.00:1			Onroad (N-m)	Onroad (kW)
4th Gear	0.75:1			1288.52	69.46
Transfer Case					
High Range	1.01:1			Wheel Torque	Wheel Power
Low Range	2.72:1			Onroad (N-m)	Onroad (kW)
Differential	2.73:1			1788.91	96.44
Wheel Reducer	1.92:1				

Appendix C.3. Sample Rangeability Output

Rangeability			Inputs	Calculated	
Parameter	Value	Units	Gradient %	Faero (N)	
m	3,500	kg	0	8.49	
m_{eq}	490	kg	Gradient Angle (rad)	Froll (N) (onroad)	
C_D	0.5	-	0.00000	446.36	
A_F	3.58	m	Gradient Angle (deg)	Froll (N) (offroad)	
r_{tire}	0.456	m	0.00	1545.08	
$C_{n1-paved}$	0.013	-	Acceleration (m/s ²)	Faccel (N)	
$C_{n1-dirt}$	0.045	-	0	0.00	
g	9.81	m/s ²	Velocity (kph)	Fgrade (N)	ESS Energy
ρ	1.23	kg/m ³	10	0.00	Offroad (kW-h)
			Velocity (m/s)		5.02
			2.78	Ftotal (onroad) (N)	
Component	Ratio		Desired Range (km)	454.85	ESS Energy
Transmission			32.2	Ftotal (offroad) (N)	Offroad (kW-h)
Torque Converter	2.10:1		Drivetrain Eff (%)	1553.57	17.16
1st Gear	2.48:1		81%		
2nd Gear	1.48:1		Motor Eff (%)	Wheel Torque	Wheel Power
3rd Gear	1.00:1		100%	Onroad (N-m)	Onroad (kW)
4th Gear	0.75:1		Battery Eff (%)	207.41	1.26
Transfer Case			100%		
High Range	1.01:1			Wheel Torque	Wheel Power
Low Range	2.72:1			Onroad (N-m)	Offroad (kW)
Differential	2.73:1			708.43	4.32
Wheel Reducer	1.92:1				

Appendix C.4. Sample Acceleration Output

Inputs:

VEHICLE CHARACTERISTICS		
VEHICLE MASS (UNLOADED) (m_u) (kg)		
2359		
VEHICLE MASS (LOADED) (m_L) (kg)		
3574		
AERODYNAMIC DRAG COEFFICIENT (C_D)		
0.5		
AIR DENSITY (kg/m³)		
1.23		
FRONTAL AREA (A_f) (m²)		
3.17		
MASS CORRECTION FACTOR (g)		
1.14		
AV ASSUMED POWERTRAIN EFF.		
0.5		
ROLLING RADIUS (m)		
0.456		
ESTIMATED TIRE CIRCUMFERENCE (m)		
2.87		
ROLLING RESISTANCE		
0.013		
OVERALL GEAR RATIOS (engine to wheel)		
1st/HIGH	27.57124	33.69818
2nd/HIGH	16.4538	20.1102
3rd/HIGH	11.22861	13.72385
1st/LOW	35.35774	43.21501
2nd/LOW	21.10058	25.7896
3rd/LOW	14.39972	17.59966
Idle speed	800	

Inputs:

						Motor Power			Engine multiplier					
						0			1.25					
						Motor			Tdi Engine			Stock Engine		
						POWER			POWER			POWER		
VEHICLE SPEED	WH Spee	ENGINE SPEED												
V (mph)	V (m/s)	RPM	1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd
0.1	0.04470	0.9	825.8	15.4	7.0	0.0	0.0	0.0	21.4014	16.8863	17.101	18.7249	-26.563	-27.072
0.25	0.11176	2.3	864.5	38.5	17.5	0.0	0.0	0.0	22.3574	16.3359	16.8334	20.6965	-25.166	-26.435
0.5	0.22352	4.7	929.1	77.0	35.0	0.0	0.0	0.0	24.016	15.546	16.4148	23.9437	-22.85	-25.375
0.75	0.33528	7.0	993.6	115.5	52.6	0.0	0.0	0.0	25.7426	14.9078	16.0296	27.1423	-20.553	-24.319
1	0.44704	9.4	1058.1	154.0	70.1	0.0	0.0	0.0	27.5226	14.4126	15.6769	30.2923	-18.272	-23.266
1.25	0.55880	11.7	1122.6	192.5	87.6	0.0	0.0	0.0	29.3425	14.0524	15.3559	33.3936	-16.009	-22.217
1.5	0.67056	14.0	1187.2	231.1	105.1	0.0	0.0	0.0	31.1906	13.8191	15.0658	36.4463	-13.763	-21.172
1.75	0.78232	16.4	1251.7	269.6	122.6	0.0	0.0	0.0	33.0562	13.7051	14.8058	39.4504	-11.535	-20.13
2	0.89408	18.7	1316.2	308.1	140.2	0.0	0.0	0.0	34.9299	13.7031	14.5751	42.4058	-9.3233	-19.092
2.25	1.00584	21.1	1380.8	346.6	157.7	0.0	0.0	0.0	36.8035	13.8059	14.3729	45.3127	-7.1294	-18.057
2.5	1.11760	23.4	1445.3	385.1	175.2	0.0	0.0	0.0	38.6696	14.0067	14.1985	48.1709	-4.9528	-17.026
2.75	1.22936	25.7	1509.8	423.6	192.7	0.0	0.0	0.0	40.5222	14.299	14.0511	50.9805	-2.7935	-15.999
3	1.34112	28.1	1574.3	462.1	210.2	0.0	0.0	0.0	42.356	14.6765	13.9299	53.7414	-0.6515	-14.975
3.25	1.45288	30.4	1638.9	500.6	227.8	0.0	0.0	0.0	44.1666	15.1331	13.8343	56.4538	1.47318	-13.955
3.5	1.56464	32.8	1703.4	539.1	245.3	0.0	0.0	0.0	45.9504	15.6631	13.7635	59.1175	3.58052	-12.938
3.75	1.67640	35.1	1767.9	577.6	262.8	0.0	0.0	0.0	47.7046	16.2608	13.7168	61.7326	5.67055	-11.925
4	1.78816	37.4	1832.5	616.1	280.3	0.0	0.0	0.0	49.4271	16.921	13.6936	64.299	7.74325	-10.915
4.25	1.89992	39.8	1897.0	654.6	297.8	0.0	0.0	0.0	51.1163	17.6386	13.6931	66.8169	9.79865	-9.9093
4.5	2.01168	42.1	1961.5	693.2	315.4	0.0	0.0	0.0	52.7711	18.4087	13.7147	69.2861	11.8367	-8.9069
4.75	2.12344	44.5	2026.0	731.7	332.9	0.0	0.0	0.0	54.391	19.2267	13.7577	71.7067	13.8575	-7.9081
5	2.23520	46.8	2090.6	770.2	350.4	0.0	0.0	0.0	55.9759	20.0883	13.8215	74.0787	15.8609	-6.9129
5.25	2.34696	49.1	2155.1	808.7	367.9	0.0	0.0	0.0	57.526	20.9892	13.9055	76.402	17.847	-5.9213
5.5	2.45872	51.5	2219.6	847.2	385.4	0.0	0.0	0.0	59.0417	21.9254	14.009	78.6768	19.8159	-4.9332
5.75	2.57048	53.8	2284.1	885.7	403.0	0.0	0.0	0.0	60.5236	22.8932	14.1314	80.9029	21.7673	-3.9488
6	2.68224	56.2	2348.7	924.2	420.5	0.0	0.0	0.0	61.9726	23.8889	14.2721	83.0803	23.7015	-2.9679
6.25	2.79400	58.5	2413.2	962.7	438.0	0.0	0.0	0.0	63.3895	24.9092	14.4305	85.2092	25.6184	-1.9906
6.5	2.90576	60.9	2477.7	1001.2	455.5	0.0	0.0	0.0	64.7752	25.9509	14.6061	87.2894	27.5179	-1.0169

Outputs:

		hybrid			stock				
		Available	Accel	time	Available	Accel	time		
V (mph)	V (m/s)	Power kW	a m/s^2	t s	Power kW	a m/s^2	t s		
0.1	0.044704	10.70072	4.9	0.009123	9.362435	4.9	0.009123	Hybrid	
0.25	0.11176	11.17869	4.9	0.022808	10.34826	4.9	0.022808	Engine Multiplier	1.25
0.5	0.22352	12.00801	4.9	0.045616	11.97186	4.9	0.045616	Motor Power	0
0.75	0.33528	12.87132	4.9	0.068424	13.57115	4.9	0.068424	0-30mph	11.9 s
1	0.44704	13.76128	4.9	0.091233	15.14613	4.9	0.091233	0-50mph	42.6 s
1.25	0.5588	14.67125	4.9	0.114041	16.69679	4.9	0.114041		
1.5	0.67056	15.5953	4.9	0.136849	18.22315	4.9	0.136849	Stock	
1.75	0.78232	16.52811	4.9	0.159657	19.72519	4.9	0.159657	0-30mph	10.3 s
2	0.89408	17.46497	4.682315	0.183526	21.20292	4.9	0.182465	0-50mph	29.4 s
2.25	1.00584	18.40174	4.378139	0.209053	22.65633	4.9	0.205273		
2.5	1.1176	19.33482	4.133973	0.236087	24.08544	4.9	0.228082		
2.75	1.22936	20.26112	3.932829	0.264504	25.49023	4.9	0.25089		
3	1.34112	21.17801	3.763472	0.2942	26.87071	4.80529	0.274147		
3.25	1.45288	22.0833	3.618193	0.325089	28.22688	4.656039	0.298151		
3.5	1.56464	22.97521	3.491553	0.357097	29.55874	4.524279	0.322853		
3.75	1.6764	23.85232	3.379615	0.390166	30.86629	4.406511	0.348215		
4	1.78816	24.71356	3.279473	0.424245	32.14952	4.300111	0.374206		
4.25	1.89992	25.55813	3.188943	0.459291	33.40844	4.20307	0.400796		
4.5	2.01168	26.38554	3.106362	0.495269	34.64306	4.113829	0.427962		
4.75	2.12344	27.19551	3.030439	0.532148	35.85335	4.031155	0.455687		
5	2.2352	27.98796	2.960169	0.569902	37.03934	3.954061	0.483951		
5.25	2.34696	28.76299	2.894753	0.60851	38.20102	3.88175	0.512742		
5.5	2.45872	29.52083	2.833549	0.647952	39.33838	3.813569	0.542048		
5.75	2.57048	30.2618	2.776041	0.688211	40.45143	3.748978	0.571859		
6	2.68224	30.98631	2.7218	0.729272	41.54017	3.687528	0.602167		
6.25	2.794	31.69477	2.670472	0.771122	42.6046	3.62884	0.632964		
6.5	2.90576	32.38761	2.621757	0.81375	43.64472	3.572597	0.664247		

Vita

Craig Rutherford was born in Bristol, Tennessee in December of 1970. He attended the University of Tennessee, Knoxville where he received a Bachelor of Science in Mechanical Engineering in May, 1998. He began work on a Master of Science degree in Mechanical Engineering at the University of Tennessee, Knoxville in the fall of 1998 which was completed in August, 2004. Drs. Jeffrey Hodgson and William Hamel served as principal advisors for this study.

Craig has been employed by Lynx Motion Technology of Greenville, Indiana since 1999 where he has performed various design and management duties related to the development of electric motor technologies for transportation, military, and commercial applications. He pursues a number of hobbies related to personal electric vehicles, solar power, and robotics.

Craig currently lives in Indianapolis, Indiana with his wife Kristy and their dog Keeli.