İSTANBUL TECHNICAL UNIVERSITY ★ INSTITUTE OF SCIENCE AND TECHNOLOGY

# FORD TOURNEO CONNECT HYBRID ELECTRIC VEHICLE TRANSFORMATION WITH ADVISOR

**M.Sc. Thesis by**

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**Department : Mechanical Engineering**

**Programme: Automotive**

**JUNE 2005**

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**PREFACE**

Growing environmental and economic concerns have driven recent efforts to produce more fuel efficient and lower emissions vehicles. Hybrid Electric Vehicles (HEVs) are automobiles that have both electric drivetrains and fuel-consuming powerplants. Ideally, these vehicles will achieve estimate three times the current fuel economy while drastically lowering emissions levels, without sacrificing the features, comfort, and performance of current conventional automobiles.

This master's thesis provides an detailed comparison between conventional and hybrid electric Ford Tourneo Connect by using Advanced Vehicle Simulator (ADVISOR)—the US Department of Energy's (DOE's) ADVISOR written in the MATLAB/Simulink environment and developed by the National Renewable Energy It is used to quantify the fuel economy, the performance, and the emissions of the vehicles.

This was so far the third largest challenge during my education. It has been very exciting to do something completely of my own and without distinct answers, but sometimes also very frustrating and difficult. Therefore I would like to express my gratitude to everyone who has assisted and encouraged me during this work. First of all thanks to my honorable advisor Assoc.Prof.Dr.Doğan Güneş, who let me perform the work with the master's thesis with great patience and empathy. He has been very helpful and has guided me through difficulties. Thanks to Prof.Dr.Ertuğrul Arslan and Prof.Dr. Metin Ergeneman for their valuable help in all discussions about the topic. Also thanks to Nuri Sönmez, Mehmet Seçkin Duru and Fuat Okan Tandoğan from Ford-Otosan A.Ş. for answering my interesting questions and sending me the real world conventional vehicle fuel consumption, emission results, engine and transmission weights

June 2005 Önder Barlas

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**ABBREVIATIONS**

| | |
|---|---|
| **ADVISOR** | : Advanced Vehicle Simulator |
| **BSC** | : Basic Control Strategy |
| **CG** | : Center of Gravity |
| **CNG** | : Compressed Natural Gas |
| **CO** | : Carbon monoxide |
| **CV** | : Conventional Vehicle |
| **CVT** | : Continuous Various Transmission |
| **DOE** | : Department of Energy |
| **ECE** | : Urban Drive Cycle |
| **EM** | : Electric Motor |
| **EPA** | : Environmental Protection Agency |
| **EUDC** | : Extra Urban Drive Cycle |
| **EUDCL** | : Extra Urban Drive Cycle for lower powered Vehicles |
| **EV** | : Electric Vehicle |
| **FTP** | : Federal Test Procedure |
| **HC** | : Hydrocarbons |
| **HEV** | : Hybrid Electric Vehicle |
| **HWFET** | : Highway Fuel Economy Test |
| **IC** | : Internal Combustion Engine |
| **LNG** | : Liquid Natural Gas |
| **NEDC** | : New European Driving Schedule |
| **NiMH** | : Nickel Metal Hybride |
| **NOx** | : Nitroxide |
| **NREL** | : National Renewable Energy Laboratory |
| **NYCC** | : New York City Cycle |
| **PM** | : Particulate Matter |
| **SOC** | : State of Charge |
| **TDCI** | : Turbo Diesel Common-Rail Injection |
| **TDI** | : Turbo Diesel Injection |
| **UDDS** | : Urban Dynamometer Driving Schedule |
| **ZEV** | : Zero Emission Vehicle |

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| | |
|---|---|
| $C_{CO}$ | **:** Correction Factor for CO emissions |
| $C_{NOx}$ | **:** Correction Factor for NOx emissions |
| $C_{HC}$ | **:** Correction Factor for HC emissions |
| $C_{PM}$ | **:** Correction Factor for PM emissions |
| $NOx_{Real}$ | **:** Real World conventional vehicle NOx emissions data |
| $NOx_{Sim}$ | **:** ADVISOR conventional vehicle NOx emission result |
| $CO_{Real}$ | **:** Real World conventional vehicle CO emissions data |
| $CO_{Sim}$ | **:** ADVISOR conventional vehicle CO emission result |
| $HC_{Real}$ | **:** Real World conventional vehicle HC emissions data |
| $HC_{Sim}$ | **:** ADVISOR conventional vehicle HC emission result |
| $PM_{Real}$ | **:** Real World conventional vehicle PM emissions data |
| $PM_{Sim}$ | **:** ADVISOR conventional vehicle PM emission result |

**ADVISOR YARDIMI ILE FORD TOURNEO CONNECT HİBRİT ELEKTRİK DÖNÜŞÜMÜ**


## ÖZET

Dünya çapında petrol fiyatları artmakta ve hava her gün kirlenmektedir. Bu şartlar altında hibrid elektrik araçlar en son çıkan araç tipleri arasında umut vaad etmişler. Düşük zararlı gaz emisyonları ve iyileştirilmiş yakıt tüketimleri onları diğerlerinden ayırmıştır.

İstanbul Teknik Üniversitesi Makine Fakültesi Otomotiv Anabilim Dalı Ford Otosan AŞ. ile beraber bir hibrid elektrik araç projesi yürütmektedir. Projenin amacı dizel motorlu Ford Tourneo Connect için EURO-4/EURO-5 emisyon normlarını sağlayan bir paralel hibrid sistemi dizayn etmektir.

Bu yüksek lisans tezi hibrid elektrik araçların yararlarını proje aracı olan Ford Tourneo Connect üzerinde, gelişmiş bir simülasyon programı olan ADVISOR vasıtasıyla göstermeye çalışmıştır. Çeşitli sürüş haritalarında konvansiyonel ve hibrid elektrik araç için bulunan ADVISOR yakıt tüketimi ve emisyon değerleri Ford-Otosan A.Ş tarafından sağlanan gerçek değerler vasıtasıyla düzeltilmiştir. Bunun yanı sıra konvansiyonel ve hibrid araç için performans ve eğim kabiliyeti ölçülmüş ve gerçek verilerle karşılaştırılmıştır.

Konvansiyonel Ford Tourneo Connect hibrid elektrik bir araca dönüştürüldüğünde yakıt tüketimi ve emisyonlar açısından yararlar ortaya çıkmıştır. Sistemin genel veriminde sürüş haritasına bağlı artışlar elde edilmiştir. Özellikle karbon monoksit emisyonları sürüş haritasından bağımsız olarak şiddetli bir şekilde düşmüştür. Buna mukabil azot oksit ve hidrokarbon emisyonları sürüş haritasına bağlı olan bir düşüş göstermiştir. Partiküler madde emisyonları dizel partikül filtresi kullanıldığında hem konvansiyonel hem de hibrid elektrik araç için problem olmaktan çıkmıştır. Sonuçlar hibrid Tourneo Connect'in EURO-4/EURO-5 emisyon normlarının altında bir gaz emisyonu ürettiğini göstermiştir. Ayrıca hızlanma ve elastikiyet değerlerinde hissedilir derecede iyileşmeler görülmüştür. Simülasyonda kullanılan elektrik motoru gereken eğim performansını verememiştir. Bu yüzden gereken eğim performansının sağlanması için ya dizel motor tek başına ya da hem dizel motor hem de elektrik motoru beraber çalışmalıdır.

**FORD TOURNEO CONNECT HYBRID ELECTRIC VEHICLE TRANSFORMATION WITH ADVISOR**


## SUMMARY

Petrol prices are rising around the world and the air is getting polluted every day. Under these circumstances hybrid electric vehicles showed promise among the latest vehicle types and stand out with their capabilities of reducing hazardous emissions and improving overall fuel consumption.

Istanbul Technical University Mechanical Engineering Automotive Department works in a hybrid electric vehicle project in association with Ford-Otosan A.Ş. The aim of this project is to design a parallel hybrid system for Ford Tourneo Connect with a diesel engine, which fulfills the EURO-4/EURO-5 emission norm.

This master's thesis tried to demonstrate the benefits of hybrid electric vehicles based on the project vehicle Ford Tourneo Connect by using ADVISOR, a powerful hybrid electric vehicle simulation tool. The ADVISOR fuel consumption and emission results for conventional and hybrid electric Ford Tourneo Connect for different drive cycles are corrected with the help of real world data received from Ford-Otosan AŞ. Also a performance and gradeability analysis was made to compare the conventional and hybrid electric vehicle results and real world data.

By transforming the conventional Ford Tourneo Connect into a hybrid electric vehicle, fuel consumption and emissions benefits will occur. The overall system efficiency increases dependent from the drive cycle. Especially CO emissions decrease strongly independent from drive cycle, whereas the decreases of NOx emissions are dependent from the drive cycle characteristics. PM emissions are not anymore a problem for conventional and hybrid electric Tourneo Connect by using a diesel particle filter for the simulation. The results showed that the hybrid electric Ford Tourneo Connect produces hazardous gasses below the EURO-4/EURO-5 emission regulations. There is also a remarkable improvement in acceleration and elasticity values. The electric motor, chosen for the simulation, alone is not capable of fulfilling the required gradeability limits. Therefore the diesel engine alone or together with the electric motor should be used to achieve the desired gradeability limits.

# 1. INTRODUCTION

The population in the world is growing and also the number of people that can afford a car. One of our biggest environmental problems to solve in the future is to avoid a huge increase in environmental pollutions and the greenhouse effect. Many new ideas and concepts need to be developed, because vehicles driven by fossil fuel are one of the largest contributors to today's air pollution [1]. Especially preventing/decreasing air pollution is a big challenge to overcome for engineers and scientist, who are searching for new solutions to be used in their related processes or productions, instead of alternatives tried before. Governments take actions and declare lots of legislations and restrictions to minimize the hazardous effects of certain processes [2].

Liquid hydrocarbon fuel based combustion is one of the main hazardous processes and is widely used in automobile engines. Liquid hydrocarbons are easily handled and posses a high energy density. As a consequence, conventional petroleum and diesel fuels have remained almost entirely unchanged since the motor vehicle was invented. However, their source is finite, reserves are not uniformly distributed and their increased usage contributes to a variety of local and regional air pollution problems and potential climate change (Greenhouse effect) [3]. According to EPA 1996 National Air Quality & Emission Trend Report motorized vehicles as cars and trucks are causing almost half of the smog-forming gases (volatile organic compounds and nitrogen oxides), more than 50% of hazardous air pollutants released and up to 90% of the carbon monoxide emissions in the urban areas [2].

Researches about different hybrid electric vehicle concepts are made all around the world. Today there are three mainstreams in HEV development:

- HEV with a gasoline engine (USA and Japan)
- HEV with a diesel engine (Europe)
- HEV in combination with fuel-cell

## 1.1 Definition Of The Problem

Istanbul Technical University Mechanical Engineering Automotive Department works in a hybrid electric vehicle project in association with Ford-Otosan A.Ş, which manufactures commercial vehicles for Ford and exports these to Europe. As mentioned before the European trend about HEVs includes the diesel engine option. Therefore the aim of this project is to design a parallel hybrid system for 1.8 L diesel engine Ford Tourneo Connect, which fulfills the EURO-4/EURO-5 emission norms. Currently 1.8 Common-Rail diesel engines allow on the vehicle emissions at EURO-3 level. As a part of this project the aim of the master thesis is to simulate a parallel hybrid electric Ford Tourneo Connect by different drive cycles and to optimize its performance values. For the simulation a special simulation program called ADVISOR will be used. After collecting the relevant data, the simulation will determine the emission and performance results. Results will be analyzed, errors will be corrected and conclusions will follow. This thesis does not content detailed information about ADVISOR. This can be found in Aktaş, D.Ö., "Hybrid Electric Vehicle Simulation in ADVISOR", Master's Thesis, Mechanical Engineering Faculty Automotive Engineering Department, 2004, which also includes a detailed comparison of hybrid components and a detailed analysis between test and simulation data of a conventional Ford Tourneo Connect.

## 1.2 Thesis Outline

An introduction of the problem will be given in the first chapter. Past researches about the project vehicle at the Istanbul Technical University will be summarized and the goal of the master's thesis will be mentioned. Also content of each chapter will be described.

Chapter 2 gives first detailed information about hybrid electric vehicles. Hybrid electric vehicle components and different concepts will be explained.

Chapter 3 presents basic information about ADVISOR. Its working principle: the forward and backward-facing approaches will be basically explained. In addition to these, attributes, functionality and limitations of ADVISOR will be given shortly. However as mentioned before detailed information about the simulation can be found in other sources.

Chapter 4 begins with determining the boundary conditions for ADVISOR input data. The project vehicle: Ford Tourneo Connect will be given in all measures and weights and defined for ADVISOR. Fuel converter, transmission, batteries, motor and control system to be used will be discussed, defined for ADVISOR and the test procedures/driving cycles will be introduced. The measure intervals for performance and gradeability conditions will be determined.

Chapter 5 begins with the presentation of emission and fuel consumption simulation results for the specified drive cycles. These results will be discussed and failure analysis will be made after comparing the simulation results with real world data. The same procedure will be undertaken for the performance and gradeability results.

Chapter 6 gives a conclusion of the emission, fuel consumption and performance results including recommendations for further improvement.

# 2. GENERAL INFORMATION ABOUT HYBRID ELECTRIC VEHICLES

## 2.1 Preview

Hybrid electric vehicles (hybrids) are powered by both an internal combustion engine and a battery-operated electric motor; hybrids can achieve up to twice the fuel economy of a conventional car and produce 30 to 50 percent fewer greenhouse gas emissions. Honda and Toyota currently lead in the manufacturing of hybrid cars, with their respective Insight and Prius models. HEVs (hybrid-electric vehicles) may not quite reach “zero emissions,” results show that they produce significantly less pollution than conventional cars. In fact, hybrid vehicles supposedly reduce air emissions of smog forming pollutants by up to 90% and cut carbon dioxide emissions in half. Furthermore, because electricity powers the car at low speeds and the engine starts at higher speeds, while conveniently recharging the batteries simultaneously, there is no reliance on any type of electric outlet. At the same time, there are fewer trips to the gas station needed. Other external benefits are that HEVs save the taxpayer money by consuming less fuel, and appeal to patriotism, by reducing the country’s reliance on foreign oil [4]. Important benefits of HEVs are listed below [5]:

• Unlike all-electric cars, hybrids do not need to be plugged in to recharge the battery. The battery recovers and stores energy normally lost as heat during braking through a process called regenerative braking: The regenerative braking technique makes the vehicle slow down by letting the wheels use the electric motor as a generator and contribute with power to the battery. The battery is also recharged by the engine when it produces more power than is needed to drive the wheels.

• Because of the extra power the electric motor provides, fuel converters in hybrids can be built smaller without compromising the vehicle’s peppiness. By allowing the engine to operate more efficiently, engine downsizing increases the environmental performance of hybrids and their fuel economy.

• Vehicles with idle-off capability can turn their gasoline/diesel engines off when stopped. This reduces emissions, which are dirtier while idling, and improves fuel efficiency. Idling off makes hybrids a particularly efficient (and quiet) option in city, stop-and-go traffic.

• Some hybrids have electric-only drive, powering the car with the battery alone at speeds up to 10 or 15 miles per hour. This provides significant fuel savings and emissions reductions because combustion engines operate least efficiently at low speeds.

**Table 2.1 :** OT Analyses of HEVs [6]

| OPPORTUNITIES | THREADS |
| --- | --- |
| • HEVs have demonstrated significant potential to reduce fuel consumption and exhaust emissions<br>• Advances in battery, power electronics technologies have made commercialization possible<br>• Performance is generally as good as or better than CVs | • Extra complexity adds significant cost<br>• Fuel efficiency improvements will vary<br>– By hybrid vehicle type<br>– By application<br>– By driving cycle |

## 2.2 Technical Background

As mentioned before in section 2.1, an internal combustion engine (ICE) runs in co-operation with an electric motor (EM). First a detailed description of HEV components will be given. There are different strategies for how to combine the ICE and the EM and four essential topologies are a series hybrid, a parallel hybrid, a series-parallel hybrid and a complex hybrid. These topologies are described in more detail after the component review section.

### 2.2.1 Components of hybrid electric vehicles

Hybrid electric vehicle (HEV) is an optimized mix of various components [7]:

1. Electric traction motors/controllers: Motors are the "work horses" of Hybrid Electric Vehicle (HEV) drive systems. In an HEV, an electric traction motor converts electrical energy from the energy storage unit to mechanical energy that drives the wheels of the vehicle. Unlike a traditional vehicle, where the engine must "ramp up" before full torque can be provided, an electric motor provides full torque at low speeds. This characteristic gives the vehicle excellent "off the line" acceleration. Important characteristics of an HEV motor include good drive control and fault tolerance, as well as low noise and high efficiency. Other characteristics include flexibility in relation to voltage fluctuations and, of course, acceptable mass production costs. Front-running motor technologies for HEV applications include permanent magnet, AC induction, and switched reluctance motors.

2. Electric energy storage systems, such as batteries and ultracapacitors: Batteries are an essential component of HEVs. Although a few production HEVs with advanced batteries have been introduced in the market, no current battery technology has demonstrated an economically acceptable combination of power, energy efficiency, and life cycle for high-volume production vehicles. Desirable attributes of high-power batteries for HEV applications are high-peak and pulse-specific power, high specific energy at pulse power, a high charge acceptance to maximize regenerative braking utilization, and long calendar and cycle life. Developing methods/designs to balance the packs electrically and thermally, developing accurate techniques to determine a battery's state of charge, developing abuse-tolerant batteries, and recyclability are additional technical challenges.

- Lead-Acid Batteries: Lead-acid batteries can be designed to be high power and are inexpensive, safe, and reliable. A recycling infrastructure is in place for them. But low specific energy, poor cold temperature performance, and short calendar and cycle life are still impediments to their use. Advanced high-power lead-acid batteries are being developed for HEV applications.

- Nickel-Cadmium Batteries: Although nickel-cadmium batteries, used in many electronic consumer products, have higher specific energy and better life cycle than lead-acid batteries, they do not deliver sufficient power and are not being considered for HEV applications.

- Nickel-Metal Hydride Batteries: Nickel-metal hydride batteries, used routinely in computer and medical equipment, offer reasonable specific energy and specific power capabilities. Their components are recyclable, but a recycling structure is not yet in place. Nickel-metal hydride batteries have a much longer life cycle than lead acid batteries and are safe and abuse-tolerant. These batteries have been used successfully in production electric vehicles and recently in low-volume production HEVs. The main challenges with nickel-metal hydride batteries are their high cost, high self-discharge and heat generation at high temperatures, the need to control losses of hydrogen, and their low cell efficiency.

- Lithium Ion Batteries: The lithium ion batteries are rapidly penetrating into laptop and cell-phone markets because of their high specific energy. They also have high specific power, high-energy efficiency, good high-temperature performance, and low self-discharge. Components of lithium ion batteries could also be recycled. These characteristics make lithium ion batteries suitable for HEV applications. However, to make them commercially viable for HEVs, further development is needed similar to those for the EV-design versions including improvement in calendar and cycle life, higher degree of cell and battery safety, abuse tolerance, and acceptable cost.

- Lithium Polymer Batteries: Lithium polymer batteries with high specific energy, initially developed for EV applications, also have the potential to provide high specific power for HEV applications. The other key characteristics of the lithium polymer are safety and good cycle and calendar life. The battery could be commercially viable if the cost is lowered and higher specific power batteries are developed.

- Ultracapacitors: Ultracapacitors are higher specific energy and power versions of electrolytic capacitors—devices that store energy as an electrostatic charge. They are electrochemical systems that store energy in a polarized liquid layer at the interface between an ionically conducting electrolyte and a conducting electrode. Energy storage capacity increases by increasing the surface area of the interface. Ultracapacitors are being developed as primary energy devices for power assist during acceleration and hill climbing, as well as recovery of braking energy. They are also potentially useful as secondary energy storage devices in HEVs, providing load-leveling power to chemical batteries. Additional electronics are required to maintain a constant voltage due to the low energy density.

3. Hybrid power units such as spark ignition engines, compression ignition direct injection (diesel) engines, gas turbines, and fuel cells

4. Fuel systems for hybrid power units: The two primary fuels used in automobiles today are gasoline and diesel. The infrastructure is in place to produce, refine, truck, or tank diesel and gasoline. Many of today's HEVs, and the ones that will be available in the near future, will use either gasoline or diesel to fuel the hybrid power units. However, to ensure the security of our oil supply and to address increasing environmental concerns associated with gasoline and diesel, alternative fuels are very attractive. The opportunity for fuels such as biodiesel, natural gas (CNG & LNG), ethanol, hydrogen, and propane to be used as alternative fuels for vehicles is great. Many alternative fuel vehicles are already being used effectively around the world. These fuels have the potential to be used in HEVs as well. The following graph shows the energy density for various fuels. The graph does not take into consideration containment weight. For instance, the energy density for hydrogen and compressed natural gas is much lower than that of gasoline if the containment weight for the fuel is taken into consideration. The containment weights are not taken into consideration in the following graph due to the variability of manufacturer's containment weight estimates.

5. HEV’s can use manuel transmissions, but a CVT is more suitable to the vehicle characteristics.

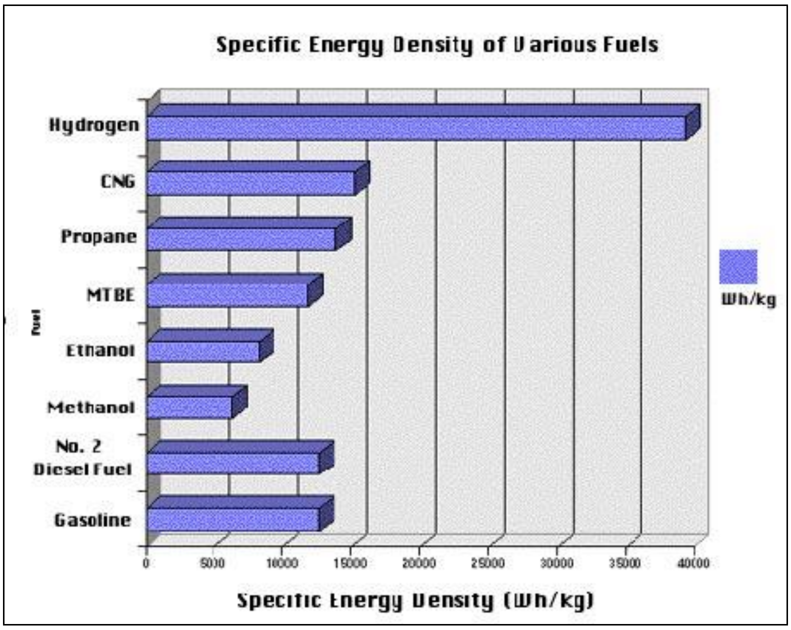



**Figure 2.1 :** Specific Energy Density of various Fuels [7]

To help reduce emissions and improve vehicle efficiencies, these systems and components are being improved through research and development.

1. Emission control systems
2. Energy management and systems control
3. Thermal management of components
4. Lightweight and aerodynamic body/chassis
5. Low rolling resistance (including body design and tires)
6. Reduction of accessory loads

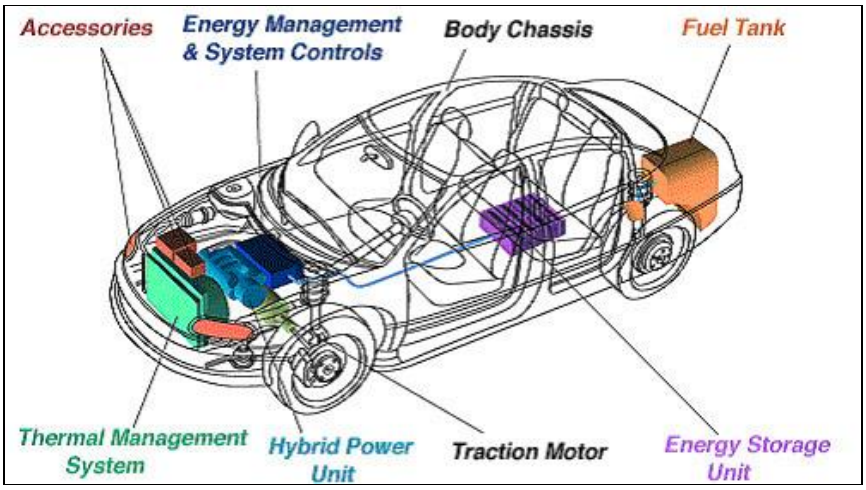



**Figure 2.2 :** HEV Components [7]

### 2.2.2 Types of hybrid electric vehicles

A series HEV has the ICE in series with a generator and the EM. The main idea is to have the ICE running at an optimal point and store the energy in the battery via the generator. The power during driving is taken from the EM and the battery supplies it with energy. When the state of charge of the battery is at a predetermined minimum, the ICE is turned on to charge the battery. The ICE turns off again when the battery has reached a desirable maximum state of charge. In a series hybrid there is no mechanical connection between the ICE and the chassis. The advantage with this configuration is that the ICE is running at its optimal combination of speed and torque all the time, thereby having a low fuel consumption and high efficiency. But, since there are two energy conversions during the transportation of the energy between the ICE and the wheels (ICE--generator and generator--EM), much energy is lost because of inner resistances and friction. The series HEV as the worst power path compared to other topologies and has the largest losses. Another drawback is that the regenerative braking technique1 cannot be used to save energy. Conceptually all HEVs can use the regenerative braking technique, the reason why series HEVs cannot use the technique can be that it requires special hardware and electronics that maybe not is available in all HEVs. The only advantage over the parallel configuration is that the series HEV creates less harmful emissions than the other topologies [8].

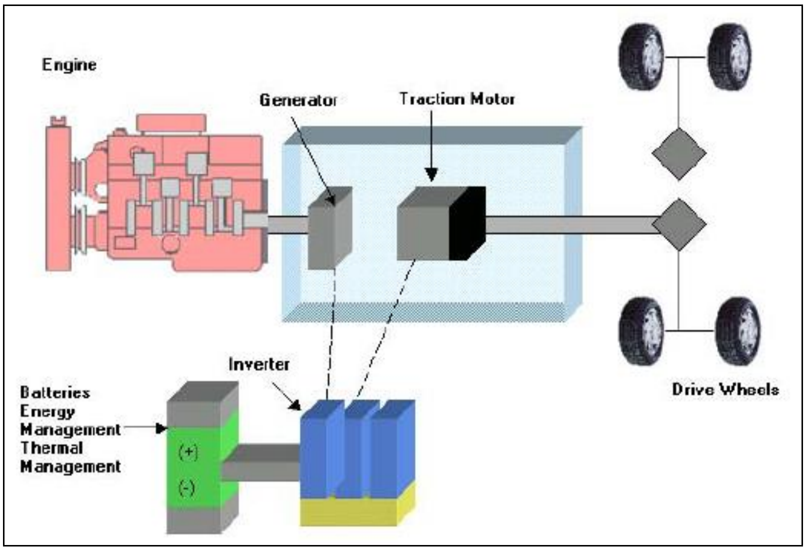



**Figure 2.3 :** Series Hybrid Configuration [8]

A vehicle with the parallel configuration has both the ICE and the HEV; the parallel HEV only needs these two propulsion devices. The vehicle can be driven with the ICE or the EM or both of them at the same time and therefore it is possible to choose the combination freely to give the required amount of torque at each time. In the parallel HEV topology, there are many ways to combine the use of the ICE and the EM. One strategy is to use the EM alone at low speeds where it is more efficient than the ICE, and then let the ICE work alone at higher speeds. When only the ICE is in use, the EM can function as a generator and charge the battery. The drawback with this excluding strategy is among other things that the battery will be discharged during long periods of very slow driving and the ICE has to be used for low speeds where it is less efficient. Another way to vary the power split between the ICE and the EM is a mixed strategy. The EM is then used alone when the power demand is low as in the excluding strategy and at ordinary driving, when the power demand is between let us say 6 kW and 50 kW, only the ICE is used. At a power demand over 50 kW, for example at accelerations and high speeds; the EM is used as a complement to the ICE in order to give extra power when needed. This speed limits deciding parameter varies of course between different vehicles and strategies. A parallel vehicle can have a continuously variable transmission, CVT, instead of a fixed step transmission. With this technique it is possible to choose the most efficient operating point for the ICE at given torque demands freely and continuously. The result is lower fuel consumption, because the fuel is used more efficiently. Energy is also saved thanks to the regenerative braking technique. The advantage with the parallel configuration is that there are fewer energy conversions compared to the series vehicle and therefore a lesser part of the energy is lost. The parallel hybrid has the lowest losses compared to the other topologies [8].

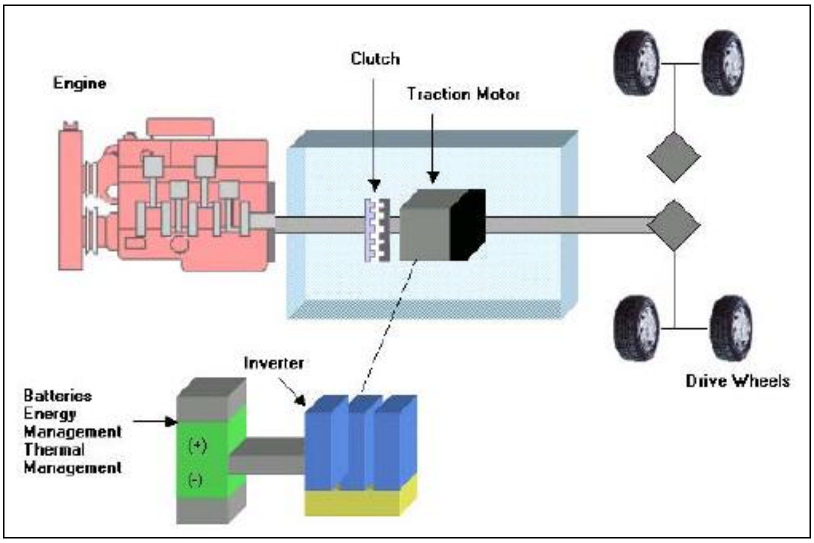



**Figure 2.4 :** Parallel Hybrid Configuration

The series-parallel HEV is a combination of the series and the parallel hybrid. There is an additional mechanical link between the generator and the EM compared to the series configuration and an additional generator compared to the parallel hybrid With this design it is possible to combine the advantages of both the series and the parallel configuration, but the series-parallel hybrid is relative to them more complicated and expensive [8].

The complex HEV is also called power split hybrid, combined hybrid or dual hybrid in some literature. It is another combination of the series and parallel hybrid, although not so distinct and clear as in the series-parallel hybrid. This topology includes a planetary gearbox, which connects the ICE, EM and generator. The ICE speed can be controlled by varied speed from the two planetary gear pinions connected to the EM and the generator [8].

# 3. HYBRID ELECTRIC VEHICLE SIMULATION WITH ADVISOR

## 3.1 What is ADVISOR?

ADVISOR is a MATLAB/SIMULINK-based, feed backward simulation of hybrid electric powertrains. ADVISOR was first developed in November 1994. Its main purpose was to help manage the U.S. Department of Energy's (DOE) hybrid electric vehicle (HEV) program subcontracts by facilitating our understanding of the technical challenges inherent in the design of high efficiency HEVs. ADVISOR allows quick analysis of the performance, emissions, and fuel economy of conventional, electric, and hybrid vehicles. The component models in ADVISOR are empirical, relying on input/output relations measured in the laboratory, and quasi-static, using data collected in steady state tests and correcting them for transient effects such as the rotational inertia of drivetrain components. In accordance with ADVISOR's mission as an analysis tool to support the U.S. DOE hybrid program, NREL designed ADVISOR to meet certain goals. It needed to be

1. Accurate, allowing meaningful comparison of different drivetrain configurations
2. Fast, allowing high-speed analysis of vehicles and design space investigations, such as multi-dimensional parametric studies and optimization
3. Flexible, allowing us to evaluate vehicles with various control strategies and combinations of components
4. Capable of modeling vehicles of any type: conventional, electric, series hybrid, or parallel hybrid
5. Easy to use, even for those without detailed knowledge of vehicle modeling [9].

### 3.2. How Does It Work?

ADVISOR uses a hybrid backward/forward approach that is closely related to the strictly backward-facing approach.

Generic backward-facing approach:

Vehicle simulators using a backward-facing approach answer the question "assuming the vehicle met the required trace, how must each component perform?" No model of driver behavior is required in such models. Instead, the force required to accelerate the vehicle through the time step is calculated directly from the required speed trace. The required force is then translated into a torque that must be provided by the component directly upstream, and the vehicle's linear speed is likewise translated into a required rotational speed. Component by component, this calculation approach carries backward through the drivetrain, against the tractive power flow direction, until the fuel use or electrical energy use that would be necessary to meet the trace is computed. The backward-facing approach is convenient because automotive drivetrain components tend to be tested in a laboratory environment such that a table of efficiency or loss versus output torque and speed (or power) is developed. This means that a straightforward calculation can determine a component's efficiency and allow the calculation to progress. The explicit nature of the efficiency/loss calculation also allows very simple integration routines (e.g. Euler) to be used with relatively large time steps on the order of 1 s. Thus, simulations using the backward-facing approach tend to execute quickly. Weaknesses of the backward-facing approach come from its assumption that the trace is met and from the use of efficiency or loss maps. Since the backward-facing approach assumes that the trace is met, this approach is not well suited to compute best-effort performance, such as occurs when the accelerations of the speed trace exceed the capabilities of the drivetrain. Also, because steady-state testing generally produces efficiency maps, dynamic effects are not included in the maps or in the backward-facing model's estimate of energy use. A related limitation of the backward-facing model is that it does not deal in the quantities directly measurable in a vehicle. For example, control signals such as throttle and brake position are absent from the model, further hindering dynamic system simulation and detailed control system development [9].

Forward-facing approach:

Vehicle simulators that use a forward-facing approach include a driver model, which considers the required speed and the present speed to develop appropriate throttle and brake commands (often through a PI controller). The throttle command is then translated into a torque provided by the engine (and/or motor) and an energy use rate. The torque provided by the engine is input to the transmission model, which transforms the torque according to the transmission's efficiency and gear ratio. In turn, the computed torque is passed forward through the drivetrain, in the direction of the physical power flow in the vehicle, until it results in a tractive force at the tire/road interface. The resultant acceleration is computed from a=F/meff, where meff includes the effect of rotational inertias in the drivetrain. The forward-facing approach is particularly desirable for hardware development and detailed control simulation. Since forward-facing models deal in quantities measurable in a actual drivetrain such as control signals and true torques (not torque 'requirements'), vehicle controllers can be developed and tested effectively in simulations. Also, dynamic models can be included naturally in a forward-facing vehicle model. Finally, the forward-facing approach is well-suited to the calculation of maximum effort accelerations, as they are essentially wide-open throttle events. The major weakness of the forward-facing approach is its simulation speed. Drivetrain power calculations rely on the vehicle states, including drivetrain component speeds that are computed by integration. Therefore, higher-order integration schemes using relatively small time steps are necessary to provide stable and accurate simulation results. As a result, forward-facing simulation can be overly time-consuming for use in preliminary design studies [9].

Combined backward/forward-facing approach:

ADVISOR uses a hybrid backward/forward approach that is closely related to the strictly backward-facing approach discussed above. ADVISOR's approach is unique in the way it handles the component performance limits in its backward-facing stream of calculations and in the addition of a simple forward-facing stream of calculations. The two overriding assumptions that describe ADVISOR's combination of the backward- and forward-facing approaches are as follows:

1. No drivetrain component will require more torque or power from its upstream neighbor than it can use.
2. A component is as efficient in the forward-facing calculations as it was computed to be in the backward-facing calculations [9].

## 3.3 Capabilities and Limitations

### 3.3.1 Capabilities

ADVISOR was originally developed as a simple analysis tool that could be used to quickly quantify the relative impacts of advanced technologies in a vehicle. It quickly evolved into a tool with a wide range of capabilities. The following is a short list of the key attributes that have lead to the adoption of ADVISOR as an analysis tool by a broad audience [9]:

• Intuitive, easy-to-use graphical interface;

• Fast solutions;

• Distributed as open source code;

• Customizable;

• Scalable component models;

• Good customer support, software maintenance, and documentation;

• Free and publicly available;

• Highly parameterized models

• Provides robust solutions

• Modular architecture

To support the DOE efforts, ADVISOR was designed to be flexible and open such that new technologies, unique energy management strategies, and alternative vehicle configurations could be easily incorporated into and evaluated within a system architecture. The user receives all of the source code when the package is downloaded. The open architecture and availability of source code allows a significant amount of customization. Users can replace the existing component models with more detailed models if necessary. Simulink makes it possible to link to other software packages for component models. Proprietary models can be compiled and linked to Simulink to protect intellectual property [9].

The ADVISOR GUI is laid out in a very intuitive manner and provides the ability to easily and quickly vary parameters and evaluate many different vehicle scenarios. Likewise, the robustness and repeatability of the solutions provided by ADVISOR greatly enhances its reputation as an unofficial "industry standard". Finally, nearly everything in ADVISOR has been parameterized. As a result, components can be scaled easily to produce new vehicles that can be compared to baseline scenarios. Optimization routines have been wrapped around parameterized models to highlight opportunities for improved vehicle design [9].

### 3.3.2 Functionality

The two most common simulations performed for a vehicle in ADVISOR include drive cycle analysis and performance tests. A drive cycle constitutes a series of vehicle speeds as a function of time. There are more than 40 different drive cycles to choose from in the ADVISOR database. Some of the drive cycles even have roadway grade associated with them like the NREL to Vail, Colorado driving cycle (CYC_NREL2VAIL). This data was collected by NREL engineers using on-board data acquisition equipment and can be used with the vehicle model to verify a vehicle’s operating characteristics in a "real world" driving scenario of crossing the Continental Divide by interstate highway [9].

A performance test allows the user to assess the acceleration and gradeability performance of a vehicle. The test routines provide many customizable parameter settings such as running the test with or without the battery pack enabled for hybrid vehicles. They can also be run at test weights other than the actual vehicle weight. The performance tests have been formatted to provide a significant amount of flexibility in determining how the vehicle performance will be assessed. Special test procedures have also been developed that build upon the standard drive cycle analysis by analyzing multiple cycles at one time and/or performing special calculations based on the results. For example, the City/Highway Test (TEST_CITY_HWY) (1) initializes the system to hot ambient conditions, (2) runs a highway cycle, (3) stores the results, (4) initializes the system to cold ambient conditions, (5) runs an FTP, (6) stores the results, and (7) calculates the combined City/Highway fuel economy value. Other available test procedures include the following [9]:

• Grade Test Procedure;

• Acceleration Test Procedure;

• FTP Test Procedure;

• FTP Test Procedure for hybrids;

• City/Highway Test Procedure;

• City/Highway Test Procedure for hybrids;

• SAE J1711 Test Procedure;

• "Real World" Test Procedure

State of charge (SOC) balancing is an important aspect of hybrid vehicle analysis. If the change in SOC of the battery between the beginning and the end of a cycle is too large, the vehicle fuel economy may be artificially very high or very low due to the battery net discharge or charge, respectively. ADVISOR offers two methods for ensuring SOC-balanced vehicle results over a drive cycle such that multiple simulation scenarios can be compared on a consistent basis. The first method uses a linear approximation approach. The vehicle is simulated first when starting from a high SOC then from a low SOC. Linear interpolation of fuel economy and emissions between the two simulations is used to determine the results at zero change in SOC. The second method is an iterative zero-delta approach. ADVISOR iteratively changes the initial conditions of the battery pack until the final state is within a specified tolerance of the initial state. Although, the zero-delta approach will typically require more simulations than the linear method, it ensures that the results are "real" and physically possible rather than mathematical estimates as they are with the linear approximations method. In future versions, ADVISOR will also include a SOC balancing routine that will be based on ensuring that the equivalent fuel energy of the change in SOC of the battery pack is less than a specified percentage of the total fuel consumed during a cycle. This approach is documented in SAE J1711 and will eliminate fluctuations in results due to variations in total battery pack capacity among vehicles (e.g. 5% SOC change in a 50 Ah pack is significantly more energy than a 5% SOC change in a 5 Ah battery pack) [9].

### 3.3.3 Limitations

ADVISOR was developed as an analysis tool, and not a design tool. Its component models are quasi-static, and should not be used alone to predict phenomena with very small time scales. For example, ADVISOR should not be used to quantify physical vibrations, electric field oscillations and other fast dynamics. ADVISOR, however, has been successfully linked with other tools that do perform dynamic analysis capability. Tools like Saber for electrical systems modeling and ADAMS/Car for vehicle dynamics have been linked with ADVISOR. These dynamic modeling tools focus on only a portion of the analysis while ADVISOR simulates the rest of the vehicle. For example, a battery modeled in Saber can be configured to communicate periodically with the rest of vehicle systems in ADVISOR during a drive cycle simulation. As an analysis tool, ADVISOR uses the required vehicle speed, as an input to determine what drivetrain torques, speeds, and powers would be required to meet that vehicle speed. Because of this flow of information back through the drivetrain, from tire to axle to gearbox and so on, ADVISOR can be classified as a backward-facing vehicle simulation with the added ability to evaluate wide-open throttle operation without the need for iteration. Forward-facing vehicle simulations include a model of a driver that monitors the required speed and responds with an accelerator or brake position, to which the drivetrain responds with a torque. This type of simulation is well suited to the design of control systems, for example, down to the integrated circuit and PC card level—the implementation level. ADVISOR is well suited to evaluate and design control logic by iterative evaluation. Control logic includes things like "when the engine torque output is low and the battery SOC is high, turn off the engine." The control logic, with which ADVISOR can work, is about what you want the vehicle to do. The control system, beyond ADVISOR's purview, relates to the details of how to make the vehicle and each component do what it needs to do in order to meet the demands of the control logic. [9] In addition to these, ADVISOR do not allow the user to program a control logic, which enables the vehicle to drive pure electric between speed intervals with a starting value different than zero. ADVISOR does not simulate a parallel hybrid vehicle with front wheel IC engine and rear wheel electric drive.

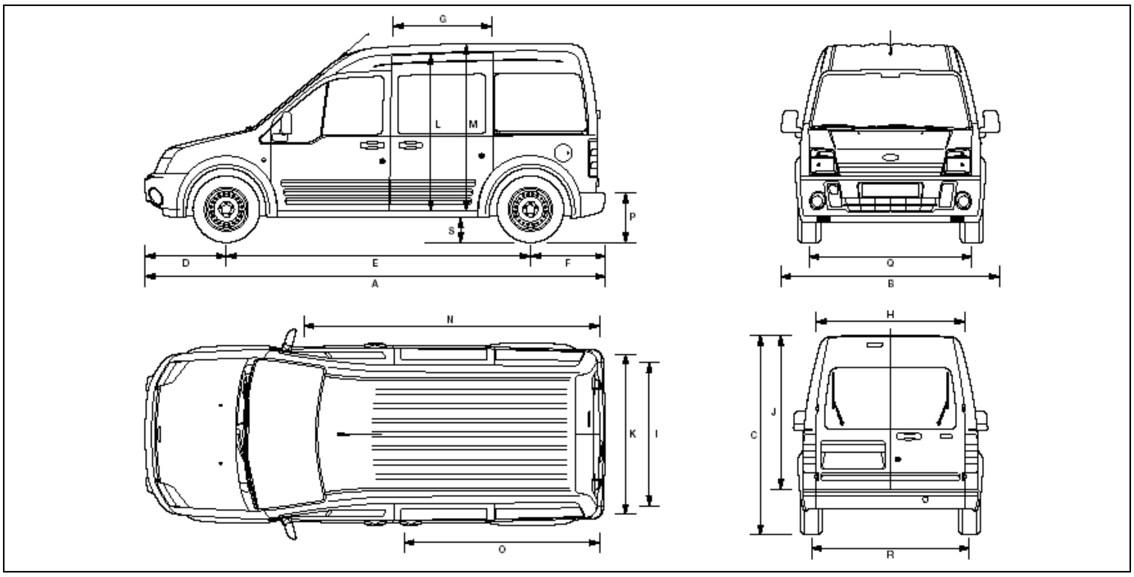
# 4. FORD TOURNEO CONNECT PARALLEL HYBRID SIMULATION WITH ADVISOR

## 4.1 Vehicle Overview and Specifications

Ford Tourneo Connect is a multi purpose vehicle. For work, you can fold down or remove the rear seats to make a spacious van. For the weekend, it’s a comfortable family vehicle with room for five people and their luggage [10].

**Figure 4.1 :** Ford Tourneo Connect [10]

Dimensions



A Overall length 4525

B Overall width with mirrors 2044

B Overall width without mirrors 1795

C Overall height (laden/unladen) 1906/1981

D Front overhang 864

E Wheelbase 2912

F Rear overhang 749

G Side door entry width 809

H Rear door opening width below belt 1293

I Load width between wheel arches 1219

J Rear door opening height 1313

K Load width 1492

L Side door opening height 1184

M Load floor to roof 1320

N Load length (max) (passenger's seat folded) 2714

O Load length (laden to belt line) 1830

O Load length (back of front seat) 1986

O Load length (passenger's fold-flat seat up) 2007

P Loading height (laden/unladen) 496/601

Q Front track 1505

R Rear track 1552

S Ground clearance 166

**Figure 4.2 :** Dimensions of Tourneo Connect [11]

Weights and Loads

| | Payload (Gross) (kg)† | Gross vehicle mass (kg) | Kerb mass# (kg) | Rear axle ratio | Max. GTM (kg)* with quoted axle ratio |
|---|---|---|---|---|---|
| Ford Tourneo Connect | | | | | |
| 1.8 Duratorq TDCi (90 PS) diesel | 800 | 2340 | 1540 | 4.06 | 3140 |

* = Maximum 12% gradeability. † = Payload = Gross vehicle mass, less kerb mass. # = Represents the lightest kerbweight assuming full fluid levels and 90% fuel levels, subject to manufacturing tolerances and options, etc., fitted.

**Figure 4.3 :** Weights and Loads of Tourneo Connect [11]

<u>Engine Data</u>

| | Engine technical features | Maximum power ° | Maximum torque ° |
|---|---|---|---|
| 1.8L Duratorq TDCi 8V 1753 cc | Cylinders – 4 in-line / Turbo common-rail fuel injection with electronic engine management system / Exhaust Gas Recirculation | 66 kW (90 PS) at 4000 $min^{-1}$ (rpm) | 220 Nm at 1750 $min^{-1}$ (rpm) |

° = Tested in accordance with ISO 1585.

**Figure 4.4 :** Engine Data of Tourneo Connect [11]

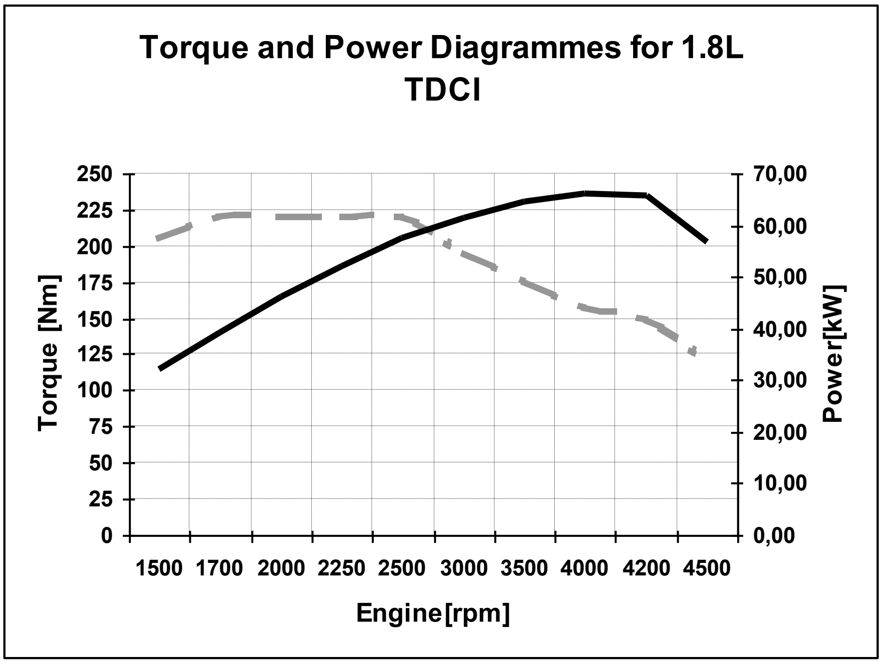



**Figure 4.5 :** Torque and Power Diagram's of Tourneo Connect [2]

<u>Fuel Consumption per 100km</u>

- Urban: 7,9 L (4x ECE)
- Extra Urban: 5,8 L (EUDC)
- Combined 6,5 L (NEDC)

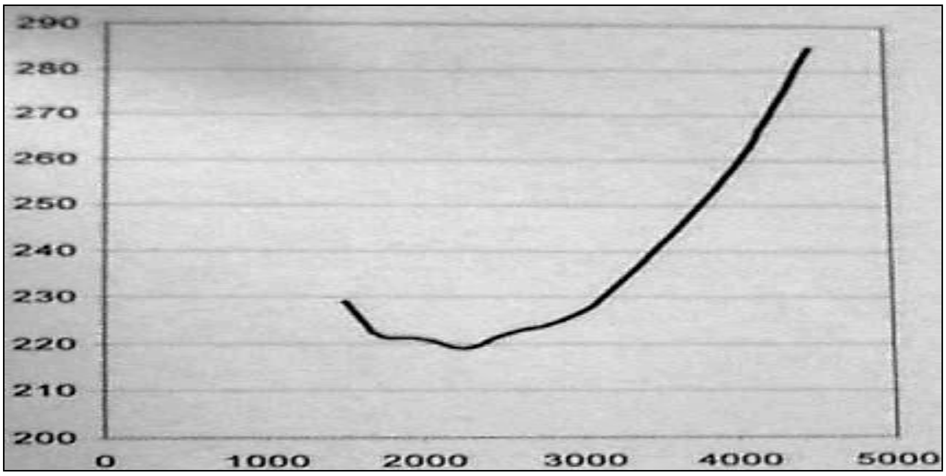



**Figure 4.6** Specific Fuel Consumption [g/kWh] of the 1.8 TDCI Engine [2]

Performance

Factory Sheet Data:

| **0-100 km/h** | **50-80 km/h** | **Top Speed** |
|---|---|---|
| 16,3 s | 14,9 s | 154 km/h |

AUTO SHOW Road Test Data [12]:

| **0-50 km/h** | **0-100 km/h** | **0-130 km/h** | **60-100 km/h** | **60-100 km/h** | **0-1000m** |
|---|---|---|---|---|---|
| 4,5 s | 15,9 s | 27,2 s | $4^{th}$ gear 11,1 s | $5^{th}$ gear 18,6 s | 39 s |

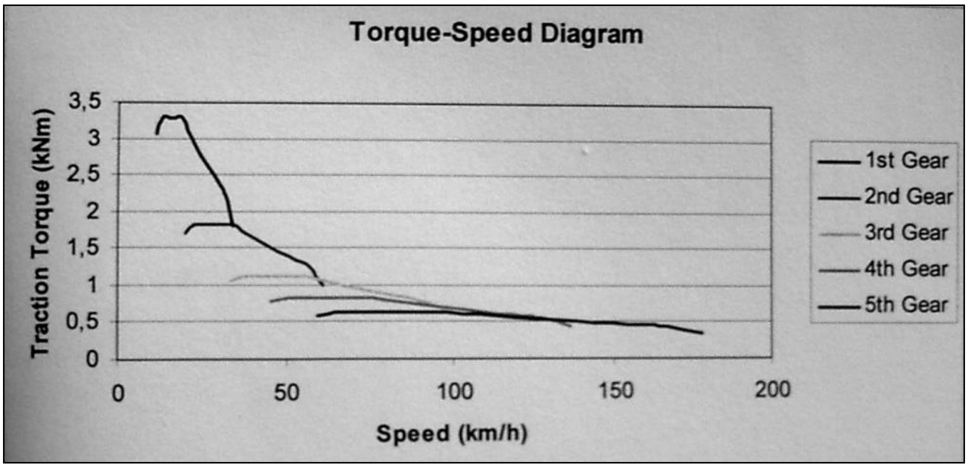



**Figure 4.7 :** Torque-Speed Diagram of Tourneo Connect [2]

## 4.2 Determining the Vehicle Input Data

ADVISOR uses MATLAB files, where the specifications of each component are defined. For each used hybrid component, the specifications will be given in detail. The user must manually define vehicles, which are not included in ADVISOR. For creating a Ford Tourneo Connect Vehicle Matlab file following values are defined by the user:

1. Vehicle curb weight= 1540 kg. From this value the engine assembly weight, the fuel system weight, the exhaust system weight and the transmission weight must be subtracted to find the stripped chassis weight.

   a) Engine assembly weight = 175 kg

   b) Fuel system weight = estimate 20 kg

   c) Exhaust system weight= estimate 20 kg

   d) Transmission = 60 kg (MTX-75)

   e) Stripped chassis weight =1265 kg

2. Coefficient of Aerodynamic Drag: 0,39 cw

3. Dimensional Inputs:

   a) Overall vehicle length = 4525 mm

b) Overall vehicle width without mirrors = 1795 mm

c) Overall vehicle height = 1981 mm

d) Frontal projection area = 3,26 mm²

4. Tyres: 195/65 R15, Rolling Resistance: 0, 013630

5. Center of Gravity

a) CG Height: 0,6

b) Weight Distribution: 50/50

After defining the chassis values the fuel converter data will be modified. The fuel converter data consists of two main parts: fuel map and emission map. There is no official data available as fuel and emission map for the 1.8 TDCI 90 hp Ford engine. Therefore, the closest engine the 1.9 TDCI Volkswagen, which gives very similar torque and power outputs at similar rpms, will be modified. The torque map will be changed with one, delivered from an existing graduation thesis [13]. The emission and fuel maps for HC, NOx, CO and PM stay unchanged, which resulted a correction on the fuel consumption and emission simulation results made in the section 5.2. Furthermore, engine weight should be defined as 175 kg. Other parameters stay unchanged.

The exhaust system will be chosen as oxidation catalyst with diesel particulate filter, selected from ADVISOR and remains unchanged as a Matlab file.

The electric motor will be selected as 56 kW. This is a prototype or small-production of a 62 kW, AC induction motor/controller. This motor is drive tested by Institute for Power Electronics and Electrical Drives at Aachen University of Technology (Germany) [14]. The only modification for the simulation is the reduction of output power from 62 to 56 kW. The reason for this reduction is to fulfill the real world project norms. The weight of the electric motor is 63 kg.

The energy storage unit must be selected to be a high power, intermediate energy battery. First of all the cargo mass of Tourneo Connect is 800 kg and second there would be no clear benefits on fuel consumption and emission, when using a heavy battery. Advantages and disadvantages of certain batteries were mentioned in section

2.2.1. Some criteria's must be chosen for eliminating the battery types and decide on the suitable one for Ford Tourneo Connect:

1. Weight
2. Nominal Voltage
3. Long Life
4. Commercial Availability

ADVISOR offers the battery types below:

- Nickel-Cadmium Batteries
- Nickel-Metal Hydride Batteries
- Lithium Ion Batteries
- Lead-Acid Batteries
- Ultracapasitors

First elimination:

- Lithium Ion and Ultracapasitors were not chosen as an energy storage unit because of their commercial unavailability for HEV's. There are only two HEV's (from Nissan) powered by these batteries [15].

- Lead-Acid batteries are not chosen because of their low power output and heavy weight.

- Nickel-Cadmium batteries are not chosen, because they do not deliver sufficient power and are not being considered for HEV applications.

- **Nickel-Metal Hydride Batteries are chosen as energy storage for the project vehicle Ford Tourneo Connect, because of their higher power output, low weight and commercial availability**. Due to the "ANNEX VII HEV Database" nearly 75 percent of all HEVs listed inside use NiMH batteries as energy storage [15].

ADVISOR offers 8 types of NiMH batteries. Second decision criteria's for choosing the right energy storage unit will be nominal voltage and total weight for each cell.

All kinds of these batteries are commercially available and even used in low mass production HEVs such as Toyota Prius. Below is list of these specifications:

**Table 4.1 :** NiMH Batteries Comparison List

| **Battery Name** | **Weight/Cell [kg]** | **Voltage/Cell [kg]** | **Voltage/Weight [V/kg]** |
|---|---|---|---|
| Annex Ovonic 28Ah NiMH HEV battery / ESS Ovonic 28Ah NiMH HEV battery * | 3,60 | 6,70 | 1,85 |
| ESS Ovonic 45Ah NiMH HEV battery | 8,4 | 13,4 | 1,59 |
| ESS 6Ah NiMH HEV battery | 8 | 8 | 1 |
| ESS Ovonic 60Ah NiMH HEV battery | 11,6 | 13,4 | 1,15 |
| ESS 80Ah NiMH EV-1Draft HEV battery | ONLY A DRAFT! NO PRODUCTION! | | |
| ESS Ovonic 90Ah NiMH HEV battery | 16,72 | 13,4 | 0,80 |
| ESS 850 NiMH Temp | 972 | 77 | 0,079 |
| ESS 93Ah NiMH HEV battery | 17,88 | 14,24 | 0,80 |

According to this table, the first battery will be chosen as energy storage because of its high voltage/ weight value. The specifications of this battery are given below:

1. Cell type = M70

2. Nominal Voltage = 6V

3. Nominal Capacity (C/3) = 28Ah

4. Dimensions (L * W * H) = 195mm X 102mm X 81mm

5. Weight = 3.6kg

6. Volume (modules only) = 1.6L

7. Nominal Energy (C/3) = 175 Wh

8. Peak Power (10s pulse at 50%DOD at 35 deg. C) = 1.6kW

After some benchmarking with the HEV examples inside the "ANNEX HEV Database", it is decided to use 30 cells of this battery for the simulation. These deliver a total output of 201 V at a weight of 108 kg.

To create the transmission Matlab file of MTX-75, which is used for FORD TDCI Endura 90-hp 1.8-L engines, the ADVISOR transmission file TX_5SPD_CI will be modified by gear ratios and weight.

Input values for the MTX-75 gearbox:

1. $1^{st}$ 3,67/ $2^{nd}$ 2,05 / $3^{rd}$ 1,26 / $4^{th}$ 0,92 / $5^{th}$ 0,71 / Axle Drive 4,06 / Rear 3,73

2. Weight: 60 kg

Torque coupling and Wheel/Axle parameters remain unchanged and used as it defined in ADVISOR for the simulation.

The ADVISOR's control strategy (BSC) uses the engine as a primary source of torque, and it uses the motor for supplemental power. When the battery SOC is low, the BCS switches to a charge mode in order to replenish the battery. The BCS attempts to minimize engine energy usage without regard to emissions or the effect of the motor or batteries during operation.

Advisor's BCS uses the electric motor in a variety of ways [16]:

1. The motor supplies all driving torque below a certain minimum vehicle speed.

2. The motor assists with torque if the required torque exceeds the maximum engine torque.

3. The motor charges the batteries by regenerative braking.

4. The engine shuts off when the torque request falls below a limit.

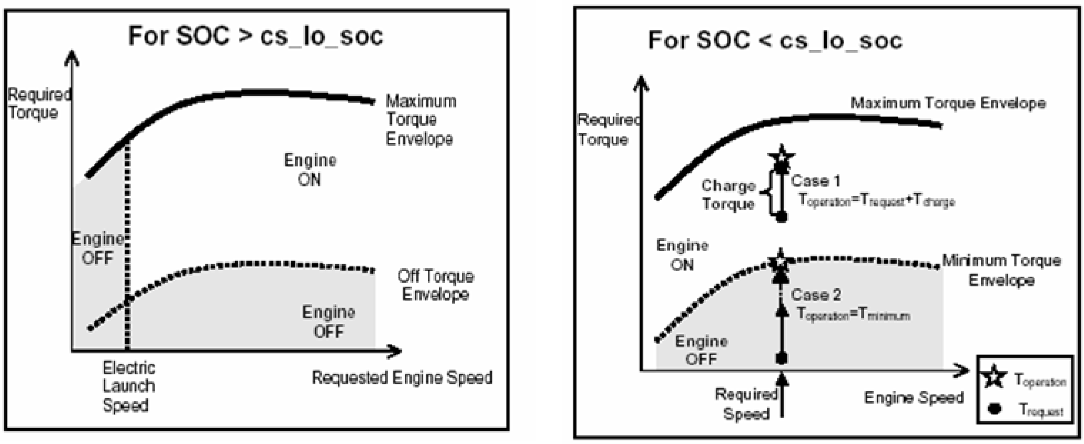



**Figure 4.8 :** SOC Conditions for Engine/Electric Drive of ADVISOR [16]

Its operation is defined by six independent input parameters [16]:

1. cs_hi_soc: highest desired battery SOC
2. cs_lo_soc: lowest desired battery SOC
3. cs_electric_launch_spd: vehicle speed below which vehicle operates as a ZEV
4. cs_off_trq_frac minimum torque threshold = fraction*Tmax (SOC>low limit)
5. cs_min_trq_frac minimum torque threshold = fraction*Tmax; (SOC<low limit)
6. cs_charge_trq: an accessory like torque loading on the engine to recharge the battery pack

To create a control strategy for the project vehicle, the powertrain control file for parallel hybrid vehicles are modified only at the section "Hybrid Control Strategy" for the above mentioned parameters.

1. highest desired battery state of charge cs_hi_soc=0.9
2. lowest desired battery state of charge cs_lo_soc=0.1

The big gap between the highest and lowest SOC enables the vehicle to drive a greater distance with less emissions. However the efficiency is dramatically decreasing by setting these values in such a big interval. A compromise should be made between high efficiency average emissions and low efficiency and lower emissions.

3. vehicle speed below which vehicle operates as ZEV at low SOC cs_electric_launch_spd_lo=25 m/s

4. at and above high SOC electric_launch_spd_hi=50 (m/s)

Setting the speed limits as 40-80 km/h enables the vehicle to drive pure electric at short distances at city and urban conditions. At high SOC the vehicle can drive even on the freeway till the SOC decreases to 0,1. In the city traffic the vehicle can drive even a greater distance, where high stop&go emissions are reduced.

5. 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; (unchanged)

6. 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; (unchanged)

7. 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=0.15*min(fc_max_trq);

8. speed above which no engine shut down occurs due to low torque requests cs_electric_decel_spd=50 (m/s)

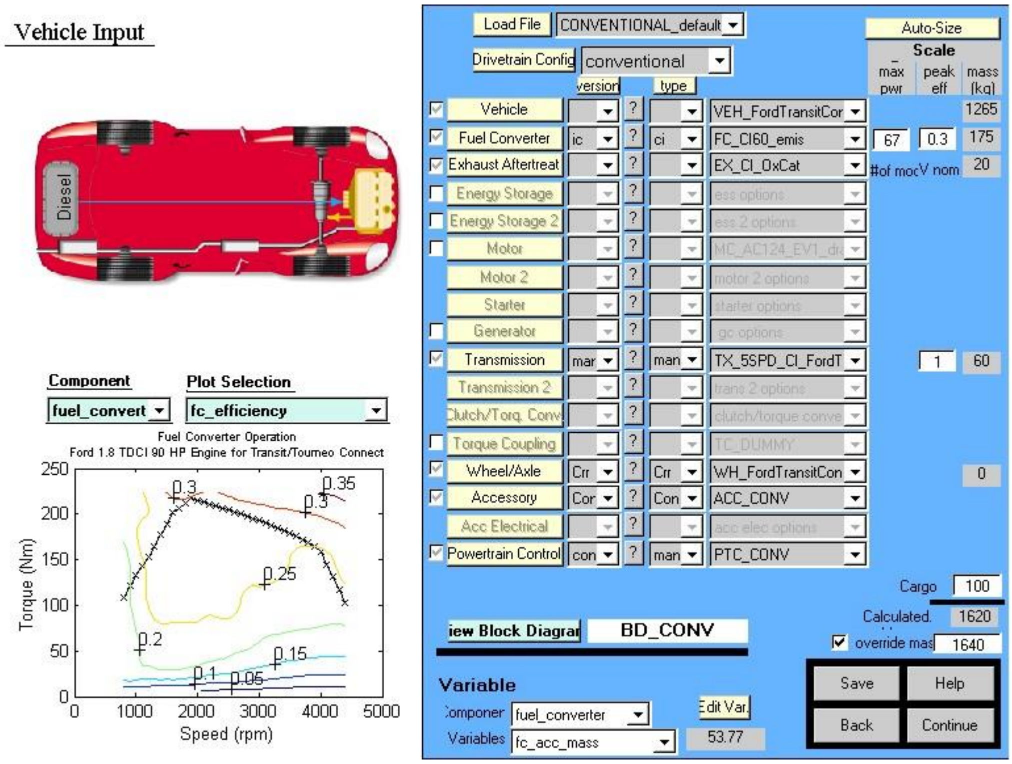



**Figure 4.9 :** ADVISOR Vehicle Input Screen (Conventional Vehicle)

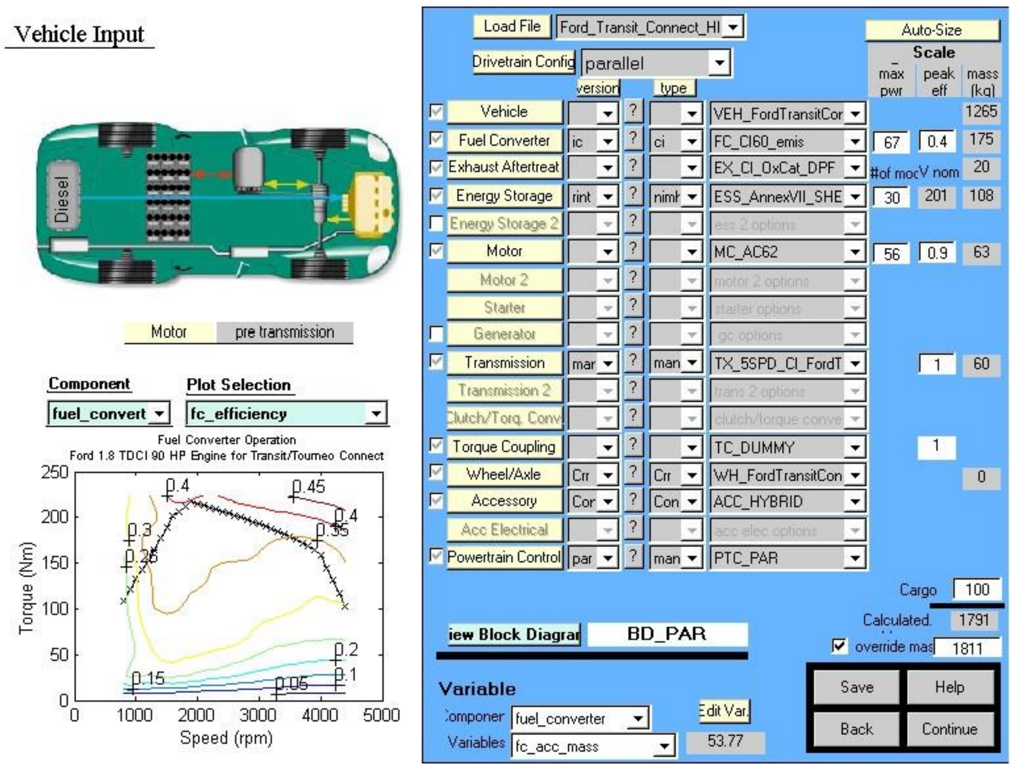



**Figure 4.10 :** ADVISOR Vehicle Input Screen (Hybrid ElectricVehicle)

## 4.3 Determining the Drive Cycles and Test Procedures

A driving cycle is a standardized driving pattern. This pattern is described by means of a velocity-time table. The track that is to be covered is divided in time-steps, mostly seconds. The acceleration during a time step is assumed to be constant. As a result the velocity during a time step is a linear function of time. Because velocity and acceleration are known for each point of time, the required mechanical power as a function of time can be determined with formulas. This function integrated over the duration of the driving cycle produces the mechanical energy needed for that driving cycle. Off the road a vehicle can execute a driving cycle on a dynamometer. In the case of ICE driven vehicles, the fuel consumption and emissions are directly measured. The same holds for the fuel conversion system of hybrid electric driven vehicles. The primary energy can be calculated from the fuel consumption. For electric vehicles (EV) or hybrid electric vehicles (HEV), which make use of an external electric source (such as the public grid), the electric energy withdrawn from that source will be separately accounted for. The electric energy is turned into the required primary energy by dividing it by the efficiency of power generation. The emissions are determined by using emission values handed up by power companies. In all driving systems the efficiency of the driving system is determined by dividing the calculated mechanical energy by the primary energy [17].

For the Tourneo Connect parallel hybrid simulation following drive cycles will be selected:

- New European Drive Cycle (NEDC/ECE EUDC/ECE EUDC Low)

The New European Drive Cycle (NEDC) consists of four ECE 15 drive cycles followed by a EUDC or EUDC Low cycle. ECE 15 This driving cycle represents urban driving. It is characterized by low vehicle speed (max.50 km/h), low engine load and low exhaust gas temperature. EUDC cycle describes a suburban route. At the end of the cycle the vehicle accelerates to highway-speed. Both speed and acceleration are higher than the ECE 15. The EUDCL is a suburban cycle for low-powered vehicles. It is similar to the EUDC but the maximum speed is 90 km/h [17]. The four EC15 cycles are also called as urban, whereas the EUDC cycle is called as extra urban.

Urban cycle

The urban test cycle is carried out in a laboratory at an ambient temperature of 20ºC to 30ºC on a rolling road from a cold start, i.e. the engine has not run for several hours. The cycle consists of a series of accelerations, steady speeds, decelerations and idling. Maximum speed is 31 mph (50 km/h), average speed 12 mph (19 km/h) and the distance covered is 2.5 miles (4 km). The cycle is shown as Part One in the diagram below [18].

Extra-urban cycle

This cycle is conducted immediately following the urban cycle and consists of roughly half steady-speed driving and the remainder accelerations, decelerations, and some idling. Maximum speed is 75 mph (120 km/h), average speed is 39 mph (63 km/h) and the distance covered is 4.3 miles (7 km). The cycle is shown as Part Two in the diagram below [18].

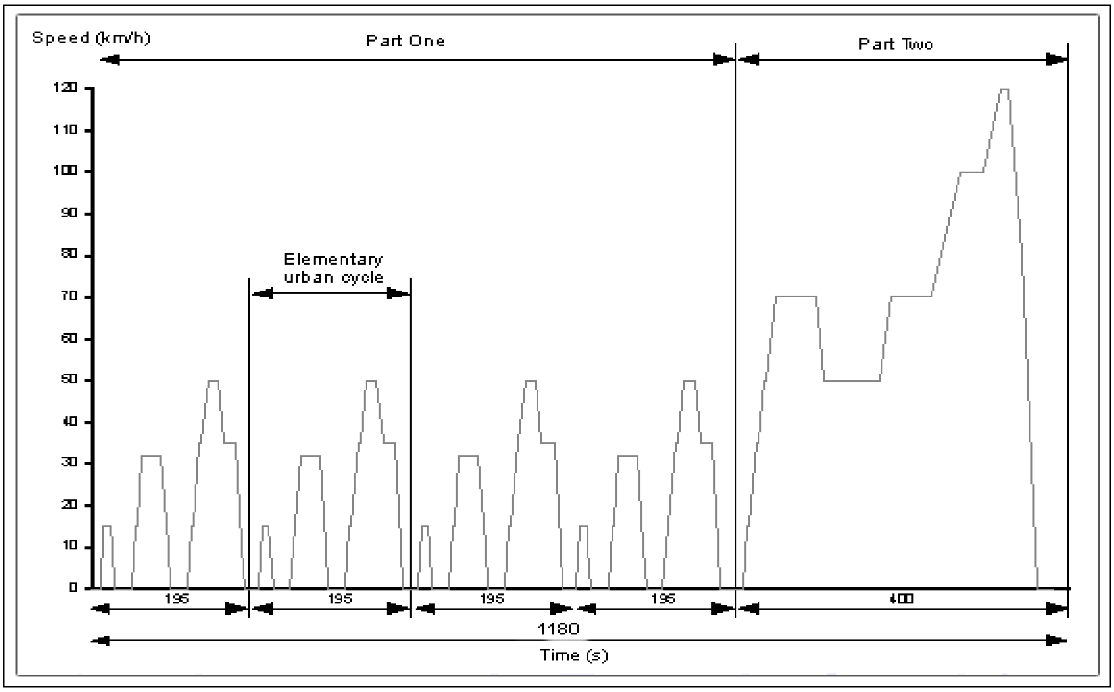



**Figure 4.11 :** NEDC/ECE EUDC Drive Cycle [18]

The European exhaust gas emission norms are measured with the help of the new European drive cycle. Therefore to be successful on this cycle, in other words causing fewer emissions and fulfilling the recent EURO-norms, carries a high importance for this thesis. NEDC is a modal driving cycle, which means it's not equal to real world driving patterns. Therefore 2 other driving cycles and a USA test procedure, which represents real driving patterns, are selected. These are:

- NYCC Drive Cycle

This cycle represents an urban route through New York. A characteristic of this cycle is the low average speed [17].

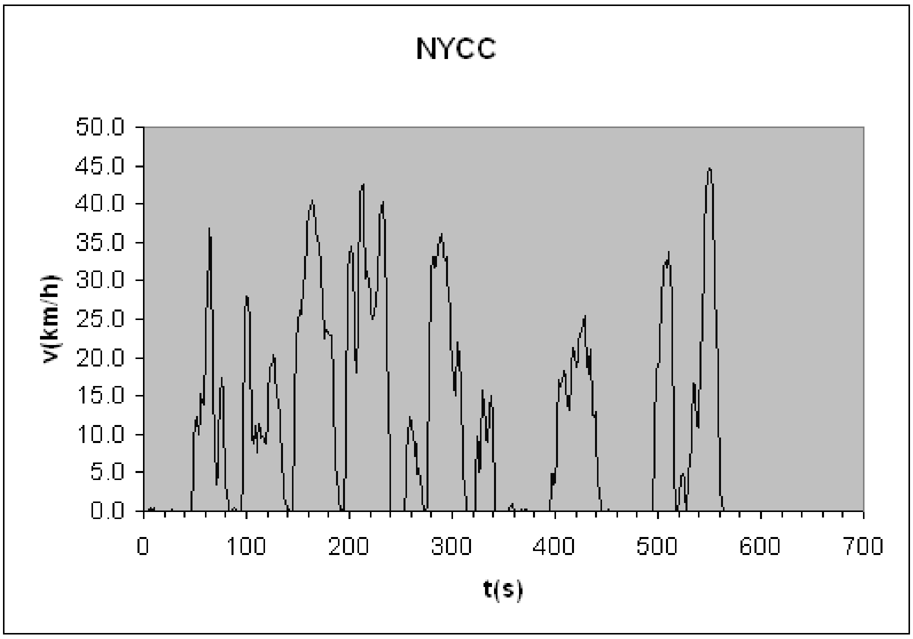



**Figure 4.12 :** New York City Drive Cycle [17]

- LA-92 Drive Cycle

In the early seventies the FTP-72 cycle has been developed to describe an urban route. The cycle consists of a cold start phase. This phase is followed by a transient phase with many speed peaks, which start from rest. The emissions are measured. In the United States weight factors are used for both phases to norm the emissions. The FTP 72 is often called FUDS, UDDS or LA-4. The LA-92 represents like the FTP 72 an urban route. The LA-92 has been developed in 1992, because the existing FTP 72 turned out to be a non-realistic representation of urban driving patterns. For example the LA-92 has a higher average speed [17].

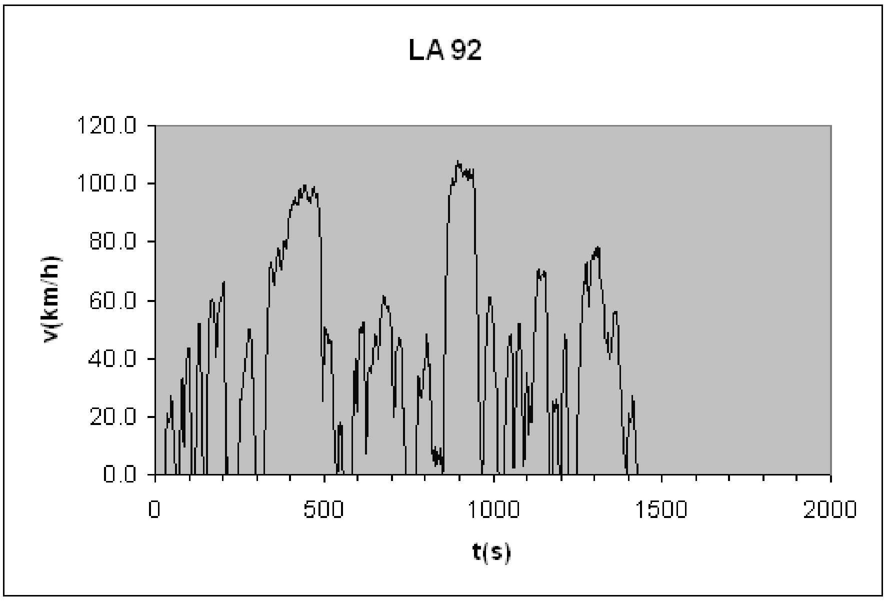



**Figure 4.13 :** LA-92 Drive Cycle [17]

- City/Highway Test Procedure

This test runs an FTP-75 cycle followed by a HWFET cycle.

<u>FTP-75</u>

The FTP-75 is the standard federal exhaust emissions driving cycle, which uses the Urban Dynamometer Driving Schedule (UDDS). This cycle has three separate phases: a cold-start (505- second) phase known as bag 1, a hot-transient (870-second) phase known as bag 2, and a hot-start (505 second) phase known as bag 3. The three test phases are referred to as bag 1, bag 2, and bag 3 because exhaust samples are collected in separate Tedlar bags during each phase. During a 10-minute cool-down between the second and third phase, the engine is turned off. The 505-second driving trace for the first and third phase is identical. The total test time for the FTP is 2457 seconds (40.95 minutes), the top speed is 56.7 mph, and the average speed is 21.4 mph. The distance driven is approximately 11 miles [19].

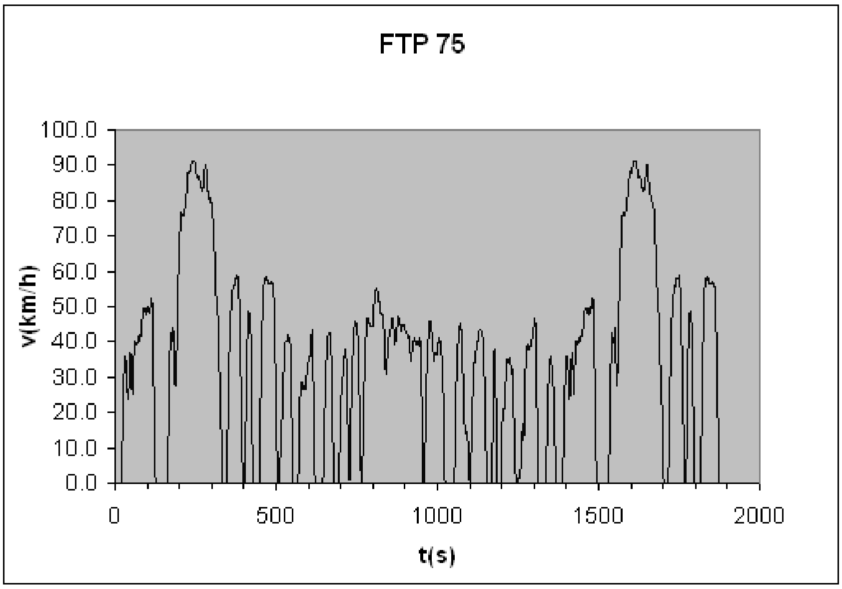



**Figure 4.14 :** Federal Test Procedure (FTP) Drive Cycle [17]

<u>HWFET/HFEDS</u>

The Highway Fuel Economy Test (HWFET) driving cycle is used to simulate highway driving and estimate typical highway fuel economy. The official test consists of a warm-up phase followed by a test phase. The driver follows the same driving trace in both the warm-up and the test phase. In ADVISOR the warm up phase is replaced by starting the vehicle with hot initial conditions. A top speed of 59.9 mph is reached with an average speed of 47.6 mph [20].

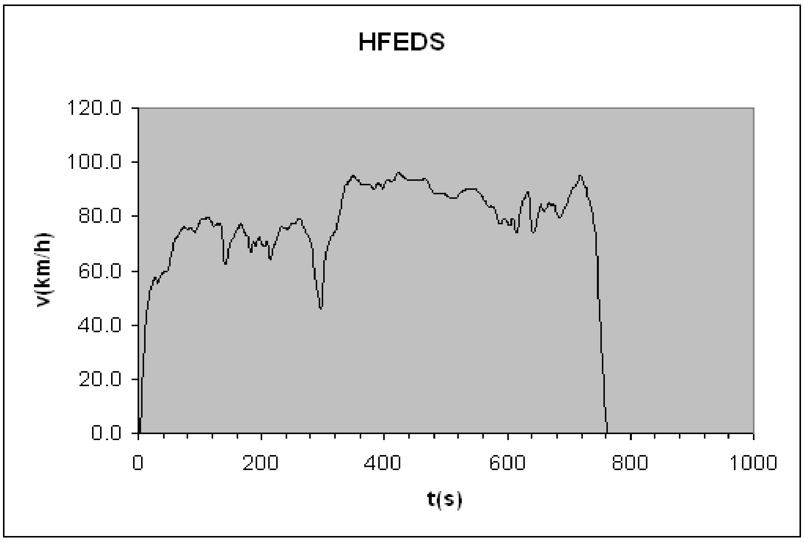



**Figure 4.15 :** Highway Test Procedure Drive Cycle [17]

**Table 4.2 :** Overview of the specified Drive Cycles [17]

| | time [s] | Distance [km] | Average speed [km/h] | Average acceleration [m/s2] | Average decelration [m/s2] |
|---|---|---|---|---|---|
| ECE EUDC | 1225 | 10,93 | 32,1 | 0,54 | 0,79 |
| ECE EUDC LOW | 1224 | 10,59 | 31,11 | 0,58 | 0,8 |
| NYCC | 598 | 1,9 | 11,41 | 0,62 | 0,61 |
| LA-92 | 1435 | 15,8 | 39,6 | 0,67 | 0,75 |

**CITY/HIGHWAY TEST PROCEDURE**

| | time [s] | Distance [km] | Average speed [km/h] | Average acceleration [m/s2] | Average decelration [m/s2] |
|---|---|---|---|---|---|
| FTP | 2477 | 17,77 | 25,82 | 0,51 | 0,58 |
| HWFET | 765 | 16,51 | 77,58 | 0,19 | 0,22 |

### 4.4 Determining the Performance and Gradeability Data

The Ford Tourneo Connect simulation process will measure following performance data. The acceleration test routine in ADVISOR will determine the acceleration performance of the current vehicle.

- Acceleration:
  1. 0-50 km/h
  2. 0-100 km/h
  3. 0-130 km/h
  4. Time in 1000 m
- Elasticity:
  60-100 km/h
- Maximum Speed

The grade test routine in ADVISOR will determine the maximum grade on which the vehicle can sustain the specified constant speed. The grade test will be made in three conditions at 88,5 km/h (55 mph):

1. All systems enabled
2. Energy storage disabled
3. Fuel converter disabled (Minimum SOC will be 0,3 , whereas the current SOC will be selected as 0,7.)

# 5. ANALYSIS OF THE SIMULATION RESULTS

In chapter 4 the input data for running ADVISOR was given. It is decided to run the simulation first with conventional Tourneo Connect input data and then with parallel hybrid Tourneo Connect input data. This enables a comparison between the simulation results of conventional and hybrid electric vehicle.

## 5.1 Fuel Consumption And Emission Results (ADVISOR)

In following the fuel consumption and emission ADVISOR results of the conventional Tourneo Connect for the selected drive cycles are given.

**Table 5.1 :** Conventional Vehicle Drive Cycle Results

| Drive Cycle | Distance | Fuel Consumption | HC | CO | N0x | PM |
|---|---|---|---|---|---|---|
| | in km | Liters per 100 km | g/km | | | |
| NEDC | 10,9 | 9,4 | 0,295 | 0,873 | 0,897 | 0,064 |
| NEDC LOW | 10,6 | 8,8 | 0,291 | 0,893 | 0,667 | 0,053 |
| LA-92 | 1,9 | 10,3 | 0,183 | 0,513 | 1,288 | 0,078 |
| NYCC | 15,8 | 19 | 1,002 | 3,146 | 2,412 | 0,132 |

In following the fuel consumption and emission ADVISOR results of the conventional Tourneo Connect for the city/highway test procedure are given.

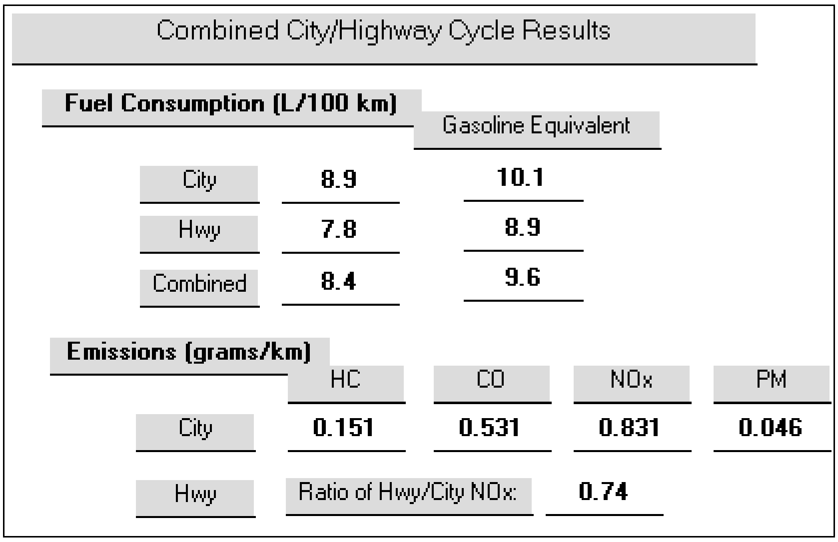



**Figure 5.1 :** Conventional Vehicle City/Highway Test Procedure Results

ADVISOR also determines the energy usage values and the overall system efficiency, which plays a significant role in fuel consumption and emission values.

**Table 5.2 :** Conventional Vehicle Energy Usage Results (NEDC)

| Energy Usage Table (kJ) | POWER MODE | | | | REGEN MODE | | | |
|---|---|---|---|---|---|---|---|---|
| | In | Out | Loss | Eff. | In | Out | Loss | Eff. |
| Fuel | 0 | 37288 | | | | | | |
| Fuel Converter | 37288 | 7615 | 29673 | 0.2 | | | 450 | |
| Clutch | 6864 | 6753 | 111 | 0.98 | 560 | 560 | 0 | 1 |
| Hyd. Torque Converter | | | | | | | | |
| Generator | | | | | | | | |
| Torque Coupling | | | | | | | | |
| Energy Storage | | | | | | | | |
| Energy Stored | | | | | | | | |
| Motor/Controller | | | | | | | | |
| Gearbox | 6753 | 6434 | 319 | 0.95 | 595 | 560 | 35 | 0.94 |
| Final Drive | 6434 | 6434 | 0 | 1 | 595 | 595 | 0 | 1 |
| Wheel/Axle | 6434 | 6023 | 411 | 0.94 | 1390 | 1379 | 11 | 0.99 |
| Braking | | | | | | | 784 | |
| Aux Loads | 858 | 0 | 858 | 0 | | | | |
| Aero | | | 3036 | | | | | |
| Rolling | | | 1597 | | | | | |

*Overall System Efficiency

0.124

*Overall energy efficiency is calculated as: (aero + rolling)/(fuel in - ess storage)

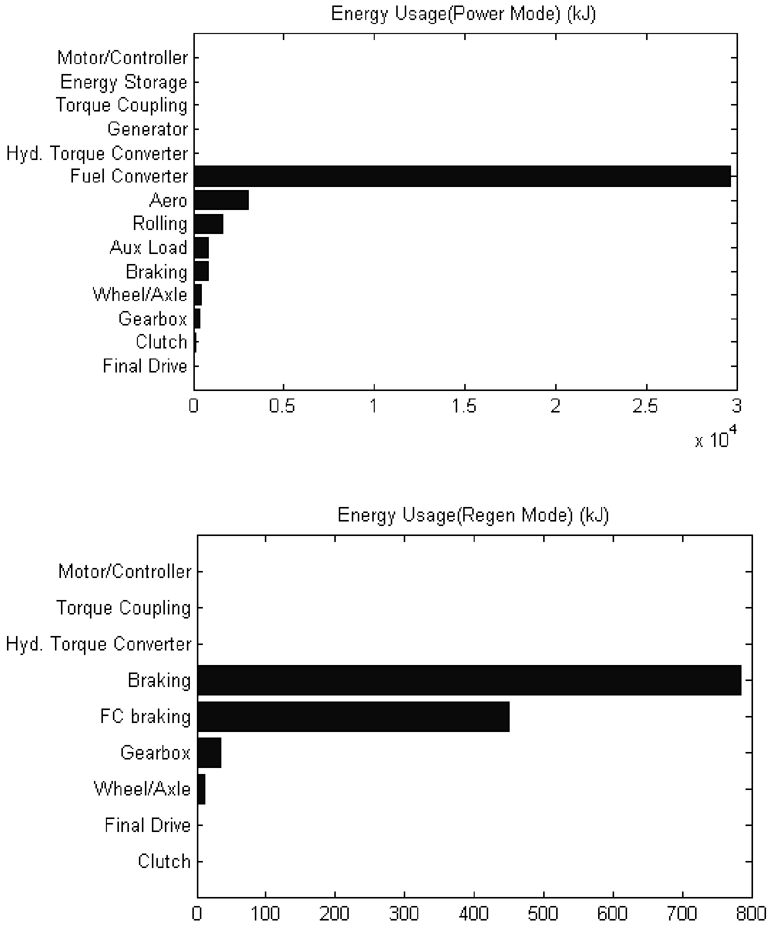



**Figure 5.2 :** Energy Usage Plots of the Conventional Vehicle (NEDC)

In following the fuel consumption and emission ADVISOR results of the parallel hybrid Tourneo Connect for the selected drive cycles are given.

**Table 5.3 :** Hybrid Electric Vehicle Drive Cycle Results

| **Drive Cycle** | **Distance** | **Fuel Consumption** | **HC** | **CO** | **N0x** | **PM** |
|---|---|---|---|---|---|---|
| | **in km** | **Liters per 100 km** | **g/km** | | | |
| NEDC | 10,9 | 0,8 | 0,143 | 0,082 | 0,090 | 0,000 |
| NEDC LOW | 10,6 | 0 | 0,000 | 0,000 | 0,000 | 0,000 |
| LA-92 | 1,9 | 2,3 | 0,123 | 0,253 | 0,363 | 0,001 |
| NYCC | 15,8 | 3,4 | 0,327 | 0,873 | 0,606 | 0,001 |

In following the fuel consumption and emission ADVISOR results of the parallel hybrid Tourneo Connect for the city/highway test procedure are given.

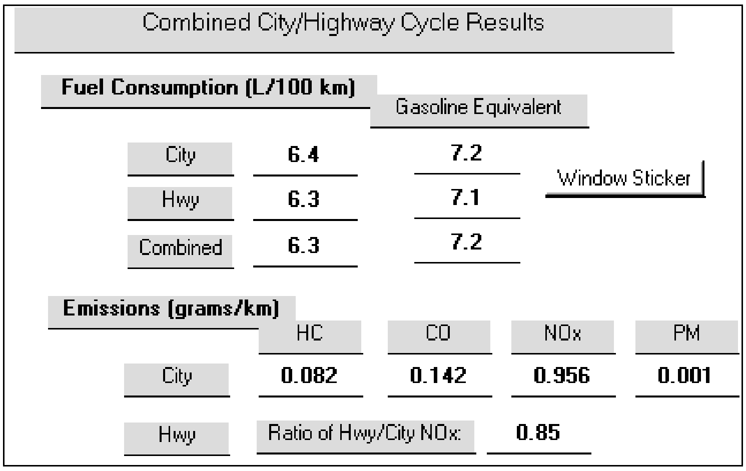



**Figure 5.3 :** Hybrid Electric Vehicle City/Highway Test Procedure Results

**Table 5.4 :** Hybrid Electric Vehicle Energy Usage Results (NEDC)

| Energy Usage Table (kJ) | POWER MODE | | | | REGEN MODE | | | |
|---|---|---|---|---|---|---|---|---|
| | In | Out | Loss | Eff. | In | Out | Loss | Eff. |
| Fuel | 0 | 6131 | | | | | | |
| Fuel Converter | 6131 | 2213 | 3917 | 0.36 | | | 0 | |
| Clutch | 2213 | 2065 | 149 | 0.93 | | 0 | 0 | |
| Hyd. Torque Converter | | | | | | | | |
| Generator | | | | | | | | |
| Torque Coupling | 7147 | 7147 | 0 | 1 | 860 | 860 | 0 | 1 |
| Energy Storage | 737 | 7291 | 645 | 0.89 | | | | |
| Energy Stored | -7199 | | | | | | | |
| Motor/Controller | 6564 | 5402 | 1161 | 0.82 | 1180 | 867 | 313 | 0.73 |
| Gearbox | 7147 | 6813 | 334 | 0.95 | 907 | 860 | 47 | 0.95 |
| Final Drive | 6813 | 6813 | 0 | 1 | 907 | 907 | 0 | 1 |
| Wheel/Axle | 6813 | 6373 | 440 | 0.94 | 1575 | 1557 | 19 | 0.99 |
| Braking | | | | | | | 650 | |
| Aux Loads | 858 | 0 | 858 | 0 | | | | |
| Aero | | | 3036 | | | | | |
| Rolling | | | 1762 | | | | | |

*Overall System Efficiency

0.36

*Overall energy efficiency is calculated as: (aero + rolling)/(fuel in - ess storage)

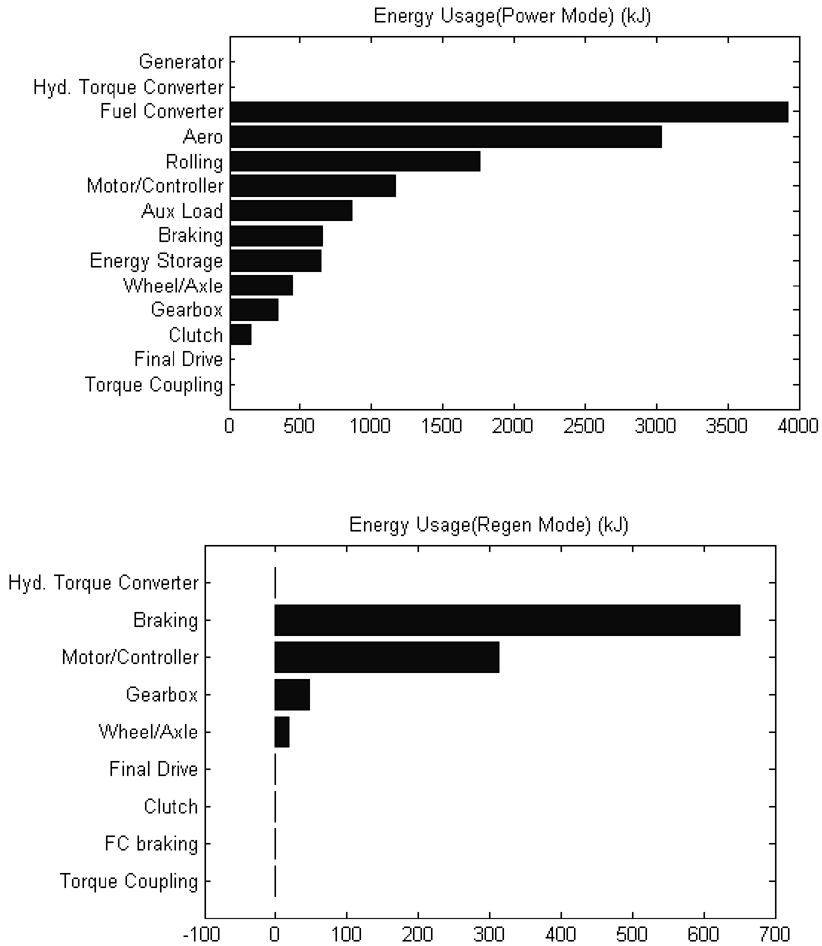



**Figure 5.4 :** Energy Usage Plots of the Hybrid Electric Vehicle (NEDC)

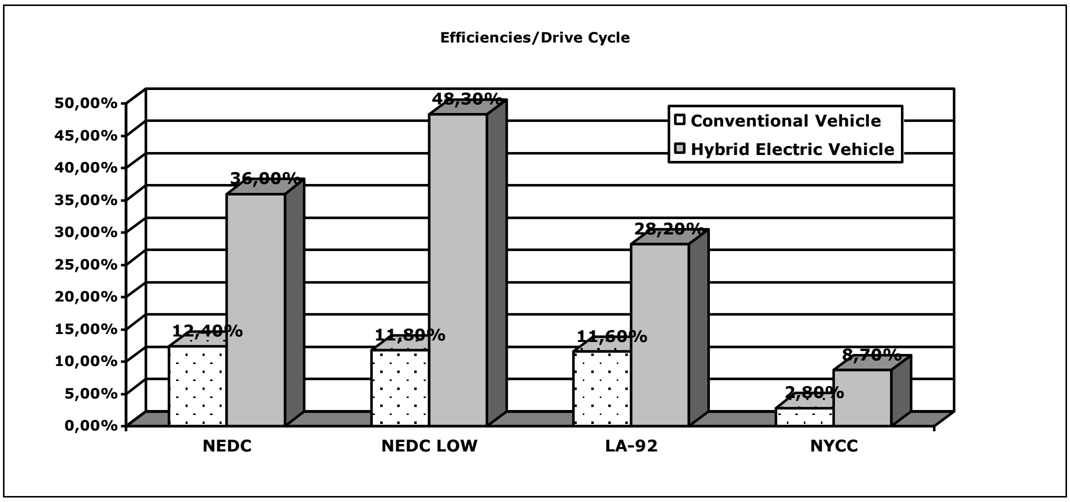



**Figure 5.5 :** Comparisons between Overall System Efficiencies per Drive Cycle

## 5.2 Failure Correction of Fuel Consumption and Emission Results

The fuel consumption and emission results, obtained through ADVISOR, must be corrected, where official NEDC drive cycle fuel consumption and emission results are chosen as a reference data.

As mentioned in previous chapter no fuel and emission maps were available for the 1.8 TDCI Ford engine. Therefore a similar engine, 1.9 TDI Volkswagen engine was modified by the torque diagram. In conventional diesel engines injection pressure is generated for each injector individually. A direct injection engine based on the common rail principle separates the two functions pressure generation and injection by first storing the fuel under high pressure in a central container ("common rail") and delivering it to the individual injection valves (injectors) only on demand. This way an injection pressure of up to 1500 bar (in the future up to 1,600 bar) is available at all times, even at low engine speeds. The high pressure produces a very fine atomization of the fuel leading to better and cleaner combustion [21]. Therefore low fuel consumption and emissions are expected compared with a TDI engine. Running ADVISOR with a TDI engine is expected to result higher fuel consumption and emission. Additionally ADVISOR overpredicts cold fuel use, HC, CO, NOx and PM emissions for a majority of the operating points on the engine map. Detailed information can be found on the Internet by NREL ADVISOR documentation.

**Table 5.5 :** Comparison between Real World Data and ADVISOR Simulation Results for the conventional Vehicle in NEDC Drive Cycle

| NEDC Drive Cycle | Fuel Consumption | HC | CO | N0x | PM |
|---|---|---|---|---|---|
| | **Liters per 100 km** | **g/km** | | | |
| Real World Data | 6,6 | 0,050 | 0,150 | 0,380 | 0,020 |
| Simulation Results | 9,4 | 0,295 | 0,873 | 0,897 | 0,064 |
| | | | | | |

To determine the correction factor for the fuel consumption, the real world NEDC fuel consumption result will be compared with the one obtained after running the simulation for the same cycle. Real word fuel consumption divided to simulation fuel consumption gives the correction factor, which we multiply with all other fuel consumption simulation results for both, conventional and hybrid electric vehicle.

$$C_{FC} = \frac{FC_{REAL}}{FC_{SIM}} = \frac{6,6}{9,4} = 0,70212766 \tag{5.1}$$

To determine the correction factor for the HC emissions, the real world NEDC HC emission result will be compared with the one obtained after running the simulation for the same cycle. Real world HC emissions divided to simulation HC emissions gives the correction factor, which will be multiplied with all other HC emission simulation results for both, conventional and hybrid electric vehicle.

$$C_{HC} = \frac{HC_{REAL}}{HC_{SIM}} = \frac{0,050}{0,295} = 0,1694915 \tag{5.2}$$

To determine the correction factor for the CO emissions, the real world NEDC CO emission result will be compared with the one obtained after running the simulation for the same cycle. Real world CO emissions divided to simulation CO emissions give the correction factor, which will be multiplied with all other CO emission simulation results for both, conventional and hybrid electric vehicle.

$$C_{CO} = \frac{CO_{REAL}}{CO_{SIM}} = \frac{0,150}{0,873} = 0,1718213 \tag{5.3}$$

To determine the correction factor for the NOx emissions, the real world NEDC NOx emissions result will be compared with the one obtained after running the simulation for the same cycle. Real world NOx emissions divided to simulation NOx emissions gives the correction factor, which will be multiplied with all other NOx emission simulation results for both, conventional and hybrid electric vehicle.

$$C_{NOx} = \frac{NOx_{REAL}}{NOx_{SIM}} = \frac{0,380}{0,897} = 0,42363434 \tag{5.4}$$

To determine the correction factor for the PM emissions, the real world NEDC PM emissions result will be compared with the one obtained after running the simulation for the same cycle. Real world PM emissions divided to simulation PM emissions gives the correction factor, which will be multiplied with all other PM emission simulation results for both, conventional and hybrid electric vehicle.

$$C_{PM} = \frac{PM_{REAL}}{PM_{SIM}} = \frac{0{,}020}{0{,}064} = 0{,}3125 \qquad \textbf{(5.5)}$$

After calculating the correction factors, fuel consumption, HC, CO, NOx and PM values, determined through ADVISOR, will be corrected, by multiplying with them for all drive cycles including the city/highway test procedure.

**Table 5.6 :** Comparison between Conventional Vehicle Real World Data and Corrected HEV Simulation Results for the NEDC Drive Cycle

| **NEDC Drive Cycle Distance = 10,9km** | **Fuel Consumption** | **HC** | **CO** | **N0x** | **PM** |
|---|---|---|---|---|---|
| | **Liters per 100 km** | **g/km** | | | |
| Conventional Vehicle Real World Data | 6,6 | 0,050 | 0,150 | 0,380 | 0,020 |
| Corrected HEV Simulation Results | 0,6 | 0,024 | 0,014 | 0,039 | 0,000 |

**Table 5.7 :** Corrected Conventional Vehicle and HEV Simulation Results

| NEDC LOW Drive Cycle<br>Distance = 10,6 km | Fuel Consumption | HC | CO | N0x | PM |
|---|---|---|---|---|---|
| | Liters per 100 km | g/km | | | |
| Corrected Conventional Vehicle Simulation Results | 6,2 | 0,023 | 0,454 | 0,283 | 0,017 |
| Corrected HEV Simulation Results | 0,0 | 0,000 | 0,000 | 0,000 | 0,000 |
| | | | | | |
| **LA-92 Drive Cycle<br>Distance = 15,8 km** | **Fuel Consumption** | **HC** | **CO** | **N0x** | **PM** |
| | **Liters per 100 km** | **g/km** | | | |
| Corrected Conventional Vehicle Simulation Results | 7,2 | 0,015 | 0,041 | 0,546 | 0,024 |
| Corrected HEV Simulation Results | 1,6 | 0,007 | 0,020 | 0,154 | 0,003 |
| | | | | | |
| **NYCC Drive Cycle<br>Distance = 1,9 km** | **Fuel Consumption** | **HC** | **CO** | **N0x** | **PM** |
| | **Liters per 100 km** | **g/km** | | | |
| Corrected Conventional Vehicle Simulation Results | 13,3 | 0,056 | 0,252 | 1,022 | 0,041 |
| Corrected HEV Simulation Results | 2,4 | 0,026 | 0,047 | 0,257 | 0,000 |

**Table 5.8 :** Corrected Conventional Vehicle and HEV City/Highway Test Procedure Simulation Results

| | **Conventional Vehicle** | | | **Hybrid Electric Vehicle** | | |
|---|---|---|---|---|---|---|
| | City | Highway | Combined | City | Highway | Combined |
| **Corrected Fuel Consumption Results [Liters/100km]** | 6,2 | 5,5 | 5,9 | 4,5 | 4,4 | 4,4 |
| **Corrected Emission Results [g/km]** | | | | | | |
| **HC** | 0,024 | | | 0,013 | | |
| **CO** | 0,091 | | | 0,024 | | |
| **NOx** | 0,352 | | | 0,405 | | |
| **PM** | 0,014 | | | 0,000 | | |

## 5.3 Discussion of Fuel Consumption And Emission Results

For each drive cycle and test procedure a detailed discussion of the corrected results (also real world data for the NEDC) will follow below. Current and future European emission norms will also be mentioned.

In section 4.3 the NEDC drive cycle was explained. The European emission norms are determined through this cycle. The following table shows the emissions required to fulfill the previous, current and future European emission norms.

**Table 5.9 :** European Emission Norms for Diesel Passenger Cars

| **Norm (Date)** | **HC (g/km)** | **HC + NOx (g/km)** | **CO (g/km)** | **NOx (g/km)** | **PM (g/km)** |
|---|---|---|---|---|---|
| **Euro2** (>1.1.1996) | | 0,7 | 1 | | 0,08 |
| **Euro3** (>1.1.2000) | | 0,5 | 0,5 | 0,5 | 0,04 |
| **Euro4** (>1.1.2005) | | 0,3 | 0,5 | 0,25 | 0,025 |
| **Euro5** (>2008) | 0,05 | | 0,5 | 0,08 | 0,0025 |

**Table 5.10 :** European Emission Norms compared with Conventional Vehicle Real World Data and HEV Corrected ADVISOR Simulation Results

| | CO | HC+N0x | N0x | PM |
|---|---|---|---|---|
| | g/km | | | |
| EURO3 | 0,5 | 0,5 | 0,5 | 0,04 |
| Conventional Tourneo Connect Real World Data | 0,15 | 0,45 | 0,38 | 0,02 |
| EURO4 | 0,5 | 0,3 | 0,25 | 0,025 |
| EURO5 | 0,5 | 0,13 | 0,08 | 0,0025 |
| HYBRID Tourneo Connect Corrected Simulation Results | 0,014 | 0,082 | 0,039 | 0,000315 |

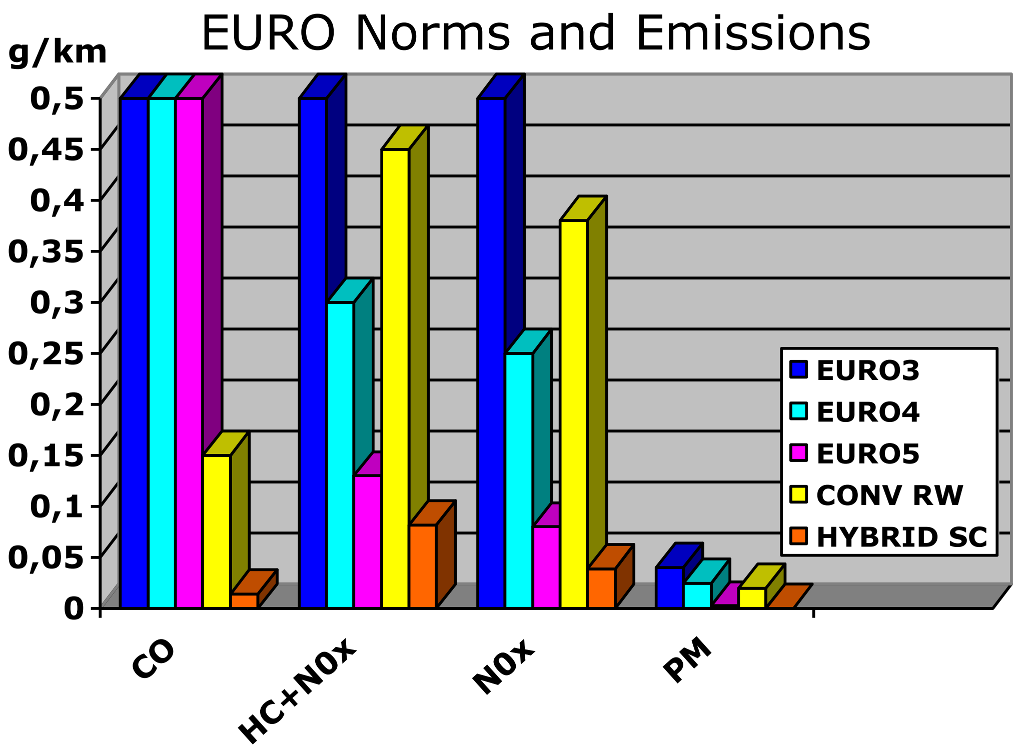



**Figure 5.6 :** European Emission Norms compared with Conventional Vehicle Real World Data and HEV Corrected ADVISOR Simulation Results

The corrected hybrid Tourneo Connect ADVISOR simulation result show, that the vehicle enables the EURO-4 and EURO-5 norms without any difficulties. In addition to this result, these values show remarkable improvements in fuel consumption and emissions compared with the conventional vehicle thanks to the high overall system efficiency 36% compared with the conventional vehicle 12,4%. These improvements are:

- 190% increase in overall system efficiency
- 91% less fuel consumption
- 50% less HC emissions
- 90% less CO emissions
- 90% less N0x emissions
- 500% less PM emissions

The reason, why the NEDC hybrid electric vehicle fuel consumption and emissions are remarkable lower than conventional vehicle, can be explained by the following figure. The vehicle uses no fuel during the 4 ECE cycles (urban), where the state of charge decreases from 0,7 to 0,6.  In the EUDC part (extra urban) the state of charge decreases to 0,3. At this point the vehicle speed is equal to 120 km/h and additional torque is needed because of the low state of charge. Therefore the diesel engine starts to produce additional torque, which causes the low emission values mentioned before. This cold start produces most of the N0x and HC emissions.

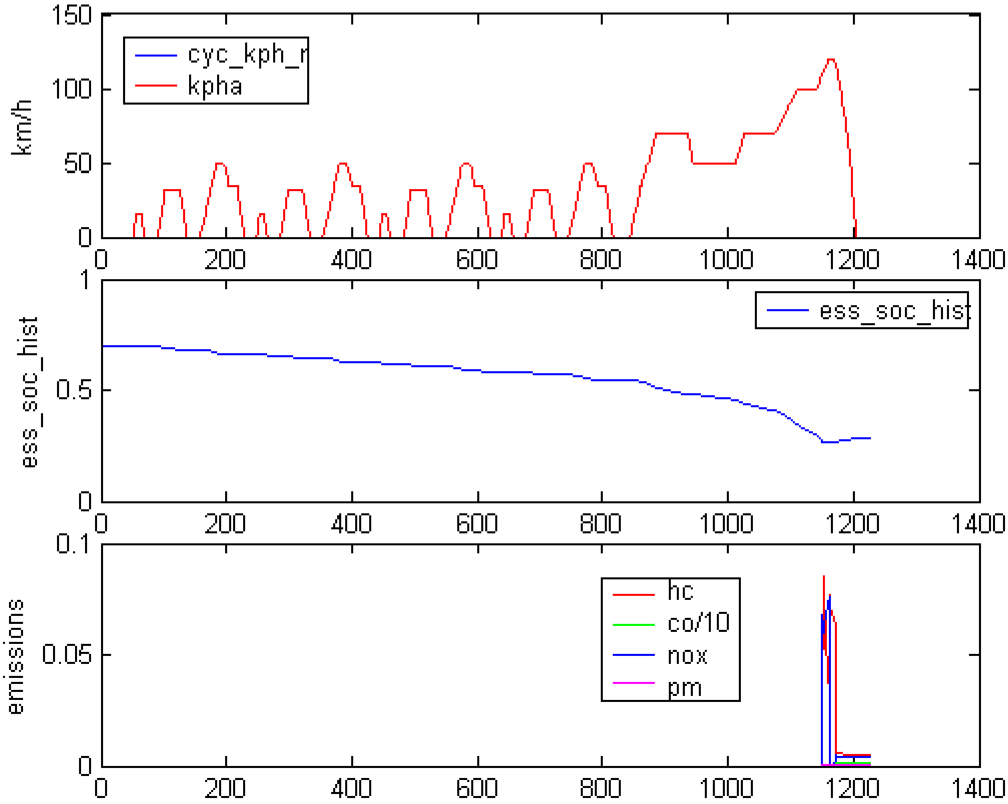



**Figure 5.7 :** NEDC State of Charge and Emission Plots

The hybrid Tourneo Connect NEDC Low results shows, that the vehicle acts as a zero emission vehicle (no need to use fuel) during this drive cycle. According to the European Commission this feature allows very low taxes compared with conventional vehicles. The vehicle hast the highest overall system efficiency in this cycle 48,3% (310% increase in overall system efficiency). The state of charge achieves its lowest point (0,3) during the acceleration for 100 km/h, but this value is still enough to give the required torque without running the diesel engine.

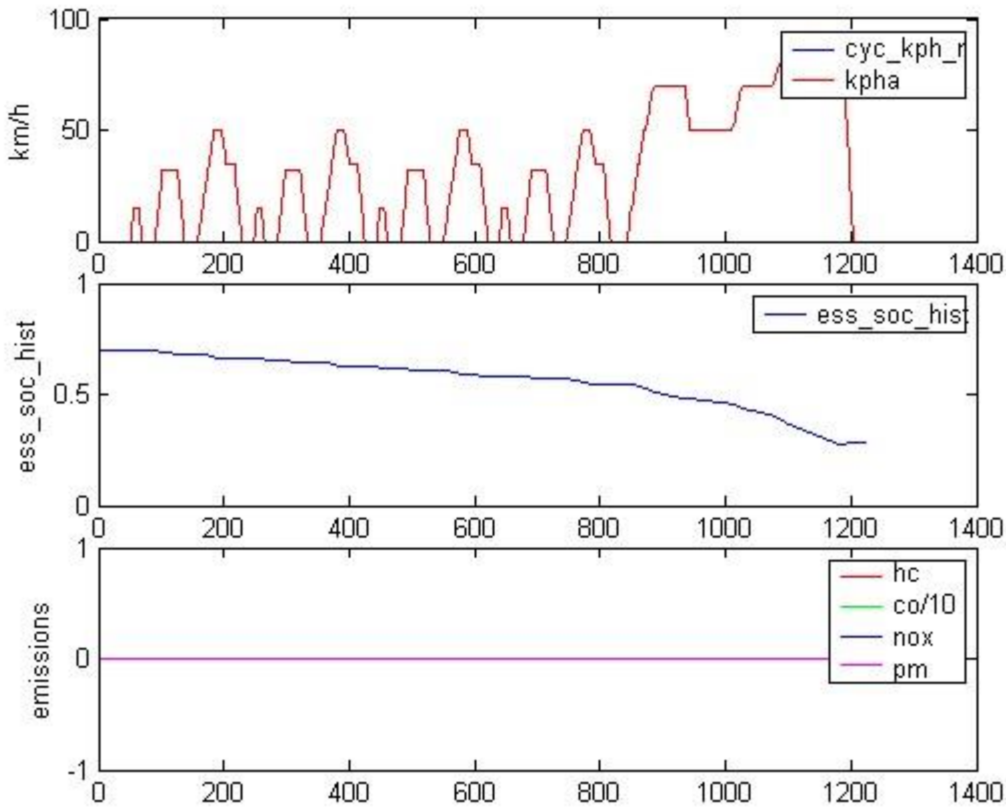



**Figure 5.8 :** NEDC LOW State of Charge and Emission Plots

The LA-92 fuel consumption and emissions values show remarkable improvements compared with the conventional vehicle. These are:

- 102% increase in overall system efficiency
- 75% less fuel consumption
- 50% less HC emissions
- 50% less CO emissions
- 70% less N0x emissions
- 87% less PM emissions

Following figure shows, that state of charge decreases to 0,1 in the end of the cycle. The diesel engine does not run all the time; it is used at the beginning of the cycle to give maximum acceleration to the vehicle. In the middle part the vehicle rarely use the diesel engine till the state of charge decreases below high SOC electric_launch_spd_hi=50 m/s and additional torque is required. This process produces high N0x emissions. In the last part the drive cycle speed is below low

SOC electric_launch_spd_low=25 m/s and the state of charge level is enough to move the vehicle pure electric. In the end of the cycle the state of charge decreases dramatically and the diesel engine must start to give the required torque.

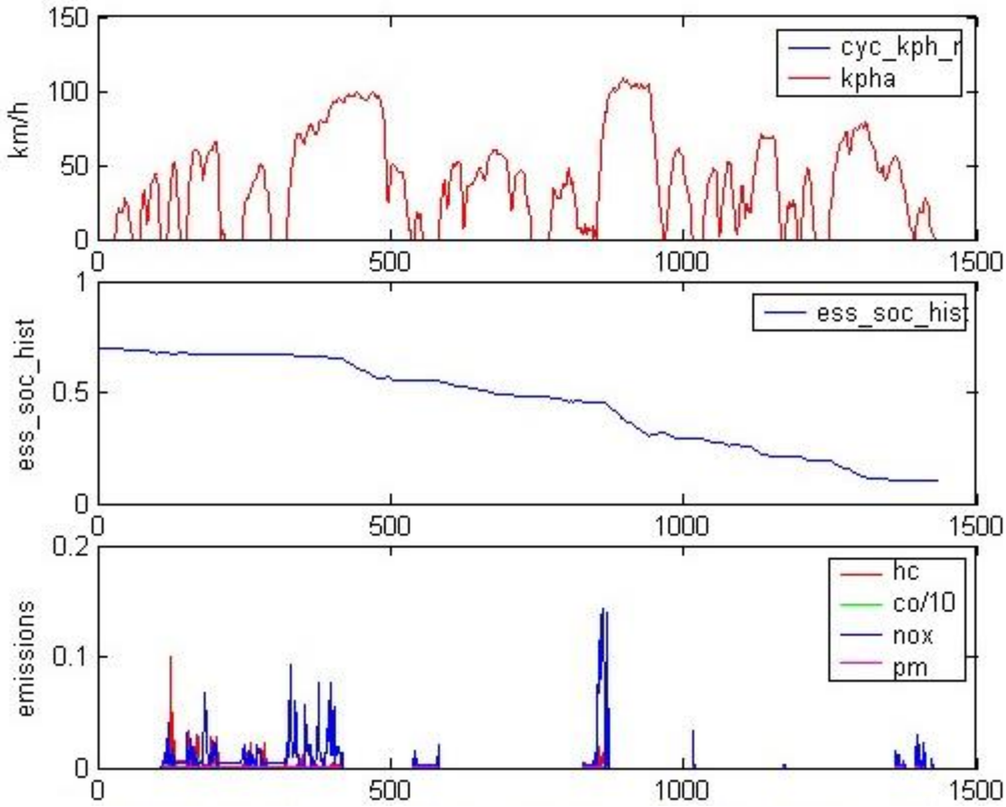



**Figure 5.9 :** LA-92 State of Charge and Emission Plots

The NYCC fuel consumption and emissions values show remarkable improvements compared with the conventional vehicle. These are:

- 221% increase in overall system efficiency
- 82% less fuel consumption
- 52% less HC emissions
- 81% less CO emissions
- 75% less N0x emissions
- 600% less PM emissions

The NYCC consist of many stop&go parts. In addition to these parts high acceleration values are needed. The vehicle needs additional torque from the diesel engine continuously. This fact produces low but permanent emissions compared with other cycles, whereas the reduction in state of charge is very low (0,06).

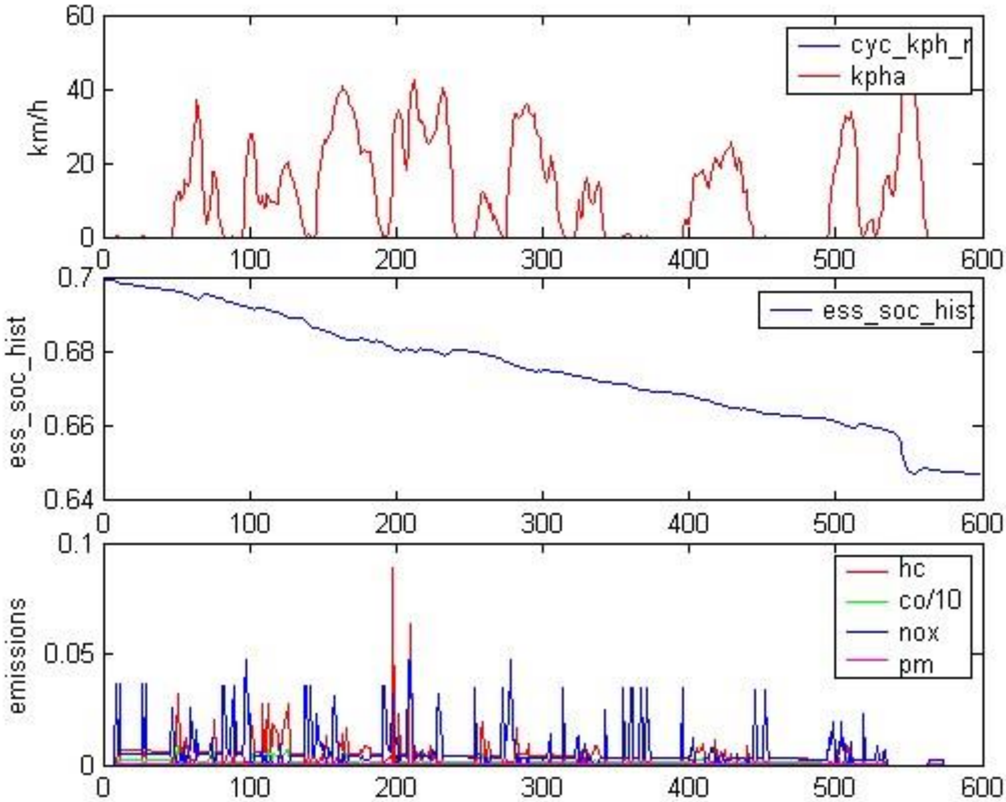



**Figure 5.10 :** NYCC State of Charge and Emission Plots

The city/highway test procedure shows following benefits of HEV compared with the conventional vehicle:

- 27% less fuel consumption in city,
- 20% less fuel consumption on the highway
- 25% less fuel consumption combined
- 15% increase in NOx emissions
- 71% decrease in CO emissions
- 48% decrease in HC emissions
- 800% less PM emissions

The decreases in fuel consumption and emissions are not as remarkable as in the drive cycles. There is an increase of 15% in NOx emissions. The reasons for that could be:

- The correction factors are not strong enough to correct the cold and hot fuel use.
- The correction factors are not strong enough to correct the cold and hot NOx emissions.
- The correction factors are determined for cycles and not specially developed for the city/highway test procedure.

### 5.4 Discussion of Performance and Gradeability Results

A comparison between conventional vehicle real world data, ADVISOR performance results and hybrid electric vehicle performance results are shown below.

**Table 5.11:** Real World and ADVISOR Performance Results

| | 0-50km/h | 0-100 km/h | 0-130km/h | 60-100 km/h | time in 1000m | Maximum Speed |
|---|---|---|---|---|---|---|
| Conventional Tourneo Connect (Real World) | 4,5s | 16,3s | 27,2s | 11,1s | 39s | 153,6 km/h |
| Conventional Tourneo Connect (Simulation) | 4,7s | 16,5s | 33,9s | 10s | 37,5s | 149,7 km/h |
| Hybrid Tourneo Connect | 3,8s | 10,6s | 17,8s | 5,7s | 32,3s | 171,5 km/h |

Following comments are made with the help of these performance values:

1. The 0-100-km/h acceleration value decreases 5,6 s, whereas the 0-130 km/h acceleration decreases 9,4 s. The reason for that performance improvement is the electric motor startup. The electric motor gives the required torque without any delays. Acoording to the determined hybrid control strategy, the vehicle acts as a 160 hp vehicle after 80 km/h, which causes this great improvement. The electric motor runs alone till 80 km/h. Therefore the 0-50 km/h acceleration gap is only 0,7 s.

2. The 60-100-km/h-elasticity values decreases from 10 s to 5,7 s. The hybrid electric vehicle acts as a 160 hp vehicle after 80 km/h, which causes this big 4,3 s improvement.

3. The maximum speed increases from 153,6 km/h to 171,5 km/h, because as mentioned twice the hybrid electric vehicle acts as a 160 hp vehicle after 80 km/h.

A comparison between conventional vehicle real world data, ADVISOR gradeability results and hybrid electric vehicle gradeability results are shown below.

**Table 5.12 :** Real World and ADVISOR Gradeability Results

| | | Gradeability at 55mph |
|---|---|---|
| Conventional Tourneo Connect (Real World) | | 12,0% |
| Conventional Tourneo Connect (Simulation) | | 11,9% |
| Hybrid Tourneo Connect | All systems enabled | 20,0% |
| | Fuel converter enabled | 10,7% |
| | Electric motor enabled | 5,9% |

Following comments are made with the help of these gradeability values:

1. The conventional vehicle real world data and simulation results are moreless the same.

2. The 70 hp electric motor alone is not powerful enough to fulfill the required gradeability goals.

3. The 90 hp diesel engine alone is powerful enough to fulfill the required gradeability goals. The extra weight of 171 kg causes only 1,3 % decrease in gradeability.

4. Both systems, electric motor and diesel engine enabled, results a gradeabiliy of 20 %, which is a very good result.

# 6. CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER RESEARCH

This master thesis tried to demonstrate the benefits of hybrid electric vehicles based on the Ford Tourneo Connect by using ADVISOR, a powerful simulation tool. The fuel consumption and emission results obtained through ADVISOR are corrected with the help of real world data. Also a performance and gradeability analysis was made. Following conclusions are reached:

- The overall system efficiency increases dependent from the drive cycle.
- By transforming the conventional Ford Tourneo Connect into HEV, fuel consumption and emissions benefits will occur. Especially CO emissions decrease strongly independent from drive cycle, whereas the decreases of NOx emissions are dependent from the drive cycle characteristics. PM emissions are not anymore a problem for conventional and hybrid electric Tourneo Connect by using a diesel particle filter.
- There is a remarkable improvement in acceleration and elasticity values by transforming the conventional Ford Tourneo Connect into HEV. The HEV configuration uses the electric motor and diesel engine together, which created these impressive results.
- The electric motor alone is not capable of fulfilling the required gradeability limits. Therefore the diesel engine alone or together with the electric motor should be used to achieve the desired limits.

HEVs are very exciting and interesting and there is a lot more to do. Unfortunately it requires much more time than has been available for this thesis. The author wants to express his recommendations about future research for hybrid electric vehicle simulation with ADVISOR.

The selection of an energy storage unit with high nominal voltage/weight value is a difficult process. Different combination must be checked to find the best suitable battery/cell configuration. Only this could be the topic of a master thesis. With increasing technology new battery types with extraordinary specifications are developed: One interesting thing to investigate is to add a supercapacitor in the HEV in connection to the battery. The supercapacitor has higher specific energy and can deliver higher power than an ordinary battery. It is an electrolytic capacitor-device and the energy is stored as electrostatic charge [22]. The current from the battery is sometimes smaller than required. Therefore you can add a supercapacitor that can deliver higher current during a certain time when it is required and be a "back up" and give extra "power" to the battery. It would be very interesting to compare a vehicle with just a battery with a vehicle with both a battery and a supercapacitor. It is possible to have a smaller ICE and battery when the supercapacitor increases the performance of the conventional vehicle. Smaller components are positive because they give a lighter vehicle with reduced fuel consumption.

Another idea to work with is to have different strategies when charging the battery. Is it better to charge the battery only when it has reached the lower limit or should it be charge continuously? Using a Real-Time Hybrid Control Strategy allows the vehicle to optimize the control parameters dependent from drive cycle. To create such a strategy and test it on ADVISOR could be another master's thesis research topic: What if the vehicle has an "electric mode button" that makes the driver able to decide only to drive with the EM, for example in cities or sensitive environmental areas?

Some modifications on the vehicle could be made to decrease the tractive force. Decreasing the aerodynamic drag coefficient of Ford Tourneo Connect with a new front bumper etc. or decreasing the total height and weight (by using lighter materials) will have a positive effect on fuel consumption. Furthermore new technology common-rail engines with higher-pressure injection up to 1800 bar, which are lighter and more efficient or even more powerful than the 1.9 TDCI engine, could be used and tested with ADVISOR.

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# APPENDIX A CONVENTIONAL FORD TOURNEO CONNECT ADVISOR M-FILES

## A.1 ADVISOR Vehicle File for Tourneo Connect

```
% ADVISOR data file:  VEH_FordTransit.m
% Data source: Barlas
% Data confirmation: OTOSAN
% Tires: 195 R 15 C 8 PR
% Created on: 12/02/02
% BY: Barlas
% Revision history at end of file.
% FILE ID INFO
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
veh_description='FordTransitConnect vehicle chassis';
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=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: VEH_FordTransit - ',veh_description])
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% PHYSICAL CONSTANTS
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
veh_gravity=9.81;    % m/s^2
veh_air_density=1.2; % kg/m^3
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% VEHICLE PARAMETERS for a TOTALLY Stripped FordTransit
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% vehicle curb wt. = 1540 kg  (ford.com)
% ***below are subtractions from base vehicle
% engine assembly wt.  = 175 kg
% fuel system wt. = estimate 15 kg
% exhaust system wt. = estimate 25 kg
% transmission = 60 kg
% ****end of subtractions list
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Wt estimate for a totally stripped FordTransit "Glider" = 1285
veh_glider_mass=1265; % (kg),
veh_CD=0.39;    % (--), coefficient of drag (given on ford.com) NOTE: can be
improved with EV!!
% vehicle width = 1795 mm
% vehicle height = 1981 mm
% vehicle length = 4525 mm
veh_FA=3.26;    % (m^2), calculated frontal area
```

% for the eq'n:  rolling_drag=mass*gravity*(veh_1st_rrc+veh_2nd_rrc*v)
% tires are 195/65 R15
% the rolling resistance data below is not verified, only estimated BJA.
veh_1st_rrc=13.630/1000;  % (--) rolling resistance = 0.013630 kg/kg
veh_2nd_rrc=0;                    % (s/m)
% fraction of vehicle weight on front axle when standing still
veh_front_wt_frac=0.50;   % (--), unknown, assume that this can be attained with battery distribution.
% height of vehicle center-of-gravity above the road
veh_cg_height=0.6;   % (m), published data - assume that this is maintained after conversion
% vehicle wheelbase, from center of front tire patch to center of rear patch
veh_wheelbase=2.912;           % (m), Ford website
veh_cargo_mass=100; % (kg) default EPA cargo/passenger weight
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% REVISION HISTORY
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Begin added by ADVISOR 2002 converter: 04-Feb-2003
clear veh_1st_rrc veh_2nd_rrc; % these variables now being declared in wh_* file as wh_1st_rrc etc.=[];
% End added by ADVISOR 2002 converter: 04-Feb-2003
% Begin added by ADVISOR 2002 converter: 30-Jul-2004
clear veh_1st_rrc veh_2nd_rrc; % these variables now being declared in wh_* file as wh_1st_rrc etc.=[];
% Modified by Barlas: 11.11.2004
% End added by ADVISOR 2002 converter: 30-Jul-2004

**A.2 ADVISOR 1.8 TDCI Fuel Converter File**
fc_description='Ford 1.8 TDCI 90 HP Engine for Transit/Tourneo Connect';
fc_disp=1.9;
fc_eff_scale=1;
fc_emis=1;
fc_emisv=0.8;
a=37;
b=34;
ex_spd=[89.01 94.25 99.48 104.7 110 115.2 120.4 125.7 130.9 136.1 141.4 146.6 151.8 157.1 162.3 167.6 172.8 178 183.3 188.5 193.7 199 204.2 209.4 214.7 219.9 225.1 230.4 235.6 240.9 246.1 251.3 256.6 261.8 267 272.3 277.5 282.7 288 293.2 298.5 303.7 308.9 314.2 319.4 324.6 329.9 335.1 340.3 345.6 350.8 356 361.3 366.5 371.8 377 382.2 387.5 392.7 397.9 403.2 408.4 413.6 418.9];
Cold and Hot fuel maps……
fc_acc_mass=53.77;
fc_base_mass=81;
fc_c2i_th_cond=500;
fc_cl2h_eff=0.7;
CO, NOx, HC, PM cold and hot emission  maps….
c_proprietary=0;
fc_pwr_scale=1;
fc_spd_scale=1;

```
fc_trq_scale=1;
fc_tstat=99;
fc_validation=2;
fc_version=2002;
i=71;
names={'fc_fuel_map', 'fc_hc_map', 'fc_co_map', 'fc_nox_map', 'fc_pm_map'};
fc_mass_scale_fun=inline('(x(1)*fc_trq_scale+x(2))*(x(3)*fc_spd_scale+x(4))*(fc_b
ase_mass+fc_acc_mass)+fc_fuel_mass','x','fc_spd_scale','fc_trq_scale','fc_base_mass
','fc_acc_mass','fc_fuel_mass');
% End added by ADVISOR 2002 converter: 27-Apr-2003
% 20-Nov-2004: automatically updated to version 2002
% 20-Nov-2004: automatically updated to version 2002
% ADVISOR data file:  EX_CI_OxCat.m
% Data source: ORNL testing
% Data confirmation:
% Masses, areas, etc. are scaled based on engine peak power (fc_pwr_max)
% Created on: Feb 26,2001
% By:  VHJ, NREL, valerie_johnson@nrel.gov
% Revision history at end of file.
```

**A.3 ADVISOR Exhaust Aftertreatment File (Oxidation catalyst)**

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% FILE ID INFO
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
ex_description='Oxidation catalyst, tested at ORNL';
ex_version=2002; % version of ADVISOR for which the file was generated
ex_proprietary=0; % 0=> non-proprietary, 1=> proprietary, do not distribute
ex_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: EX_CI_OxCat - ',ex_description])
ex_calc=1;         % 0=> skip ex sys calc (if fc has no emis maps or no cat info avail)
                   % 1=> perform ex sys calcs including tailpipe emis
ex_ornl_bool=1;                        %1->Use efficiencies from ORNL data
                                                        %0->Use      basic      ADVISOR
removal efficiencies
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% CAT EFF VS TEMPERATURE catalyst's temperature-dependent
% conversion efficiencies indexed by ex_cat_tmp_range
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
ex_cat_tmp_range=[-100 1200]; % (deg. C)
% The HC, CO, and NOx removal efficiencies are hard-coded in the lib_exhaust for
% the NOx Absorber
ex_cat_hc_frac=zeros(size(ex_cat_tmp_range));
ex_cat_co_frac=zeros(size(ex_cat_tmp_range));
ex_cat_nox_frac=zeros(size(ex_cat_tmp_range));
ex_cat_pm_frac=[0 0];
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% CAT "BREAKTHROUGH" LIMITS (MAX g/s for each pollutant)
```

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
ex_cat_lim= [1.25 17.0 2.0 0.4]';     % g/s  "break-thru" limit of converter (HC, CO,
NOx, PM)                              % assumed to be ~5X the Tier 1 g/mi limits
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% NEW CONVERTER, ETC DATA
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% CONVENTIONAL CONVERTER
ex_mass=0.3*fc_max_pwr/fc_pwr_scale;             % kg      mass of exhaust system
assumes mass penalty of 0.3 kg/kW)
%ex_mass=0.3*fc_max_pwr;            % kg     mass of exhaust system assumes mass
penalty of 0.3 kg/kW)                             %       (vs 0.26 for SI from 1994 OTA
report, Table 3)
 ex_cat_mass=ex_mass*0.36;           % kg     mass of catalytic converter (from 1994
OTA report, Table 3)
  ex_cat_mon_mass=ex_cat_mass*0.22;   % kg     mass of cat monolith (ceramic)
ex_cat_int_mass=ex_cat_mass*0.33;      %  kg         mass  of  cat  internal  SS  shell
ex_cat_pipe_mass=ex_cat_mass*0.17;  % kg     mass of cat inlet/outlet pipes
ex_cat_ext_mass=ex_cat_mass*0.28;   % kg     mass of cat ext shell (shield)
ex_manif_mass=ex_mass*0.20;         % kg     mass of engine manifold & downpipe,
turbo (if applicable)
 ex_muf_mass=ex_mass-ex_cat_mass-ex_manif_mass;  % kg     mass of muffler and
other pipes downstream of cat
ex_cat_pcm_mass=0;               % kg     mass of cat phase change mat'l heat storage
ex_mass=ex_mass+ex_cat_pcm_mass;    % kg     add mass of PCM (if any) to ex sys
mass
ex_cat_mon_cp=1070;       % J/kgK  ave cp of cat mon: CERAMIC SAE #880282)
%ex_cat_mon_cp=636;       % J/kgK  ave cp of cat mon: METAL (SAE #890798)
ex_cat_int_cp=460;        % J/kgK  ave cp of cat int: SS (SAE #890798)
ex_cat_pipe_cp=460;       % J/kgK  ave sens heat cap of cat i/o pipes (SAE #890798)
ex_cat_ext_cp=460;        % J/kgK  ave sens heat cap of cat ext (SAE #890798)
ex_manif_cp=460;           % J/kgK  ave sens heat cap of manifold & dwnpipe (SAE
#890798)
ex_gas_cp=1089;           % J/kgK  ave sens heat cap of exh gas (SAE #890798)
ex_cat_pcm_tmp=[-100 1200];  % C   temp range for cat pcm ecp vec
ex_cat_pcm_ecp=[0 0];     % J/kgK  ave eff heat cap of pcm (latent + sens)
ex_cat_mon_sarea=0.1*(fc_max_pwr/100)^0.67;         % m^2  outer surface area of
cat monolith (approx. 0.1 m^2/100 kW)
ex_cat_monf_sarea=ex_cat_mon_sarea/4;      %  m^2   surface  area  of  cat  monolith
front face
ex_cat_moni_sarea=ex_cat_mon_sarea*50;   % m^2  inner (honeycomb) surf area of
cat monolith
ex_cat_int_sarea=ex_cat_mon_sarea*1.3;   % m^2  surface area of cat interior
ex_cat_pipe_sarea=ex_cat_mon_sarea/2;    % m^2  surface area of cat i/o pipes
ex_cat_ext_sarea=ex_cat_mon_sarea*1.4;   % m^2  surface area of cat ext shield
ex_man2cat_length=0.7;                 % m    length of exhaust pipe between manifold
and cat conv
ex_manif_sarea=(fc_max_pwr/600)*(0.3+ex_man2cat_length);      %  m^2    surface
area of manif & downpipe: pi*D*L
```

```
ex_cat_m2p_emisv=0.1;       %       emissivity x view factor from cat monolith to cat
pipes
ex_cat_i2x_emisv=0.5;      %       emissivity from cat int to cat ext shield
ex_cat_pipe_emisv=0.7;     %       emissivity of cat i/o pipe
ex_cat_ext_emisv=0.7;      %       emissivity of cat ext shield
ex_manif_emisv=0.7;        %       emissivity of manif & dwnpipe
ex_cat_m2i_th_cond=[0.7 1.3 2.65 6.5]*0.1/0.003 ; % W/K   cond btwn CERAMIC
mono & int (from SAE#880282)
ex_cat_m2i_tmp=[-40 97 344 1200];                 % C      corresponding temperature
vector
ex_cat_i2x_th_cond   =1.0;                    % W/K    conductance btwn cat int & ext
ex_cat_i2p_th_cond   =0.2;                    % W/K    conductance btwn cat int & pipe
ex_cat_p2x_th_cond   =0.02;                   % W/K    conductance btwn cat pipe &
ext
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% STUFF FOR OLD CAT TEMP APPROACH
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
ex_cat_max_tmp=400;                         % deg. C, maximum catalyst temperature
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% DEFAULT SCALING
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% user definable mass scaling function
ex_mass_scale_fun=inline('(x(1)*fc_pwr_scale+x(2))*ex_mass','x','fc_pwr_scale','ex
_mass');
ex_mass_scale_coef=[1 0]; % mass scaling function coefficients
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% REVISION HISTORY
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% 02/26/01: vhj file created from EX_CI, added ex_abs_bool
% 02/27/01: vhj repalced NOx Abs with OxCat
% 02/28/01: vhj changed ex_abs_bool to ex_ornl_bool
% 7/30/01:tm added mass scaling relationship mass=f(ex_mass,fc_pwr_scale)
% ADVISOR data file:  TX_5SPD_CI.m
% Data source: Mass was taken from "Automotive Technologies
% to Improve Fuel Economy to 2015" prepared for the Office
% of Technology Assessment by Energy and Environmental
% Analysis, Inc. Draft report Dec. 1994.
% Gear ratios from VW brochure for Jetta.
% Data confirmation:
% Notes:
% This file defines a 5-speed gearbox by defining gear ratios and gear number,
% and calling TX_VW to define loss characteristics.
% Created on: 24-Jun-1998
% By:  MRC, NREL, matthew_cuddy@nrel.gov
% Revision history at end of file.
```

**A.4 ADVISOR Transmission file (MTX-75)**

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%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='manual 5 speed';
tx_version=2002;
disp('Data Loaded: TX_5SPD_CI -Ford MTX-75 Gearbox for 1.9 TDCI Engines');

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% INITIALIZE
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% The tested transmission had four gears, with the gear ratios listed
% as the first four entries in 'gb_ratio,' below.
gb_ratio=[3.667 2.048 1.258 0.921 0.705]*4.06;
gb_gears_num=5;
%TX_VW % FILE ID, LOSSES
load tx_97jetta_26_50_5; % loads the efficiency map and information for this transmission
% ...with above stated gear ratios
gb_mass=60; % (kg), mass of the gearbox -
%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;
gb_inertia=0;  % (kg*m^2), gearbox rotational inertia measured at input; unknown
% trq and speed scaling parameters
gb_spd_scale=1;
gb_trq_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=1;   % (--), =(final drive input speed)/(f.d. output speed)
fd_inertia=0; % (kg*m^2), rotational inertia of final drive, measured at input
fd_mass=0; % (kg), mass of the final drive - 1990 Taurus, OTA report
tx_mass=gb_mass+fd_mass;% (kg), mass of the gearbox + final drive=(transmission)
% user definable mass scaling relationship
tx_mass_scale_fun=inline('(x(1)*gb_trq_scale+x(2))*(x(3)*gb_spd_scale+x(4))*(fd_mass+gb_mass)','x','gb_spd_scale','gb_trq_scale','fd_mass','gb_mass');
tx_mass_scale_coef=[1 0 1 0]; % coefficients for mass scaling relationship
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% REVISION HISTORY
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% 08/28/98:tm gb_mass added
%9/30/98:ss added fd variables and added tx_mass
```

%10/16/98:ss renamed to TX_5SPD, was GB_5SPD
%12/22/98:ss added variable tx_type to determine what block diagram to run.
%04/01/99:mc started w/ TX_5SPD, updated gb_ratio to TDI-powered Jetta values
% 11/03/99:ss updated version from 2.2 to 2.21
% 7/30/01:tm added transmission mass scaling function mass=f(gb_spd_scale,gb_trq_scale,fd_mass,gb_mass)
% Begin added by ADVISOR 2002 converter: 31-Jul-2004
tx_description='manual 5 speed transmission with 100% efficiency gearbox';

% End added by ADVISOR 2002 converter: 31-Jul-2004
% 31-Jul-2004: automatically updated to version 2002
% 01-Aug-2004: automatically updated to version 2002
% 12-Nov-2004: automatically updated to version 2002
% 12-Nov-2004: automatically updated to version 2002

**A.5 ADVISOR Wheel/Axle File**

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% FILE ID INFO
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
wh_description='Wheel/axle assembly for small car';
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_SMCAR - ',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 1500];   % (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"
wh_axle_loss_trq=[4 24]*.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=0.308;      % (m), rolling radius of 195/65R15 tire from a Ford Transit Connect
% rotational inertia of all wheels, tires, and axles
% below uses OTA's '94 estimate of Taurus wheel, tire & tool mass as mass of
% solid cylinders of radius wh_radius, rotating at wheel speed in this vehicle

```
wh_inertia=181/2.205*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_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)
% 22-Mar-2002: automatically updated to version 3.1
% Begin added by ADVISOR 2002 converter: 04-Feb-2003
wh_1st_rrc=0.009;
wh_2nd_rrc=0;
% End added by ADVISOR 2002 converter: 04-Feb-2003
% Apr 2003 updated wh_radius and wh_axle_loss_mass
% 30-Jul-2004: automatically updated to version 2002
% 30-Jul-2004: automatically updated to version 2002
```

**A.6 Conventional Vehicle Powertrain Control File**

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% FILE ID INFO
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
ptc_description='5-spd conventional-drivetrain control';
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_CONV - ',ptc_description])
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% CLUTCH & ENGINE CONTROL
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% compute idle speed such that
% fc_max_trq(vc_idle_spd) >= 2 * accessory_torque(vc_idle_spd) and
% vc_idle_spd >= 800 rpm
fc_max_pwr_vec=fc_map_spd.*fc_max_trq;
last_index=min(find(diff(fc_max_pwr_vec)<=0));%ss added '=' in '<=' spot on
7/9/99
if isempty(last_index)
   last_index=length(fc_max_pwr_vec);
end
temp=interp1(fc_max_pwr_vec(1:last_index),fc_map_spd(1:last_index),2*acc_mech
_pwr);
if isnan(temp) % if 2*accessory power is off the map (too low)...
   vc_idle_spd=800*2*pi/60;  % (rad/s), engine's idle speed
else
vc_idle_spd=max(temp,800*2*pi/60);
end
% 1=> idling allowed; 0=> engine shuts down rather than
vc_idle_bool=1;  % (--)
% 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(max(fc_map_spd)/5,1.5*vc_idle_spd); % (rad/s)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% 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=[799.9*pi/30  800*pi/30  0.5*max(fc_map_spd)*fc_spd_scale
...
     0.501*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=[1499.9*pi/30          1500*pi/30
0.98*max(fc_map_spd)*fc_spd_scale];  % (rad/s)
% 0.98* 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)
% duration of shift during which no torque can be transmitted
gb_shift_delay=0;  % (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
%%%%%%%%%%%%%%% 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_speed_dep=0;        % Value for the switch in the gearbox control
%                      If tx_speed_dep=1, the speed dependent gearbox is chosen
%                      If tx_speed_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
%%%%%%%%%%%%%%%
% CLEAN UP
```

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
clear last_index temp
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% REVISION HISTORY
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% 08/21/98:mc calculate idle speed and torque from accessories and engine maxT
% 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
% 7/9/99: ss updated the last_index calculation.  Updated the last index to be where
%           the difference in the power vector was <=0 not just <0  if 0 it is not
%             monotonically increasing which causes problems with interp1 in the next
couple lines of code
% 10/7/99:tm added *fc_spd_scale to shift speed definitions
% 11/03/99:ss updated version from 2.2 to 2.21
% 07/31/01:mpo added speed dependent shifting functionality
```

## APPENDIX B HYBRID ELECTRIC TOURNEO CONNECT ADVISOR M- FILES

Vehicle, Fuel Converter, Transmission, Wheel Axle files are the as the conventional vehicle files!

### B.1 ADVISOR Exhaust Aftertreatment File (Oxidation catalyst+Diesel particle filter)

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% FILE ID INFO
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
ex_description='Oxidation catalyst with Diesel Particulate Filter, tested at ORNL';
ex_version=2002; % version of ADVISOR for which the file was generated
ex_proprietary=0; % 0=> non-proprietary, 1=> proprietary, do not distribute
ex_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: EX_CI_OxCat_DPF - ',ex_description])
ex_calc=1;          % 0=> skip ex sys calc (if fc has no emis maps or no cat info avail)
                    % 1=> perform ex sys calcs including tailpipe emis
ex_ornl_bool=1;                              %1->Use efficiencies from ORNL data
%0->Use basic ADVISOR removal efficiencies
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% CAT EFF VS TEMPERATURE catalyst's temperature-dependent
% conversion efficiencies indexed by ex_cat_tmp_range
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
ex_cat_tmp_range=[-100 1200]; % (deg. C)
% These removal efficiencies are hard-coded in the lib_exhaust for
% the NOx Absorber
ex_cat_hc_frac=zeros(size(ex_cat_tmp_range));
ex_cat_co_frac=zeros(size(ex_cat_tmp_range));
ex_cat_nox_frac=zeros(size(ex_cat_tmp_range));
ex_cat_pm_frac=[.98 .98];    %Diesel Particulate Filter (DPF)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% CAT "BREAKTHROUGH" LIMITS (MAX g/s for each pollutant)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
ex_cat_lim= [1.25 17.0 2.0 0.4]';      % g/s  "break-thru" limit of converter (HC, CO,
NOx, PM) % assumed to be ~5X the Tier 1 g/mi limits
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% NEW CONVERTER, ETC DATA
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% CONVENTIONAL CONVERTER
ex_mass=0.3*fc_max_pwr/fc_pwr_scale;              % kg      mass of exhaust system
assumes mass penalty of 0.3 kg/kW)
```

%ex_mass=0.3*fc_max_pwr; % kg mass of exhaust system assumes mass penalty of 0.3 kg/kW)
% (vs 0.26 for SI from 1994 OTA report, Table 3)
ex_cat_mass=ex_mass*0.36; % kg mass of catalytic converter (from 1994 OTA report, Table 3)
ex_cat_mon_mass=ex_cat_mass*0.22; % kg mass of cat monolith (ceramic)
ex_cat_int_mass=ex_cat_mass*0.33; % kg mass of cat internal SS shell
ex_cat_pipe_mass=ex_cat_mass*0.17; % kg mass of cat inlet/outlet pipes
ex_cat_ext_mass=ex_cat_mass*0.28; % kg mass of cat ext shell (shield)
ex_manif_mass=ex_mass*0.20; % kg mass of engine manifold & downpipe, turbo (if applicable)
ex_muf_mass=ex_mass-ex_cat_mass-ex_manif_mass; % kg mass of muffler and other pipes downstream of cat
ex_cat_pcm_mass=0; % kg mass of cat phase change mat'l heat storage
ex_mass=ex_mass+ex_cat_pcm_mass; % kg add mass of PCM (if any) to ex sys mass
ex_cat_mon_cp=1070; % J/kgK ave cp of cat mon: CERAMIC SAE #880282)
%ex_cat_mon_cp=636; % J/kgK ave cp of cat mon: METAL (SAE #890798)
ex_cat_int_cp=460; % J/kgK ave cp of cat int: SS (SAE #890798)
ex_cat_pipe_cp=460; % J/kgK ave sens heat cap of cat i/o pipes (SAE #890798)
ex_cat_ext_cp=460; % J/kgK ave sens heat cap of cat ext (SAE #890798)
ex_manif_cp=460; % J/kgK ave sens heat cap of manifold & dwnpipe (SAE #890798)
ex_gas_cp=1089; % J/kgK ave sens heat cap of exh gas (SAE #890798)
ex_cat_pcm_tmp=[-100 1200]; % C temp range for cat pcm ecp vec
ex_cat_pcm_ecp=[0 0]; % J/kgK ave eff heat cap of pcm (latent + sens)
ex_cat_mon_sarea=0.1*(fc_max_pwr/100)^0.67; % m^2 outer surface area of cat monolith (approx. 0.1 m^2/100 kW)
ex_cat_monf_sarea=ex_cat_mon_sarea/4; % m^2 surface area of cat monolith front face
ex_cat_moni_sarea=ex_cat_mon_sarea*50; % m^2 inner (honeycomb) surf area of cat monolith
ex_cat_int_sarea=ex_cat_mon_sarea*1.3; % m^2 surface area of cat interior
ex_cat_pipe_sarea=ex_cat_mon_sarea/2; % m^2 surface area of cat i/o pipes
ex_cat_ext_sarea=ex_cat_mon_sarea*1.4; % m^2 surface area of cat ext shield
ex_man2cat_length=0.7; % m length of exhaust pipe between manifold and cat conv
ex_manif_sarea=(fc_max_pwr/600)*(0.3+ex_man2cat_length); % m^2 surface area of manif & downpipe: pi*D*L
ex_cat_m2p_emisv=0.1; % emissivity x view factor from cat monolith to cat pipes
ex_cat_i2x_emisv=0.5; % emissivity from cat int to cat ext shield
ex_cat_pipe_emisv=0.7; % emissivity of cat i/o pipe
ex_cat_ext_emisv=0.7; % emissivity of cat ext shield
ex_manif_emisv=0.7; % emissivity of manif & dwnpipe
ex_cat_m2i_th_cond=[0.7 1.3 2.65 6.5]*0.1/0.003 ; % W/K cond btwn CERAMIC mono & int (from SAE#880282)
ex_cat_m2i_tmp=[-40 97 344 1200]; % C corresponding temperature vector

ex_cat_i2x_th_cond =1.0; % W/K conductance btwn cat int & ext
ex_cat_i2p_th_cond =0.2; % W/K conductance btwn cat int & pipe
ex_cat_p2x_th_cond =0.02; % W/K conductance btwn cat pipe & ext
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% STUFF FOR OLD CAT TEMP APPROACH
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
ex_cat_max_tmp=400; % deg. C, maximum catalyst temperature
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% DEFAULT SCALING
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% user definable mass scaling function
ex_mass_scale_fun=inline('(x(1)*fc_pwr_scale+x(2))*ex_mass','x','fc_pwr_scale','ex_mass');
ex_mass_scale_coef=[1 0]; % mass scaling function coefficients
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% REVISION HISTORY
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% 02/26/01: vhj file created from EX_CI, added ex_abs_bool
% 02/27/01: vhj repalced NOx Abs with OxCat
% 02/28/01: vhj changed ex_abs_bool to ex_ornl_bool
% 7/30/01:tm added mass scaling relationship mass=f(ex_mass,fc_pwr_scale)

**B.2 ADVISOR Energy Storage File**

ADVISOR data file: ESS_AnnexVII_SerHyb_NIMH28_OVONIC.m
% Data source:
% Dennis Corrigan, Vice President of EV Battery Systems, Ovonic
% Data confirmation:
% Data provided by manufacturer.
% Notes: These are designed to be a high power, intermediate energy battery.
% Cell type = M70
% Nominal Voltage = 6V
% Nominal Capacity (C/3) = 28Ah
% Dimensions (L * W * H) = 195mm X 102mm X 81mm
% Weight = 3.6kg
% Volume (modules only) = 1.6L
% Nominal Energy (C/3) = 175 Wh
% Peak Power (10s pulse @ 50%DOD @ 35 deg. C) = 1.6kW
% Created on: 4/7/00
% By: TM, NREL, tony_markel@nrel.gov
% Revision history at end of file.
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% FILE ID INFO
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
ess_description='Ovonic 28Ah 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=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: ESS_AnnexVII_SerHyb_NIMH28_OVONIC.m -
',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_ah_cap=[28 28 28];% (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=[11 1]*0.99;  % (--);
% module's resistance to being discharged, indexed by ess_soc and ess_tmp
ess_r_dis=[0.01266 0.00685  0.00644    0.00599    0.00587    0.00575
    0.00568    0.00581    0.00623    0.00667  0.00635
         0.01266 0.00685    0.00644    0.00599    0.00587
    0.00575    0.00568    0.00581    0.00623    0.00667  0.00635
    0.01266 0.00685    0.00644    0.00599    0.00587    0.00575
    0.00568    0.00581    0.00623    0.00667  0.00635
   ]; % (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]/10*5; % (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]/10*5; % (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]/10*5; % (V), Source:
Ovonic Charge-increasing
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% LIMITS
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
ess_min_volts=0.87*1.05*5; % (V), 0.87*105% safety factor volts time 5 cells
ess_max_volts=1.65*0.95*5;% (V), 1.65*95% safety factor volts times 5 cells
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% OTHER DATA
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
ess_module_mass=3.6;  % (kg), mass of a single ~6 V module
```

```
ess_module_volume=0.195*0.102*0.81; % (m^3), length X width X height
ess_module_num=65;  %a default value for number of modules
% 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*(0.195*0.081+0.102*0.081);        % 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*(0.195+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
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% 4/7/00:tm file created
% 9/7/00:tm updated OCV data and removed fliplr from charge resistance definition
% Begin added by ADVISOR 2002 converter: 17-Apr-2002
ess_cap_scale=1;
ess_mass_scale_coef=[1 0 1 0];
ess_res_scale_coef=[1 0 1 0];
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_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');
```

```
% End added by ADVISOR 2002 converter: 17-Apr-2002
```

### B.3 ADVISOR Electric Motor File

```
% This is a prototype or small-production 62 kW, AC induction motor/controller.
% Efficiency/loss data appropriate for a rated voltage system.
% Created on:  5/12/99
% By:  Marco Santoro,  Dresden University of Technology (Germany),
% marco@eti.et.tu-dresden.de
% Revision history at end of file.
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% FILE ID INFO
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
mc_description='62 kW (continuous), AC induction motor/controller';
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=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: MC_AC62 - ',mc_description]);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% SPEED & TORQUE RANGES over which data is defined
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% (rad/s), speed range of the motor
mc_map_spd=[0 500 1000 1500 2000 2500 3000 3500 4000 4500 5000 5500 6000
6500 7000 7500 8000]*(2*pi/60);
% Conversion from RPM to rad/s
% (N*m), torque range of the motor
mc_map_trq=[0 25 50 75 100 125 150 175 200];
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% EFFICIENCY AND INPUT POWER MAPS
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% (--), efficiency map indexed vertically by mc_map_spd and
% horizontally by mc_map_trq
mc_eff_map=[...
    0.2   0.2   0.2   0.2   0.2   0.2   0.2   0.2   0.2
    0.2   0.58  0.61  0.62  0.61  0.62  0.62  0.61  0.6
    0.2   0.71  0.76  0.77  0.765 0.77  0.76  0.755 0.75
    0.2   0.765 0.809 0.828 0.822 0.826 0.82  0.817 0.818
    0.2   0.79  0.836 0.855 0.853 0.856 0.85  0.848 0.846
    0.2   0.81  0.852 0.872 0.871 0.873 0.87  0.869 0.866
    0.2   0.822 0.87  0.885 0.885 0.885 0.883 0.882 0.881
    0.2   0.832 0.88  0.893 0.892 0.891 0.89  0.889 0.888
    0.2   0.84  0.888 0.9   0.897 0.894 0.894 0.894 0.894
    0.2   0.85  0.894 0.9   0.897 0.895 0.895 0.895 0.895
    0.2   0.86  0.9   0.9   0.898 0.898 0.898 0.898 0.898
    0.2   0.87  0.9   0.9   0.897 0.897 0.897 0.897 0.897
    0.2   0.879 0.9   0.899 0.89  0.89  0.89  0.89  0.89
    0.2   0.882 0.9   0.893 0.88  0.88  0.88  0.88  0.88
    0.2   0.885 0.896 0.882 0.86  0.86  0.86  0.86  0.86
    0.2   0.884 0.89  0.87  0.87  0.87  0.87  0.87  0.87
```

```
     0.2   0.88  0.878 0.86  0.86  0.86  0.86  0.86  0.86];
%if ~exist('mc_inpwr_map')
 %  disp('Converting: MC_AC62 motor map efficiency data --> power loss data')
          %% 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)*mc_outpwr1_map;  %
for torque and speed > 0
          %% 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
          mc_losspwr_map=[fliplr(mc_losspwr_map)                mc_losspwr_map(:,1)
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;   % for torque and speed >=0
  [T2,w2]=meshgrid(mc_map_trq(pos_trqs),mc_map_spd);
  temp=T2.*w2;   %  torque>0 and speed >=0
  mc_outpwr_map=[-fliplr(temp) mc_outpwr_map];
  mc_inpwr_map=mc_outpwr_map+mc_losspwr_map;  % (W)
  mc_map_trq=[-fliplr(mc_map_trq(pos_trqs)) mc_map_trq]; % negative torques are
represented too
  mc_eff_map=[fliplr(mc_eff_map(:,pos_trqs)) mc_eff_map]; % the new efficiency
map
  % considers regenerative torques too
%end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% LIMITS
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% max torque curve of the motor indexed by mc_map_spd
mc_max_trq=[198 198 198 198 197 195 183 165 147 127 119 105 98 90 83 76 73];
% (N*m)
mc_max_gen_trq=-1*[198 198 198 198 197 195 183 165 147 127 119 105 98 90 83
76 73]; % (N*m), estimate
% maximum overtorque (beyond continuous, intermittent operation only)
% below is quoted (peak intermittent stall)/(peak continuous stall)
mc_overtrq_factor=62/62; % (--), estimated
mc_max_crrnt=480; % (A), maximum current allowed by the controller and motor,
estimated
mc_min_volts=120; % (V), minimum voltage allowed by the controller and motor,
estimated
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

% 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=0.0235;  % (kg*m^2), rotor's rotational inertia
mc_mass=63;  % (kg), mass of motor and controller, estimated     % motor/controller thermal model
mc_th_calc=1;     % --     0=no mc thermal calculations, 1=do calcs
mc_cp=430;          % J/kgK   ave heat capacity of motor/controller (estimate: ave of SS & Cu)
mc_tstat=45;         % C        thermostat temp of motor/controler 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_outpwr1_map mc_losspwr_map T1 w1 pos_spds pos_trqs temp T2 w2
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% REVISION HISTORY
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% 5/12/99 (MS): created modifying MC_A75.m
% 11/03/99:ss updated version from 2.2 to 2.21
% 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_scale','mc_trq_scale','mc_mass');
% End added by ADVISOR 3.2 converter: 30-Jul-2001

**B.4 ADVISOR HEV Ford Tourneo Connect Powertrain Control Strategy File**

% ADVISOR data file:  PTC_PAR.m
% Data source:          NREL
% 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: 30-Jun-1998

```
% By:  MRC, NREL, matthew_cuddy@nrel.gov
% Revision history at end of file.
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
if ~exist('update_cs_flag')
  %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
  % FILE ID INFO
  %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
  ptc_description='multi-spd parallel electric-assist hybrid w/ electric launch';
  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_PAR - ',ptc_description])
   %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
  % CLUTCH & ENGINE CONTROL
  %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
  % engine idle speed
  vc_idle_spd=0;  % (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=1; % (--)
  % 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
  %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
  if 1 % use new auto scaled shift maps
    % 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=min(fc_map_spd)+[0.01 0.05 0.10 0.15]*(max(fc_map_spd)-min(fc_map_spd))*fc_spd_scale;  % (rad/s)
gb_gear2_dnshift_spd=min(fc_map_spd)+[0.01 0.05 0.10 0.15]*(max(fc_map_spd)-min(fc_map_spd))*fc_spd_scale;  % (rad/s)
gb_gear3_dnshift_spd=min(fc_map_spd)+[0.01 0.05 0.10 0.15]*(max(fc_map_spd)-min(fc_map_spd))*fc_spd_scale;  % (rad/s)
gb_gear4_dnshift_spd=min(fc_map_spd)+[0.01 0.05 0.10 0.15]*(max(fc_map_spd)-min(fc_map_spd))*fc_spd_scale; % (rad/s)
gb_gear5_dnshift_spd=min(fc_map_spd)+[0.01 0.05 0.10 0.15]*(max(fc_map_spd)-min(fc_map_spd))*fc_spd_scale;  % (rad/s)
gb_gear1_upshift_spd=min(fc_map_spd)+[0.20 0.3 0.98]*(max(fc_map_spd)-min(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=min(fc_map_spd)+[0.20 0.30 0.98]*(max(fc_map_spd)-min(fc_map_spd))*fc_spd_scale;% (rad/s)
gb_gear3_upshift_spd=min(fc_map_spd)+[0.20 0.30 0.98]*(max(fc_map_spd)-min(fc_map_spd))*fc_spd_scale;  % (rad/s)
gb_gear4_upshift_spd=min(fc_map_spd)+[0.20 0.30 0.98]*(max(fc_map_spd)-min(fc_map_spd))*fc_spd_scale;  % (rad/s)
gb_gear5_upshift_spd=min(fc_map_spd)+[0.20 0.30 0.98]*(max(fc_map_spd)-min(fc_map_spd))*fc_spd_scale;  % (rad/s)
else % use v3.1 shift maps
% 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)
  end

  % 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
```

```
  %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
  % highest desired battery state of charge
  cs_hi_soc=0.9;  % (--)
  % lowest desired battery state of charge
  cs_lo_soc=0.1;  % (--)
  % vehicle speed below which vehicle operates as ZEV
  % at low SOC
  cs_electric_launch_spd_lo=25;  % (m/s)
  % at and above high SOC
  cs_electric_launch_spd_hi=50;  % (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=0.15*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=50;  % (m/s)
 %%%%%%%%%%%%%% 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_speed_dep=0;       % Value for the switch in the gearbox control
%                     If tx_speed_dep=1, the speed dependent gearbox is chosen
%                     If tx_speed_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
% 7/30/01:tm updated version from 3.1 to 3.2
% 7/30/01:tm added new auto scaled shift map
% 7/31/01:mpo added variables for speed dependent shifting

## VITA

Önder Barlas was born in Istanbul, in February 1980. After primary school education in Dortmund/Germany, he studied in the Sankt Georg Austrian College of Istanbul. He entered the Istanbul Technical University, Mechanical Engineering undergraduate course in 1998. Following graduation with the title B.Sc., in 2002, he entered the automotive engineering M.Sc. program of Institute of Science and Technology in ITU. He is still single and resides in Bahçelievler/Istanbul. He speaks Turkish, German and English.