

# Numerical Simulation Study of a Hybrid Road Vehicle Regarding Fuel Economy and Ambient Emission Delivery

Nicolae Stelian Lontis, Nicolae Liviu Mihon, Ion Vetres

POLITEHNICA University Timisoara, Romania  
{nicolae.lontis,liviu.mihon,ion.vetres}@upt.ro

**Abstract.** The scientific paper presents a numerical simulation comparison study regarding fuel efficiency and emissions, of a hybrid vehicle, when altering temperatures values and state of charge of the energy storage system parameters from the initial conditions occurs, and the vehicle follows a standard test cycle (UDDS). The comparison study aims, the usage of the same vehicle with hybrid – parallel configuration.

**Keywords:** fuel efficiency, emissions, UDDS cycle, hybrid electric vehicle – HEV, parallel configuration, state of charge (SOC).

## 1 Introduction

In this scientific paper the ADVISOR (Advanced Vehicle Simulator for System Analysis) 2.0 tool will be used to perform the comparison study. Version used for the numerical simulation is 2003-00-r0116. The first version of ADVISOR software was developed and released in November 1994. At the request of U.S. Department of Energy (DOE) for understanding hybrid vehicles behavior, the tool was developed, used later in consultancy and R&D contracts with the automotive big players in that time. The success of the tool developed combined with flexibility and progress, conducted in usage of many other clients in order to assess and understand the system-level interactions of hybrid and electric vehicle components [1].

The ADVISOR tool analyzes vehicle powertrains, focusing on power flows among the components. When used on a model that follows a driving cycle, such as the Federal Urban Driving Schedule (FUDS), its main outputs are fuel consumption and tail-pipe emissions. Other capability is to simulate the vehicle in maximum effort acceleration, where outputs are 0-60 mph time or 40-60 mph time, or to determine the maximum road grade the vehicle can climb at constant speed [1].

In accordance with the goals designed, ADVISOR approximates the continuous behavior of a vehicle as a series of discrete steps. During each step, the components are at steady state assumed. This assumption allows the use of efficiency maps or power-usage for the components, derived from steady-state tests in the laboratory. This main assumption is short-duration drivetrain dynamics; however, this not allows

investigation in detailed. For example, vibrations in the driveline or oscillations in electric fields is a phenomenon beyond ADVISOR's scope [1].

ADVISOR is an open source license software, developed in MATLAB®/Simulink® environment/graphical program. The program runs under MATLAB® (from 5.2 version on)/ Simulink® (from 2.2 version on), and it can be loaded/started from the command prompt in the MATLAB®/Simulink® software. The simulation tool is composed form three Graphical User Interface (GUI) windows, where the operator can modify certain fields and parameters according to the necessary outputs of the study.

The first GUI presented in Figure 1, is the **Vehicle Input Page** where the operator will introduce the main parameters of the simulation. The layout of this window is typical for all the 3 GUI windows, in that the left-hand side of the window is the graphical representation of vehicle information; the right-had side is where the user can alter the parameters. On the right-hand side of the window, the user specifies what he wants to see and do to the model (vehicle), and controls the next action for ADVISOR to perform [1].

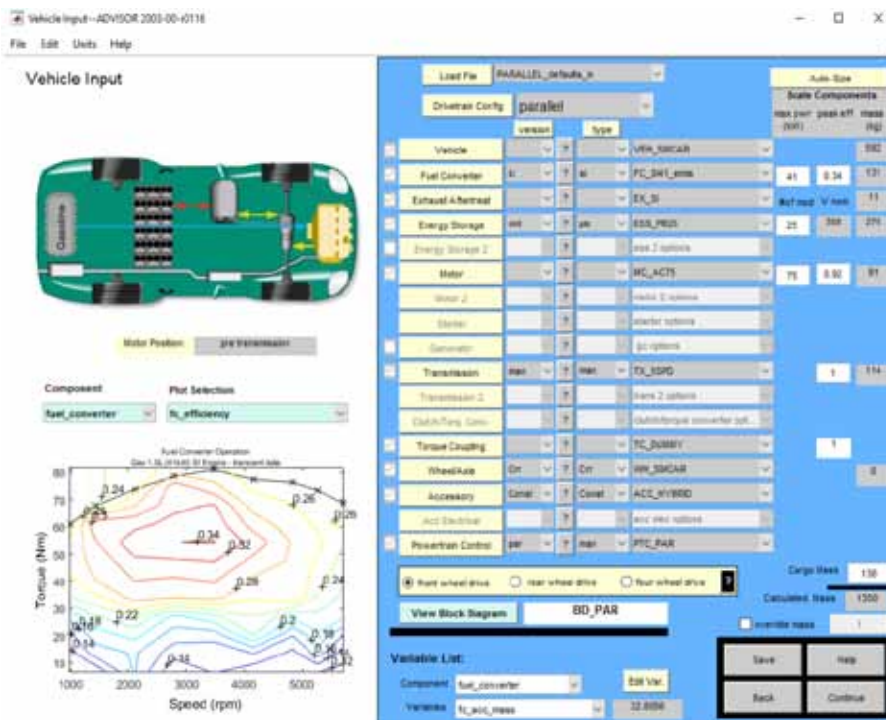


Fig. 1. ADVISOR 2.0 Vehicle Input Screen [2]

In figure 1, vehicle input screen, the picture in the upper left serves as a graphical indication - configuration of the vehicle selected (conventional, series, parallel, fuel cell, or electric vehicle). The user-selectable graphs in the lower left allows the user to view immediately the performance information on the components, that have been

selected, such as efficiency lineament for the engine and motor, emissions lineament, and performance graphs for the batteries [1].

On the right-hand side of the vehicle input screen, in the table, the user has control over what type of vehicle is simulated. The user can also replace or add details of all the components (variables) that make up the drive system. Each variable has a pull-down menu that allows different values; selected from the ADVISOR library. The two columns of numbers under the “maximum power” and “peak efficiency” headings initially indicate these values from the data files. Typing in a new number, causes the GUI to linearly-rescale the entire map to match that peak efficiency while preserving the map’s original shape. Just above these columns is an “auto-size” knob that simplifies the task of iteratively sizing drivetrain components (engine, motor, and batteries) to meet user-defined minimum performance requirements of acceleration and gradeability. For parallel vehicles, the auto-size function also allows the user to select the degree of hybridization, which reflects the relative sizing of the engine, motor, and batteries [2,3].

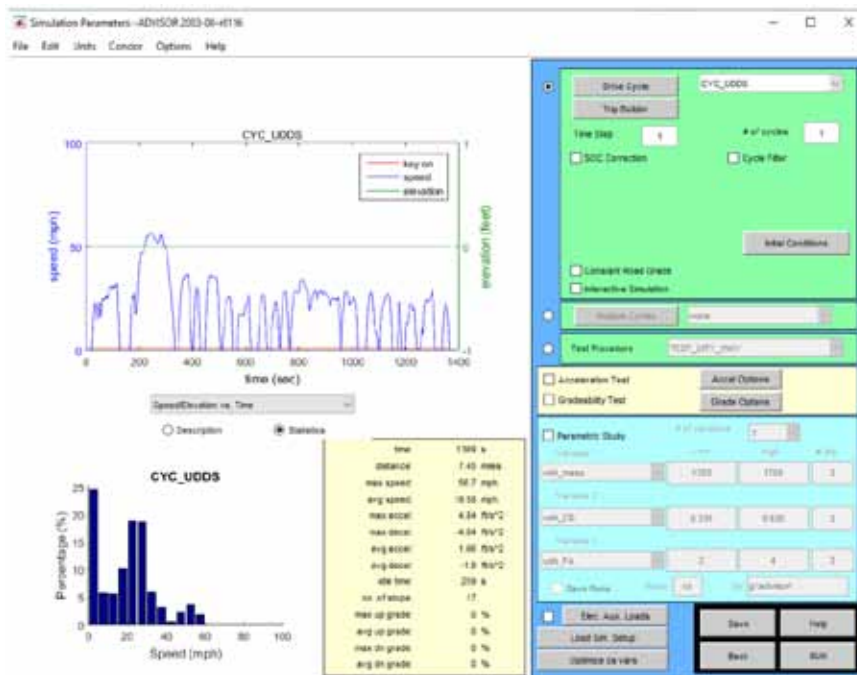


Fig. 2. ADVISOR 2.0 Simulation Setup Screen

The second GUI window of the ADVISOR is the Simulation Setup Page. The primary decision for the user on this screen is whether to run a single desirable cycle or a test procedure, which can consist of special initial conditions, multiple cycles, and significant post processing (such as the test procedure to determine combined city/highway fuel economy).

In the case of single cycle option, initial conditions (primarily thermal and battery) can be set, and for hybrid-vehicles, the type of battery state of charge (SOC) correction routine is selectable. The two SOC correction options available are a zero-delta or a linear correction routine. The zero-delta routine iterates on the initial SOC until the final SOC is within some tolerance (0.5%), while linear correction routine starts the battery at both its extreme high and low SOC, and then performs a linear interpolation to estimate the fuel economy at the zero-delta SOC crossing. Additionally, evaluation of the gradeability and acceleration is also allowable.

Finally, because parametric studies are often useful to explore the design space of a given vehicle, ADVISOR 2.0 allows the option of doing a 1-, 2-, or 3-parameter design sweep of any scalar value on the workspace. This allows the evaluation of the sensitivity of a vehicle to its various input parameters, not only on fuel economy, but also on performance [1,2,3].

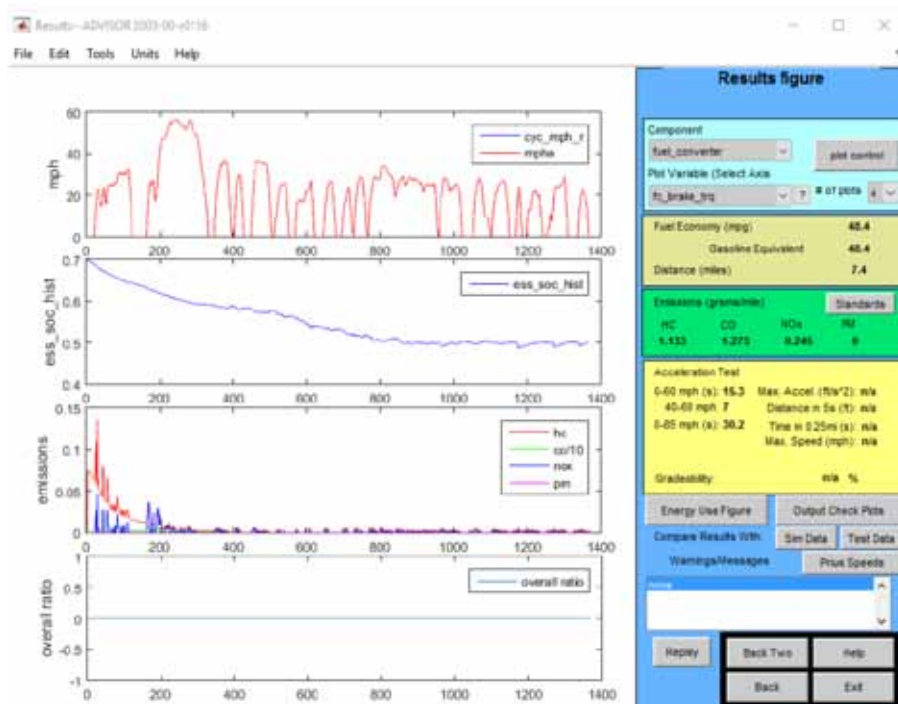


Fig. 3. ADVISOR 2.0 Results Page Screen

The last GUI window of the ADVISOR is the Results Page. The results page presented in figure 3 allows the user to see the summary results of fuel economy, emissions, acceleration, and gradeability on the right hand side, and plots of any of the time-dependent variables that the tool puts onto the workspace on the left-hand side.

When selecting test procedures rather than single cycles the results screen has separate pop-up windows if. ADVISOR 2.0 allows full usage of the built-in plotting features of MATLAB including zoom, layering multiple curves on the same plots, and

applying gridlines. In Figure 3, which shows a sample Results Screen, it can be seen four plots, chosen as representative plots: vehicle speed, battery SOC, regulated emissions, and temperatures at various places within the exhaust system [4].

Two action buttons pull up an energy usage figure and a series of diagnostic plots. The energy usage figure, tracks all of the energy through the drivetrain, and where it is used performs an energy balance to make sure that there is no unaccounted-for energy. In all windows, is a 'HELP' button that takes the user directly to the online web browser documentation to clarify the upcoming problems.

## 2 Experimental Setup

### 2.1 Model Setup

**Model.** The model used for comparison test in ADVISOR 2.0 tool is the TOYOTA PRIUS Model powered by internal combustion engine operating in Atkinson cycle, 1.5 l cubic capacity, maximum power 43-kW@4000 rmp, and maximum torque 101 Nm@4000 rpm, correlated with publishing sources, NREL and ANL data. The comparison study starts with vehicle input data (1st GUI); by selecting the PRIUS\_JPN\_defaults\_in model form the Load File knob. For further analysis, basic values of the model are considered.

The next step in the numerical simulation of the Prius model is choosing the condition for the vehicle to run. The proposed driving conditions for the study are UDDS (Urban Dynamometer Driving Schedule) drive cycle.

The study will reflect the behavior of the vehicle in terms of: fuel economy (mpg)/gasoline equivalent, distance (miles) and emissions of HC, CO (divided by 10 units), NO<sub>x</sub>, PM (grams/mile), while the initial conditions (ambient air temperature, specific heat of air, catalytic converter temperature, fuel converter – internal combustion engine/electric engine and engine bay temperature, temperature of the energy storage system (ESS), temperature of the motor/controller and initial state of charge of the ESS) are altered in steps, presuming that the temperature of the systems mentioned above are changing gradually, over one UDDS cycle.

### 2.2 Results and Discussions

The study considered is the vehicle setup describe above and performing the simulation with the initial conditions offered by ADVISOR. Table 1 presents the values selected as initial conditions - ambient setup.

**Table 1.** Ambient setup - parametrization.

Variable	Value	Unit [-]	Specification
amb_tmp	20	[°C]	Ambient temperature
air_cp	1009	[J/(kg*K)]	Specific heat of air

ex_cat_mon_init_tmp	20	[°C]	Monolith converter temperature
ex_cat_int_init_tmp	20	[°C]	Internal converter temperature
ex_cat_pipe_init_tmp	20	[°C]	In/out converter pipe temperature
ex_cat_ext_init_tmp	20	[°C]	External converter temperature
ex_manif_init_tmp	20	[°C]	Manifold temperature
fc_c_init_tmp	20	[°C]	Initial temperature of the engine cylinder
fc_i_init_tmp	20	[°C]	Initial engine interior temperature
fc_x_init_tmp	20	[°C]	Initial engine exterior temperature
fc_h_init_tmp	20	[°C]	Initial hood temperature
ess_mod_init_tmp	20	[°C]	Initial temperature of the energy storage system module (ESS)
mc_init_tmp	20	[°C]	Initial temperature of the motor/controller
ess_init_soc	$x^1$	[-]	Initial state of charge of the ESS

**Table 2.** Half hot - parametrization.

Variable	Value	Unit [-]	Specification
amb_tmp	20	[°C]	Ambient temperature
air_cp	1009	[J/(kg*K)]	Specific heat of air
ex_cat_mon_init_tmp	250	[°C]	Monolith converter temperature
ex_cat_int_init_tmp	250	[°C]	Internal converter temperature
ex_cat_pipe_init_tmp	150	[°C]	In/out converter pipe temperature
ex_cat_ext_init_tmp	75	[°C]	External converter temperature

<sup>1</sup> The initial state of charge of the Energy Storage System will be presumed as 0.00, 0.35 and 0.70, while maintaining the rest of the parameters from initial condition for the Ambient setup with the values presented in the table above.

ex_manif_init_tmp	150	[°C]	Manifold temperature
fc_c_init_tmp	75	[°C]	Initial temperature of the engine cylinder
fc_i_init_tmp	48	[°C]	Initial engine interior temperature
fc_x_init_tmp	45	[°C]	Initial engine exterior temperature
fc_h_init_tmp	30	[°C]	Initial hood temperature
ess_mod_init_tmp	30	[°C]	Initial temperature of the energy storage system module (ESS)
mc_init_tmp	30	[°C]	Initial temperature of the motor/controller
ess_init_soc	$x^2$	[-]	Initial state of charge of the ESS

For this experimental setup the initial state of charge of the energy storage system is also altered in three steps (0,00; 0,35; 0,70 – percentage correspondence) while maintaining the values of the numerical simulation parameters constant.

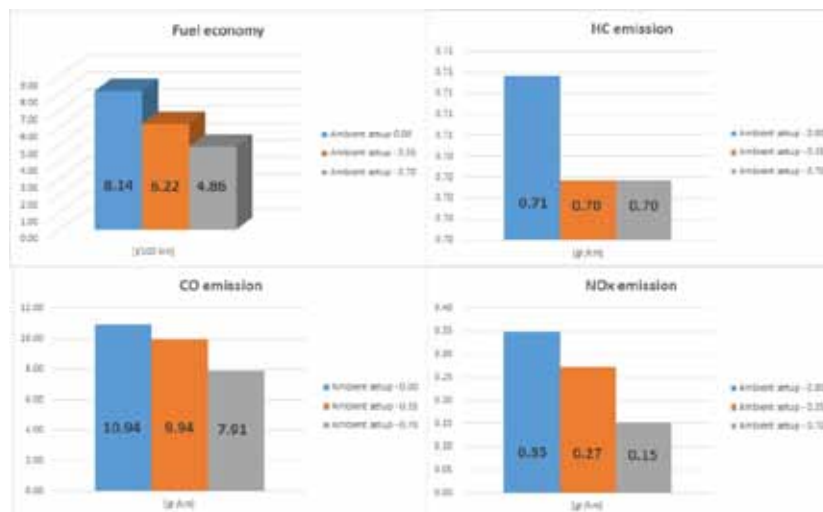


Fig. 4. Ambient setup parametrization results

<sup>2</sup> The initial state of charge of the Energy Storage System will be presumed as 0.00, 0.35 and 0.70, while maintaining the rest of the parameters from initial condition for the Half hot setup with the values presented in the table above.

The three situations proposed for the initial state of charge (SOC) for the ambient setup parametrization in terms of fuel economy and emissions revealed as a first conclusion that the optimum condition for driving of the Prius vehicle is with the battery fully loaded. The results are presented in figure 4.

As punctual conclusion it can be observed that when the initial SOC is 0.00, the internal combustion engine has the task to follow the UDDS cycle and also recharge the battery, therefore a higher fuel consumption is experienced, thus resulting higher emissions for HC, CO and NOx.

The same principle was applied in the second case of the numerical simulation when the initial conditions were changed by dividing the hot setup by 2. The parametrization of the simulation is presented in table 2.

The results of the numerical simulation by altering the parametrization of the initial conditions is presented in figure 5.

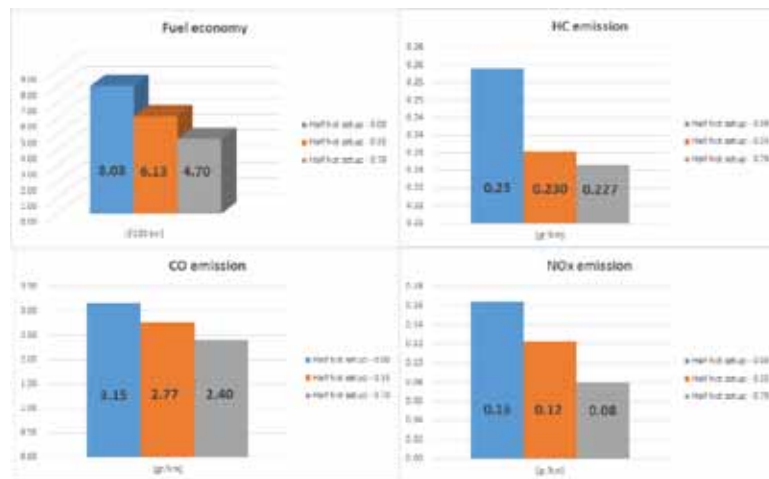


Fig. 5. Half hot setup parametrization results

Table 3. Hot setup - parametrization.

Variable	Value	Unit [-]	Specification
amb_tmp	20	[°C]	Ambient temperature
air_cp	1009	[J/(kg*K)]	Specific heat of air
ex_cat_mon_init_tmp	500	[°C]	Monolith converter temperature
ex_cat_int_init_tmp	500	[°C]	Internal converter temperature
ex_cat_pipe_init_tmp	300	[°C]	In/out converter pipe temperature
ex_cat_ext_init_tmp	150	[°C]	External converter temperature



ex_manif_init_tmp	300	[°C]	Manifold temperature
fc_c_init_tmp	150	[°C]	Initial temperature of the engine cylinder
fc_i_init_tmp	96	[°C]	Initial engine interior temperature
fc_x_init_tmp	90	[°C]	Initial engine exterior temperature
fc_h_init_tmp	35	[°C]	Initial hood temperature
ess_mod_init_tmp	35	[°C]	Initial temperature of the energy storage system module (ESS)
mc_init_tmp	40	[°C]	Initial temperature of the motor/controller
ess_init_soc	$x^3$	[-]	Initial state of charge of the ESS

The same trend of decreasing the fuels consumption and emissions is experienced, therefore the usage off the vehicle is recommended to be used like in the previous case, always whit battery fully loaded in order to obtain economy. Another conclusion is that, when the operating temperature of the internal combustion engine was increased the fuel consumption slightly decreased. In terms of emission there is a considerable advantage for this situation, due to the fact that the catalytic converter temperature has increased.

For the third numerical simulation setup, was proposed the hot setup parametrization (in table 3 are presented the values of the simulation parameters), a default situation that the simulation software provides, when it is appealed.

The results, presented in figure 6, conclude that the decreasing trend of the fuel consumption and emissions occurs, when the temperature of the internal combustion engine and catalytic converter is optimal.

Comparing the results for the fuel consumption, for the three numerical simulation parametrization and three initial SOC, it can be attested that the an average of 0.17 l/100 km of fuel is saved, for the first case (ambient setup / hot setup parametrization and initial SOC 0.00 / 0.35).When the initial SOC is increased – translated to fully battery charged when starting the vehicle and diving on the UDDS cycle – the fuel economy is increased by 0.44 l/100 km.

Regarding the HC emissions in the first setup parametrization – ambient consideration, the values are the same for every initial SOC value; in other words the vehicle in cold state can be driven in any situation (battery full or discharged), the HC emission

---

<sup>3</sup> The initial state of charge of the Energy Storage System will be presumed as 0.00, 0.35 and 0.70, while maintaining the rest of the parameters from initial condition for the Hot setup with the values presented in the table above.

remaining the same. When the parametrization is changed and the second and third step occurs, the temperature of the catalytic convertor increases and the emissions are apprehended. The difference is more than 50% less HC emissions comparing to the second case of parametrization (half hot – setup), and even more decreases when the hot setup is performed.

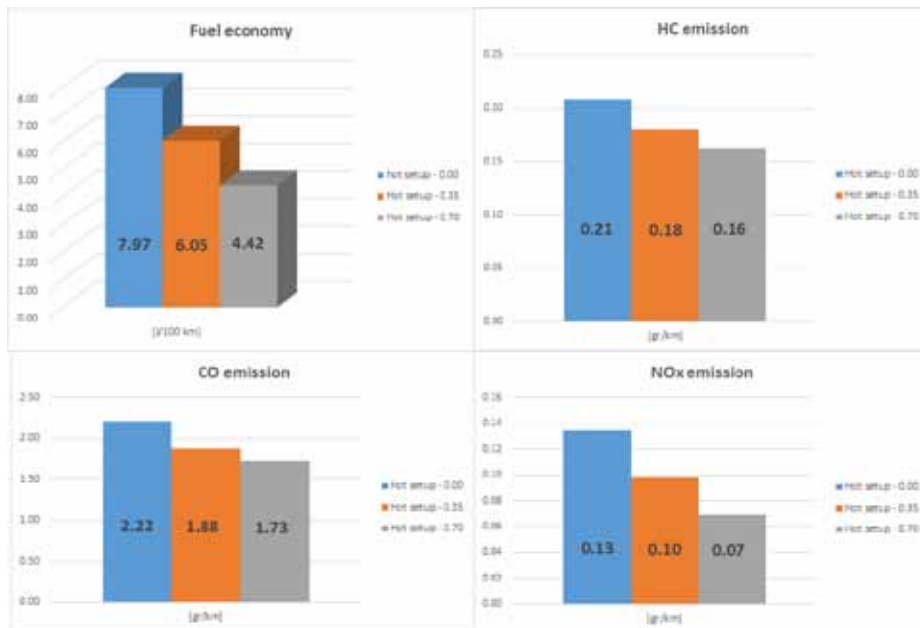


Fig. 6. Hot setup parametrization results

The Carbon Monoxide emission is dramatically reduced when the temperature of the catalytic converter is increased, and continuous to decrease when the initial SOC is also increased; in average the gain of carbon monoxide emission is approximately 80 %.

For the NOx emission, the gain is lower than in the case of CO, but considerable taking into account that the average value is approximately 50% less the ambient setup parametrization in comparison with the second and third situation.

### 3 Conclusions

One global conclusion of this study reflects the fact that, when the hybrid vehicle is used as a mean of transportation, certain obligations of the driver/owner of the vehicle emerges. The first obligation is that the driver has to connect the vehicle to the power grid when the vehicle is stationary (newer Toyota Prius Model), or check permanently the SOC indicator of the vehicle, in case the fuel economy and emissions decrease is a priority.

Another conclusion of the present study in this paper is that the vehicle has a good behavior when is operated at optimum temperature, therefore is prolific for it when is used as a door to door service provider.

## References

1. Advisor 2.0: A Second- Generation Advanced Vehicle Simulator for Systems Analysis – NREL/TP-540-25928 Technical report (March 1999)
2. Markel, T., Brooker, A., Hendriks, T., Jhonson, V., Kelly, K., Kramer, B., O’Keefe, M., Wipke, K.: ADVISOR: a system analysis tool for advanced vehicle modeling, *Journal of Power Sources*, Volume 110, Issue 2, 255 – 266 (2002)
3. Wipke, K.B., Cuddy, M.R., Bruch, S.D.: ADVISOR 2.1: a user-friendly advanced power-train simulation using a combined backward/forward approach, *IEEE Transaction on Vehicular Technology*, Volume:48, Issue:6, (1999)
4. Gao, D.W., Mi, C., Emadi, A.: Modeling and Simulation of Electric and Hybrid Vehicles, *Proceedings of the IEE* (Volume: 95, Issue: 4 (2007)
5. Advisor 2.0 Software version 2003-00-r0116
6. <http://www.epa.gov/nvfel/testing/dynamometer.htm>

