EcoGest - Numerical modelling of the dynamic, fuel consumption and tailpipe emissions of vehicles equipped with spark ignition engines

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Abstract

A numerical code capable of predicting the dynamic and environmental performances of vehicles is presented. The program, named EcoGest, solves the dynamic laws of vehicles for specific acceleration and deceleration curves of typical driving modes. Main inputs of EcoGest are the type of driving mode, vehicle characteristics, number of passengers, time spent at idle and the route - characterized by the topography, number and localization of stop signs and maximum allowed speed. Based on those inputs EcoGest is capable of calculating along the trip the localization of the vehicle, vehicle velocity, position of the accelerator pedal, gearbox selection, and the engine rotation speed. In addition, using the throttle position and the engine speed, EcoGest is capable of estimating instantaneous fuel consumption as well as instantaneous and average NOx, CO, CO2 and HC exhaust emissions. These calculations are done using emissions and fuel consumption distribution maps as a function of engine speed and throttle position. These maps can be obtained either numerically, or experimentally. For numerical data, due to the lack of experimental data for a large range of engines and running conditions, a numerical model, named MotorIST, was developed which simulates the real thermodynamic cycle of a four stroke spark ignition engine were a full discretization in time is adopted. Instead of performing a driving simulation for specific acceleration and deceleration curves of typical driving modes (slow, normal and fast), EcoGest can calculate the driving parameters (such as position of the accelerator pedal and engine rotation speed needed for the calculation of fuel consumption and tailpipe emissions) from a given driving cycle (speed against time), position of speed gear box chosen by the driver along the driving time, vehicle characteristics and number of passengers inside.
1 Introduction

The emission of vehicle pollutants into the atmosphere is an important health and environmental issue. For example, hydrocarbons (HC) irritate man’s mucous, some compounds have a carcinogenic effect and together with nitric oxides (NO) leads to the formation of ground level ozone which can cause lung tissue damage and respiratory illness. Also, high amounts of carbon monoxide (CO) can lead to poisoning because of it’s strongest adherence to hemoglobin and can impair visual perception, manual dexterity and exercise capacity. Low concentrations of nitrogen dioxide (NO$_2$) are sufficient to cause lung irritation, tissue damage and irritation of mucous membranes. NO$_x$ together with water can also lead to acid rains. Carbon dioxide has no direct effect on man at the concentrations present in engine operation but contributes to long term environmental damage caused by atmospheric changes such as global warming (greenhouse effect) - see Barrio [1] and Schäfer and Basshuysen [2]. Such a direct link between vehicle emissions and societal and environmental health shows the importance of knowing what do vehicles emit when they travel from one location to another so traffic analysts could minimize vehicle emissions in designing a roadway or timing a signal system. Besides the above, this study could also help driving schools to give a more environmental friendly education.

Although experimental studies involving on-road vehicle emissions and engine data measurement as the vehicle is driven under real world conditions have been done (see [3]), it is important to built a simulation tool (a software) that allows the same results (emissions and engine data) with the advantage of being less expensive, more flexible, powerful and user-friendly than the real world measurement. As far as authors know, EcoGest is a unique solution because it combines in a single tool driving simulation, internal combustion modeling, fuel consumption and tailpipe emissions released to the atmosphere.

2 EcoGest

EcoGest is a Visual Basic program that solves the dynamic laws of vehicles for specific acceleration and deceleration curves of typical driving modes (slow, normal and fast). Main inputs of EcoGest are vehicle characteristics, number of passengers, the route (characterized by the topography), and either the driving cycle with speed gear box selection, or the type of driving mode, time spent at idle, number and localization of stop signs and maximum allowed speed. Based on those inputs EcoGest is capable of calculating along the trip the localization of the vehicle, vehicle velocity, position of the accelerator pedal, gearbox selection, and the engine rotation speed. In addition, using the throttle position and the engine speed, EcoGest is capable of estimating instantaneous and average fuel consumption as well as instantaneous and average NO$_x$, CO, CO$_2$ and HC exhaust emissions. These calculations are done using emissions and fuel consumption distribution maps as a function of engine speed and throttle position. These maps can be obtained either numerically, or experimentally.
Figure 1 shows an input window and Figure 2 shows an example of one of the distribution maps as a function of engine speed and throttle position.
2.1 Internal combustion engine simulation: MotorIST

In order to build the fuel consumption and emissions distribution maps as a function of engine speed and throttle position, a numerical code was developed, named MotorIST, that simulates the real thermodynamic cycle of a four stroke spark ignition engine covering the range of time between the closing of the intake valves all the way to the opening of the exhaust valves. It uses a pseudo-zero dimensional approach where average values in space are considered while a full discretization in time is adopted. As input values MotorIST requires a full characterization of the geometrical parameters that characterize the engine, namely number of cylinders, bore, stroke, compression ratio, valve dimensions and geometry, valve timing (opening and closing angles) among others. In addition, it is necessary to describe the atmospheric conditions, namely ambient pressure and temperature. Finally, fuel composition (carbon and hydrogen atoms, octane number) and information about the air fuel mixture (λ) is also required. With these input variables, and considering the compression and expansions strokes as isentropic evolutions, heat transfer to the inner surface of the combustion chamber (cylinder walls, piston and cylinder head), the energy released during combustion (taking into account dissociation) and expansion (taking into account CO, H₂ and O₂ recombination due to temperature decrease), actualization of the mixture properties due to temperature and composition changes along the cycle, MotorIST allows the user to calculate, for example, the temperature, pressure, heat transfer coefficient and work evolutions along time as well as indicated and brake power, mean effective pressure, torque, engine efficiency, instantaneous fuel consumption and formation of pollutants (HC, CO and NOₓ) for different engine speeds and throttle positions. The combustion modeling involves a space discretization in three zones: unburned mixture, flame (reaction zone, limited by the trailing edge and leading edge of the flame) and burned mixture in order to improve the NOₓ emission simulation.

MotorIST (see Morais [4]) is being further developed within the EcoGest project. For information on internal combustion engines see Mendes-Lopes [5] and Heywood [6].

2.2 Driving simulation

Typical acceleration and deceleration curves were obtained from experimental data measured on board of a Renault Megane 2.0 IDE using Flowtronic 206-208 (a measurement system with an electronic distance sensor to be mounted onto the vehicle’s wheel with a impulse cable connected to the display screen which enables the accurate measurement of distance, speed and acceleration). Some of those curves are shown in Figure 3. The sport (fast) driver has the most aggressive driving patterns. Besides the above typical curves, each driving mode is characterized by the minimal and maximum rpm at which they change the gearbox selection as shown in Table I.
Figure 3: Experimental readings for acceleration curves.

Table I: Adopted rpm values for which the driver changes the gearbox selection for the Ford vehicles mentioned below.

<table>
<thead>
<tr>
<th></th>
<th>Sport</th>
<th>Normal</th>
<th>Slow</th>
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<tbody>
<tr>
<td>Minimal rpm</td>
<td>2000</td>
<td>1750</td>
<td>1500</td>
</tr>
<tr>
<td>Maximum rpm</td>
<td>4000 or 4500</td>
<td>3750</td>
<td>3000</td>
</tr>
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The driving simulation principles, for each driving profile, are: the vehicle starts from idle (hot start is assumed), accelerates according to the driver profile (sport, conventional or slow) till it reaches the specified cruise velocity. Once reached, the driver keeps that speed. If a stop sign or any other kind of obstacle is ahead of the vehicle in such a distance that equals the necessary brake distance for that driver, decelerating process starts until iddle is reached again (at the obstacle position) and after a certain specified idling time the vehicle goes on accelerating till it reaches the cruise velocity, and so on. The actual speed is calculated knowing the prior speed and a certain acceleration/deceleration curve. The actual rpm are calculated knowing the actual speed, transmission relation and tire geometrical relations (Bosch [7]). The maximum allowed delivered power is calculate knowing rpm. The actual acceleration is calculated knowing the speed variation within the time step. The necessary power is calculated knowing inertial force (total mass multiplied by the actual acceleration), friction forces (drag and rolling resistance), gravitational force and the actual speed. The position of accelerator pedal is calculated knowing the relation between necessary and maximum power and it is directly related with throttle position. At acceleration, the vehicle's position is calculated from the polynomial rectilinlear constant acceleration motion equation. At deceleration the vehicle's position is calculated knowing the distance versus speed curve (necessary brake distance curve). If a driving cycle and a speed gear box selection is given, the
driving simulation principles are similar with the difference that the actual velocity is given, therefore EcoGest doesn’t have to calculate it.

2.3 Tailpipe Emissions

For every rpm and throttle position of the driving simulation EcoGest uses bilinear interpolation (Press et al. [8]) to obtain instantaneous fuel consumption and emissions from distribution maps.

Both emissions obtained by bilinear interpolation from experimental or numerical distribution maps are non-treated emissions (without catalytic treatment). To calculate the vehicle’s real released emissions to the atmosphere it is necessary to account for the conversion efficiency of the three-way catalytic converter (Heywood [6]).

The CO₂ emission is given by subtracting from the stoichiometric CO₂ emission the amount of CO₂ that would be formed from tailpipe HC and CO₂, accounting for their molecular weights.

These calculations are valid only if it is not considered the HC evaporative emissions. For the the Ford vehicles mentioned below the catalytic conversion efficiency was assumed to have a constant value of 95% corresponding to the maximum efficiency of a fresh three-way catalyst (Schäfer and Basshuysen [2]). This means that it was not considered cold start. For more information on catalytic converters see Heck and Farrauto [9].

Bilinear interpolation for a certain rpm and throttle position yields grams per second data. Numerically integrating these values with respect to traveling time yields grams per trip. Dividing the total mass emissions by the trip length yields grams per kilometer.

3 Results

With the propose of demonstrating the potentialities of the program, EcoGest was applied considering three different gasoline engines of which experimental data concerning fuel consumption and non-treated emissions were supplied by Ford Motor Company, namely: V6 2.49L, V6 4.2L and V8 4.6L. Main characteristics of the reference course selected are as follows: 10 km in length, flat, four stop signs along the course and a total time spent at idle of eight seconds (two seconds in each stop sign). The reference cruise velocity was 90 km/h with only one passenger inside the vehicle (the driver). Figure 4 shows, as an example, some results of the study made for the analysis of the impact of driving mode of the Ford Contour equipped with the V6 2.49L gasoline engine. Although 10 km is the total length of the route in those figures it is only represented part of the course in order to improve graphic readability. Similar results (not shown) were obtained for Ford Windstar Minivan equipped with V6 4.2L gasoline engine and Ford Explorer Sport Utility equipped with V8 4.6L gasoline engine. A comparison between the energetic (fuel consumption) and environmental (pollutant emissions) performances of those three vehicles was
also made using the same reference situation (not shown). Main conclusions of this case study are presented in the next section.

![Graph](https://via.placeholder.com/150)

**Figure 4:** Position of accelerator pedal (100% corresponding to full load) and instantaneous vehicle HC emission.

In order to validate the program concerning driving simulation and fuel consumption calculations, EcoGest was also applied to an urban bus of CARRIS (the bus company responsible for exploring the bus routes within the central area of Lisbon, Portugal). It was introduced an experimental driving cycle and the positions of the bus along traveling time, obtained with a DATRON microwave Doppler sensor M3 [10]. It was also introduced the automatic transmission (ZF 5HP_502) management and the variable weight of the bus along the traveling time due to the variable number of passengers inside it. Emission calculations were not performed due to the lack of experimental and literature data. For fuel consumption calculations, the bus’ brake specific fuel consumption was known only at full load. Hence, the map shown in was built from the map for a 8 cylinder, 12 dm$^3$, naturally aspirated M.A.N. engine, assuming that the relation between the brake specific fuel consumption of the engine of the bus (a 6 cylinder, 11967 cm$^3$, turbocharged Mercedes) and of the M.A.N engine at full charge remains constant for each rpm. Results from EcoGest are 13% less than measurements from CARRIS.
Figure 6 shows vehicle speed measurements along part of the selected route of the bus and the results obtained for instantaneous and average fuel consumption.

Figure 5: Estimated brake specific fuel consumption contours (g/kWh) for the engine of the urban bus.

Figure 6: Speed measurements and calculated instantaneous fuel consumption of the bus. The average fuel consumption calculated for the total route was 57.7 l/100km.
4 Conclusions – future work

A numerical model named EcoGest was presented. This model simulates the driving, fuel consumption and pollutant emission for a certain type of driving mode or driving cycle and speed gear box selection, vehicle characteristics, number of passengers, time spent at idle, route (characterized by the topography, number and localization of stop signs and maximum allowed speed), conversion efficiency of the three-way catalytic converter and fuel consumption and emissions (HC, CO, NOx) distribution maps as a function of engine speed and throttle position. These maps can be built using software named MotorIST, that was developed to simulate the real thermodynamic cycle of a four stroke spark ignition engine. A methodology for calculating the real atmosphere emissions (HC, CO, NOx, CO2) of gasoline internal combustion engines was presented assuming a constant conversion efficiency of the three-way catalytic converter. In order to demonstrate the potentialities of EcoGest, an application to three Ford vehicles was performed. Main conclusions of that study can be summarized as follows:

- the slow driver appears to be the most economical and environment friendly (for example it can emit less 22% of CO2, 17% of HC, 50% of CO and 48% of NOx than the normal driver)
- for each 20 km/h increase in the cruise velocity the vehicle can emit more 40% of CO2, 50% of HC, 37% of CO and 86% of NOx
- the HC emissions are the most affected with the increase in time spent at idle
- the topography of the route has a significant influence on fuel consumption and emissions
- for each additional passenger the vehicle can emit more 2% of CO2, 3% of HC, 2% of CO and 8% of NOx (variations in the number of passengers in the vehicle appear to be the parameter that causes less environmental impact, highlighting the importance of promoting car sharing).

In order to validate the program concerning driving simulation and fuel consumption calculations, EcoGest was applied to an urban bus of CARRIS. The results concerning fuel consumption show a difference of 13% less between CARRIS data and EcoGest results.

In summary, EcoGest is a software capable of estimate the influence of the impact of the driving mode, number of passengers, time spent at idle, cruise velocity, course inclination and type of vehicle on fuel consumption and atmosphere pollutant emissions of a vehicle equipped with gasoline internal combustion engine.

The focus of ongoing research is on the following subjects:

- study the influence of considering stationary fuel consumption and emission maps instead of transient data
- validate the model with experimental on board vehicle emission measurements using a portable exhaust gas analyzer
- extend the application of EcoGest concerning emissions to vehicles using other alternative fuels such as natural gas, methanol, diesel and biodiesel
improve the driving simulation considering more representative acceleration and deceleration curves for the driving modes and introducing oscillations on the cruise velocity

- improve the emissions simulation considering the cold start, more accurate idle measurements and modeling the catalyst conversion efficiency with the engine exhaust flow temperature and kilometers traveled by the vehicle.

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Nomenclature

WOT wide-open throttle

$\lambda$ relative air/fuel ratio

References