Development of a software tool to evaluate the energetic and environmental impact of Electric and Hybrid Vehicles in Brussels

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Abstract

How to simulate and evaluate Electric Vehicle’s emissions? Vehicle Simulation Program, VSP, is a modular interactive program [1,2], allowing to compare different drive trains in electric and hybrid vehicles. This comparison can be made on the level of performances, energy consumption and exhaust emissions. The air pollution in urban areas is reaching unacceptable limits. Electric vehicles (EV) are an important solution due to their zero emissions. But electric vehicles uses electricity to recharge their battery after a run. This electricity delivered by different kinds of power plants will produce also air polluting emissions. With the help of this software we will compare the emissions of electric vehicles with the one of internal combustion engine vehicles. After a description of the drive train and the component library, the methodology to take into account the electricity production is explained. This includes the battery model, the model for the battery charger and the ‘Electricity production and distribution’ model. On the basis of an internal combustion engine model we can calculate the emissions of a thermal vehicle and compare this results with the results of the power plant emissions. A second software tool, developed at the VUB, aims to link a city Traffic Simulation Program (TRIPS) with VSP, in a way that the global impact on energy consumption and emissions can be seen. The tool is a dynamic way to examine different scenarios of the introduction of EV’s and HV’s in Brussels.

Simulation algorithm

In this section the simulation tools for drive trains components, battery, battery charger and electricity production park are described.

The drive train and component library.

Based on a number of measurements we have build up models for different types of electric and hybrid vehicles. If measurements are not possible one can use theoretical formulae and equivalent circuits. In the data base of VSP models for asynchronous motors, direct current motors with separate field excitation and series excitation, choppers, converters, nickel cadmium batteries, lead acid batteries, different gears, differentials, wheels, generators, internal combustion engines, battery chargers and power managers are listed. The database is still growing. At this moment we are developing models for permanent magnet motors and corresponding converters. Figure 1 shows an example of the drive train of a hybrid vehicle

In reference [1] the main characteristics of VSP are described: what is VSP, the main simulation loop, the drive train, the component library, power management strategy, parameter tracers, etc. Different simulation methodology and algorithms like "cause - effect" or "effect - cause" method are described in reference [2], as well as speed cycle definitions (time index or distance) and a comparison, calibration and validation on the bases of on road measurements. In this paper we will continue our research by explaining the models from battery to electricity production, the internal combustion engine and a comparison on the level of emission of an unleaded Citroën AX with the electric equivalent.

At the end of the paper we use VSP to simulate the impact of electric vehicles on the global environment of the city of Brussels.

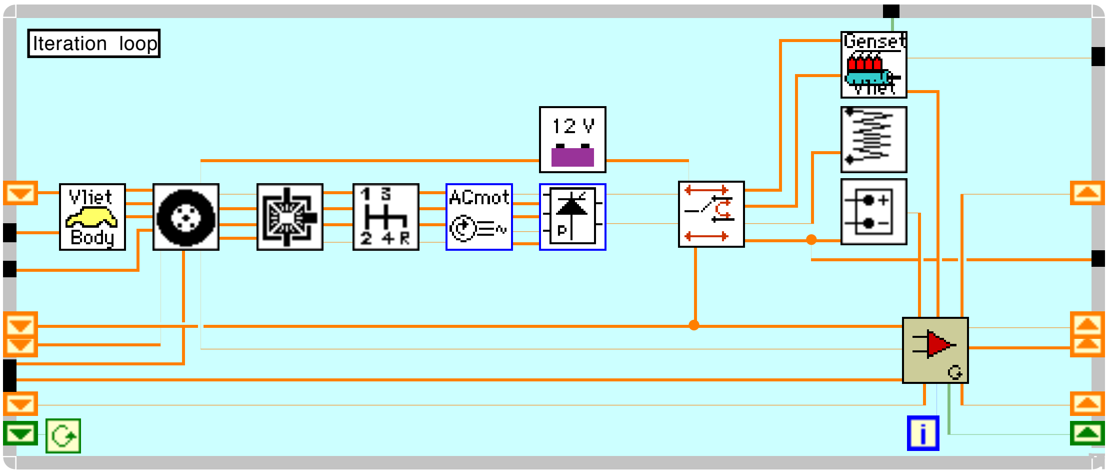

Figure 1:

Drive Train Of An Hybrid Vehicle.

The battery model

In this paragraph a model example for a lead acid battery is described. The component library contains similar models for NiCd batteries. Specific battery management and test infrastructure has recently been developed at the VUB to perform dynamic battery test in a well controlled environment.

The battery has been characterized by its internal impedance. The dependency of the internal impedance with the state of charge, (SoC) is bound to the battery type. The capacity of a battery is not constant but can change in function of the discharge current (I(A)). Not only the current has an influence on the total battery capacity, but also the temperature (Temp(°C)). The influence of age, numbers of discharge/charge cycles are not taken into account at this time.

The battery is characterized by two figures: the open circuit voltage (U_o) and the internal resistance (R_i), both dependent on the State of Charge (SoC) and on discharge or charge conditions. The dependency of the internal resistance with the SoC is due to the variation of electrolyte conductivity and on the low conducting lead-sulfate deposed on the electrodes in the case of a lead-acid battery.

$$Uo = Uo((SoC, Temp) \tag{1}$$

$$Zi = Zi(SoC, Temp) \tag{2}$$

The capacity of a battery is not constant but can change in function of the discharge current. The capacity C_5 is the numbers of Ampere hours (Ah), which can be drawn out of battery during five hours with a current equal to C_5 devised by five. On the bases of the actual battery current and the time increment Δt, the variation of State of Charge (ΔSoC) is calculated for negative power as well as for positive power. It is primarily based on the empirical law of Peuckert (3) which relates capacity (Ah) and current for a complete discharge at that current. We use this equation assuming that the current remains constant during one sampling period.

$$\Delta SoC = -\frac{I * \Delta t}{C_5}\left(\frac{I}{I_5}\right)^{k-1} \tag{3}$$

Not only the current has an influence on the total battery capacity, but also the temperature (Temp(°C)). The effect of temperature on the capacity is taken into account in according IEC 254-1

$$C_a = \frac{C_5}{1 + 0.006 * (30 - Temp)} \qquad (4)$$

For lead acid batteries gassing occurs above 2.4 Volts. At that moment a constant charge acceptance of 80% is assumed in the simulation during regenerative braking.

Modeling of a battery is extremely difficult. Understanding what is going on in battery during a discharge is already a research subject of several years. Finding the right equation to describe these phenomena is even worse. Developing a simulation program to calculate and solve the mathematical equations is thus one of the most difficult tasks in the modeling of an electric vehicle.

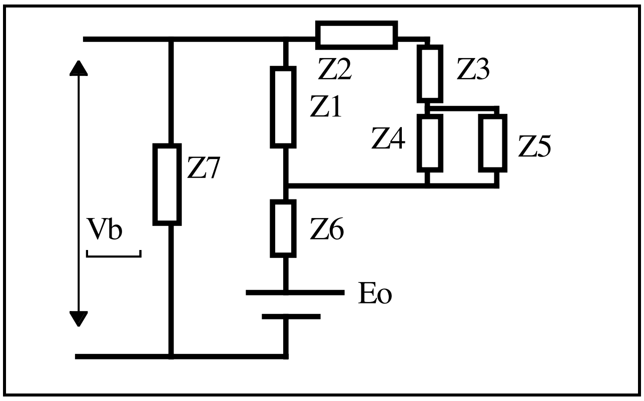

Figure 2

Dynamic battery model.

The time constant of the dynamic characteristics of the battery are of the same order of magnitude as the mechanical driving time constants. A dynamic battery model is thus necessary to have very accurate simulation results. Different theoretical models are already proposed, but experimental data is very hard to find. At our university we are developing a special testing setup to perform dynamic tests on the basis of multisinue charging and discharging signals. With the help of powerful surface fitting algorithms we are developing dynamic models as well as a new type of SoC-indicator. Figure 2 illustrates a dynamic battery model

Battery charger

The model for the charging algorithm starts from the actual SoC of the battery after the speed cycle simulation run. The model uses as a sub programs the ‘battery cell model’ as describe in the previous paragraph, and a ‘’charge profile model’.

Mostly this profile is an I-U curve. This means that the battery will be charged with a constant current until a certain maximum voltage is reached. At this moment the current is decreased to not exceed the maximum voltage. Figure 3 illustrates an other charge profile (WIUI). It starts with a constant power curve until a minimum current is reached. At this moment it keeps charging the battery as long as the voltage doesn’t exceed the gassing voltage. When this is the case the battery will be charged with a very low current until the final charge is complete.

The upper curve is the current in function of the time (in hours) and the lower curve the voltage (scaled to fit into the same graph)

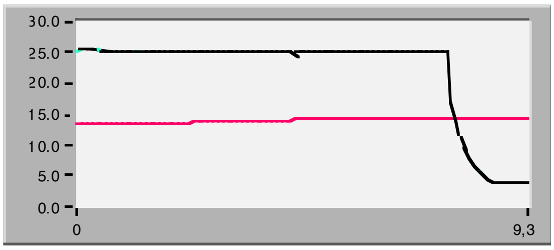

Figure 3

Example of charge characteristic.

Based on the charge current coming from the 'charge curve model' and the battery voltage coming from the battery model, the battery charge power is calculated within a 'While' loop. Together with the sampling time, the covered distance and the charger efficiency, the energy drawn from the mains (E_m(Wh/km)) can be calculated. We take also into account the gassing of the battery, the temperature and the voltage and current limits and the eventually battery heating.

Electricity production park

The electricity necessary to recharge an EV battery can be delivered by a normal domestic socket. Due to the fact that the electricity needs to be transported and transformed from the power plants (E_{pp}(Wh/km)), were it is produced, to the customer, it is necessary to take the losses of the grid into account. This is done by an average distribution efficiency η(grid).

$$E_{pp} = {E_m}/{\eta(grid)} \qquad (5)$$

The 'Background Emissions' are the emissions caused by the electricity production. This is of course related to the composition of the electricity production park. Our model contains data from almost every country of the European Union [4]. Using the specific emission (SE(kg/GJ)) for each type of power plant, its relative contribution (RC(%) and efficiency (η(PP)) one can calculate the total background emissions (BE(g/km)) corresponding to the consumed fuel (E_{pp})

$$BE(g/km) = 0.0036 * Epp(Wh/km) * \left\{ \sum_{all\ power\ plants} \frac{RC(\%) * SE(kg/GJ)}{\eta(PP)} \right\} \qquad (6)$$

This formula is used to calculate the background emissions for CO, CO2, Nox, HC, SO2 and particles (if all data are available).

To use the average electricity production mix as a basis to calculate the total energy consumption of electric vehicles seems at first sight a straight forward approach. Indeed it is not possible to mention of which power plant the electricity of a certain customer is coming from. But it is a wrong approach.

First of all electric vehicles will be charged mostly during the night, with a total different composition of electricity production then the average.

Further, the average contains also old power plants. If one wants to take into account the introduction of electric vehicles in the next ten years, then one needs to consider the investment policy of the electricity production companies. In Belgium the main company's new power plants are of the type Combined Heat Power (CHP) and Steam and Gas Combined Cycle (SGC). The first system produces electricity (with an efficiency of 50%) as well as heat for the heating of buildings (with an efficiency of 30%). The second SGC has an efficiency of 53%.

A third approach is the one of individual electricity production. Companies, institutes (like universities, governments administrations,...), can combine their central heating system with a high efficient electricity generator. In this case one can consider that the fleet of electric vehicles of that company is charged by their own power plant. A private person can install solar cells or other renewable energy sources like wind or water.

A comparison by taking the average electricity production for electric vehicles, would be the same as taking all types of thermal vehicle – old and new, diesel and petrol – together to describe one specific case of an internal combustion engine vehicle.

ICE direct emissions

The model of the internal combustion engine contains several features like maximum torque limits, acceleration reduction, no-load working point, inertia, fuel consumption and emissions.

Required torque is calculated in function of the acceleration (a), the inertia (J), the torque necessary to accelerate the vehicle (Ta) and the resistive part of the driving torque (Tr).

$$T = T_a + J * a + T_r \tag{7}$$

If this torque becomes higher than the maximal motor torque, an acceleration reduction is calculated to allow the iteration loop to converge to the maximum possible corresponding working point. When a gear is engaged the emissions and consumptions (SFC) are calculated on the basis of iso-emission and consumption curves. Out of the desired speed and torque the emissions are calculated using bilinear interpolation of the discretised iso-emission curves, which are entered in several ‘Arrays’.

$$SFC(g / kWh) = Function(n(rpm), T(Nm)) \tag{8}$$

Comparison of thermal Citroën AX with its electric equivalent.

Vehicle characteristics

To obtain a valuable comparative assessment of different vehicle types it is necessary to eliminate external influence factors like wind, rain, driver’s behavior, etc. This can be done by simulation programs in which one can simulate exactly the same speed cycles for two different kinds of vehicle. With the help of our powerful simulation tool, VSP, two Citroën AX vehicles are compared: a petrol fueled Citroën AX (TV) and an electric Citroën AX (EV). Their characteristics are described in table A.

Table A

Vehicle Characteristics

	TV	**EV**
Power (kW)	32.5	11
cylinder	954 cm^3	
energy source	unleaded fuel	electricity
Mass (kg)	768	994
Cx	0.33	0.33
Friction coefficient	0.012	0.012
Frontal surface (m2	1.74	1.74

Simulation results

To compare the energy content of the consumed fuel (TV) with electricity consumption of the mains (EV), one can calculate the primary energy to be used in a power plant in order to produce the electric energy for charging the EV. This implies considering the electricity production mix and the electricity transportation losses.

The next comparison is made on the bases of an ECE-speed cycle. The final battery equalizing charge consumption is not taken in consideration.

Carbon dioxide (CO_2), Carbon oxide (CO) and hydrocarbons (HC) emissions are compared in figure 4. The reference (100%) is the ICE AX with warm engine. This is compared with simulation results while using a cold ICE. This results in 30% more CO_2 emissions, more than 7 times extra CO emissions and 11 times HC. If you consider that the average covered distance in Brussels is 10 km, one can see clearly that a the car is mostly driven with a cold engine and thus with very high emissions.

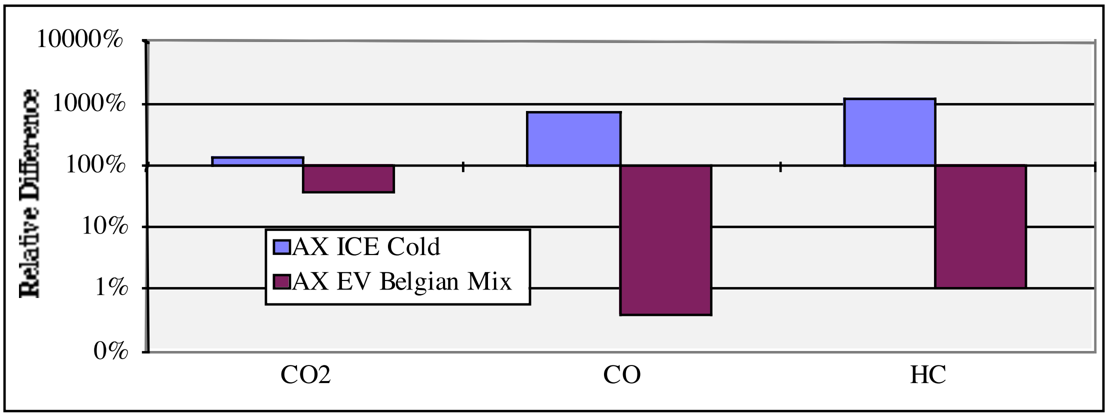

Figure 4

Relative emissions comparison

At the other hand electric vehicles provoke 65% less CO_2, more than 99% less CO and HC while using the Belgian electricity production mix. The main reduction is due to the non-fossil energy production (more than 50%)

In figure 5 one can find the simulation result when using other scenario's to produce the electricity. The first bar illustrates the CO2 emissions provoked by the internal combustion engine Citroën AX. The four other bars represents the result of the simulation of the electric Citroën AX in which:

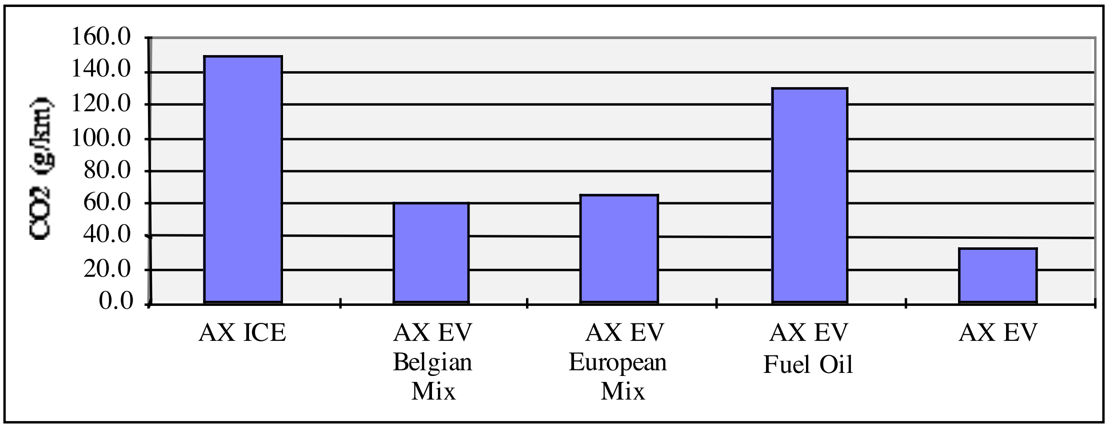

Figure 5

Comparison of CO_2 emissions

- 'Belgian Mix' stands for the average Belgian electricity production mix.
- 'European Mix' stands for the average European electricity production mix

- ‘Fuel Oil’ corresponds with the emissions if the electricity would be produced only by a power plant which uses fuel oil as fuel and with an efficiency of 36%.
- ‘SGC’ is the new type of electricity production plant with a combined Steam and Gas cycle

The energy flow simulation result is shown in figure 6. Starting from 100% energy content in the fuel the energy input through the grid, the battery charger and the drive train to come at the energy at the wheels. This energy correspond with driving the ECE cycle with the electric AX. The power plant chosen for this simulation is the Steam and Gas Combined Cycle (SGC). At the right, one can see the low energy efficiency of an internal combustion engine while driving the ECE city cycle. This is a result of the fuel consumption at stand still and the fact the ICE is operated at working points different from the optimal working point (corresponding with highest efficiency). People are used to find efficiencies of more then 25% for ICE’s. This is a power efficiency at optimal conditions and not an energy efficiency, which corresponds with the real fuel consumption.

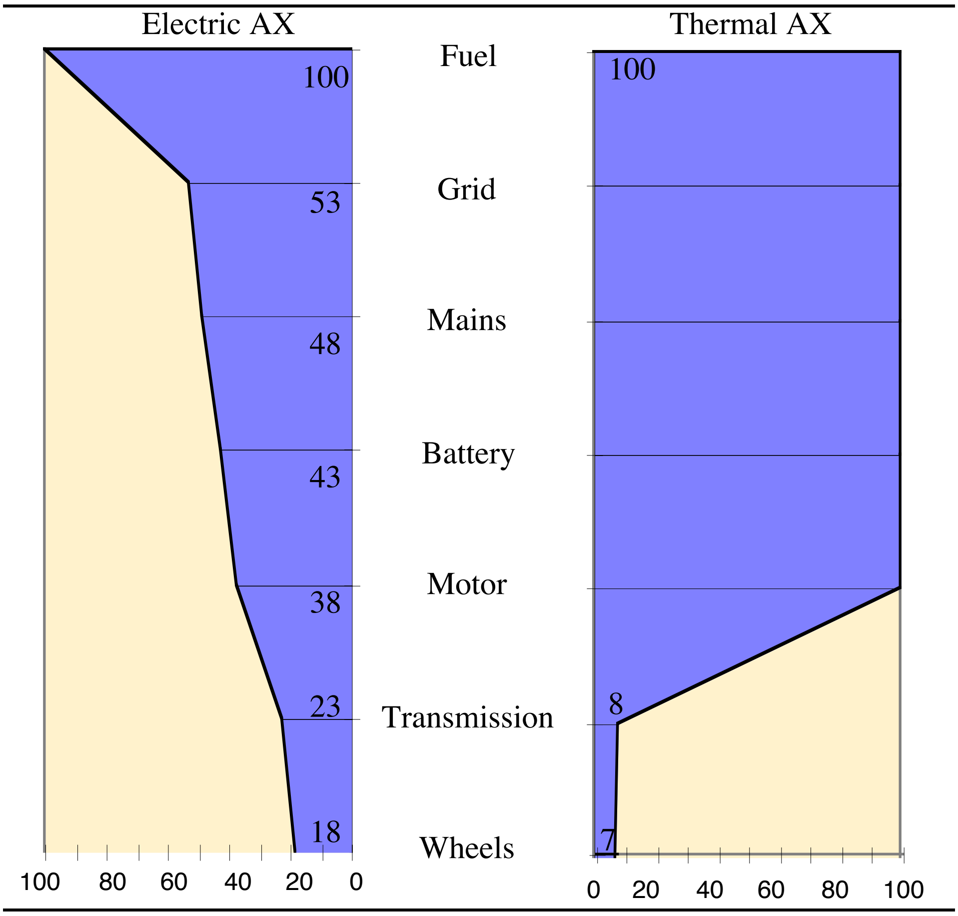

Figure 6

Energy flow in electric and internal combustion engine vehicle

EV’s in Brussels

introduction

The city of Brussels is, as most big European and other cities, undergoing more and more problems with air pollution. An introduction of EV’s will most probably solve part of this problem. To get a reliable evaluation of the effect of introducing EV’s, the VUB is developing a tool that is able to evaluate the energetic and environmental impact of EV’s and HV’s in the city of Brussels. This tool is a combination of 2 parts : a Traffic Simulation Program (TRIPS) and the Vehicle Simulation Program (VSP).

TRIPS is able to simulate traffic streams in the whole Region of Brussels, including traffic jams. The software tool, that is being developed, aims to link VSP with TRIPS in a way that the global impact on energy consumption and emissions when introducing EV's and HV's, can be seen. The tool is also written in LabVIEW and is a dynamic way to examine different introduction scenarios:

- The first step considers the penetration of EV's and HV's through a one by one replacement. They will replace an amount of thermal vehicles. This will be done for different percentages taking into account the origin and destination of the cars (urban, sub-urban or further away).
- The next step in the scenario-building is to prohibit thermal vehicles in certain zones of the city center. Still taking into account the origin and destination of the cars.
- Other steps can be taken into account, such as the implementation of automatic rent-a-car systems or specialized goods distribution centra using electric vehicles.

Results

The traffic simulation program contains a data base of the morning traffic in Brussels. By combining this data with the data of different vehicles out of VSP, we can calculate the emissions provoked by all vehicles at this time.

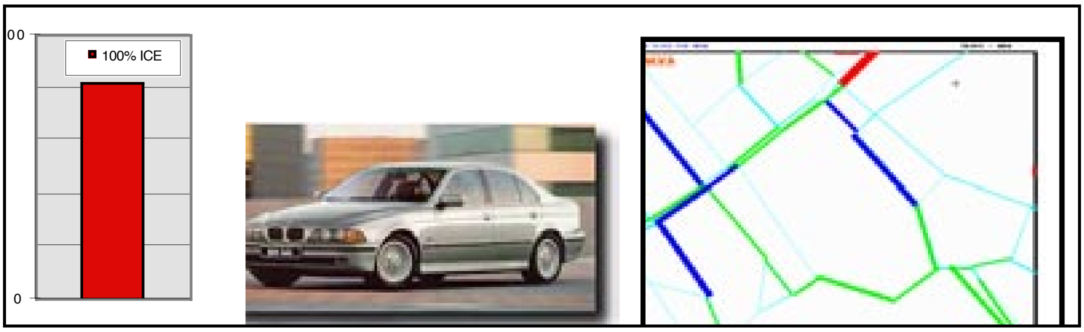

Figure 7

VUB-area CO_2-emissions (tons) with : **100 % ICE**

Figure 7 contains the simulation results. A part of the data is shown in the map (at the right) with illustrates the CO_2 emissions on the roads in the area of our university campus. In total there are 412 tons CO_2 emitted by all ICE cars during one hour.

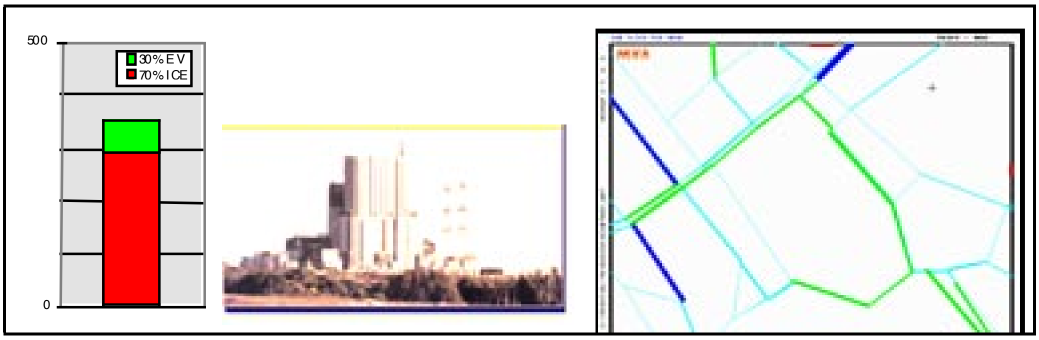

Figure 8

VUB-area CO_2-emissions (tons) with : **70 % ICE and 30 % EV**

With the same total amount of vehicles and trips, but by replacing 30% of them by electric cars, one can simulate the impact on the Brussels environment, as illustrated in figure 8. On the right screen one can see more light blue and green lines than in figure 7. This illustrates the reduction of emissions : from 412 to 290 tons. To produce the electricity CO_2 is emitted which is the extra amount in the left bar graph (60 tons). The photo in the middle is just an illustration of a power plant.

Conclusion

The proposed simulation package has allowed to assess the energetical and environmental impact of both electric and thermal vehicles, through a calculation based on the characteristics of vehicle components and the energy generation mix. This has highlighted the superior efficiency of the electric drive train and its environmental benefits. Furthermore, the integration of the package with traffic simulation software has allowed to devise area-wide scenarios where the environmental impact of traffic can be locally assessed.

The performed work has underlined the important role that can be played by simulation techniques in the evaluation and assessment of electric and hybrid vehicles and their local and global impact on energy and environment.

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