



# **The SIMULCO software: description of modelling and examples of application**

J.-P. Roumégoux

*Energy-Air Pollution Laboratory, The French National Institute for Transport and Safety Research (INRETS-LEN), 69675 Bron, France*

## **Abstract**

To assess the pollutant unit emissions for road vehicles, we combine engine emissions maps with engine operating conditions as calculated by a vehicle simulation model. The SIMULCO software, using Windows on a PC microcomputer, takes into account: the vehicles characteristics (engine, transmission, mass, aerodynamics ...); various operating parameters, such as the vehicle load or the use of accessories (lighting, air conditioning ...); the trips characteristics (road gradients and curves, speed limits, stops); and the drivers characteristics (throttle opening, engine revolution speeds ...). This model calculates instantaneous operating conditions, in particular the engine torque and speed, which in turn enables the calculation of pollutant emissions ( $\text{CO}_2$ , CO, HC,  $\text{NO}_x$ , particulate) and of fuel consumption. It offers three possibilities: firstly driver simulation, where operating conditions and the vehicle dynamics are dependent on driving practice; secondly the kinematic following, as the case of a driving cycle, where the vehicle dynamic is imposed; and thirdly the calculations at steady speed. Results show the great influence on fuel consumption and pollutant emissions of vehicle mass, vehicle speed, road gradient, air conditioning use ..., for different kinds of vehicles travelling on various trips or driving cycles.

## **1 Introduction**

Global concerns in terms of preservation of the environment and energy savings led to an ever increasing attention being paid to such requirements and a more accurate consideration of these phenomena in all the fields related to road freight and passenger transport. In France it is estimated that road transport account for about 70% of gas pollutant emissions such as carbone monoxide,

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CO, unburnt hydrocarbons, HC, and nitrogen oxides, NO<sub>x</sub>, and for 25% of carbone dioxide, CO<sub>2</sub>, emissions, which are all contributors to the greenhouse effect. There is thus no need to demonstrate the adverse effects of vehicle-related pollution on people health. Reduction in CO, HC and NO<sub>x</sub> emissions requires exhaust gas treatment, and reduction in CO<sub>2</sub> emissions requires reduction in fuel consumption. The SIMULCO computation model, which is a technical assessment software package, has been developed considering all these conditions. The first version was designed and developed with the financial support of the French Agence de l'Environnement et de la Maîtrise de l'Energie (ADEME: the French Agency of the Environment and Energy Control).

## 2 Software overview

The SIMULCO software package concern various assessments relating to road vehicles (passenger cars, buses and coaches, duty vehicles and heavy vehicles). It enables to calculate vehicle operating conditions, fuel consumption and pollutant emissions using simulation methods. This software is operated using a PC type microcomputer under Windows <sup>TM</sup>.

### 2.1 Operating principles

Four computation modes are available:

- the driving simulation mode: vehicle dynamics is determined by system input data including vehicle, road and driver parameters; at each computation step, corresponding to a second time interval, the vehicle instant speed is compared to a "target" speed which allows determining the driver's decision: accelerating, maintaining the speed or slowing down depending on the cases, gear changing ;
- the cycle monitoring mode: speed and engaged gear are imposed as a function of time; this corresponds to regulatory test cycles such as European cycles ECE15 and EUDC;
- the kinematic monitoring mode: only speed is imposed as a function of time; this can include for example data recording under real-world vehicle operating conditions;
- the steady speed mode: the vehicle is driven at steady speed on the road considering a prescribed road gradient and gear ratio.

### 2.2 Input data

Input data includes parameters related to the vehicle, the driver and the trip to be performed. Relevant files are created using software integrated modules and are stored in corresponding libraries. Vehicle-related data includes various vehicle technical characteristics (mass, aerodynamics, tires, engine and drive train), engine fuel consumption and pollutant emissions maps (CO<sub>2</sub>, CO, HC, NO<sub>x</sub> and PM) and control and energy consumption features of the auxiliaries (alternator, engine cooling fan, lighting and air conditioning systems, ...).

Driver-related data, mainly used in the driving simulation mode, includes vehicle dynamic behaviour (centrifugal and longitudinal accelerations experienced, maximum speed), the gearbox use and the engine operating range (rotation speeds). Trip-related data differs depending on whether the trip is to be performed in the driving simulation mode, or considering the cycle or the kinematic to be used. In the first case, data must be collected as a function of the distance travelled. This includes road types (city, road and motorway) to which correspond speed limits, road gradients, curve positions and radii, stop positions and durations. In the second case, data is collected as a function of time: vehicle speed and if required the gear ratio selected. In addition, a number of data, considered as parameters, is entered when running the simulation programme: vehicle load (constant or variable), auxiliary uses, engine operating conditions at stop ( idling or switched off engine).

### **2.3 Available results**

In the most general case, i.e the driving simulation mode, the model calculates the vehicle position, speed, the gear ratio engaged, the engine torque and rotation speed, the energy of external forces applied to the vehicle, fuel and pollutant mass flows at second-time intervals over a prescribed trip. From the results obtained which can be stored optionally in a specific file, the integrated values over the whole trip are calculated:

- average vehicle speed (in km/h),
- average fuel consumption (in liter per 100 km),
- average pollutant emissions (in g/km and in g/kWh),
- energy balances of the power train (efficiencies in %) and of the vehicle (energies of applied forces in MJ/100 km),
- statistical data relating to engine operating conditions versus engine torques and rotation speeds (in % of time).

The software package enables to graph the results obtained (values calculated at second-time intervals), or a number of input data (for example road longitudinal profile), using a graph plotter after file formatting.

## **3 Description of modelling**

### **3.1 Formulation of the physical phenomena**

Simulation includes programming logics; computation as such is carried out using different formulations such as power transfer equation and motion equation.

#### **3.1.1 Power transmission equation**

The power available at the vehicle driving wheels for the vehicle drive equals the engine supplied power less the transmission mechanical loss power, and less the auxiliaries mechanical power. During an acceleration, the engine supplied power is reduced by its angular acceleration power and the power available at

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the driving wheels is also reduced by the angular acceleration power of all the rotating parts (transmission and wheels). The application of the kinetic moment and of energy conservation theorems allows drawing up the following equation:

$$C_{rm} \cdot V/r = \eta \cdot k_b \cdot k_p \cdot (C_m - C_{aux}) \cdot V/r - I \cdot \gamma \cdot V/r^2 \quad (1)$$

where  $C_{rm}$  is the torque available at the driving wheels for the vehicle drive,  $C_m$  is the engine torque,  $C_{aux}$  is the auxiliaries torque,  $V$  is the road linear speed,  $r$  the driving wheels radius,  $\eta$  is the transmission mechanical efficiency,  $k_b$  and  $k_p$  are the gear box and driving axle ratios,  $I$  is the moment of inertia of all the rotating parts (engine, transmission, wheels), reduced to the driving wheel axle and  $\gamma$  is the vehicle acceleration.  $\eta$ ,  $k_b$ ,  $k_p$  and  $I$  are function of the gear selected.

### 3.1.2 Motion equation

Using the power transmission equation and the balance of the forces applied to the vehicle, the motion equation which determines the  $\gamma$  longitudinal acceleration from the  $C_m$  engine shaft torque and the  $F_r$  running resistance can be written as follows:

$$\gamma \cdot (M + I/r^2) = \eta \cdot k_b \cdot k_p \cdot (C_m - C_{aux})/r - F_r \quad (2)$$

$$\text{with } F_r = R \cdot M \cdot g \cdot \cos \alpha + 1/2 \cdot \rho \cdot S \cdot C_d \cdot V^2 + M \cdot g \cdot \sin \alpha \quad (3)$$

where  $\alpha$  is the road horizontal inclination angle,  $R$  is the tire rolling resistance factor (function of vehicle speed  $V$ ),  $M$  is the vehicle mass,  $g$  the acceleration due to gravity,  $\rho$  the air density,  $S$  the vehicle frontal area, and  $C_d$  the aerodynamic drag coefficient. Acceleration  $\gamma$  is assumed to be constant for the computation step duration.

### 3.2 Engine torque

The calculation of engine torque depend on the computation mode selected (see 2.1). In the case of driving simulation mode, this torque is determined by the driver's decision; in particular, if the driver decide to accelerate, the engine torque is a function of the full load torque:

$$C_m = \text{dtr} \cdot C_{mf} \quad (4)$$

where  $\text{dtr}$  is the driver's torque ratio (generally between 0.5 and 1.0) and  $C_{mf}$  is the full load torque depending on engine speed. The driver's torque ratio is also dependent on the fuel injection control system: with an engine speed control system (case of lorries diesel engines) in the place of an engine load control system (case of cars petrol engines),  $\text{dtr}$  is always equal to 1.0.

In the others cases (cycle or kinematic monitoring and steady speed modes), the engine torque is calculated using eqn (2), after auxiliaries torque determining.

### 3.3 Auxiliaries torque

Modelling the power absorbed by auxiliaries is performed in a very simple way: input data includes the mean load at which each auxiliary is used on the travel to be follow (using ratio). The auxiliaries torque is thus a function of engine speed only. Modelling the auxiliaries features is also very simplified.

#### 3.3.1 Alternator

Alternator input characteristics are the voltage  $U_a$ , the speed's ratio (alternator/engine) and two points of the full load curve (speed, maximum current intensity, and efficiency). These two points allows us determining the coefficients of expressions giving us the maximum current intensity  $I_{max}$  as a function of alternator speed  $N_a$ , and the electrical and mechanical power loss  $P_{a\_loss}$  as a function of speed and current intensity  $I$  delivered:

$$I_{max} = i_0 + i_1 \cdot N_a \quad (5)$$

$$P_{a\_loss} = p_{0a} \cdot N_a + p_{2a} \cdot I^2 \quad (6)$$

Giving us the full load electrical power  $P_{e\_aux}(i)$ , and thus the total  $I$  intensity, and a using ratio  $r_{e\_aux}(i)$  of each (i) electrical auxiliary (fans, lighting, ...), we calculate the whole electrical power and finally the total power  $P_a$  absorbed by the alternator:

$$P_a = \sum r_{e\_aux}(i) \cdot P_{e\_aux}(i) + P_{a\_loss} \quad (7)$$

#### 3.3.2 Air conditioning

Air conditioning (cold air) input characteristics are the fan's electrical power, the speed's ratio (compressor/engine) and the mechanical compressor rated speed  $N_{c0}$  and power  $P_{c0}$ . These last values allows us determining the mechanical power absorbed by the compressor  $P_c$  as a function of compressor speed  $N_c$  and of the using ratio  $r_{cond}$ :

$$P_c = r_{cond} \cdot P_{c0} \cdot N_c / N_{c0} \quad (8)$$

#### 3.3.3 Mechanical fan and other mechanical driven auxiliaries

Mechanical driven auxiliaries input characteristics are two points of the full load curve (engine speed, power absorbed, and mechanical efficiency). These two points allows us determining the coefficients of expressions giving us the maximum available mechanical power  $P_{m\_aux}$  and the power loss  $P_{m\_loss}$  as a function of engine speed  $N_e$ :

$$P_{m\_aux} = m_0 + m_1 \cdot N_e \quad (9)$$

$$P_{m\_loss} = p_{0m} + p_{1m} \cdot N_e \quad (10)$$

The total power  $P_m$  absorbed by the mechanical driven auxiliaries is also determined by the using ratios  $r_{m\_aux}(i)$  of each (i) mechanical auxiliary :

$$P_m = \sum r_{m\_aux}(i) \cdot P_{m\_aux}(i) + P_{m\_loss}(i) \quad (11)$$

### **3.4 Fuel consumption and pollutant emissions**

Input data for each vehicle comprises massics flows of fuel consumption and pollutant emissions at idle, and fuel and pollutants maps (massics flows too) as a function of engine torque and speed. These maps have been established on engine test bench, at steady state under stationnary thermal conditions (warm engine). For a given engine operating point, defined by torque and speed values as calculated by the model, fuel consumption and pollutant emissions flows are determined by a double interpolation (or extrapolation) following the torque and speed on test bench measured values. If the so calculated fuel consumption is zero or less, then the fuel consumption and pollutant emissions are set to zero. With an engine speed control system (acting on fuel injection), the fuel consumption is set to zero when the vehicle is slowing down with a negative engine torque.

## **4 Examples of results**

Four examples demonstrating the influence of the driver, the vehicle use and the road infrastructure were selected. They include two vehicles: a passenger car of Renault Clio type, equipped with a catalyst petrol engine, and a heavy vehicle of tractor-semi trailer type, eg. Renault R340, equipped with a diesel direct injection turbocharged engine.

### **4.1 Driving mode influence: Speed on motorway**

Simulated driving modes for a 65 km motorway trip correspond to the following maximum speeds; gentle driving style : 110 km/h for the passenger car and 70 km/h for the heavy vehicle; average driving style : 140 km/h for the passenger car and 100 km/h for the heavy vehicle; very fast driving style : 180 km/h for the passenger car and 140 km/h for the heavy vehicle (heavy vehicle speed did not actually exceed 127 km/h).

The results shows the significant influence of maximum speed. For example, as regards the passenger car (table 1), fuel consumption can vary by a factor of 2 and CO emission by a factor of 40. It should be noted that NOx emission from the passenger car reached the maximum value for an average driving style and nearly equals zero for a very fast driving style.

With respect to heavy vehicle (table 2), pollutant emissions and fuel consumption vary to a lesser extent as compared to passenger cars. The mass effect is all the more significant since the vehicle weight is high.

Table 1: Fuel consumption and pollutant emissions for a passenger car on motorway, as a function of the driving style. Calculation parameters: half load operated vehicle (total weight 1175 kg) , no auxiliary use.

Driving style	gentle	average	very fast	fast-average (%)
average speed (km/h)	107.8	134.8	155.5	+ 15 %
consumption (l/100 km)	6.2	8.5	12.2	+ 44
CO <sub>2</sub> (g/km)	140	181	204	+ 13
CO (g/km)	1.25	8.33	47.5	+ 470
HC (g/km)	0.06	0.21	1.04	+ 395
NO <sub>x</sub> (g/km)	0.41	1.02	0.07	- 93

Table 2: Fuel consumption and pollutant emissions for a heavy vehicle on motorway, as a function of the driving style. Calculation parameters: half load operated heavy vehicle (total weight: 26750 kg), no auxiliary use.

Driving style	gentle	average	very fast	fast-average (%)
average speed (km/h)	66.1	89.5	97.3	+ 9 %
consumption (l/100 km)	28.4	35.0	38.4	+ 10
CO <sub>2</sub> (g/km)	642	790	853	+ 8
CO (g/km)	2.47	1.77	1.64	- 7
HC (g/km)	1.05	0.91	0.96	+ 5
NO <sub>x</sub> (g/km)	7.76	8.66	8.96	+ 3
particles (g/km)	1.08	0.85	0.73	- 14

## 4.2 Influence of auxiliary use: The air conditioning unit case

About ten years ago, very few upper range European passenger cars were equipped with air conditioning units. At present, air conditioning units are available as a common optional extra, even for lower range vehicles such as Citroen AX or Renault Clio. The conditioning unit operating conditions have a significant impact on fuel consumption and pollutant emissions (table 3), both under road or motorway driving conditions and under urban conditions (European cycle ECE15). It should be noted that the conditioning compressor rated power amounts to about 4 kW, which is considerable. The results recorded were used to compare continuous conditioning unit operating conditions at full load (actually it is usually operated under intermittent conditions), and no use conditions. The car was equipped with other auxiliaries which were not operated (no load auxiliary conditions) thus generating no power consumption, except for the alternator which derived power from the engine shaft, even when it was not supplying any current. The significant impact of the air conditioning unit in urban conditions must be highlighted: fuel



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consumption and pollutant emissions are increased by 30%, and NO<sub>x</sub> emission by a factor of 3.

Table 3: Influence of the air conditioning unit operating conditions (no or with and variation in %) on fuel consumption and pollutant emissions for a passenger car, as a function of the route type. Calculation parameters: half load operated passenger car (total weight 1175 kg), for an average driving style.

	on the motorway			on the road			urban cycle		
	no	with	%	no	with	%	no	with	%
average speed (km/h)	135.1	133.3	-1%	82.6	81.0	-2%	18.7	18.7	0%
consumption (l/100 km)	8.7	9.7	+11	5.8	6.5	+12	8.2	10.6	+29
CO <sub>2</sub> (g/km)	185	196	+ 6	131	148	+13	186	243	+30
CO (g/km)	9.42	16.6	+76	0.91	1.14	+25	0.59	0.78	+32
HC (g/km)	0.24	0.42	+75	0.06	0.06	+ 0	0.10	0.13	+30
NO <sub>x</sub> (g/km)	1.04	0.92	- 12	0.21	0.37	+76	0.03	0.10	+200

### 4.3 Influence of engine operation at stop: idling or switched-off engine

Engine switching-off under interrupted traffic conditions is contemplated in the aim of reducing fuel consumption and pollutant emissions. The impact of such a measure depends on stop duration and on the system used for engine restarting. Potential gains are assessed (tables 4&5) for a passenger car over the ECE15 cycle and for a bus over an INRETS cycle. The gains recorded are significant, in particular with respect to the passenger car: 13% for fuel consumption and 10 to 20% for pollutant emissions.

Table 4: Influence of engine operating conditions at stop on fuel consumption and pollutant emissions for a passenger car in urban conditions. Calculation parameters: equivalent inertia 1130 kg, no auxiliary use.

Operation	idling engine	switched-off engine	variation %
consumption (l/100 km)	8.2	7.1	-13 %
CO <sub>2</sub> (g/km)	186	161	-13
CO (g/km)	0.59	0.47	-20
HC (g/km)	0.10	0.09	-10
NO <sub>x</sub> (g/km)	0.03	0.02	- ? (*)

(\*) insufficient accuracy

The gains to be obtained under real-world conditions are lower than the indicated values. Pollutant emissions and fuel consumption under engine restarting conditions must be taken into account, except if the energy required for engine starting has been previously regenerated (under deceleration conditions for example) and stored.



Table 5: Influence of engine operating conditions at stop on fuel consumption and pollutant emissions for a bus. Calculation parameters: 1/3 load operated bus (total weight 14100 kg), no auxiliary use.

Operation	idling engine	switched-off engine	variation %
consumption (l/100 km)	39.7	38.2	- 4 %
CO <sub>2</sub> (g/km)	1100	1065	- 3
CO (g/km)	6.36	5.92	- 7
HC (g/km)	1.66	1.50	- 10
NO <sub>x</sub> (g/km)	25.3	24.6	- 3
particles (g/km)	0.75	0.67	- 11

#### 4.4 Road gradient influence under steady speed conditions

Fuel consumption and NO<sub>x</sub> emission shows the following variations as a function of the road gradient (figure 1). With respect to the passenger car, at 130 km/h, fuel consumption increases with the road gradient by about 1 litre/100 km per gradient percent. NO<sub>x</sub> emission which is very low under high gradient conditions (- 4% and + 4%) reaches its maximum value for a gradient close to 0.5%. With respect to the heavy vehicle, relative fuel consumption variations are similar to those observed for NO<sub>x</sub> emission. At 100 km/h, fuel consumption and pollutant emissions equal zero for gradients lower than or equal to - 2%. Between - 2% and + 4%, fuel consumption increases with the road gradient at a rate of about 24 litres/100 km per gradient percent. The 42 l/100km value, on a horizontal road at 100 km/h, using the 18th gear, increases to 145 litres/100 for a 4% gradient travelled at 30 km/h using the 10th gear.

## 5 Conclusions

### 5.1 Anticipated applications

SIMULCO has a twofold application: computer-aided design and evaluation. The model is used to assess the impact of a number of variations in the road-vehicle-driver system, in energy consumption, pollutant emissions and vehicle performance. In terms of computer-aided design these applications can be of interest to car makers and motor vehicle equipment manufacturers (impact of technological changes), and to developers of road infrastructures (studies into alternative road projects), etc...In the evaluation field, these applications are aimed at organizations such as ADEME and a number of R&D departments: comparison of various routes, vehicle selection aid, influence of the driving mode, etc.

## 5.2 Development prospects

The first SIMULCO version must be considered temporary; studies must be continued to test good software operating conditions under all possible cases, and to validate the results recorded on the vehicles using a comparative method. Then a number of enhancements will be contemplated: considering vehicle operation under cold engine conditions, leading to excess fuel consumption and pollutant emissions with respect to stabilized thermal conditions; this will require developing the modelling of thermal exchanges to predict temperature changes (cooling water, exhaust gases, etc.). In addition, software adaptations can be anticipated considering specific applications such as assessing the energy-air pollution balance for a road infrastructure, which requires the development of a number of interfaces in terms of software input data and additional calculation in terms of output data.

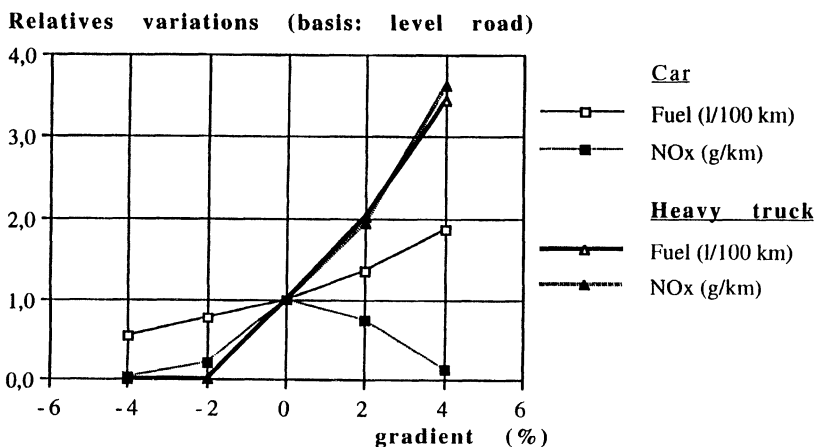


Figure 1: Relative variations in fuel consumption and NOx emission at steady speed as a function of the road gradient (base: horizontal road). Calculation parameters: half load operated passenger car (total weight 1175 kg), no auxiliary use; full load operated heavy vehicle (total weight 40000 kg) , no auxiliary use.

## Reference

Roumégoux, J-P. *Modèle de simulation Simulco, Version 1.0 - Organisation, fonctionnalités, utilisation*, rapport LEN 9501, INRETS-ADEME, 1995.