Simulation methodologies for innovative vehicle drive systems

Van Mierlo Joeri[1] , Maggetto Gaston[2] Van den Bossche Peter[3],

[1,2)]VRIJE UNIVERSITEIT BRUSSEL
Pleinlaan 2, Brussels, Belgium
[3)] ERASMUS HOGESCHOOL BRUSSEL
Nijverheidskaai 170, Brussel, Belgium

1) joeri.van.mierlo@vub.ac.be, Tel: +32 2 629 28 39, Fax: +32 2 629 36 20
2) gmagget@vub.ac.be, Tel: +32 2 629 26 04, Fax: +32 2 629 36 20
3) peter.van.den.bossche@docent.ehb.be, Tel. +32 2 526 00 95, Fax +32 2 520 71 23

***Abstract** - An overview of different methodologies for the simulation of vehicle drive systems will be expounded. The simulation tools are able to assess conventional vehicles with an internal combustion engines as well as advanced vehicles such electrical driven vehicles (EDV), like battery, hybrid and fuel cell electric vehicles. Advantages and drawbacks of the different approaches will be highlighted. Finally comprehensive approach will be proposed.*

Since years ago the automotive industry and several research institutes have developed simulation models to evaluate vehicle performance, fuel consumption and emissions. These models are principally developed for internal combustion engine vehicles. Furthermore several research institutes have developed dedicated simulation models for special applications or case studies of e.g. a specific hybrid dive train.

In this paper an overview will be given of the different approaches. The simulation methodologies will be compared with VSP, Vehicle Simulation Programme, developed at the Vrije Universiteit Brussel [1,2,3,4].

I. SIMULATION OBJECTIVES AND BASIC MODELLING STRATEGY

The last ten years simulation programmes developed for the evaluation of vehicles has known an important progress. Multimedia technology allows now relatively rapid development of highly graphical and interactive user interfaces. Most simulation tools were originally designed to evaluate specific drivetrains and each model has been implemented for its own particular scenario. They were mostly written in text-based languages, with data structures that were difficult to access. Admission to many of these programmes is limited by commercial considerations.

Vehicle simulation software can be developed for different purposes: drive train analysis, evaluation, bench marking, but also new drive train design, dimensioning, development, etc.

The goal of a vehicle simulation programme is to study power flows in drivetrains of vehicles and corresponding component losses, as well as to compare different drivetrain topologies. This comparison can be realised for consumption (fuel and electricity) and emissions (CO_2, HC, NOx, CO, particles, etc.) as well as for performances (acceleration, range, maximum slope, etc.).

The type of vehicle simulation software described in this paper is *longitudinal dynamics simulation*. It is a well-tried and trusted method [5,6,7,8,9] of dividing the drive cycle into a number of time steps and calculating the characteristics of the vehicle at the end of each time interval. The simulator approximates the behaviour of a vehicle in a continuous series of discrete steps (time increment) during each of which the components are assumed to be in steady state. The smaller this step is the higher the accuracy. Longitudinal dynamics simulation serves to calculate the time characteristics of several quantities in a vehicle. Therefore it is a good tool to detect the weak points in the drivetrain and moreover to assess further improvements of single drive components [10].

A. *Forward, backwards, hybrid or closed loop method*

In handling the modelling process it is important that the energy flow in the drive train can have a forward as well as a reverse direction, corresponding with driving or braking the vehicle [11]. Two main modelling methods can be distinguished: the forward and the backward calculation [12].

1) *Forward method*

The forward method, also called cause-effect, engine-to-wheel or rear-to-front method, starts at the setpoint set by a driver (acceleration pedal) or controller. With this setpoint the programme calculates the force acting on the wheels. The speed profile of the vehicle is thus depending on the setpoint. An example of such an approach is HY-ZEM (Hybrid-Zero Emission Mobility) developed by Ricardo Consultants [13].

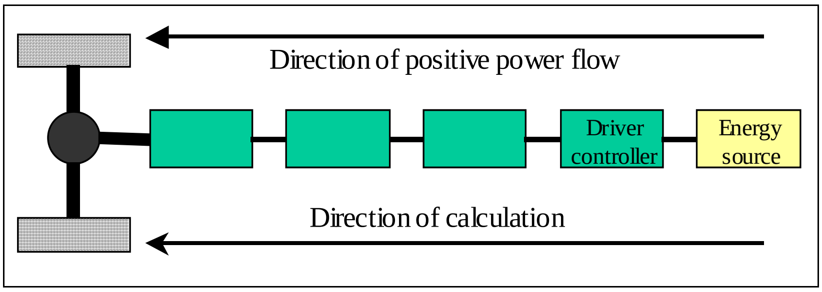

Fig. 1: **Direction of calculation: cause-effect method [1]**

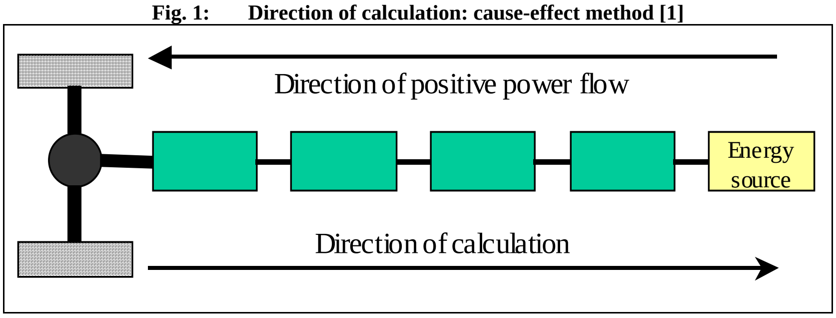

Fig. 2: **Direction of calculation: effect-cause method [1]**

This type of method is principally based on physical equations of drivetrain component behaviour and the dynamic interaction between the different components. This method is interesting to include and evaluate control algorithms (for example PID-controller). Also the behaviour of the driver can be evaluated.
Reproduction of identical speed profiles is not possible without a speed controller. Through feedback loops dynamic behaviour can be incorporated into the model. The forward method requires a very high runtime due to the complex feedback loops and control algorithms. However they allow incorporation of rapid prototyping and hardware in the loop features [14].

2) *Backward method*

The effect-cause method, also called the wheel-to-engine or front-to-rear method operates backwards. With an imposed speed cycle one calculates the forces acting on the wheels and processes backwards through the drivetrain up to the primary energy sources, which is either fuel or electricity.

The basic modelling strategy used in the backwards simulation approach starts from the demand imposed by a required drive cycle, to calculate the properties of the powertrain components as they attempt to meet this demand. For a vehicle simulation typically the following steps are carried out [15].

- The tractive effort required from the vehicle is calculated from the required acceleration and resistive forces such as aerodynamic and gravitational drag.
- This tractive effort is converted by the wheels into the required torque and speed.
- The torque and speed are transformed through the powertrain by the successively intervening system components (such as differential or gearbox) until a prime mover such as an engine or electric motor is reached.
- The prime mover typically uses an efficiency map to predict its energy requirements (f.i. in terms of fuel consumption for an IC engine or power to be drawn from a battery).

This calculation is repeated at each time increment during the speed cycle.

Fig. 3 illustrates the longitudinal calculation algorithm. The left part represents a drive cycle and the right part is the resulting power drawn out the energy source.

As a consequence of the reverse causality the model can be considered to be less physical mathematically sound [14]. The backward method is more a black box approach, allowing modelling each component of the drivetrain as a separated module.

A component model can be as sophisticated or simple as the programmer’s time and budget permits. This approach allows the integration of look-up tables, efficiency maps, etc without requiring modelling all physical phenomena. Backward methods have mostly a higher modularity and are especially characterised by fast software development and much faster simulation runtimes.

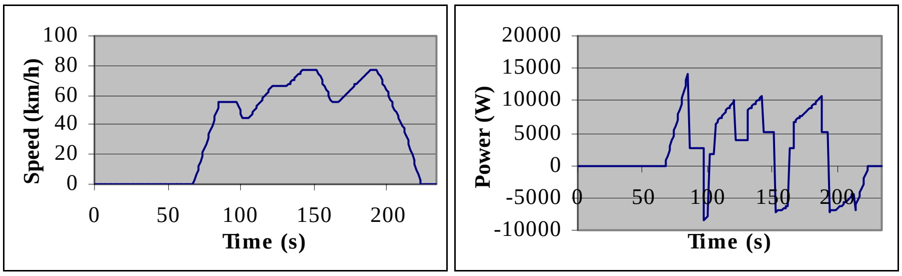

Fig. 3: Longitudinal dynamics simulation (e.g. Japan 15 reference cycle)

An example of a backward approach is Simplev (Simple Electric Vehicle Simulation) Model, developed by Idaho National Engineering and Environmental Laboratories (INEEL) beginning in 1990 [16].

B. *Component operating boundary*

Each system or component of the drive train is identified by its operating limits. While simulating the behaviour of a drivetrain performing a chosen cycle it is possible that one of the components cannot satisfy the demanded requirements. For instance a motor can reach its maximum torque or can come in overspeed, a battery or inverter can be overloaded.

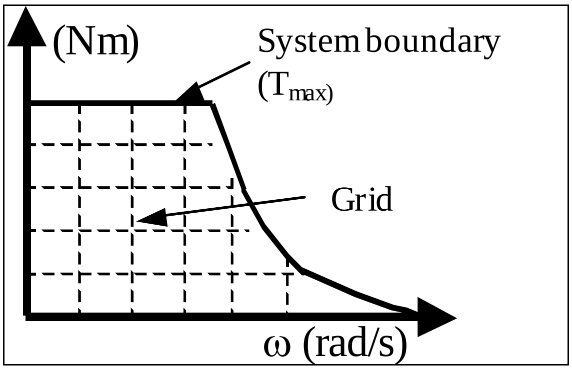

Fig. 4: System boundary

Most simulation programmes do not pay much attention to these boundaries. Some of them use algorithms to limit the actual performance when the desired performance (torque, speed, power) exceeds the maximum available performance in the system. However the results are less accurate, due to the fact that e.g. the efficiency of downstream[1] components is calculated with parameters that do not take into account the available best performances of the upstream components. If a component is not able to supply the value required by the previous downstream component the operating point of the requested component should be corrected. If component characteristics vary largely over the operating regime, then ignoring the change of operating point could impose a large error on the results. Dynamic interaction between components should be taken into account in modern vehicle simulations.

3) *Combined backward/forward method*

Some approaches (e.g. ADVISOR [17,18]) make use of combined backward/forward algorithms. These kinds of hybrid methodologies have two models for each component of the drivetrain: a forward and a backward model.

The methodology first simulates backwards like in the effect-cause method. When an operating boundary of a component of the drivetrain is reach the model limits the output (in the direction of upstream components) parameters and simulates backwards to the primary energy sources. Next it simulates forwards starting from the energy sources towards the wheels making use of forward component models and its efficiency parameters calculated in the backward model, inclusive the operating limits occurred during the backward simulation process. An ADVIDSOR example is illustrated by Fig. 6

Such combined backward/forward methods have a faster runtime then forward facing models, but a slower runtime than backward methods. The main drawback is the necessary to have two different models (as illustrated by Fig. 7) for the same component leading to a large programming overhead for introduction of new components. The top of Fig. 7 represents the backwards model and the bottom the forward model.

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[1] Upstream components are components closer to the energy source. Downstream components are components closer to the wheels.

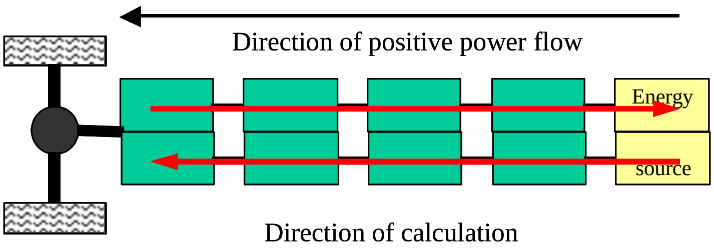

Fig. 5: **Direction of calculation: Combined backward/forward method**

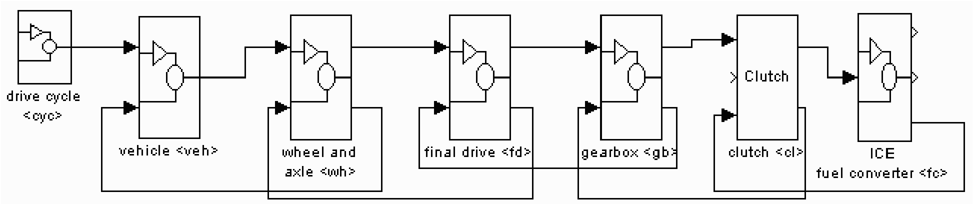

Fig. 6: **Example of ADVISOR combined backward/forward method**

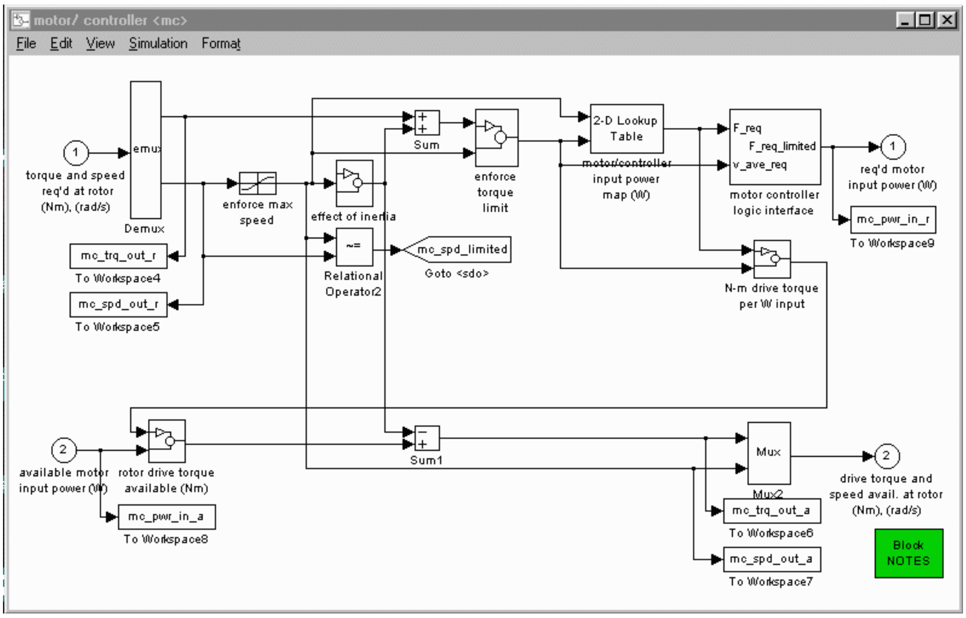

Fig. 7: **Example of ADVISOR double motor model [19]**

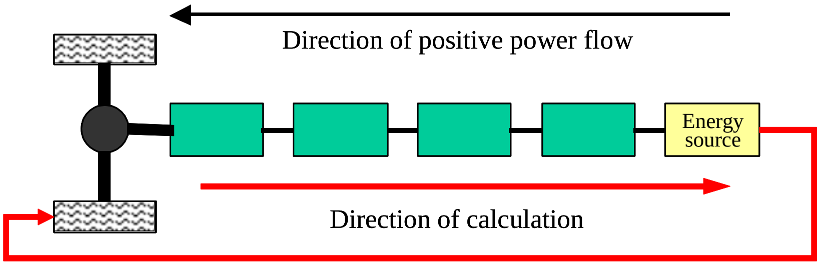

Fig. 8: **Direction of calculation: Closed loop iterative backward facing method**

4) *Closed loop iterative backward facing method*

An other approach able to consider component operating limits is a backward facing method including a closed loop iterative solution. The limiting components communicate their limit back to the feedback component [20].

Such a feedback loop is implemented in the VSP, Vehicle Simulation programme, software, developed by the Vrije Universiteit Brussel. The iterative process in VSP allows high calculation speed and high simulation accuracy. VSP is a closed loop simulation with a unique comprehensive and standardized iteration algorithm dedicated for the flexible implantation of different kind of conventional and hybrid drivetrain topologies and powerflow control algorithms taking into account each component operating boundaries or desired operating conditions.

To ensure that all components operate within defined boundaries, corresponding to loading limitations, the iterative algorithm acts on the requested acceleration of the vehicle. An acceleration reduction (AR) is used to iterate towards the possible vehicle speed domain. These AR's are calculated in each component in function of its maximum performance [3].

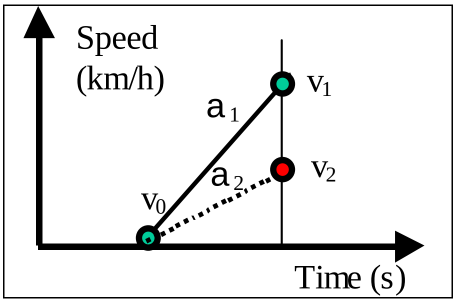

Fig. 9: **Possible speed calculation**

Fig. 9 illustrates the reduction of the required acceleration a_1, corresponding to a desired velocity v_1 into the possible acceleration a_2, resulting in a possible velocity v_2.

Principally this approach can be explained as follows [3]. During the iteration process (at a certain time increment) the vehicle velocity will remain constant, which corresponds to a constant resistive torque. When the required torque is higher than the maximum torque, the iteration process will act on the acceleration to reduce the acceleration torque Ta, which is proportional to the acceleration a. When the required torque exceeds the maximum torque T_{max} the AR will be calculated by taking the ratio between the part of maximum torque that can be effectively used for acceleration (T_{max} - T_r) and the required acceleration torque (T_a) (equation (1)).

$$AR = \frac{T_{\max} - T_r}{T_a} \qquad (1)$$

$$a_{pos} = a_{req}.AR \qquad (2)$$

Complementary to the basic backward approach, the implemented iterative algorithm leads also to forward approach features, like simulating driver behaviour and control algorithms.

During the simulation the desired speed can be set to a maximum value that never will be reached by the drivetrain. In this way an acceleration reduction is always calculated. In a special model for the driver the acceleration reduction (AR) is implemented in the same way as it is done in all other components of the drivetrain. In the driver model a setpoint for power, speed or torque is evaluated as if it would be a maximum limit or boundary. Due to the iteration process the programme will calculate the speed corresponding with this setpoint.

In the graph, Fig. 10, the controller algorithm is demonstrated. In this case, with same programme using its special iteration algorithm, one can change in real time a setpoint for the torque (dashed line). This setting is coming for instance from an acceleration pedal. The actual speed is following this setpoint (straight line).

In the case of hybrid vehicles the problem of components boundaries becomes even more complex, since it is possible to reduce vehicle acceleration as well as to change the power management strategy of the drivetrain.

In VSP the powerflow control strategy of hybrid drivetrains is implemented with the same iteration process as for calculating the vehicles performance. This allows e.g. to use an engine model in a series hybrid drive train to drive a generator as well as to use this same model in a diesel vehicle to drive the wheels without any reprogramming requirements. In VSP the power distribution between the several mechanical shafts or energy sources is controlled with the help of a Power Distribution Factor (PDF).

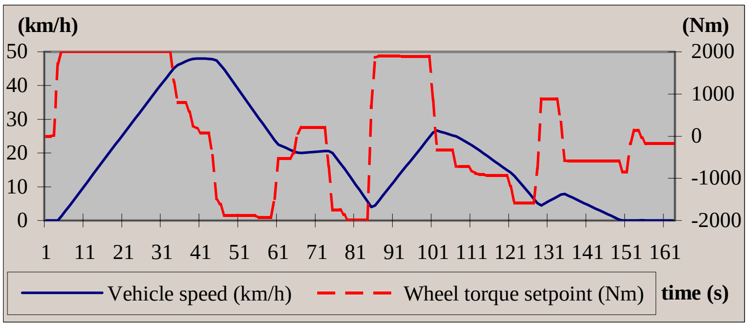

Fig. 10: **Demonstration of the controller algorithm**

When exceeding the operating boundaries, instead of using an acceleration reduction, a Power Reduction (PR) will be introduced to regulate the power split (the PDF) in the different components that are in charge of the power division in the hybrid drivetrain (e.g. DC-bus controller). This results in controlling the power management with an overall control with the help of the Vehicle Control System (VCS) unit that defines the total power management and a local action acting on the level of drive train components characteristics. Opposite to the Acceleration Reduction the Power Reduction is not used to change the vehicle acceleration performance, but to control the powerflow in the hybrid drivetrain. In more complex hybrid structures a second PDF and Power Reduction can be necessary: for instance in a series hybrid vehicle with a traction battery (AR), a generator (PR1) and a Flywheel (PR2)

In the case of hybrid vehicles the iteration process is much more complex: the PR can change the power split or the AR can reduce the acceleration. Due to the fact that several reductions can occur within one drivetrain an intelligent iteration sequence is required. Hence a hierarchy of different hybrid control strategies is developed and inherently implemented in the software. This means that the control algorithm is not a separate block of the simulation programme (like this is mostly in forward facing approaches), but makes part of the different components on which it has an influence. This is necessary because there is a high degree of interaction between components models, particularly with respect to operation limits, and powerflow control strategy.

II.HOW TO DESCRIBE THE FORCES ACTING ON THE VEHICLE ?

In this second chapter the main forces acting on the vehicle will be described. Using primary parameters for vehicle's body shell and chassis (e.g. cumulative mass of powertrain components, payload, body design characteristics, etc.) and route parameters (gradient, wind velocity, etc.), the longitudinal dynamics simulations calculate the forces acting on the vehicle.

The tractive force (Ftrac) acting via the tyre contact surface of the driven wheels is determined by the engine or motor torque and by the gear ratios and inertias of the driveline

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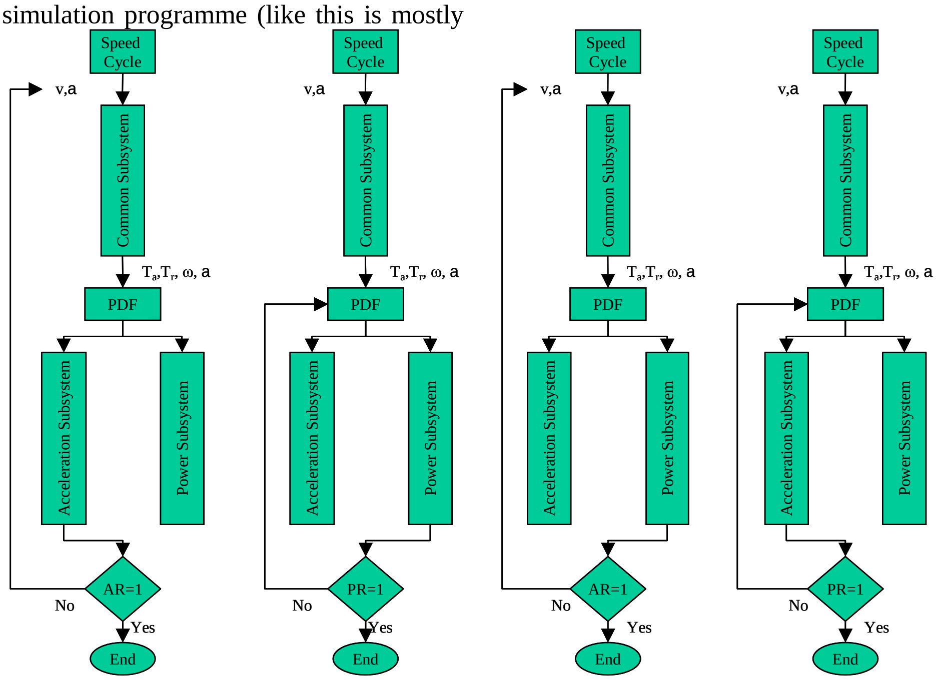


Fig. 11: **AR and PR of acceleration subsystem or power subsystem**

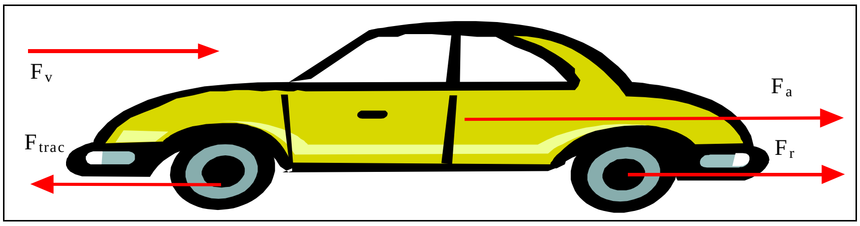


Fig. 12: **Forces acting on the vehicle**

For level driving, the resistive forces acting in the direction of motion are the components rolling resistance (Fr) and air resistance (Fv). If the propulsion forces are not in equilibrium with the driving resistance at the considered steady speed, vehicle acceleration (a) or braking occurs, producing an inertial force (Fa), which acts at the vehicle centre of gravity.

When driving uphill (road inclination) or when there is a head wind (velocity v_w) additional forces are acting on the vehicle. The total resistive force can be expressed with equation (3).

$$F_R = \frac{1}{2}.\rho.S.C_x\left(\frac{v_{cur}+v_w}{3,6}\right)^2 + M.g.f_r.\cos(\alpha) + M.g.\sin(\alpha) \qquad (3)$$

For accelerating the vehicle an additional force, corresponding to Newton's law of motion (4), has to be delivered by the traction system.

$$F_a = M.a_v \qquad (4)$$

In most simulation models the supplementary force corresponding to the inertia of the different rotating components is taken into account by adding a fictive mass to the total mass. In VSP however this inertia is taken into account in each individual drive train component model resulting in an enhanced modularity of the programme and a higher accuracy.

III. Component Characteristics Modelling

In the third chapter different approaches to develop components models and databases are described.

While reading the literature concerning simulation programmes the same remark systematically came back: 'due to lack of information', 'data is hard to find', 'the availability of the required information to implement is not a trivial point' and 'parameters will not be easily at disposal'. It is clear that one of the problems of vehicle simulation software is the availability of data.

A component model can be as sophisticated or simple as the programmer's time and budget permits. Different parameters and even different modelling methods can be used to describe a component.

Some approaches allow a flexible and modular programming structure, resulting in the abilities of co-simulation using in-house developed or commercial software add-ons.

Since the general aim of a simulation programme is to know the energy consumption of a vehicle, all parameters, which have an influence on this energy consumption, have to be defined. With the forces acting on the vehicle corresponds a certain power level. The battery or fuel does not only need to deliver this power, but also the losses of the different components of the drivetrain. A good description of these losses is thus essential. The different parameters defining these losses should be calculated. The accuracy of the model will define the accuracy of the overall energy consumption.

5) Efficiency covering the whole working field

Some models use a constant value for the efficiency of a component, generally corresponding to its maximum value. They multiply the different efficiencies to describe the overall efficiency. This approach is a very rough estimation and corresponds mostly to a very optimistic energy consumption. This is also the reason why one can find in literature so many different results on the energy comparison of different drivetrain. A more accurate solution would be to simulate the behaviour taking into account the whole map of working points.

6) Analytical models

The components (electric motor, chopper, charger, etc) can be defined by physical equations and equivalent circuit (analytical models) or by measured efficiency characteristics (statistical models).

Physical laws and equivalent circuits can describe the characteristics of a component. Such theoretical models can be used for different motors or inverters, only the component parameters are to be changed. However the component parameters are not always available. If they are received from the manufacturer, they are generally measured under laboratory conditions (sinusoidal voltage, standard measuring points, etc). They can be fine-tuned while calibrating the entire vehicle model.

Fig. 13 shows the interface of the VSP model of an induction motor. It is a backward model in which the motor slip is estimated on the basis of an analytical model. With an internal iterative loop the slip is found in such a way that the theoretical electromagnetic torque corresponds with the required torque input.

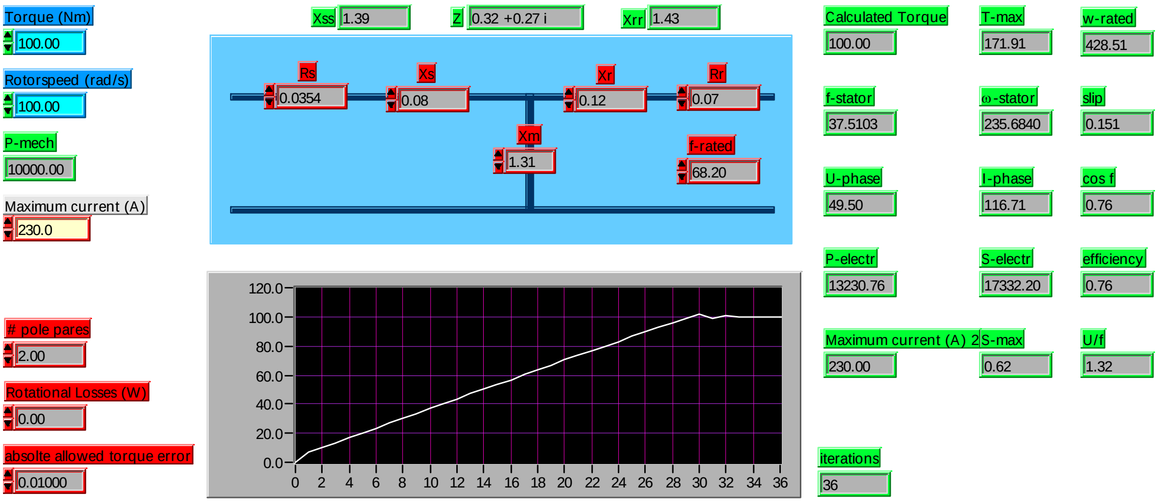

Torque (Nm) 100.00
Rotorspeed (rad/s) 100.00
P-mech 10000.00
Maximum current (A) 230.0
pole pares 2.00
Rotational Losses (W) 0.00
absolte allowed torque error 0.01000
Xss 1.39
Z 0.32 +0.27 i
Xrr 1.43
Rs 0.0354
Xs 0.08
Xr 0.12
Rr 0.07
Xm 1.31
f-rated 68.20
Calculated Torque 100.00
T-max 171.91
w-rated 428.51
f-stator 37.5103
ω-stator 235.6840
slip 0.151
U-phase 49.50
I-phase 116.71
cos f 0.76
P-electr 13230.76
S-electr 17332.20
efficiency 0.76
Maximum current (A) 2 230.00
S-max 0.62
U/f 1.32
iterations 36

Fig. 13: Example of analytical model of an induction motor

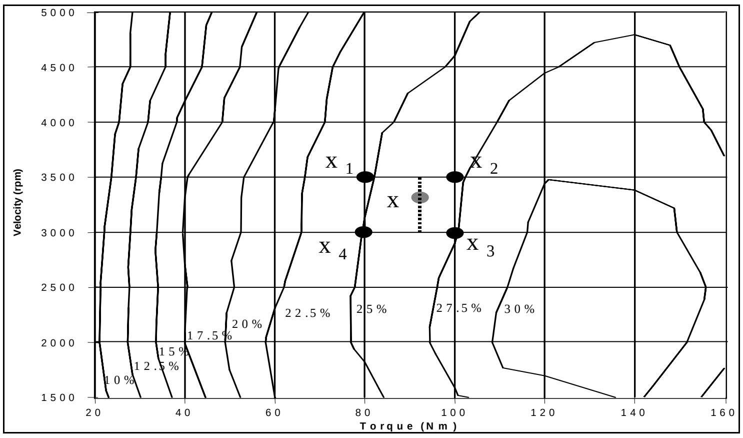


Fig. 14: Bilinear interpolation of a two-dimensional efficiency curve

7) Statistical models

On the basis of numerous measurements one can calculate statistical models for the components. These measured data can be stored in one or two dimensional look-up tables or arrays. Parameters can be calculated by bilinear interpolations on a network of two dimensional efficiency curves. The precision depends on the density of the points of the map. This approach is explained by example of Fig. 14. The considered parameters can be emissions, fuel consumption, voltage, efficiency, etc.

A parameter (efficiency, power, etc) can be defined e.g. in function of torque and speed, or current and voltage. Other models can be a one-dimensional table of only one parameter, e.g. the maximum torque in function of speed.

In some cases it can be necessary to have a multiple dimensional function. In this later case a interpolation in a look-up table will become very complex. The use of statistical formulae will be required. Using statistical equations has the benefit to use less memory and to allow a faster simulation. It is thus recommended to transform the look-up table into statistical formulae.

Statistical piecewise models, derived out of the measurements data, have the advantage of being closer to the reality then theoretical models, and thus are mainly used, as an accurate input, in the database of VSP.

The more parameters used to define these statistical equations or look-up tables, the more complicate the simulation programme becomes and the slower the programme will run. It is thus advisable to determine those parameters, which have an important influence on the required end-result (the energy consumption).

8) Steady state or transient models

Especially for internal combustion engines one could ask the question if steady state maps are adequate enough to describe the behaviour of the engine.

Within the European project DECADE a vehicle emission level simulation tool (VETESS) was developed for the simulation of fuel consumption and emissions of vehicles in real traffic transient operation conditions [**21**]. Based on three independent variables from the experimental procedure, namely engine speed, engine torque and change in torque, four parameters are defined for each pollutant (see **Fig. 15**):

- the steady state emission rate;
- the jump fraction;
- the time constant;
- the transient emissions.

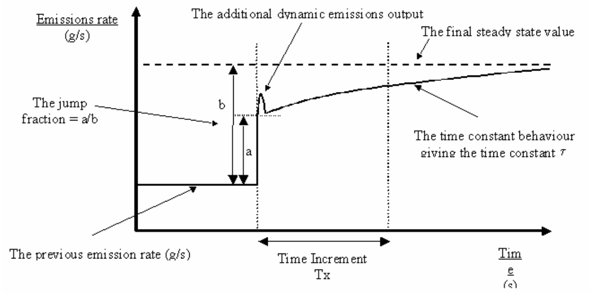


Fig. 15: Transient emissions [22]

The steady state emission rate is the rate at which the pollutant is produced as the engine runs under steady state, i.e. at constant speed and torque. The jump fraction characterizes the fraction by which the emission rate increases or decreases after a change in torque not taking into account the dynamic behaviour. The time constant is a measure for the time required to approach the steady state emission value after a torque change. The transient emission is a discreet amount of additional pollutant generated after the change of torque [22].

Comparison between emissions measured in real traffic and simulated data gives an accuracy within 10 % to 20 % for NOx and particulate matter (PM), which are the main emissions of a diesel engine. For gasoline vehicles the model is less accurate. Differences up to 100% between measured and simulated CO emissions are found.

The transient corrections which can be derived with the VETESS simulation tool do not affect the emission results for NOX for diesel vehicles. However, for particulate matter, CO and HC, the calculated emissions are found to increase with 15 % to 200 % depending on the pollutant and the specific driving conditions [22].

Developing such dynamic engine models are timing consuming and the question is if this is worthwhile when remarking that the model error is mostly of the same magnitude as the transient correction (see paragraph above).

IV. The Vehicle Simulation Programme, VSP

In this forth and final chapter the main features of VSP will be highlighted.

The flow chart of Fig. 16 gives an overview of the software. One can recognise two different simulation loops: one that defines each step a new required velocity in function of the chosen speed cycle (the backward approach) and another that contains an iteration algorithm to define the possible vehicle performance in the case the vehicle is not able to follow the imposed speed cycle (the closed loop iterative method). Additionally there is a very small loop that is used to temporary halt the simulation process.

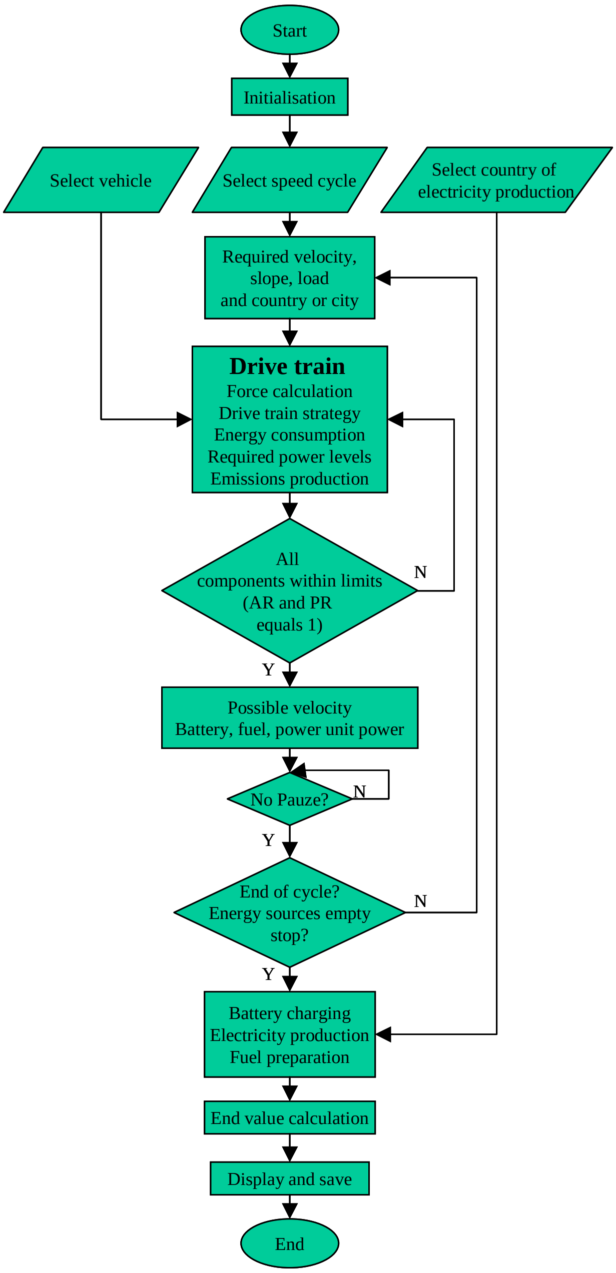
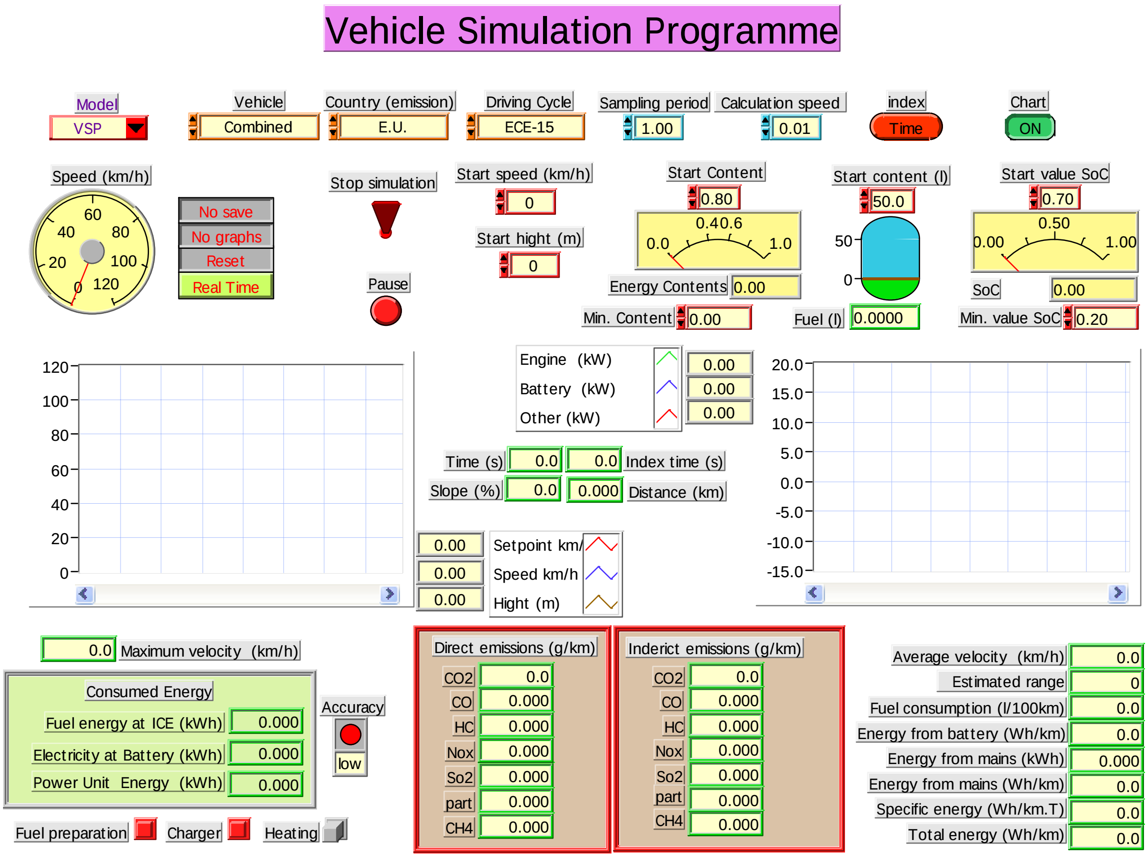


Fig. 16: Flow chart of Vehicle Simulation Programme


Vehicle Simulation Programme

Model VSP
Vehicle Combined
Country (emission) E.U.
Driving Cycle ECE-15
Sampling period 1.00
Calculation speed 0.01
index Time
Chart ON
Start speed (km/h) 0
Start hight (m) 0
Start Content 0.80
Energy Contents 0.00
Min. Content 0.00
Start content (l) 50.0
Fuel (l) 0.0000
Start value SoC 0.70
SoC 0.00
Min. value SoC 0.20
Engine (kW) 0.00
Battery (kW) 0.00
Other (kW) 0.00
Time (s) 0.0
Index time (s) 0.0
Slope (%) 0.0
Distance (km) 0.000
Setpoint km/ 0.00
Speed km/h 0.00
Hight (m) 0.00
Maximum velocity (km/h) 0.0

Consumed Energy
Fuel energy at ICE (kWh) 0.000
Electricity at Battery (kWh) 0.000
Power Unit Energy (kWh) 0.000
Accuracy low

Direct emissions (g/km)
CO2 0.0
CO 0.000
HC 0.000
Nox 0.000
So2 0.000
part 0.000
CH4 0.000

Inderict emissions (g/km)
CO2 0.0
CO 0.000
HC 0.000
Nox 0.000
So2 0.000
part 0.000
CH4 0.000

Average velocity (km/h) 0.0
Estimated range 0
Fuel consumption (l/100km) 0.0
Energy from battery (Wh/km) 0.0
Energy from mains (kWh) 0.000
Energy from mains (Wh/km) 0.0
Specific energy (Wh/km.T) 0.0
Total energy (Wh/km) 0.0

Fig. 17 Main user interface of VSP

After the initialisation phase the required velocity of the vehicle is defined by the speed cycle that the user has selected on the main user interface. The model of this speed cycle contains also the load of the vehicle, the slope of the road and whether or not the vehicle is driving in the city (centre). Based on these parameters and the characteristics and weight of the selected vehicle body and of the wheels, the forces acting on the vehicle can be calculated. In function of the powerflow in the drivetrain (the hybrid drivetrain power strategy), the component losses and the energy consumption from the battery, fuel tank or other energy source is processed. In the case of non-pure electric vehicles the direct tailpipe emissions are simulated too.

When the end of the drivetrain is reached, this means one has processed all calculations from the wheels to the energy sources, the iteration algorithm checks if all components were able to deliver the required torque, speed, power, current, etc. If one or more components were out of data range, the required acceleration is adapted (via the acceleration reduction) and the drivetrain is simulated again until all components are within limits.

The power levels of the energy sources are visualised in the main user interface (Fig. 17) and the next required speed step is used to calculate the forces acting on the vehicle. If the speed cycle is completely simulated or all energy sources are empty or the user stops the simulation, the programme will go to the last part. In this part the battery will be recharged, the corresponding background emissions are calculated and possibly the additional energy consumption due to fuel refinery is defined. The end results are displayed and if wanted saved on hard disc.

VSP is developed in a graphical languages LabVIEW™. The programming structure of LabVIEW™ lends itself to a top down approach. The programme, VSP, therefore can be seen as a three level structure.

- The top level is the main programme of which the user interface is described in Fig. 17. This level contains the icons of the subprogrammes for the different vehicles and also for drive cycles, electricity production, etc.
- The second level is consequently the level of the different drivetrains. Each drivetrain is composed of different vehicle components. The manner these components are connected together will represent the topology of the drivetrain. This second level represents in fact the energy flow and conversion through the vehicle drivetrain. Each component is modelled as a separate subprogramme (see Fig. 18).
- The third level is the level of the different component models.

C. *Combined hybrid drivetrain*

As an example of the methodology a model of a combined hybrid is illustrated. The combined hybrid drivetrain, like in the Toyota Prius, is one of the most complex models of the Vehicle Simulation Programme. It combines a series hybrid drivetrain with a parallel hybrid drivetrain.

Fig. 18 illustrates the block diagram (LabVIEW programming language) containing the actual iteration loop and the different components of the combined hybrid drivetrain. The input parameters (actual speed, number of passengers, slope and required speed) are coming from the main programme. The drivetrain is built up with the subprogrammes for the drivetrain components. One can recognise first the elements of the common subsystem: the body (1), the wheels (2) and the differential (3). Besides one can find the torque splitter (toothed gear) (4) that divides the required traction torque between the planetary gear (5) on one side and electric motor (6), inverter (7) and battery (8) on the other side. The torque division is controlled via the Power Distribution Factor 1 (PDF1).

Additionally the planetary gear introduces a second degree of freedom in comparison with a parallel hybrid drive. The planetary gear set divides the engine (9) driving torque into two torques: one that drives the wheels, via the torque splitter, and the other that drives a generator (10). The electrical energy, produced by the generator, is re-converted into mechanical energy through the electric motor or stored in the battery. Within the iteration process a second PDF2 will control the power path of the generator. This PDF2 is not entirely independent of PDF1, due to the fact that the generator power is dependent from the power division in the torque splitter (see Fig. 18). The generator velocity setting determines the speed of the engine. Hence the working of the internal combustion engine can be fully controlled independently from the required traction force and vehicle velocity.

Finely one can also find the model for the auxiliaries (11) and the model controlling the iteration process (12). In this last subprogramme the acceleration and PDF's are controlled via the Acceleration Reduction (AR) factor and/or the Power Reduction (PR) factors.

D. *Validation*

As for each simulation software a validation process is necessary. The example chosen here is an on-road driven ECE cycle performed by an electric passenger car. This passenger car is equipped with a DC separated excited motor and a NiCd battery. Since the real speed can differ from the theoretical ECE speed, the speed is measured during driving and used as input file for VSP. Hence the same cycle is simulated as the one driven on road. The comparison of both simulated and measured parameters demonstrates a good correlation (see Table 1). The relative error is less than 5 % [3].

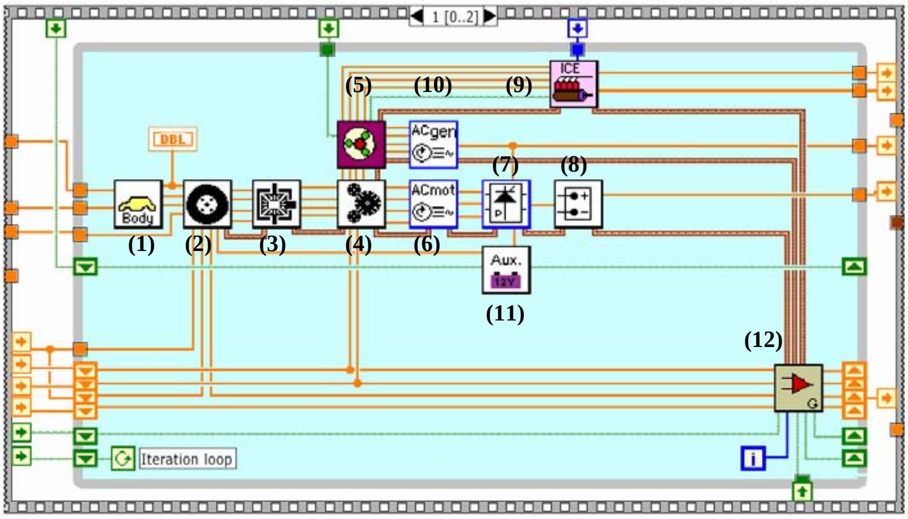


Fig. 18: Block diagramme of the Combined Hybrid Electric Vehicle model

TABLE 1: SPEED CYCLE: SIMULATION VS. MEASUREMENTS

	Measured	Simulation	ECE-15
Ah discharged	1.52	1.46	1.53
Ah charged	0.19	0.18	0.19
Tot Ah	1.33	1.28	1.34
% recuperation	12.35	12.20	12.71

One of the most difficult experiments to simulate is an acceleration test. Contrary to a comparison based on a pre-defined speed cycle, one is not performing a straightforward step-by-step calculation, but for each point the simulation has to iterate towards the possible working point. A little error in the beginning can, due to integration, result in a large deviation at the end of the simulation.

In Fig. 19 one can find the measured speed compared against the simulation results when the acceleration of the vehicle is at its maximum. The boundaries of the motor are the maximum speed and torque. This motor was current controlled. A current limit (as a function of the revolutions per minute) is introduced too. Simulated values are marked with '-s' and measured values with '-m'. The good correlation between the measurement and the simulation demonstrates the performance of the iteration algorithm. An average deviation of 2% is found.

In Fig. 20 one can see the deceleration test. During this test only regenerative braking by the motor was performed, without using any mechanical brakes. The graph of Fig. 21 compares the DC motor current (Imot) and DC voltage (Umot) for the acceleration and deceleration test. The little deviation in current can be explained by a possible minor wind and road inclination during the on-road measurement. The graph of Fig. 22 shows, for the same acceleration test, the variations in current (Ibat) and voltage (Ubat) of the battery.

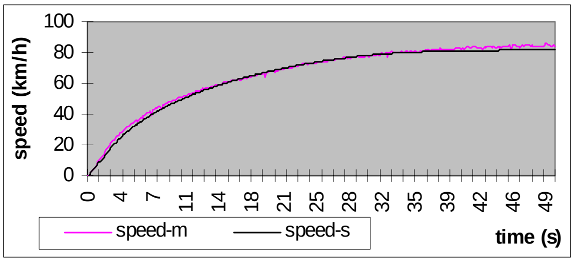


Fig. 19: Acceleration simulation vs. measurement

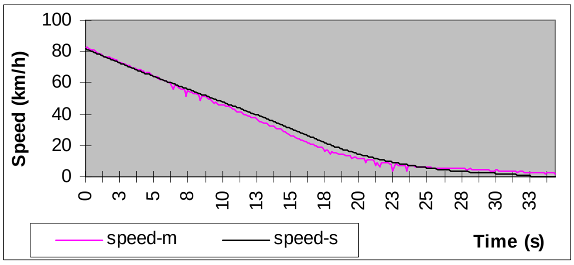


Fig. 20: Deceleration simulation vs. measurement

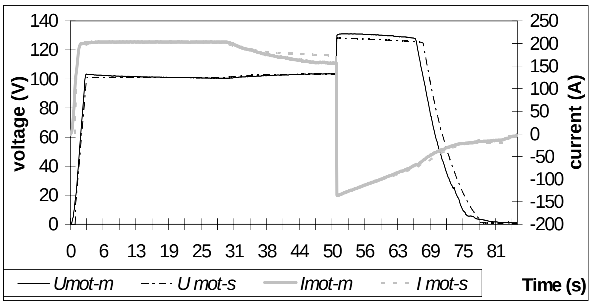


Fig. 21: DC Motor current and voltage comparison

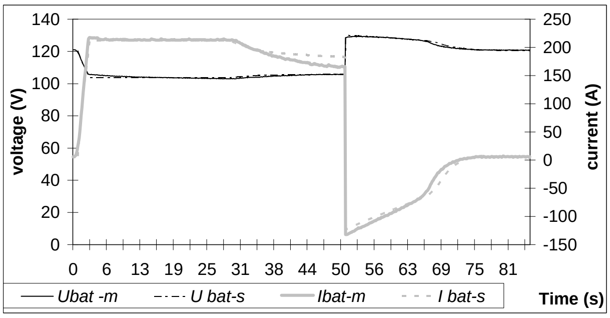


Fig. 22: Battery voltage and current

V. Conclusions

Since years ago the automotive industry and several research institutes have developed simulation models to evaluate vehicle performance, fuel consumption and emissions.

Engine-to-wheel or forward vehicle simulation programmes contain several feed back loops with makes them sometimes slower.

Most Wheel-to-Engine or backward simulation programmes do no have an iteration algorithm. Some of them use algorithms to limit the actual performance when the desired performance (torque, speed, power) exceeds the maximum available performance in the system. However as stated in this paper, without a closed loop iteration process, the results are less accurate, due to the fact that e.g. the efficiency of downstream components is calculated with parameters that do not take into account the available best performances of the upstream components. Additionally hybrid backward/forward algorithms require two models for the same component.

In this paper a comprehensive iteration algorithm is described allowing to combine backward and forward simulation techniques. The algorithm is able to handle all kind of working limits of all types of components in different types of drive trains.

Furthermore complex power management strategies in hybrid vehicles can be evaluated. The unique iteration algorithm is also dedicated for the flexible implantation of different kind of hybrid drivetrain topologies and powerflow control algorithms taking into account the component operating boundaries or desired operating conditions. VSP has an in-depth worked out programme modularity in which almost all parameters are only accessible in the module of the component itself. VSP has a flexible database structure, integrated in the component models, allowing an easy implementation of different kind of component data in the form of look-up table, maps, theoretical equations, or empirical formula, in function of the available data.

Nevertheless the approach is principally based on a backward approach, due to the iteration algorithm the simulation is also able to mimic the actual driving of the vehicle with a driver and controllers, like it is done in forward simulation programmes.

A good correlation between measurements and simulation results is found, which demonstrates the high simulation accuracy.
To conclude it should be noticed that once all components are able to deliver the required power and follow the speed cycle, no iteration is required and fast simulation is possible. When the desired performance (torque, speed, power) exceeds the maximum available performance in the system, the iteration algorithm allows calculating this maximum performance with a very high accuracy and without double modelling.

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