Models of Automotive Transmissions for Fuel Consumption Studies

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Abstract: In the last years more and more transmission types are developed in order to respond to the ever-increasing demands on fuel economy and environment protection. Also previously standard configurations are optimized in order to meet the new requirements.

To choose an appropriate configuration in respect with the desired application and to correctly dimensioning it is a difficult task for which the numerical simulation is a very useful tool. In consequence models of transmissions suitable for fuel consumption studies are necessary in order to have a rapid evaluation of envisaged solutions. Nevertheless, the comfort is a key issue that cannot be ignored and the level of modelling must allow a basic comfort evaluation.

This paper aims to show typical modelling and simulation issues that occur in automotive transmissions studies. The models are compared using the 1D multi-domain simulation platform LMS Imagine.Lab AMESim.

Keywords: Transmission models, comfort, LMS Imagine.Lab

1. Introduction

Simulation has become a common practice in automotive developments. The major benefit is the reduction of time and cost during the system design and development stage.

A task for which the simulation is well fitted is that of matching engine/transmission components and determining the control strategies in order to provide maximum fuel economy while satisfying the emission and comfort constrains.

Models of transmissions suitable for fuel consumption studies are necessary in order to have a rapid evaluation of envisaged solutions. These are in general simple global models used to introduce the transmission ratios and efficiency. However, more detailed models are needed for better estimation of the transmission losses. Furthermore the comfort is a key issue that cannot be ignored and so the level of modelling must allow a basic comfort evaluation.

The response of these problems is the use of physical modelling of the transmissions.

This paper describes the use of both global and physical mechanical transmission models for fuel consumption and comfort studies.

2. Methods and tools

Three methods are employed for fuel consumption studies [5]:

- Average operating point;
- Quasistatic simulation;
- Dynamic simulation.

These methods are usually applied using numerical computer tools.

2.1 Average operating point

This method is adequate for first preliminary estimation of fuel consumption. A single representative average operating point is determined and the fuel consumption of the propulsion system is computed at that regime.

The test cycle must be specified a priori. So, the mean mechanical wheel power is estimated and then used to “work backwards” through the powertrain. For this approach the transmission is considered by the mean efficiency and the mean gear ratio.

2.2 Quasistatic simulation

In quasistatic simulation, the input variables are the vehicle speed v and acceleration a, the road slope p and the wind velocity v_w. The needed driving force to follow the chosen profile is then computed. The vehicle is assumed to run at constant speed, acceleration and slope for a short time period h. The losses of the powertrain are considered by a power balance and the fuel consumption is calculated.

An advantage of this simulation is the possibility to use variable efficiency for the transmission. This is important for fuel consumption studies due to the high variation of the transmission input torque and speed during a driving cycle (figure 1). The results are obtained with a complex quasistatic powertrain model for fuel consumption [1], [2].

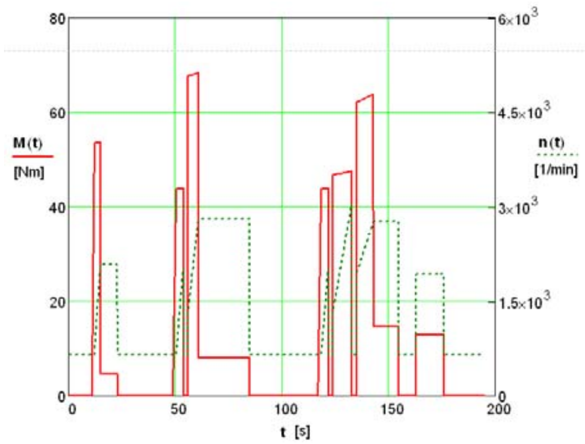


Figure 1: Variation of the transmission input torque and speed during a city driving cycle**.**

In this model the transmission efficiency is considered using a semi-empirical equation [7]. The efficiency curves obtained using these equations are shown in figure 2.

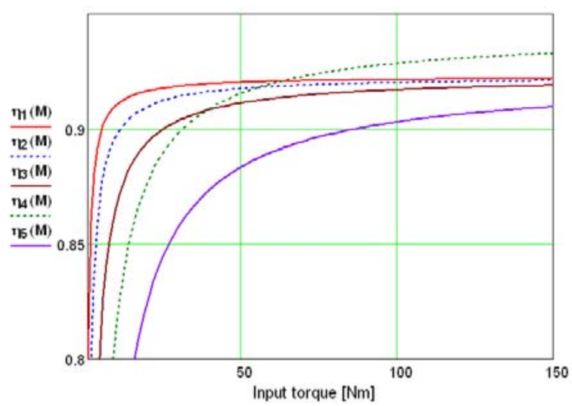


Figure 2: Gearbox efficiency

The model can be used to study the influences of key parameters (vehicle mass, engine efficiency etc) on fuel consumption and also o estimate the impact of different methods for fuel economy improvement.
Figure 3 shows the influence of three parameters combination (engine efficiency, vehicle weight reduction and regenerative braking) in connection with EP and ACEA targets for a compact-class passenger car.

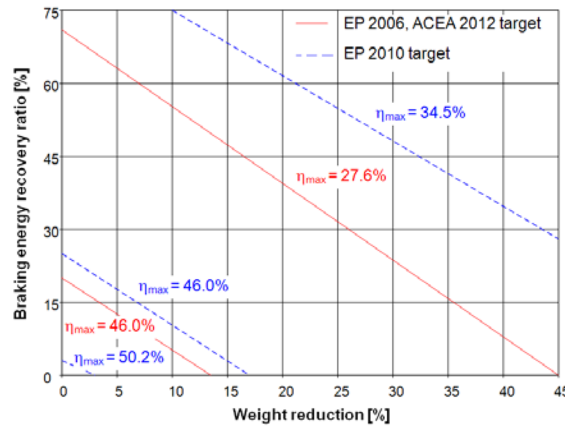


Figure 3: Possible combinations to met the CO2 targets

2.3 Dynamic simulation

The dynamic approach is based on a “correct” mathematical description of the system. The powertrain model is formulated using sets of ordinary differential equation on the state-space form but many others descriptions are possible (partial differential equations or algebraic differential equations). In this way many dynamic effects in powertrain can be descried. While some of these effects are relevant for fuel consumption estimation others are not. The majority of the relevant effects for fuel consumption are relatively slow. The fast effects are usually significant for the analysis of comfort, drivability and pollutant emission.

2.4 Software tools

Most non-trivial problems of system synthesis and analysis can only be solved using numerical approaches. Numerical computer tools are used to resolve these problems. Two approaches are used:

- Use the basic function of general-purpose software packages and develop dedicated scripts, tool-boxes or software packages;
- Use independent dedicated software packages.

The usual choice for a general-purpose software package used as support is the Matlab/Simulink environment.
Some of the dedicated software packages for vehicle performance, comfort and fuel consumption studies are: LMS Imagine.Lab (AMESim), ADVISOR, Dymola, Easy5, SimulationX.

AMESim is a complete virtual system analysis platform that allows users to design multi-domain systems. The package combines strong numerical capabilities with advanced tools to study the static/dynamic behaviour of any component or system in a graphical, user-friendly environment.

These capabilities make AMESim an effective platform for system design in automotive, aerospace, off-highway and heavy equipment groups.
The package provides structured libraries of physical models and provides various complexity levels for almost all models. It is a open platform that can interface with CAE software such as Matlab, Simulink, Adams, Flux or in-house code.
A series of analysis tools are included: sensitivity analysis, design exploration tools, FFT and linear analysis, animation. The integration method is automatic selected using an adaptive algorithm.

In LMS Imagine.Lab environment already exist a number of libraries dedicated for powertrain analysis. The basic library for global powertrain analysis is IFP-Drive. This library is the result of a close technical collaboration between Imagine and the “Institut Français du Pétrole” (IFP), [8].

The IFP-Drive is fully integrated in the LMS Imagine.Lab environment and it is essentially dedicated to:

- Simulating a vehicle’s ability to meet a velocity/time profile of a standard drive cycle;
- Simulating fuel consumption;
- Simulating and analyzing emissions;
- Predicting vehicle performances (acceleration ability, maximum climbed slope, maximum speed etc.);
- Testing different motorizations or drive trains;
- Simulating hybrid vehicles;
- Testing the performance of an actual control system.

For comfort studies the environment relies on the Powertrain library.

3. Manual transmissions

Basic manual transmission models for performance and fuel consumption studies already exist in IFP Drive library. Using this library is easy to construct a complete powertrain model as shown in figure 4.

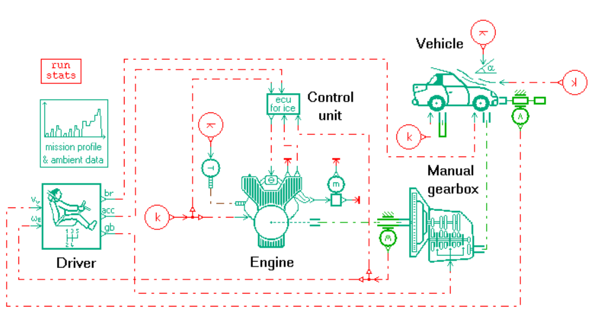


Figure 4: Powertrain model for fuel consumption

If a more detailed transmission model is needed this can be constructed using the dedicated Powertrain library. A sketch of the transmission is constructed and then submodels are selected for the components.
Using the standard components icons the sketch created is normally close to a technical plan of a gearbox. This is made to facilitate the recognition of the different elements as shown in figure 5. Nevertheless some custom elements can be added in order to follow more closely all types of gearboxes. For example a new gear with auxiliary coupling teeth is compulsory for modelling of the input shaft of three-shaft gearboxes, figure 5.

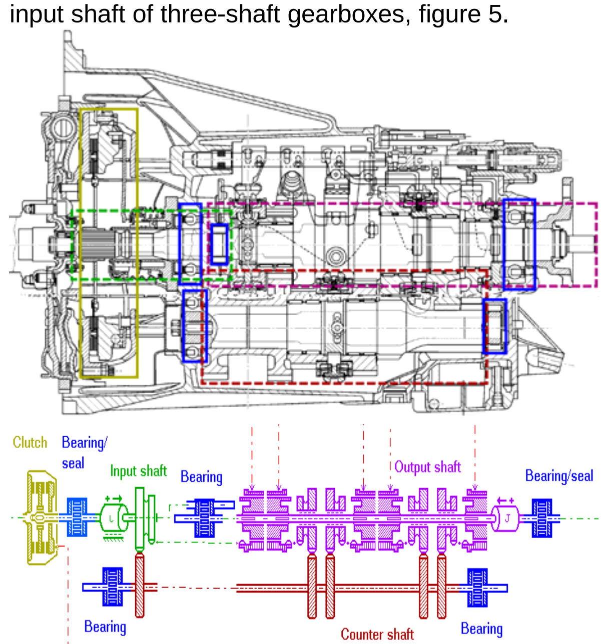


Figure 5: Detailed model of three-shaft gearbox

The detailed model can have different complexity levels by:

- Considering a different complexity sketch;
- Use various complexity levels for the same submodel (figure 6).

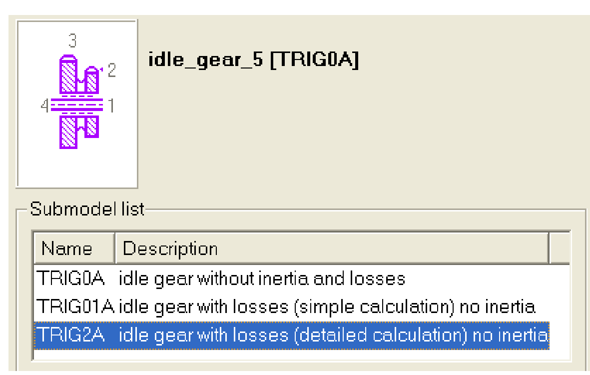


Figure 6: Submodels available for an idle gear

This model can be used to study in detail the transmission losses. There are two ways to consider these losses in a vehicle fuel consumption study:

- Use the results to compute the efficiency maps of the gearbox (depending of gear, input speed, input torque etc.) and use these maps as parameter in a global transmission model.
- Replace the global transmission model with the detailed one. This is facilitated if the model is encapsulated in a supercomponent as shown in figure 7. A standard IFP-Drive icon can be use in order to facilitate the work whit these supercomponents.

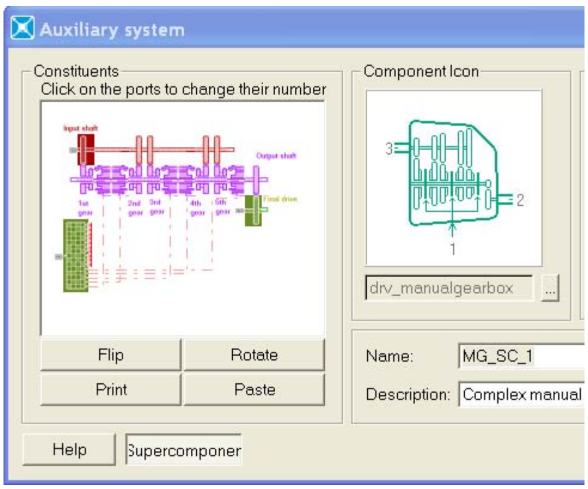


Figure 7: Supercomponent of a transaxle gearbox

In the same way other detailed models for powertrain components can be constructed and encapsulated in supercomponents. Usually this is the case for the model of vehicle dynamics when the comfort is studied, figure 8.

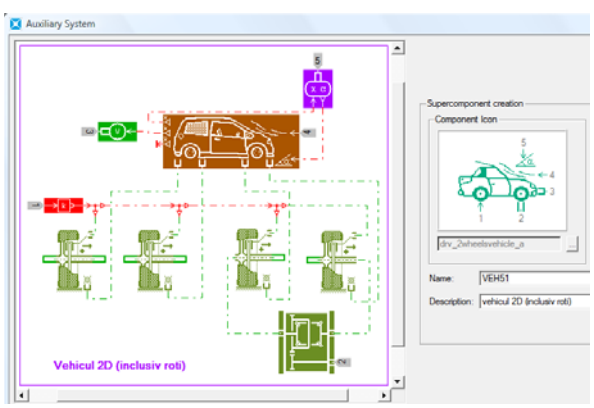


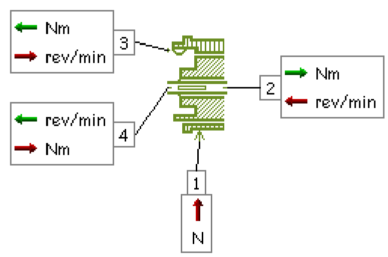
Figure 8: Supercomponent of a 2D vehicle with wheels and suspension

A key submodel for a manual transmission is the synchronizer. Until this point two synchronizer models were available in LMS Imagine.Lab. A very simple one with only friction force considered between the sleeve and the idle gear to synchronize the two velocities. This model can be satisfactory for fuel consumption studies but is not suitable for comfort ones.

A complex synchroniser model is also provided. With such a model one can perform detailed dynamic analysis of the synchromesh mechanism during any phase of the synchronising process. Nevertheless, this model is too complex, difficult to be parameterized and increase the simulation time.

A special model was developed for the synchronizer, figure 8. This new model ensures three phases and uses a state variable to switch between them: disengaged (the state is 0 and no torque is transmitted), synchronization (the state is 1 and the synchronizer is similar with a clutch) and coupled (the state is 2 and the synchronizer is similar with a shaft).

The engagement is commanded using as input a command signal (0 for disengagement and 1 for engagement) or a force applied to the sleeve, see figure 4. Beside this the relative rotary velocity is used to determine the state of the synchroniser.



Command	0	1	2
Relative angular velocity	$\omega_{rel} = \omega_2 + \omega_3$ (Attention: AMESim sign convention)		
		$\omega_{rel} > \omega_{limit}$	$\omega_{rel} \leq \omega_{limit}$
State	0 neutral	1 synchronization	2 coupled
Torque at port 3	$T_3 = 0$ N	$T_3 = T_{\sin c} \cdot \tanh\left(\frac{2\omega_{rel}}{d\omega}\right)$	$T_3 = k \cdot \theta_{rel} + c \cdot \omega$
Torque at port 2	$T_2 = T_3 + T_4$		
Angular velocity at port 4	$\omega_4 = \omega_2$		
Similitude	Open clutch	Slipping clutch	Shaft

Figure 2: Synchroniser model description

The stiffness of the shafts and gear pears is considered inside the synchronizers models. This synchronizer model is particularly feet for real time simulation.

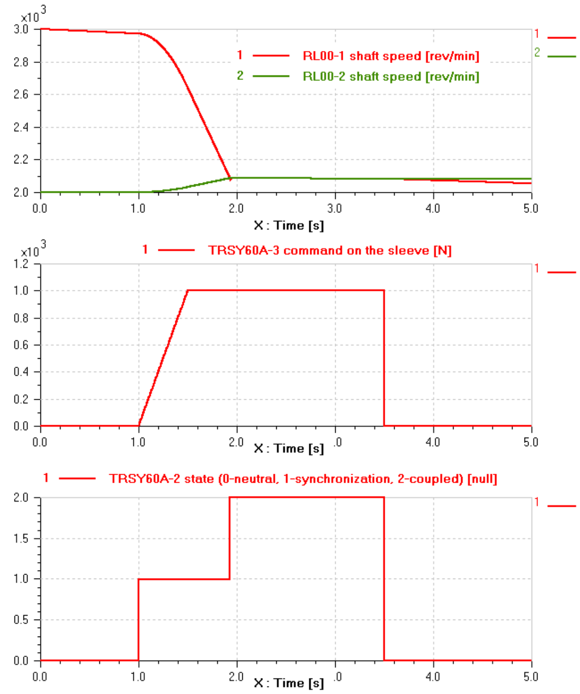


Figure 9: The synchronizations process in the new model

Using this model different control strategies for the engine and clutch can be tested in the case of AMT as show in figure 10, 11 [3]. The vehicle acceleration (a_V), engine speed (n_M), input shaft speed (n_P), normalized output shaft speed (n_S) and the control input (normalized control signals) for engine (E), clutch (C) and synchronizers (S1 for 1st gear, S2 for 2nd gear) are plotted.

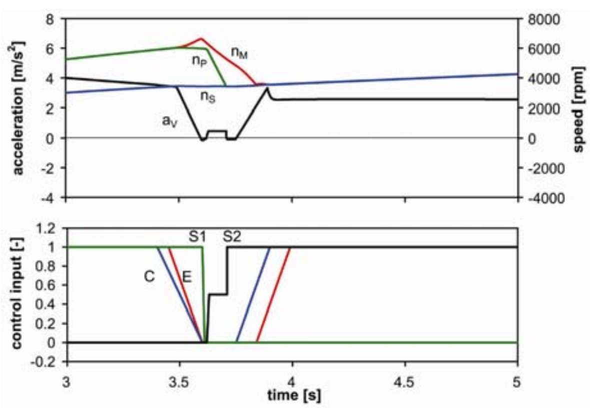


Figure 10: Simulation of a rapid gearshift process from 1st to 2nd gear at full throttle (AMT)

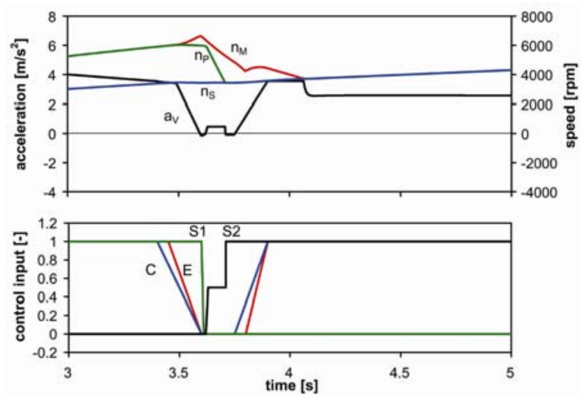


Figure 11: Simulation of a smooth gearshift process from 1st to 2nd gear at full throttle (AMT)

4. Dual clutch transmissions

Using the same components as for the manual transmissions we can build complex models of other mechanical transmissions such as DCT, figure 12.
Advanced models of the clutches can be used to better estimate the transmission losses. In particular the windage torque modelling is essential in the case of wet clutches.
This model can be integrated in a full powertrain model in order to study equally the fuel consumption, comfort.

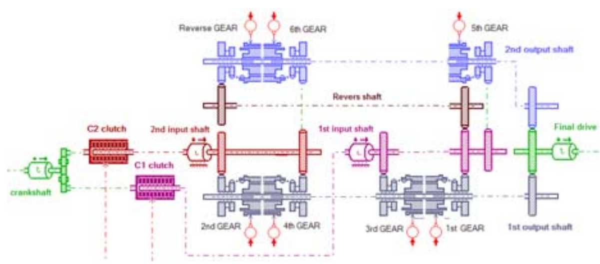


Figure 12: 6 gear DCT model

A model of the control system (hydraulic or electromechanic) can be added. Figure 13 shows a simplified hydraulic circuit model for DCT clutches control developed for a RT application of the presented transmission [4].

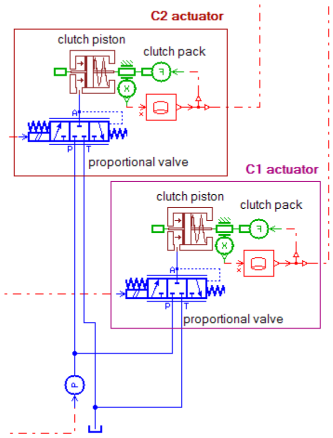


Figure 13: Simplified hydraulic circuit for DCT

The model is completed with a 2D vehicle with suspension and tires. It complies very wheel the demands of RT simulation and can be use both for comfort and fuel consumption optimisation of the transmission control unit. Figure 14 shows the results of a simulated vehicle WOT start on the RT platform.

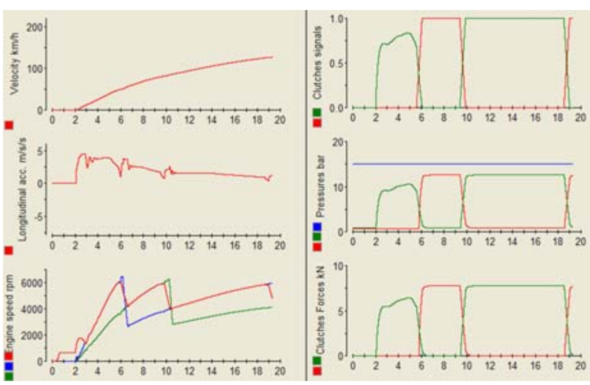


Figure 14: Simulation of WOT start of a DCT equipped vehicle on a RT platform

5. Automatic transmissions

The modelling and simulation of the AT using LMS.Imagine.Lab can be treated in the same way as the manual ones. At first stages of the design process, IFP-Drive library can be used both to show the proof of concept of the upcoming development and to provide outputs for further control specification.
The global model of the AT can then be replaced with a detailed one, figure 15. For AT with planetary gear sets this essential due to the difficulty of efficiency estimations.

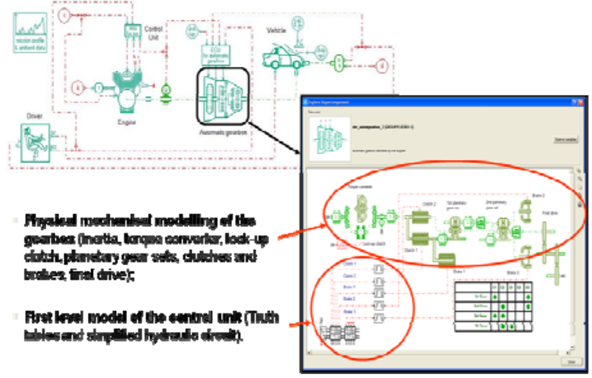


Figure 15: Use of a AT physical model in a powertrain global model for fuel consumption

The detailed model is also more fitted to study the control strategies for the coupling elements as can be seen when we compare the longitudinal acceleration profile obtained with the global AT model and with the physical mechanical AT model, figure 16.

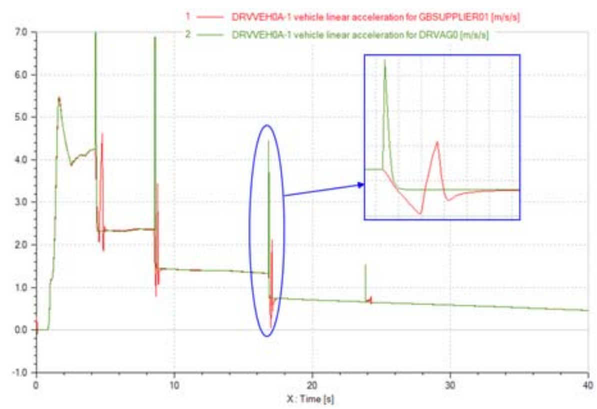
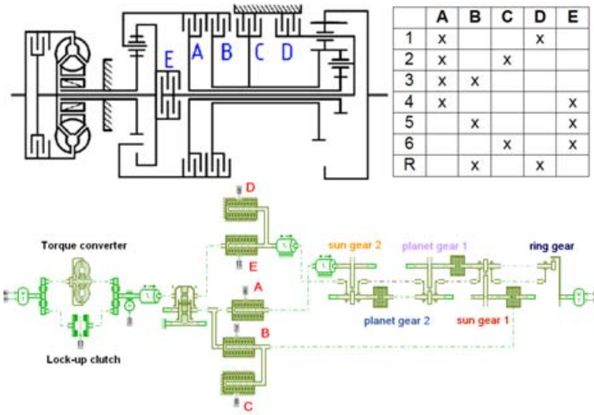


Figure 17: Longitudinal acceleration profile obtained with the global and with the physical AT model

The submodels provided by the Powertrain library are adequate for the complete modelling of AT with planetary gearsets. Figure 18 shows a model of a 6-gear automatic transmission based on Lepelletier aran. The model includes a physical mechanical model of the gearbox: inertia, torque converter, lock-up clutch, planetary gear sets (with basic elements for the Ravigneaux gear set), clutches and brakes, bearing loss models and final drive.



	A	B	C	D	E
1	x			x	
2	x		x		
3	x	x			
4	x				x
5		x			x
6			x		x
R		x		x	

Figure 18: Advanced model of a 6 gear Lepelletier transmission with speed dependant losses

6. Hybrid driveline

Developing hybrid drive vehicles is currently a major focus of automotive industry. This is seen as the right solution on the customer's demands for improved fuel economy, increased dynamic performances and good comfort.
A variety of hybrid drive concepts are now in series production or in an advance developing phase. Hybrid drive are use successfully to obtain a fuel economy improvement of 10-25 % but this came with a cost increase. To choose an appropriate configuration in respect with the desired application and to correctly dimensioning it is a difficult task for which the numerical simulation is a very useful tool.
LMS.Imagine.Lab can be use in every developing stage of a hybrid powertrain:

- Adaptation of the transmission (automatic, automated, double clutch, CVT) to the current application;
- Testing of various hybrid architectures in terms of fuel economy and comfort;
- Developing and testing the control strategy of the hybrid;
- Testing the control software of the powertrain and the control unit using real time simulation and HIL.

The first three developing stage are exemplified from a passenger car hybrid driveline research project [6].
A dedicated model is used in order to evaluate the driving and braking (regenerative) power needed to drive the vehicle in an imposed cycle, figure 19.
Figure 20 shows the vehicle velocity and engine power evolution for the NDEC driving cycle.

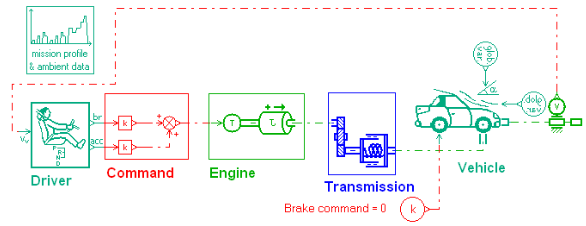


Figure 19: Dedicated model for power distribution studies

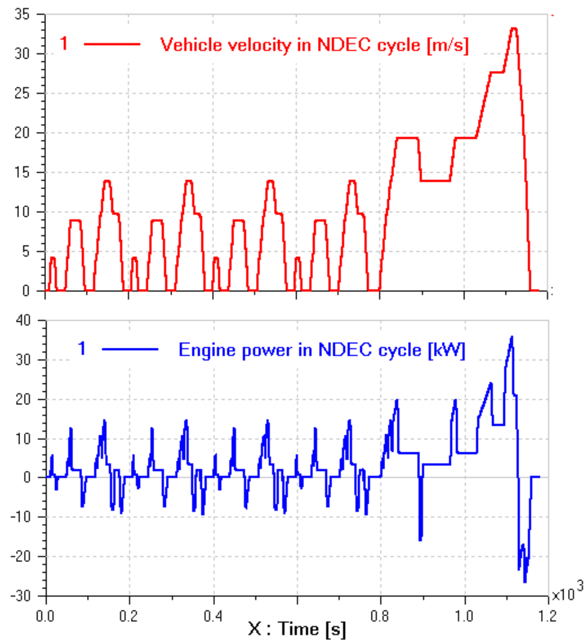


Figura 20: Vehicle velocity and engine power evolution for the NDEC driving cycle

The power distribution obtain (figure 21) can be used to correctly adopt the electric motor.

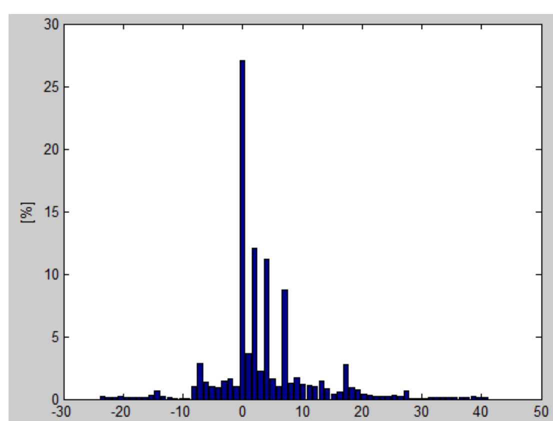


Figura 21: Power distribution in NEDC driving cycle

Various hybrid architectures can be compared in terms of fuel economy and comfort. One o this architecture is show in figure 22. Using this model a complex energy analysis for the hybrid driveline can be performed (figure 23).

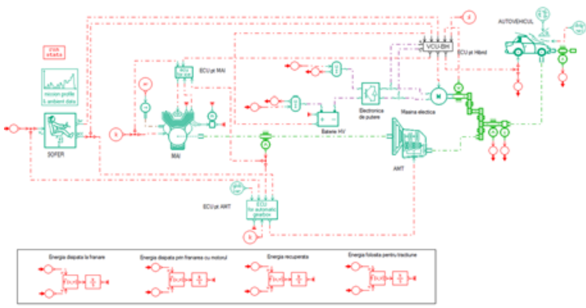


Figura 22: A hybrid configuration tested for a passenger car

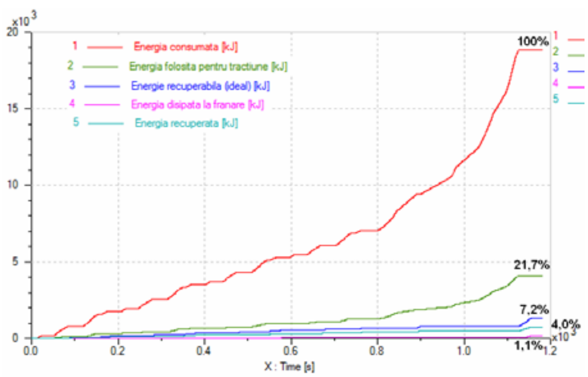


Figura 22: Energy analysis for the hybrid driveline

Figure 23 shows the comparative simulation results in terms of fuel consumption improvement for two different hybrid solutions in basic or advance configuration (with / without Stop&Go, with / without engine drag). The improvements due to control optimisation can also be seen.

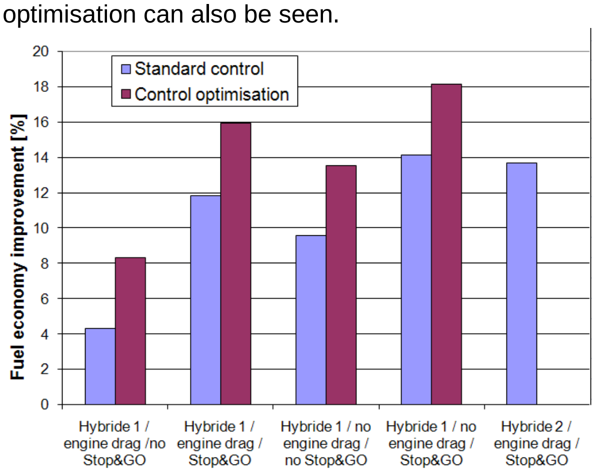


Figura 22: Comparative results of two different hybrid configuration

7. Real-time simulation

For the new electronically controlled transmissions (AT, DCT, AMT) the logic features implemented in software are combined with the hardware to provide good performance and shift quality over a wide operating range. To test and calibrate the control software of the transmission or even the entire ECU the car manufactures and OEM's use hardware-in-the-loop (HIL) simulation. The HIL simulation can be used both to improve gearshift comfort and fuel economy.
The command strategy is a key issue in maximizing the benefice of a given transmission and keeping low operating costs. For example if the command strategy must be change in order to maintain a good level of comfort this can have a big influence on the fuel consumption.
A model of the hardware able to run in real time is necessary in order to test the control software of the transmission.
In order to be able to use fix step solver is compulsory to:

- Use submodels compatible with real time;
- Simplify the model (reduce the number of states and especially the ones with higher dynamic)
- Use adequate parameters for real time in order to limit the system dynamic.

For example the friction based submodels are based on different types of friction models: hyperbolic tangent, Dahl, LuGre, Karnopp and reset-integrator. The reset-integrator models are the most adequate for real time simulations demands.

For the model simplification LMS.Imagine.Lab build-in tools are very useful. Important facilities are: linear analysis, run statistics, activity index and state count. They allow the user to easy identify time consuming submodels, the states with high dynamics and the simulation time at which high dynamics appear.

The gearshift control is critical for AT gearshift comfort. Figure 23 shows simulation results for a powertrain equipped with AT obtained on a dSPACE RT platform. The gear change acceleration profile from 1 to 2 under WOT is improved using a better command for the coupling elements.
The same model can be used for fuel consumption studies. Figure 24 shows the fuel consumption and the engine operating points obtained when an imposed driving cycle is follow.

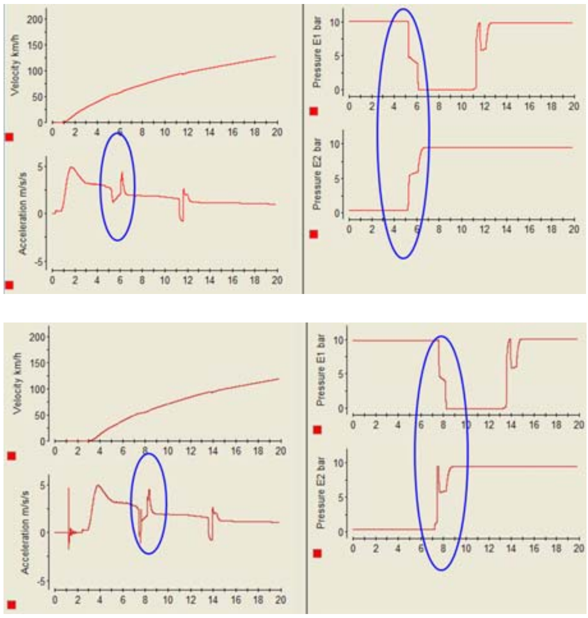


Figura 23: Improvement of acceleration profile by better control of coupling elements

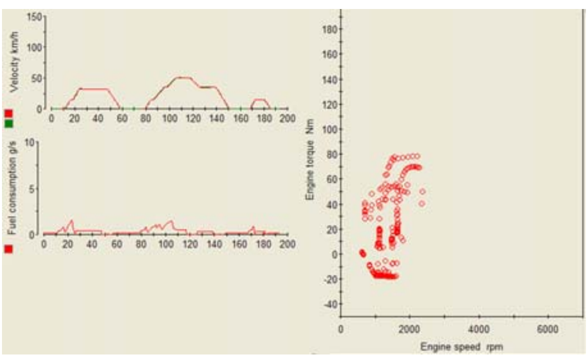


Figura 24: Fuel consumption and engine operating points for a imposed driving cycle

8. Conclusion

The paper shows the typical modelling and simulation issues that occur in automotive transmissions studies. After a brief introduction the accent is place on the dynamic modelling and simulation techniques.

The models are implemented using the 1D multi-domain simulation platform LMS Imagine.Lab AMESim.

Various transmission examples (MT, AMT, DCT, AT and hybrid) were used to demonstrate the different demands of fuel consumption, comfort and control and calibration studies. It is demonstrated that today the restriction of using detailed transmission models is imposed by the difficulty of parameterisation rather than by the limits of computational power. Nevertheless, simple transmission models are used especially in the first stages of the design to show the proof of concept of the upcoming development and to provide outputs for further control specification.

It is show that is possible using an adequate simulation platform to simulate high-fidelity models of transmissions coupled with complex vehicle dynamics models in order to study both the fuel consumption and comfort issues.

9. Acknowledgement

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11. Glossary

2D: Two dimensional
ACEA: European Automobile Manufacturers Association
AMT: Automated Mechanical Transmission
AT: Automatic Transmission
CAE: Computer-Aided Engineering
CVT: Continuously Variable Transmission
DCT: Dual Clutch Transmission
EP: European Parliament
FFT: Fast Fourier transform
HIL: Hardware-in-the-loop
IFP: Institut Français du Pétrole
NDEC: New European Driving Cycle
OEM: Original Equipment Manufacturer
RT: Real Time
WOT: Wide Open Throttle