Faculty of Mechanical Engineering
Department of Automotive, Combustion Engine and Railway Engineering
Master of Automotive Engineering

Master's Thesis

HYBRIDIZATION OF A BATTLE TANK

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MASTER'S THESIS ASSIGNMENT

I. Personal and study details

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Study program: **Master of Automotive Engineering**

Branch of study: **Advanced Powertrains**

II. Master's thesis details

Master's thesis title in English:

Hybridization of a battle tank

Master's thesis title in Czech:

Hybridizace bitevního tanku

The objective of the project is to replace the powertrain of a battle tank by a hybrid one. A MATLAB/Simulink model will be developed in order to perform simulations to estimate the fuel consumption gains. The project is led by a team of three interns in collaboration with other entities. In this project the student is in charge of the dimensioning of the batteries as well as their modeling. The student will also study the energy management strategy to define a strategy to meet certain performance criteria while optimizing fuel consumption.

Guidelines:

- Model and determine battery sizing
- Analyze the state of art and develop the energy management strategy
- Create a Matlab/Simulink model for the simulation
- Compare the results with a non-hybrid model

Name and workplace of master's thesis supervisor:

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Name and workplace of second master's thesis supervisor or consultant:

Date of master's thesis assignment: **30.04.2023** Deadline for master's thesis submission: **11.08.2023**

Assignment valid until: ___________

Ing. Rastislav Toman	doc. Ing. Oldřich Vítek, Ph.D.	doc. Ing. Miroslav Španiel, CSc.
Supervisor's signature	Head of department's signature	Dean's signature

III. Assignment receipt

The student acknowledges that the master's thesis is an individual work. The student must produce his thesis without the assistance of others, with the exception of provided consultations. Within the master's thesis, the author must state the names of consultants and include a list of references.

20/06/2023

Date of assignment receipt

Student's signature

CVUT-CZ-ZDP-2015.1

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First of all, I would like to thank my internship tutor François Deloumeau for welcoming me to the company and sharing his passion for military vehicles through his many suggestions and ideas, as well as Frederic Poil for sharing his expertise on hybridization and vehicle modeling.

I also thank my university tutor Rastislav Toman for guiding me during this internship.

I wish to express my gratitude to all the people involved in this project who helped us to achieve this work by accompanying and assisting us.

I am also grateful to my professor at ENSTA Bretagne, Alain Poulhalec, who helped me find this internship and actively participated in the project.

Résumé

Ce stage dans le domaine de la défense et particulièrement des véhicules militaires avait pour but de préparer l'hybridation d'un char de combat. Il s'agit d'un stage orienté sur la modélisation du groupe motopropulseur hybride. Il a été réalisé au sein de l'entreprise Arquus. L'objectif de ce dernier et du rapport et de dimensionner et modéliser un groupe motopropulseur hybride. Il a été réalisé par trois stagiaires. La partie présentée dans ce rapport porte sur la mise en place d'une stratégie hybride permettant de satisfaire à des critères en performances ainsi que de réduire la consommation du char au cours de sa mission. Le second grand axe porte sur le dimensionnement et la modélisation des batteries à haut et bas voltage. L'ensemble du projet a été modélisé et simulé sur MATLAB Simulink. Ceci afin de valider des critères en performances tout en comparant les critères de consommation par rapport à un char à propulsion uniquement thermique. Ce dernier a également été modélisé sur MATLAB Simulink.

Abstract

The purpose of this internship in the field of defense, and particularly military vehicles, was to prepare the hybridization of a battle tank. The training course focused on modeling the hybrid powertrain. It was carried out at the company Arquus. The goal of the course and the report is to design and model a hybrid powertrain. Three trainees where in charge of the project. The report showcases the implementation of a hybrid strategy to meet the performance criteria and reduce the tank's fuel consumption during its mission. The second main axis concerns the sizing and modeling of high and low voltage batteries. The entire project was modeled and simulated using MATLAB Simulink. This was done in order to validate performance criteria, while comparing consumption criteria with those of a purely combustion-powered tank. The thermal-only tank was also modeled in MATLAB Simulink.

Contents

List of abbreviations

BEV	Battery electric vehicle
BMS	Battery management system
CC	Constant current
CV	Constant voltage
DGA	Direction Général de l'Armement / French procurement agency
DP	Dynamic Programming
EBRC	Engin blindé de reconnaissance et de combat/Armored combat and reconnaissance vehicle
ECMS	Equivalent consumption minimization strategy
EM	Electric machine
HEV	Hybrid electric vehicle
ICE	Internal combustion engine
LPM	Loi de programmation militaire / Military planning law
MGCS	Main ground combat system
MHEV	Mild hybrid electric vehicle
NATO	North Atlantic treaty organization
PHEV	Plug-in hybrid electric vehicle
PI	Proportional integral controller
PMP	Pontryagin's minimum principle
RB	Rule-based
SOC	State of charge
UGV	Unmanned ground vehicle
VAB	Véhicule de l'avant blindé / Front armored vehicle
VBMR	Véhicule blindé multi-rôles / Multi-role armored vehicle
VSP	Variable shift pattern
WLTP	Worldwide harmonized light vehicles test

Symbols and indices

$Capacity$	Battery capacity	U	Nominal voltage
C_x	Vehicle drag coefficient	v	Vehicle speed
F	Force	V_{oc}	Open-circuit voltage
g	Gravitational acceleration	x	State variable
H	Hamiltonian	α	Slope angle
I_x	Current	η	Efficiency
J_i	Inertia	λ	Lagrange multiplier
J	Performance measure	ρ	Air density
K_i	Integral coefficient	ω_x	Rotational speed
K_p	Proportional coefficient		
M	Vehicles mass	aux	Auxiliaries
P_x	Power	$batt$	Battery
R_x	Resistance	$cell$	Cell
s	Adaptive ECMS coefficient	$coul$	Coulombic
S	Aerodynamic vehicle surface	$fuel$	Fuel
SOC	State of charge	gb	Gearbox
T_x	Torque	ICE	Internal combustion engine
T	Mission duration	ME	Electric motor
u	Control variable	HV	High voltage Battery

1. Introduction

As part of the final year of a master's degree at a Czech university, a final internship must be completed. The aim of this report is to describe and present the progress and content of my final year training project or master's internship. It took place at Arquus, a French company operating in the defense sector and more specifically in military road-vehicles. As this master's degree is a double diploma between the Czech Technical University in Prague and the French engineering school ENSTA Bretagne, where I studied as a military student, it was only natural that I turned to the defense sector for this training period.

1.1. Context

Included in the LPM (French Military Planning Law) 2024-2030 [1], dealing with vehicle obsolescence in the military is a growing concern, especially with older vehicles such as the French Leclerc Tank. As the tank ages, and the MGCS program [2] faces industrial and political obstacles, the need for Powertrain modernization is becoming even more pressing. As a member of the Volvo group, Arquus would like to offer various solutions of its own, using Volvo Truck engines like the one presented at the Technodays 2023 [3]. In parallel with this purely thermal solution, and with hybrid solutions progressing on other ranges of wheeled vehicles, a pre-study on the feasibility of hybrid motorization of the tank was launched in 2022, in the form of an end-of-study internship carried out by ENSTA Bretagne students.

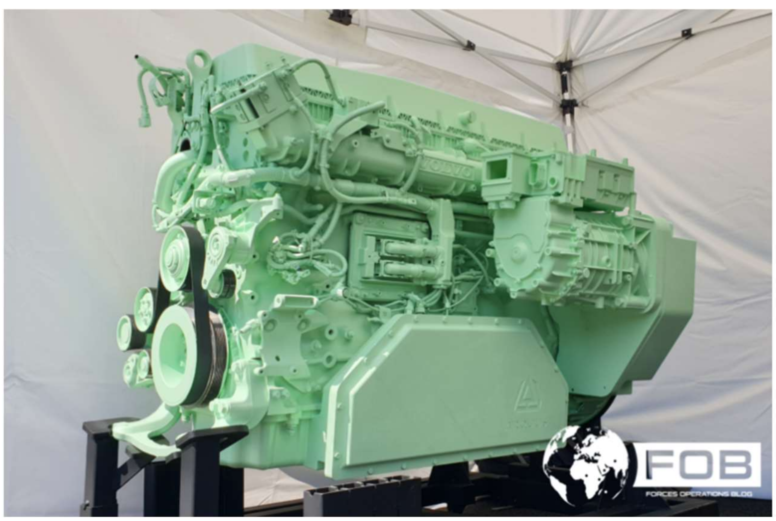


Figure 1 Volvo motor presented during the Technodays 2023

1.2. Previous project presentation

The goal of the pre-study was to use MATLAB-Simulink to determine and compare the fuel consumption of different main battle tank archetypes based on NATO standards and the Leclerc tank. The purely longitudinal model included a control-command section and a mission profile giving a set speed at each instant. This control system piloted a drive train including motors, gearbox, transmission, and sprocket, which required power from a battery/power electronics sub-part. Dynamic feedback was used to control the entire system at the set point.

These models were tested with different purely thermal or hybrid engines and different tracks, including flexible tracks. The fuel consumption of different configurations could therefore be estimated.

While the results showed high fuel consumption gains compared with the existing purely combustion-powered tank, these gains are attributable to a variety of factors: weight reduction, hybridization, track technology change and so on. Furthermore, the physics of the model is relatively simple: the complexity of the subject and the breadth of the areas involved having crystallized a large part of the project time. This model is therefore considered to be an excellent way of 'clearing the brush' on the subject, enabling to obtain a first set of results, while leaving many opportunities for improvement.

1.3. Objectives

With the basis of the model in place, and the political and industrial situation having changed, the definition of the need and the objectives of the subject were reviewed. The change in mass and track type was left aside. The problem is now centered on a comparison between the combustion engine tank and the hybrid tank, in order to demonstrate the operational viability of a hybrid tank in terms of performance, fuel consumption and range. The new challenge is to demonstrate, for equivalent or superior performances, and all other things being equal, that the choice of hybrid architecture offers a significant gain in fuel consumption over a typical mission. To achieve this, several aspects of the model will be completed and improved.

Vehicle dynamics will now incorporate transverse dynamics, and the modeling of interactions on soft terrain will be refined. The mission profile will consequently be completed by the addition of routes followed by the vehicle.

Power electronics will be enhanced to better take account of battery behavior, and the current hybrid strategy will be replaced by a more sophisticated and precise hybrid strategy.

Real-life mapping of the combustion and electric motors will be incorporated, to obtain behavior as close as possible to that of a hypothetical hybrid tank. In addition, numerous functions used with hybrid architectures will be added, such as regenerative braking and Start and Stop.

The final result will be a more accurate model, both in terms of components and physics, capable of simulating an entire mission with trajectory tracking. The ultimate objective, as formulated by the supervisor of this internship, would be to demonstrate a significant fuel consumption gain when switching to a hybrid tank.

The work was divided between three students. The part presented here will focus on the work I carried out, namely the study and implementation of a hybridization strategy to optimize fuel consumption while meeting performance criteria, as well as the sizing and modelling of the high voltage and low voltage batteries and finally the comparison between the hybrid model and the purely thermal one.

2. Company presentation

Arquus is a well-known defense and security company specialized in the design and manufacture of military vehicles. With its rich heritage and technical expertise, Arquus has established itself as one of the world's leading companies in the defense industry.

Initially known as Renault Truck Défense, it grew out of the Renault group, whose defense activities began during the First World War with the creation of the Renault FT 17 light tank. In 2001, Renault Truck Défense was acquired by the Swedish Volvo Group, which then bought Panhard Defense and ACMAT. The Volvo Group's organization chart, shown below, illustrates the diversity of its production activities [4].

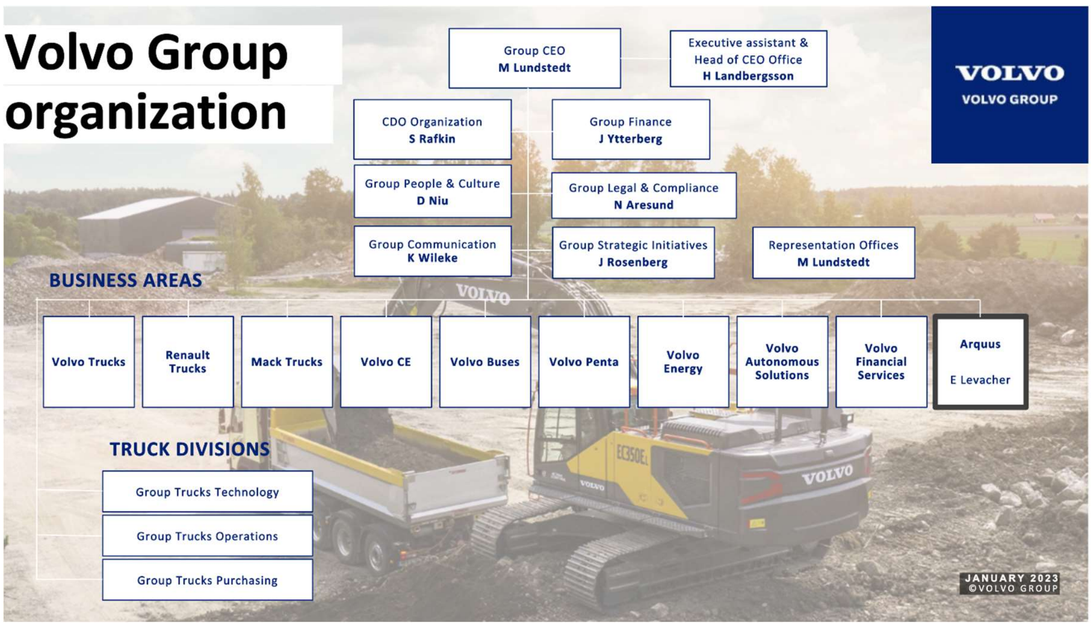


Figure 2 Volvo group organization

One of Arquus' most popular products is the renowned VAB (Véhicule de l'Avant Blindé/ Front armored vehicle) armored fighting vehicle, which has earned an international reputation for its reliability and performance in the field. The VAB has been deployed in numerous conflicts around the world and has proven its operational value. Arquus also offers a complete range of armored vehicles, from reconnaissance and patrol vehicles to troop transports as well as command and logistics vehicles. These vehicles are designed to provide optimum protection for crews while ensuring exceptional mobility and maneuverability on all terrains.

In addition to its emblematic products, Arquus is also recognized for its expertise in the field of protection and tactical mobility. The company develops and integrates ballistic protection and threat detection systems, as well as advanced mobility solutions such as hybrid transmission to reduce fuel consumption and increase vehicle range. Arquus is committed to providing customized solutions that meet the specific needs of each customer and works closely with the armed forces to develop technological innovations that advance operational capabilities.

One of Arquus' key projects is its involvement in the Scorpion program [5], a major initiative to modernize the French Army. As part of the Scorpion program, Arquus is working with other defense industry players to develop and supply new land combat platforms and systems. This includes the development of the VBMR Griffon multi-role armored vehicle, which will be used to transport troops and equipment, and the EBRC Jaguar reconnaissance and combat vehicle, designed for reconnaissance and armed combat missions. Arquus is bringing its expertise in mobility, protection, and on-board systems to support these new state-of-the-art vehicles.

In addition to its activities in France, Arquus is also present on the international market, exporting its vehicles and expertise all over the world. Thanks to its global presence and cooperation with strategic partners, the company is helping to strengthen security and defense in many countries.

3. Hybrid vehicles

3.1. Degree of electrification

Between the purely ICE vehicle and the purely electric vehicle, there are several categories of so-called hybrid vehicles (Figure 3). This categorization is based on the degree of electrification [6].

Figure 3 Degree of electrification

Micro: A micro-hybrid is a combustion engine vehicle with the addition of a start&stop system. At low speeds, this tool is used to switch off the internal combustion engine and then restart it more quickly.

Mild: The mild hybrid is a micro-hybrid to which a boost is added. Pure electric drive is not possible, but thermal propulsion can be assisted, as well as the supply of auxiliaries such as ventilation.

Full: The full hybrid has an electric motor that can be used for purely electric driving, but only on a limited domain (for a few kilometers for example). The electric motor is mainly used at low loads and low speeds, i.e., when the combustion engine is less efficient. With this type of hybridization, there is a noticeable improvement in consumption, particularly in city driving, where speeds are low and there is regenerative braking.

Plug-in: The plug-in hybrid is identical to the full hybrid but with larger batteries. They can be recharged from the grid. Unlike the full hybrid, which has to recover energy solely from the combustion engine and therefore operates mainly on a charge-sustaining basis, the plug-in can be used with higher battery consumption, charge-depleting, before moving on to a charge-sustaining phase with a lower target SOC. For a full vehicle, the target state of charge must be higher because the aim is to maintain the battery SOC and have a final charge corresponding to the initial charge.

3.2. Types (series, parallel)

There are several types of hybrid vehicle for full and PI hybrid: series, parallel and series parallel HEVs [6], [7]. The last one has most of the advantages of the parallel and series vehicle, but it is more complex and requires a higher cost and volume.

- Series HEV

In this type of configuration, the mechanical power generated by the internal combustion engine is converted into electrical power by a generator, and then it is again converted into mechanical energy by an electric motor.

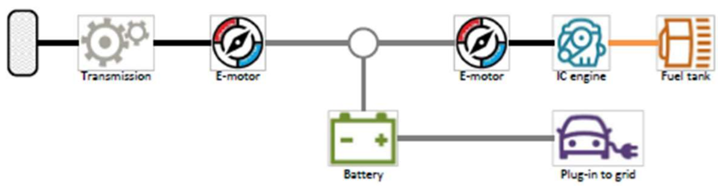


Figure 4 Diagram of a series architecture

There are six possible modes:

- Battery mode: the vehicle is powered only by the battery
- Engine mode: the electric motors are powered by an electric power supplied by the internal combustion engine and the generator
- Combined mode: the power is supplied to the electric motor by the internal combustion engine, the generator and the battery
- Power split mode: the power supplied by the ICE and the generator is split between the electric motor and the battery
- Stationary charging mode: the vehicle is parked, and the power supplied by the ICE and the generator is used to charge the battery
- Regenerative braking mode: braking is achieved by using the electric motor as a generator. The energy generated is stored in the battery

The series hybrid vehicle offers several advantages. First, the decoupling of the motorization and the wheels offers great flexibility in the design of the vehicle. Electrical wires can be used to transfer power for propulsion around the vehicle instead of having rigid and bulky driveshafts and differentials. This not only increases the reliability of the vehicle but also reduces the logistical burden.

As the electric traction motors are sized for all the vehicle's operating points, it is possible to offer extended electric driving (which only depends on the size of the battery). The use of electric motor can be implemented at each wheel, which lead to an increase in the mobility potential of the vehicle. This also enables to change the type of suspension and the implementation of less bulky suspensions. All these elements allow for an increase in the volume available in the vehicle or to reduce its size and height as well as to reduce the mechanical complexity. Moreover, the drive shafts, if there are any in the vehicle, become projectiles in case of mine explosion. Removing them therefore increases survivability.

Although the hybrid vehicle in series has many advantages, there are also disadvantages to the use of this system. First of all, as explained above, the power supplied by the ICE is converted twice. This means that there are more losses. The efficiency of the series HEV is therefore generally worse than that of a parallel HEV. In addition, the design of this vehicle is a radical shift from the design used for the internal combustion engine vehicles that have been used so far.

Besides, if the hybrid system were to fail, there would be no mobility (unlike a parallel hybrid, which can still move around using the combustion engine alone).

- Parallel HEV

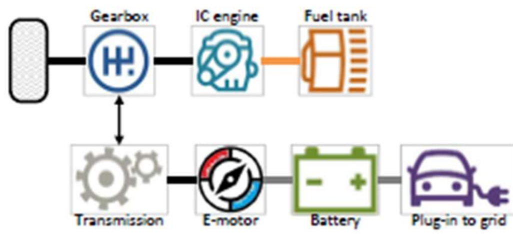


Figure 5 Diagram of a parallel architecture

The parallel HEV allows the vehicle to powered by both the internal combustion engine and the electrical motor. An essential element of the transmission of this vehicle is the mechanical coupling. This determines the different operating modes. The possible modes can be as follows:

- Electric motor mode: the ICE is switched off and the electric motor powers the vehicle using the battery energy (e.g., silent mobility)
- Engine mode: the vehicle is powered by the ICE
- Combined mode: the vehicle is powered by the electric motor and the ICE
- Power split mode: the power delivered by the ICE is used to power the vehicle and charge the battery using the electric motor as a generator
- Stationary charging mode: the vehicle is stationary, and the power supplied by the ICE is used to charge the battery using the electric motor as a generator
- Regenerative braking mode: braking is performed using the electric motor as a generator. The energy generated is stored in the battery

The advantages of parallel hybrid vehicles are as follows: the transmission of parallel HEVs is generally smaller than that of series vehicles. This is due to the fact that the ICE and the electric motor provide torque to the wheels. It is therefore sufficient that the sum of the power of the two motors is equal to the required power. Moreover, the efficiency is generally higher for parallel vehicles because the torque generated by the ICE is directly transmitted to the wheels. Finally, as far as the overall architecture is concerned, the parallel hybrid vehicle is closer to vehicles using only an internal combustion engine, thus simplifying its implementation. Finally, if there is a problem related to the electric motors, this does not imply the immediate stopping of the vehicle. Robustness is a crucial point for military vehicles.

Hybrid vehicles in parallel also have disadvantages such as complexity. Indeed, since there are two ways of producing power and the different modes of operation, the parallel vehicle is complex. The fact that the ICE is not totally decoupled from the wheels makes it difficult to use it in an optimal range, which affects its efficiency. In this vehicle, in contrast to series HEV, it is necessary to implement a drive shaft. This also involves logistical problems.

There are also several types of hybrid vehicle with a parallel architecture depending on the position of the electric motor coupling in the powertrain [8].
P0: the motor is coupled to the combustion engine via a belt drive. This type corresponds to a mild hybrid. However, this method has limitations in terms of torque and rotation speed. In addition, the electric motor cannot be decoupled from the combustion engine.

P1: In this case, the electric motor is mounted on the crankshaft. The belt drive constraint is removed, but the motor cannot be decoupled from the combustion engine either. As the ratio between modifications and gains is not worthwhile, this type is rarely used. The electric motor assists the internal combustion engine during acceleration and performs regenerative braking during deceleration.

P2: The electric motor is connected between the electric motor and the transmission and can be decoupled from the combustion engine. This type offers significant gains in purely electric operation. Like P1, it assists the motor during acceleration and performs regenerative braking during deceleration. It also provides more power to the wheels.

P3: The electric motor is connected to the gearbox output shaft or differential. The torque to be supplied and the speed must cover a wider range. This model is slightly more efficient than P2 but must provide a high request of torque in return.

P4: In this mode, the electric motors are mounted directly on the wheel axles or wheels. Electric drive efficiency is the highest. There is greater control over the torque delivered to the wheels.

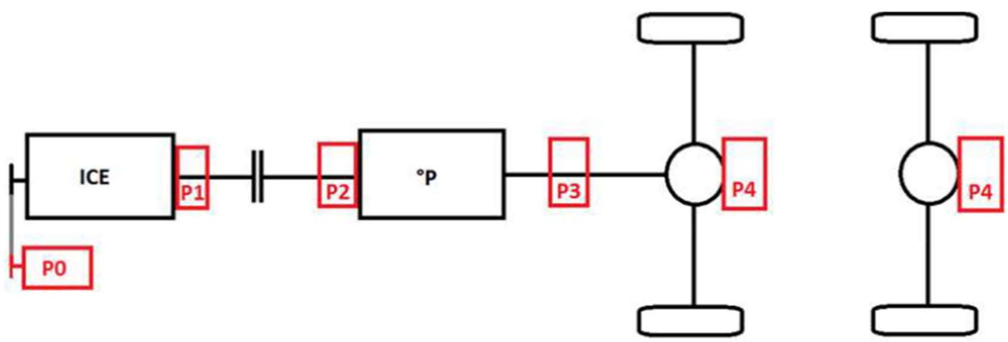


Figure 6 Position of electric motor/generator

3.3. Military hybrid vehicle

Arquus has started to develop hybrid engines for the “Scarabée” vehicle or for the “VAB Electer” and “Griffon” which bring interesting gains in consumption. The “Scarabée” is the first hybrid military vehicle in the world. The “Griffon” is an internal combustion engine vehicle, but a hybrid version has been presented using lithium-ion batteries [9].

Hybridization is a relevant solution for battle tanks, infantry fighting vehicles or tactical trucks. In addition to reducing emissions and fuel consumption, hybridization can limit maintenance and increase capabilities in the field.

Oshkosh (an American company) presented last year a hybrid version of its JLTV (joint light tactical vehicle) [10]. The eJLTV uses a commercially available battery. It takes only 30 minutes to charge the lithium-ion battery. However, there is still work to be done as this addition increases the weight of the vehicle by over 400kg.

The Swedish project SEP (Splitterskyddad Enhets Platform) is a project to develop modular, flexible, and transportable vehicles to replace part of the Swedish army's vehicles. Hybrid and electric vehicles are the focus of this project [11].

Hybrid electric vehicles offer many advantages in the military domain. Firstly, an electric drive alone reduces the vehicle's noise and thermal signature. This enables silence mobility. These vehicles also reduce the mechanical bulk and thus potentially increase the space available within the vehicle and increase the modularity of the vehicle.

Many elements of a military vehicle require continuous or peak power. These include weapons, active protection systems, terrain management systems, various sensors, etc. The HEV increases the electrical power available on board the vehicle. It also reduces logistical requirements such as the need for an additional generator.

It is difficult to compare the fuel economy of military and civilian vehicles due to many differences in use, but test, like the last year internship or studies [12],[13], have shown that for military vehicles the fuel economy would be on average 20%. This saving is mainly due to regenerative braking. The ICE is used at an optimal load and speed and the energy is recovered during braking. This savings allows for an increase in vehicle's range, a reduction in logistics requirements. The transport of fuel in war zone is very costly.

There are other tactical advantages, such as the improved silent watch. As previously mentioned, the use of batteries reduces acoustics and thermal signatures. The presence of an energy storage system allows to extend this watch over a longer period [12],[13].

The difficulties that hybrid vehicles may encounter are related to their implementation in the market. There is the cost of introducing and maturing electric drive motors, motors, storage systems, and power electronics. There is also the limited amount of reliability data and the overall life cycle cost that comes into consideration.

The disadvantage of the vehicle architecture is that today's military vehicles are improvements of older generations that are constantly evolving, yet they remain ICE-powered vehicles. The addition of the hybrid engine adds a whole new element to consider in the vehicle architecture. Moreover, hybrid vehicles are the result of only a few iterations of design and prototyping thus there is not enough hindsight and feedback yet [12].

4. Vehicle models

4.1. Hybrid model

The overall MATLAB model of a tank's hybridization was redesigned this year. This was done to avoid redundancies and to separate the physical part from the command and control signals part.

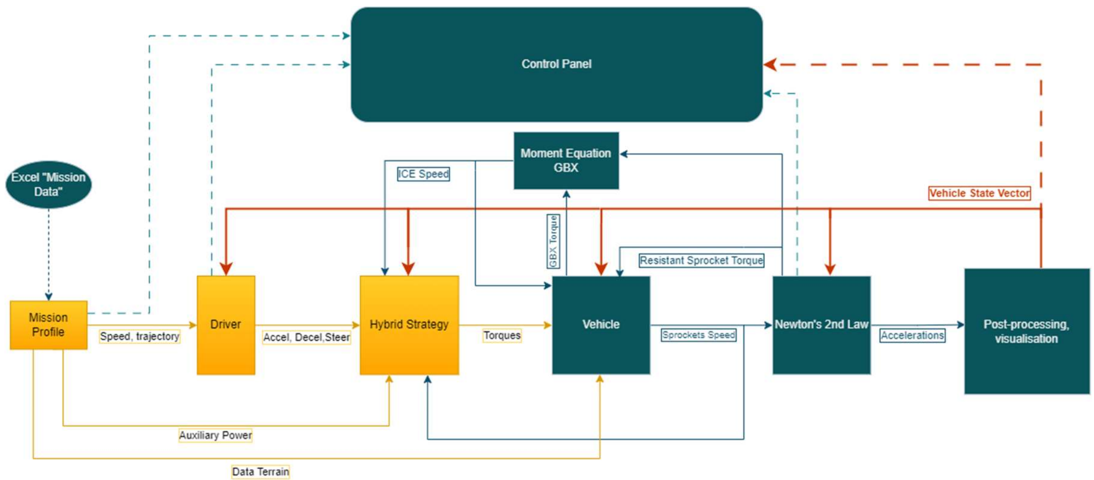


Figure 7 Global model with MATLAB Simulink

The MATLAB model view above shows how the model is organized. Field data are transmitted to the driver and control unit, which forward the command to the hybrid strategy. The hybrid strategy distributes the power demand between the electric and thermal parts. At this point, we move on to modeling the physical part of the vehicle. The batteries transmit power to the electric motors. These motors, together with the internal combustion engine, deliver torque to the transmission table. This transfers torque to the gearbox. Finally, we can observe the fundamental principle of dynamics, which provides accelerations and resisting torques.

In this model the vehicle has a parallel architecture and will be considered as a full hybrid vehicle for the calculation. However, if said vehicle would be produced, it would very likely be a PHEV, that would be able to fully work during an entire mission without being recharge from the grid and return to the initial state of charge of the batteries at the end of this mission.

4.1.1 Electrical part

The electrical section, which is already a sub-sections of the vehicle block in Figure 7, consists of three sub-sections:

- Distribution and DC/DC converter

- High voltage and low voltage batteries

- Power redistribution

The power distribution sub-section manages power distribution between the low voltage battery and the high voltage battery with the DC/DC converter, depending on the batteries' state of charge. It determines the power required by the high voltage and low voltage batteries respectively, based on the power set by the strategy block.

The battery sub-section models the high voltage and low voltage batteries, each with an upstream power limiter to manage power peaks. Each battery provides power and data on battery voltage and state-of-charge.

The redistribution sub-section distributes power between motors and priority and non-priority auxiliaries according to any limitations and provides a torque command for the electric motors as well as the power supplied to the auxiliaries.

4.1.2 Strategy

The strategy section is composed of several blocks. The main block is the ECMS (equivalent consumption minimization strategy) updated to this project. This block is preceded by a regenerative braking block, and an accelerator pedal-based torque calculation block. There are also electric and combustion motor mappings, as well as ventilation control and auxiliary power calculations based on the grid used (LV or HV) and prioritization.

4.2. Internal combustion engine - only model

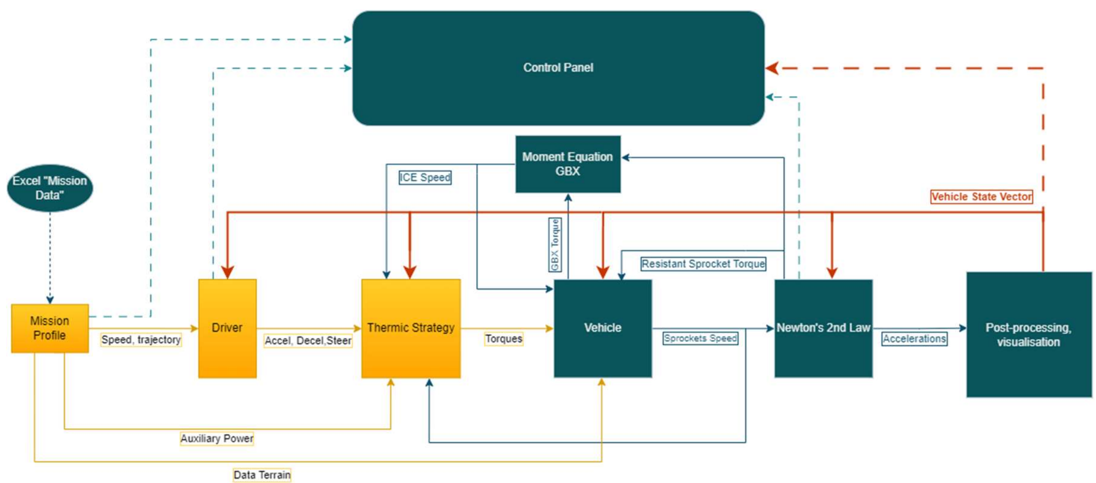


Figure 8 Diagram of the thermal model

The organization of the combustion model does not differ from that of the hybrid model, as the main model structure and components remain identical. On the other hand, component structure varies, particularly in the hybrid strategy block, renamed "thermal strategy", which is now simply responsible for supplying the thermal engine torque required to set the car in motion and ventilate it. The part linked to the distribution of torque between the different engines has therefore logically disappeared.

4.3. Mission profile

The previous work carried out (PFE2022) focused on the longitudinal dynamics of the vehicle, predicting but not utilizing a component of cornering force based on their frequency and the terrain on which the tank operates. Consequently, the model was controlled in terms of speed, similar to the type of approval cycle for hybrid electric civilian vehicles WLTP. The cycle consisted of a series of speed commands over a defined duration of several hours. This speed command was then used to feed a "driver" block in MATLAB, and a feedback loop allowed for the correction of acceleration over time.

The speed profile was established in order to best correspond to the tank's operational use. A modular approach was chosen, associating a specific tank operating mode, such as "eco," "combat," "long-duration stop," etc., with a segment of the route. This modular approach allows for both associating a speed setpoint at each instant and determining which auxiliary devices will be active and which mode of propulsion will be used. The mode also controls the battery usage strategy. For example, mode "combat" allows for depleting the batteries for performance, while mode "road" maintains a constant level of charge.

The chosen approach appears coherent, as it follows the feedback offered by tank drivers and military high-command, and the close collaboration with the product's users makes it an excellent starting point for adapting to current objectives. The work carried out was retained and adapted to incorporate the lateral dynamics. In order to add the vehicle's lateral dynamics to the current MATLAB model, a path needed to be implemented. This path consists of a series of segments between waypoints in 3D space (x, y, z) to determine the trajectory to follow and the slope the vehicle will face at each moment. The route needed to align with the established mission profile's timeline and correspond to the model tank's range (several hundred kilometers).

Furthermore, it seemed consistent and judicious to associate a different route with each major type of movement to align as closely as possible with reality. The three main segment types are: liaison (transit), combat approach, and combat.

The liaison segment represents the vehicle's journey to its mission location. It is the longest segment, arbitrarily designed with gentle curves. The slope between two waypoints was also chosen arbitrarily, keeping it low and nearly flat on average throughout the segment. The types of terrain encountered only include roads and dry clay paths.

The second segment corresponds to an approach to a conflict zone, characterized by more challenging terrain such as soft ground, mud, snow, sand, etc., as well as sharper curves.

The last segment corresponds to a high-intensity combat phase, where the vehicle encounters numerous small turns, stops, and forward jumps during an erratic route on difficult terrain. This segment not only represents a realistic situation faced by the tank but also highlights the advantages of hybrid propulsion by relieving the thermal engine during successive decelerations and accelerations at low speeds. This route has been plotted on a map of a hilly area but remains relatively arbitrary. The encountered terrains include soft and challenging ground.

By simulating this combat phase, the model can capture the vehicle's behavior and performance in demanding scenarios. It also allows for demonstrating the benefits of hybrid powertrain, showcasing how the combination of electric and thermal propulsion systems can enhance maneuverability, energy efficiency, and overall effectiveness in combat situations. The challenging terrain encountered in this segment tests the vehicle's capabilities and showcases the advantages of the hybrid system in navigating difficult terrains.

By combining the different segment types, including liaison, combat approach, and combat, along with the inclusion of specific waypoints for various stops, the final mission route reflects a realistic scenario. This approach allows for a comprehensive representation of the tank's trajectory, taking into account different types of terrain, maneuvers, and operational requirements throughout the mission.

Incorporating stops at specific waypoints adds further realism to the model, as it considers the need for the tank to pause, rest, or engage in various activities during the mission. This enhances the accuracy and relevance of the model, ensuring that it reflects the actual operational conditions and requirements of the vehicle.

This segment-based approach to the mission allows for adaptability of the input data provided to the model. The data is stored in Excel spreadsheets, where each row corresponds to a "waypoint" along the route. Each waypoint is defined by its coordinates (x, y, z) and spans until the next waypoint. The Excel sheet includes the following information for each waypoint:

- Slope value: The gradient or incline of the terrain.
- Terrain: The specific type of terrain on which the vehicle will operate, identified by its code.
- Setpoint speed: The desired speed assigned to the vehicle.
- Occasional events: The presence of specific events at certain waypoints, such as firing or decoy deployment.
- Movement mode: The mode of movement assigned to the segment, identified by its code.
- Stop time: The duration of the vehicle's halt before starting the segment.
- Restart speed: The speed at which the vehicle should resume after the stop. This is a redundant value with the setpoint speed but is necessary for the modeling.

Additionally, the Excel sheet defines the yaw angle, in the global reference frame, at which the tank should arrive at each waypoint. This angle is crucial for the proper functioning of the driver block and is given by a formula.

This Excel spreadsheet format allows for clear organization and easy customization of the mission profile, facilitating the input of data for the model.

The connection between the Excel file and the Simulink model is established in the variable initialization file.

The modes in the model are incorporated similarly to the terrains, using a matrix where columns represent the modes and rows represent the auxiliaries. The matrix is filled with values representing the utilization rate of each auxiliary. A value of 1 indicates that the auxiliary is consuming its nominal power, a value of 0 means it is inactive, and a value of 1.2 indicates it is consuming 120% of its nominal power.

Auxiliaries that are not continuously used, such as firing or radar, are included in the matrix but managed differently through the presence of "events" in the mission profile. These events indicate when specific auxiliaries consume power for a determined duration.

To prioritize the auxiliaries in case of excessive power demand, a prioritization matrix is provided as well. Its columns represent the different modes, and its rows represent the auxiliaries. It is filled with zeros (non-prioritized auxiliary) and ones (prioritized auxiliary).

This approach allows for the modeling of various operating modes and the associated utilization rates of the vehicle's auxiliaries. It provides flexibility in simulating different scenarios and power demands, ensuring realistic behavior, and capturing the impact of auxiliary usage on the overall system performance.

4.4. Traction chain

The powertrain model links the traction components to the vehicle-ground interaction. Powertrain is controlled through a torque set of signals coming from the command center, which holds the strategy, all the command rules and command controllers for the various powertrain components.

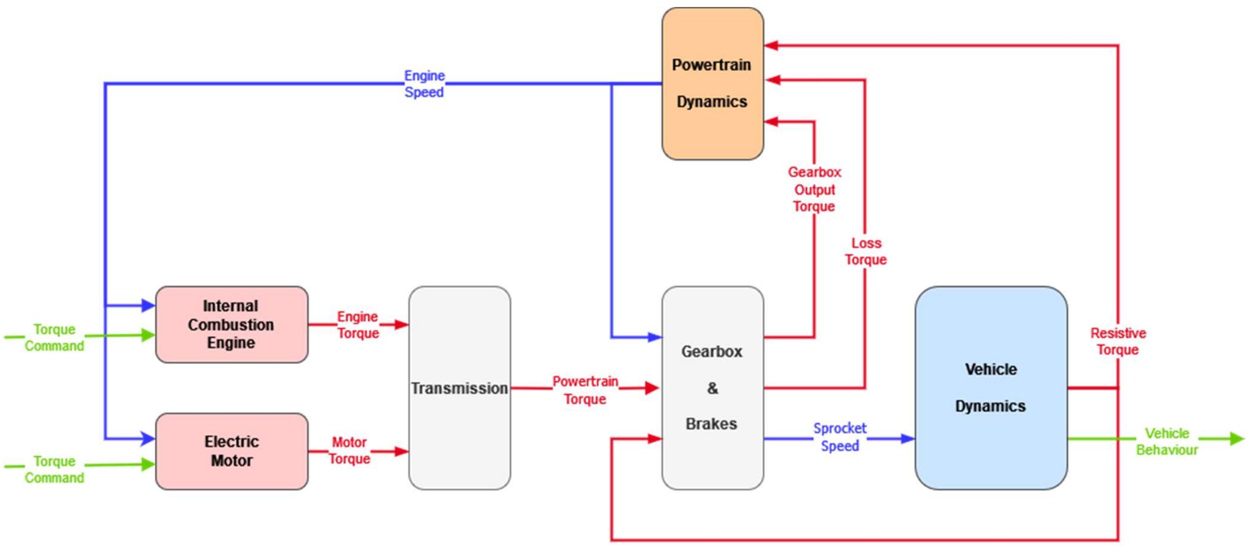


Figure 9 Powertrain configuration & Set-up

We obtain the state of the various organs through a dynamic feedback loop, centered around the gearbox behavior, which links sprocket speed to engine speed through dynamics equations:

$$\sum Torque = J_i * \frac{dw}{dt}$$

J being the inertia of the ensemble (in kg.m²) and w the rotational speed of said ensemble

The ICE and electric motors are modeled using empiric maps taken from their "real" counterparts. The model is precise enough to consider the organ's dynamic responses, depending on the torque commanded by their respective controllers. The combustion engine boost model is also technology-dependent, allowing for various response-time curves depending on the boost technology implemented within the model (Turbo, Bi-Turbo, eTurbo, etc.).

The transmission works as a gearset who links the power between the various engines and motors together, as the chosen hybridization configuration does not allow for an uncoupling of the engine and motors.

The gearbox is vehicle-specific, as it handles both the propulsion and steering, through differential-drive system: power is split to the outputs, at various speeds, allowing for a vehicle turning radius (speed variation between the two sprockets at a given speed), up to a “pivot” position (both sprocket speeds have opposite signs, allowing for the vehicle to rotate on itself)

The brakes are modeled similarly to regular vehicles, through a disk/pad combo, with the braking torque commanded as a brake pressure command. The brakes are located after each gearbox output and are activated once the driver hits the brake pedal, using brake blending controls: all the powertrains’ components capable of slowing the vehicle down are activated (engine through engine braking, electric motors for regenerative breaking, and brakes), in order to have a vehicle deceleration that matches the command, and regenerating as much energy as possible.

4.5. Forces

To determine the vehicle’s behavior, a Simulink bloc is calculating the forces applied to it. With Newton’s second law, it is then possible to compute the longitudinal and lateral accelerations and the angular acceleration. Therefore, by integrating on each step, the speed, orientation, and position of the vehicle at the next time step are determined.

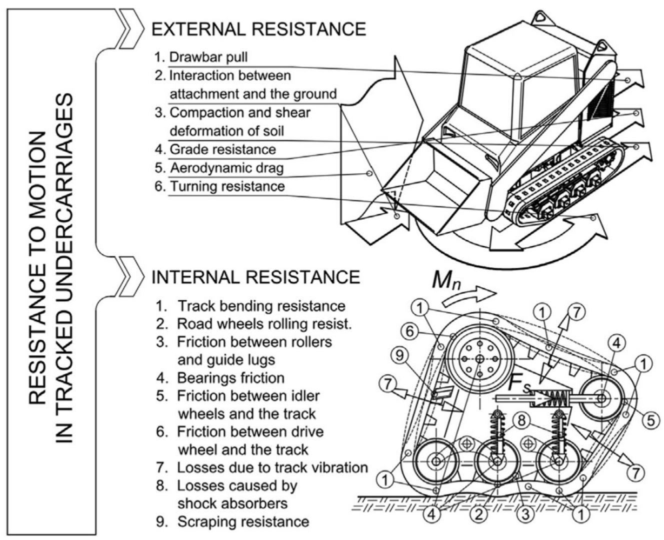


Figure 10 Resistance force diagram

Forces acting on the vehicle are either applied directly to its center of gravity or are acting on the tracks [14], [15]. In the first category are the aerodynamic drag and the slope, both longitudinal forces:

$$F_{slope} = -Mgsin(\alpha) \qquad F_{aéro} = -\frac{1}{2}\rho SC_x v^2$$

With M, SCx, v the vehicle’s mass, aerodynamic surface and speed, ρ the air density, α the slope and g the gravity.

Forces acting on the track are the most interesting in this study. There are three contributions: the action of the terrain on the track, the resistance due to parts in motion, and the soil compaction when the vehicle is advancing on soft terrain.

The internal resistance is determined by the speed of the vehicle and type of tracks. It can be expressed as follows:

$$F_{res,int} = -C_R(v).M * g = -(C_{R0} + A_1 v + A_2 v^2).M * g$$

Where A_1, A_2, C_{RO} are specific to the vehicle. Values can be found in the literature for the most common track types.

The compaction of the soil is resistive, and determined using Bekker-inspired theories, that are part of the “terramechanics” mainly theory developed by Jo Yi Wong in the 1970s [16], [17], [18]. It can be expressed as follows:

$$\overrightarrow{F_{compaction}} = -b * z * (\tan(\phi) + \tan(\delta)) * p(x_{sprocket})\vec{x}$$

Where b is the track width, δ its angle of attack, $p(x_{sprocket})$ the pressure on the track, ϕ the angle of internal friction of the soil. The track sinkage z is dependent of the pressure applied by the vehicle on the soil via the track, and of the track slip ratio:

$$z = \frac{1+i}{1-0.5i} * \left[\left(\frac{k_c}{b} + k_\phi\right)^{-1} p(x_{sprocket})\right]^{\frac{1}{n}}$$

k_c, k_{phi}, n are coefficients of the ground detailed by Bekker in his theory.

Last but not least, the action of the track on the soil is limited by the soil ability to withstand shear forces without displacement, and therefore apply an opposite force on the track that will propel the vehicle forward. This phenomenon is represented in the formula giving the longitudinal and lateral forces acting on the track, as well as the moment of resistance around the z axis linked to them.

$$F_{shear,x} = \int dF_x = \int_{-\frac{b}{2}}^{\frac{b}{2}} \int_{-\frac{L}{2}}^{\frac{L}{2}} [c + p(x_t, y_t) tan\phi] \left(1 - e^{-\frac{j(x_t, y_t)}{K}}\right) \frac{v_{jx}(x_t, y_t)}{v_j(x_t, y_t)} dx_t dy_t$$

$$F_{shear,y} = \int dF_y = \int_{-\frac{b}{2}}^{\frac{b}{2}} \int_{-\frac{L}{2}}^{\frac{L}{2}} [c + p(x_t, y_t) tan\phi] \left(1 - e^{-\frac{j(x_t, y_t)}{K}}\right) \frac{v_{jy}(x_t, y_t)}{v_j(x_t, y_t)} dx_t dy_t$$

$$M_{shear,z} = \int x_t dF_y = \int_{-\frac{b}{2}}^{\frac{b}{2}} \int_{-\frac{L}{2}}^{\frac{L}{2}} [c + p(x_t, y_t) tan\phi] \left(1 - e^{-\frac{j(x_t, y_t)}{K}}\right) \frac{v_{jy}(x_t, y_t)}{v_j(x_t, y_t)} \mathrm{x_t} dx_t dy_t$$

Here, c, K are the ground cohesion and the characteristic displacement of its plastic behavior. v_{jx}, v_{jy}, v_j are values calculated from the track and vehicle speed, and their ratio represent a pseudo-drift angle, used to project the forces on the x and y axis. $j(x_t, y_t)$ is the shear displacement of the soil under the track. L is the length of the track.

With all the forces, Newton’s second law applied to the tank center of gravity is written:

$$m_{eq} a_x = F_{comp,l} + F_{comp,r} + F_{shear,x,l} + F_{shear,x,r} + F_{aero} + F_{res,int} + F_{slope}$$

$$m_{eq} a_y = F_{shear,y,l} + F_{shear,y,r}$$

$$I_z \dot{\omega} = (F_{shear,y,l} + F_{shear,y,r}) L_x + \frac{B}{2}(F_{shear,x,r} - F_{shear,x,l}) + M_{shear,z,l} + M_{shear,z,r}$$

Where I_z is the vehicle moment of inertia, L_x the displacement of the center of gravity on the x axis, B the vehicle width, a_y,a_x, $\dot{\omega}$ the accelerations and yaw rate.

5. Strategy

The hybridization strategy consists in finding the most fuel-efficient way of getting from point A to point B. This involves several options: the eco route, which consists in finding the most energy-efficient route; the eco driving strategy, which consists in finding the most energy-efficient driving strategy; and finally, the distribution of torque between the electric motors and the internal combustion engine to achieve optimum fuel consumption over the entire route, while keeping the battery's state of charge within predefined limits - the energy management strategy. In the rest of this report, we will focus on the last option.

In a parallel hybrid vehicle, the required torque can be provided by the combustion engine, the electric motor, or a combination of both. The aim of the hybridization strategy is to distribute power control to satisfy the energy management strategy. This strategy takes as input a torque command calculated here from pedal pressure, and from the state of the vehicle and batteries calculates the torque distribution. [19], [20]

5.1. Different energy management strategies

Strategy for the control of HEV	Causality	Causal
		Non causal
	Optimality	Heuristic
		Optimal

Table 1 Hierarchy of the different type of strategy

The hierarchy of the different energy management strategy methods is shown in Table 1.

If the torque command is decoupled from the strategy, this is a so-called causal control method. In this case this form of strategy only considers past and present information. There is no information about the rest of the path or about future conditions. Non-causal methods optimize using information about the entire trip. Because of their complexity, they are known as offline methods, as they cannot be calculated in real time, whereas causal methods are known as online methods.

Strategies can be divided into two groups: rule-based and model-based optimization methods.

Rule-based methods

Rule-based methods are based on a set of rules to be applied to determine the value of the controller at each point in time. These rules are derived from the analysis of human behavior or from experiments, for example. These are known as heuristic methods. These methods are very efficient in real time and robust. An example of such a rule is to use the internal combustion engine only when its efficiency is very high; in other cases, purely electric propulsion is used. These methods can be divided into two other categories: deterministic methods and fuzzy logic methods [21].

The deterministic method compares input values with threshold values, and from these comparisons a reference setpoint is identified. These are Boolean expressions that lead to a specific type of use. For example, if the SOC is below a threshold value and the efficiency of the internal combustion engine is high, i.e., above a threshold value too, then the vehicle will use internal combustion propulsion only. With this type of method, the vehicle modelling required is simple, and the calculations are quite simple and fast. However, with this type of method, the model is not optimal, and the results will not be optimal either. Furthermore, the rules are applicable to a particular driving cycle or route and will therefore not necessarily be applicable to a different route, leading to inaccurate results.

One could upgrade upon this last method using fuzzy-logic method. This method is based on the same principle as the deterministic method, but instead of a simple Boolean being a value of 0 or 1, the value is in a range between 0 and 1. With this method, the response is more continuous. The torque supplied by the combustion engine increases progressively as the SOC decreases, whereas with the previous method, once a certain threshold has been passed, the vehicle switches directly to internal combustion only mode.

Model-based method

In model-based optimization methods, a cost minimization function is used over a known and fixed driving cycle to calculate the optimal set of variables. Because of their complexity, these methods cannot be used directly for real-time implementations [19], [22], [23], [24].

Several algorithms can be used to obtain solutions to this optimization problem, such as those listed below:

- Pontryagin's minimum principle
- Dynamic programming
- Genetic algorithm
- ...

Dynamic programming and Pontryagin's minimum principle are frequently used to manage the hybridization strategy of hybrid vehicles, as they can be used in real time/online with sufficiently precise and optimal results.

For numerical optimization methods (dynamic programming, genetic algorithms, etc.), the entire driving cycle is considered. The global optimum is found numerically. Dynamic programming makes it possible to implement non-linear behavior and limits, but requires an important level of computational complexity, especially with a high-dimensional system. Genetic algorithms use population generation to determine the optimum but require a high number of iterations to gain precision, which is not compatible with real-time control.

In contrast, analytical optimization methods (Pontryagin's minimum principle, equivalent consumption minimization strategy) use an analytical formulation to speed up numerical solutions. They enable causal online control but remain sub-optimal.

5.2. Context and choice

5.2.1 Context

The hybridization strategy was defined in several stages. The subject of this internship has several unusual aspects, which had to be considered and a specific strategy had to be found for each of these aspects. For example, this hybridization subject has the particularity of having two electric motors in addition to the combustion engine. Moreover, the power required for the vehicle to function properly is relatively high, as many auxiliaries are used in this type of vehicle. Finally, the operating mode varies greatly depending on the mission profile. During battle phases, for example, a large number of auxiliaries are activated.

During the previous project on this subject, the decision was made to adopt a rule-based strategy with target SOCs. For example, recharging began when the battery SOC fell below 50%. The target SOCs were defined according to the state of the vehicle (propulsion phase (Figure 11), stationary phase excluding silent watch, silent watch phase). For the propulsion phase, target SOCs separated the cases of purely thermal propulsion and hybrid propulsion, as well as the cases of slow or fast recharging. In practical terms, this strategy was modelled in MATLAB using state diagrams.

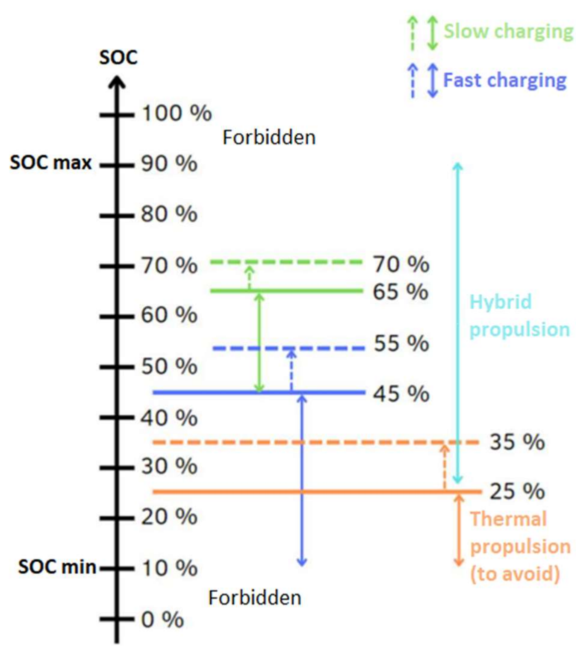


Figure 11 Diagram of the strategy by target SOC for propulsion of the 2022 internship

For this year's project, a new strategy had to be developed in order to obtain more optimal results, more suited to the different conditions of use and with the aim of improving consumption gains.

5.2.2 Choice

After a review of the state of the art on the various hybridization strategies presented above, the following methods were studied:

- Rule based
- Model based: ECMS/PMP
- Model based: Dynamic programming

The Dynamic Programming method produces optimal results, but it is impossible to use them in real time since it is too costly computationally.

The Rule Based method is quick and easy to implement but is highly path dependent. Optimization is therefore not possible on unknown routes. In addition, as mentioned in the previous section, optimization is highly dependent on calibration.

The strategy for minimizing energy consumption, ECMS, offers the best compromise in terms of performance and computing time. This strategy is derived from Pontryagin's minimization principle. The solutions are sub-optimal, but calibration produces results close to those of the Dynamic Programming method. Computation times are slow, but still allow real-time online processing. Moreover, this method is flexible and can be adapted to different routes.

Given the particular application of the hybridization strategy (multiple routes, modes, field, etc.) and the need for real-time simulation, the best compromise is to use the ECMS. There are several variants of this method [19], [23], [25]. These are listed below:

- ECMS
- Adaptative ECMS
- VSP ECMS (variable shift pattern)

These methods are all used to calculate a minimum instantaneous energy consumption based on the components.

For the classic ECMS, the equivalence factor is calibrated according to the vehicle and its characteristics. This method depends on the vehicle and the route. With adaptive ECMS, on the other hand, the equivalence factor is modified by a PI controller. This means that optimization is possible for an unknown route. Finally, for the VSP ECMS, the equivalence factor is adapted by controlling the gearbox according to consumption. However, in the context of this course, it is not possible to control the gearbox because it is represented by a black box supplied by the company which manufactures the gearboxes for the tanks. The company therefore keeps control of the gearbox.

Given the constraints imposed by this project, the "Adaptive ECMS" method was naturally selected.

Moreover, it has been decided that the strategy will be use-case dependent (for example: charge sustaining type for “road” mode and charge depleting during “combat” mode). This in order to use the full potential of the batteries and increase the performances of the vehicle in “combat” mode while maintaining a good state of charge in the first phase (“road” mode) and returning to the initial state of charge in the last phase (“road” mode).

5.3. Modeling

A first version of the strategy was implemented in order to run the first simulations. This version uses the MATLAB/Simulink "ECMS" module, with a few modifications to the input data. Indeed, this module was created with the objective of minimizing fuel consumption by distributing the torque setpoints between an internal combustion engine and an electric motor. The mapping has been adjusted to act as if there were two identical motors working simultaneously.

Several modifications and improvements were made to the ECMS in order to match the subject as closely as possible and achieve the best possible optimization: this version takes three motors into account in the calculation: two electric motors and one internal combustion engine, it also allows to be dependent of the different modes and use-cases. The model also allows batteries to be used over wider SOC ranges, which was impossible with the ECMS block supplied by MATLAB (SOC_{min} constraint of 0.2 for example). Moreover, depending on how the vehicle is used, the target state of charge setpoint varies. This makes it possible to have a case of significant use of the battery in modes where performance is a priority, and a case of maintaining the battery in other modes.

In the following, the different modes provided by the mission profile have been divided into two categories:

Case 1: Performances	Case 2: Maintaining the state of charge of the battery
M3 “watch”; M4 “silence watch”; M6 “furtive idle speed”; M7 “combat”; M9 “leap forward”; M10 “erratic operation”	M1 “short stop”; M2 “long stop”; M5 “Idle” ; M8 “road”

Table 2 Repartition of the different modes for hybrid strategy

In addition, as the global model is overly complex and requires a fairly long calculation time, particular attention was paid towards optimizing the computations and the model in order to reduce the calculation time. After refining the model, a 48% saving in calculation time was observed between the pre-existing MATLAB ECMS block and the new block created for this project without reducing the performances of the block.

In optimization methods such as the one chosen for this project, the purpose is to minimize a predefined performance (fuel consumption in this study) measure as a function of a control variable and a state variable, as well as a series of limits [7], [19], [26]. The general form of the performance measure J is:

$$J(u) = \int_{t_0}^{t_f} g(x(t), u(t), t)dt$$

With x: the state variable, u: the control variable.

In our case, the previous equation takes the following form:

$$J = Q_{lhv}\int_{t_0}^{t_f} \dot{m}_f(T_{ICE}, \omega_{ICE})dt = \int_{t_0}^{t_f} P_{fuel}(T_{ICE}, \omega_{ICE})dt$$

With $\dot{m}_f$: the fuel mass flow, $P_{fuel} = Q_{lhv}\dot{m}_f$: the power equivalent to the fuel flow rate.

The performance to be minimized is the total fuel consumption of the combustion engine. The setpoint torque required, taking into account the gearbox ratio T_{gb}, corresponds to the sum of the torques supplied by the three engines (T_{ICE}, T_{ME} $, T_{ME}$).

$$T_{gb} = T_{ICE} + T_{ME1} + T_{ME2}$$

Fuel power, which is proportional to fuel consumption, is a function of torque and engine speed, and is calculated from vehicle speed, torque control and the torques of the electric motors.

$$P_{fuel} = Q_{lhv}\dot{m}_f(T_{ICE}, \omega_{ICE}) = P_{fuel}(T_{gb}, T_{ME}\ , T_{ME}\ , v_{ve}\ )$$

The battery power is defined as the sum of the electrical power required by the electrical motors in order to produce the torque T_{ME} at speed ω_{ME}.

$$P_{batt} = P_{ME1}(T_{ME}\ , \omega_{ME1}) + P_{ME2}(T_{ME2}, \omega_{ME}\ )$$

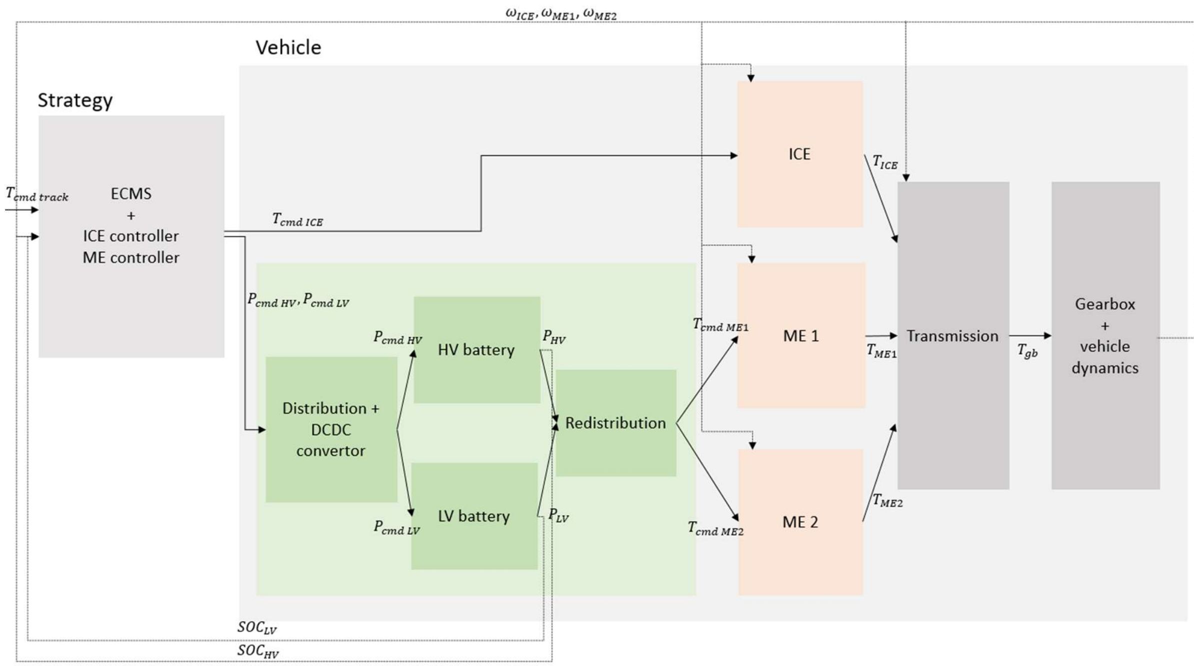


Figure 12 Schematic of the variables' integration in the hybrid strategy and cinematic of the vehicle

Obviously, all the variables presented previously must remain within predefined limits. These limits are as follows:

$$T_{ICE,min}(\omega_{ICE}) \leq T_{ICE} \leq T_{ICE,max}(\omega_{ICE})$$

$$T_{ME\ \ ,min}(\omega_{ME1}) \leq T_{ME1} \leq T_{ME\ \ ,max}(\omega_{ME}\ )$$

$$T_{ME\ \ ,min}(\omega_{ME}\ ) \leq T_{ME2} \leq T_{ME\ \ ,max}(\omega_{ME2})$$

$$P_{batt,min}(SOC) \leq P_{ME}\ + P_{ME}\ \leq P_{batt,max}(SOC)$$

$$SOC_{mi}\ \leq SOC(t) \leq SOC_{max}$$

$$\omega_{ICE,min} \leq \omega_{ICE}(t) \leq \omega_{ICE,max}$$

$$\omega_{ME1,min} \leq \omega_{ME}\ (t) \leq \omega_{ME\ \ ,max}$$

$$\omega_{ME2,min} \leq \omega_{ME2}(t) \leq \omega_{ME\ \ ,max}$$

There are also boundary conditions such as:

$$SOC(t_0) = SOC(t_f) = SOC_{init}$$

$$t_0 = 0 \; et \; t_f = T$$

With T, the mission duration.

In order to determine the torque distribution that minimizes fuel consumption, the Pontryagin's minimum principle was used. This method, based on the calculation of variations, seeks to determine the global extremums of a function. In this case, it is the minimum of the performance measure, i.e., overall fuel consumption. The Hamiltonian function is used to find the conditions that minimize the reference function in which the Lagrange multiplier is used.

The Hamiltonian for this type of method has the following form:

$$H(x(t), u(t), \lambda(t), t) = L(x(t), u(t), t) + \lambda(t)^T [f(x(t), u(t), t)]$$

With L representing the instantaneous cost, f representing the dynamic equation and λ the optimization variables vector/the Lagrange multiplier. The function f verifies:

$$\dot{x}(t) = f(x(t), u(t), t)$$

According to Pontryagin's minimum principle, if u^* is the optimal control, it is minimizing the Hamiltonian and so it verifies:

$$H(x^*(t), u^*(t), \lambda^*(t), t) \leq H(x^*(t), u(t), \lambda^*(t), t) \qquad \forall t \in [t_0, t_f]$$

(And for all admissible controls x and λ). Another condition, relating to the cost of the final state, is necessary but is verified in this type of problem because the time is fixed, and the final state of charge corresponds to the initial state of charge.

In the case studied, this Hamiltonian takes the form:

$$\begin{aligned} H\big(T_{ME} \ , T_{ME2}, E_{batt_{chem}}, T_{gb}, v_{ve} \ \big) & \\ &= P_{fuel}\big(T_{ME1}, T_{ME2}, T_{gb}, v_{ve} \ \big) \\ &+ \big(\lambda + w(SOC)\big) P_{batt_{chem}}(T_{ME} \ , T_{ME} \ , E_{ech}, v_{ve} \ ) \end{aligned}$$

With: w a penalty factor only activated when the previously defined limits are not respected.

The selected torques are those who are minimizing the previous function. So, we are searching for:

$$\frac{\partial H}{\partial P_{bat_{chem}}} = 0 \; or \; \frac{\partial H}{\partial E_{bat_{chem}}} = \dot{\lambda}$$

$$\dot{\lambda}\big(T_{ME1}, T_{ME} \ , E_{ba \quad chem}, v_{veh}\big) = -\frac{\partial H}{\partial E_{batt_{chem}}} = -\lambda \frac{\partial S\dot{O}C(P_{batt_{chem}}, SOC)}{\partial SOC}$$

The variation of the state of charge of the battery for a simple RC model is defined as follow:

$$S\dot{O}C = -\frac{1}{\eta_{coul}^{sign(I(t))} Q_{nom}} \left[\frac{V_{oc}(SOC)}{2R_0(SOC)} - \sqrt{\left(\frac{V_{oc}(SOC)}{2R_0(SOC)}\right)^2 - \frac{P_{batt}}{R_0(SOC}} \right]$$

$$E_{batt_{chem}} = E_{batt}(SOC(t_0) - SOC(t))$$

$$\dot{E}_{batt_{chem}} = P_{batt_{chem}} = -E_{batt_{chem}}\dot{SOC}$$

In practical application, in the MATLAB model, H takes the following form:

$$H = P_{fuel} + s * p * P_{batt} + Penalty_{limit} + Penalty_{P_{err}} + \Delta P_{ICE}$$

In the case of adaptive ECMS, s has a proportional integral form.

$$s = s_{init} + K_p\left(SOC_{target} - SOC(t)\right) + K_i\int_0^t (SOC_{target} - SOC(\tau))d\tau$$

$$p = 1 - \left|\frac{SOC - SOC_{target}}{(\frac{SOC_{max} - SOC_{min}}{2})}\right|^a$$

In these expressions, the SOC_{target} depends on the use case presented in Table 2. In addition, the $Penalty_{limit}$ and $Penalty_{err}$ values are penalties activated only when the limits mentioned above are not respected for the first and when the torque at the track supplied does not correspond to the torque at the track requested for the second. For ΔP_{ICE} the error between the previous and the new engine torque value is calculated.

Finally, the block modelling takes the following form:

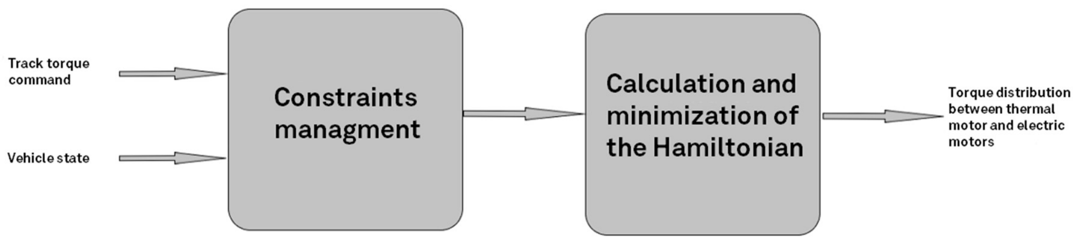


Figure 13 Schematic diagram of the ECMS overall functioning

5.4. Calibration

In order to calibrate the parameters of the ECMS model, an experimental plan was designed [27], [28]. The aim was to study the influence of proportional gain, integral gain and the weight factor of the adaptive ECMS on SOC variation, simulation time and fuel consumption gains. For each parameter studied, a range of values is established. For example, we have $s \in [s_{min}; s_{\max}]$. In the following, s_{min} and s_{max} will be referred to as the low and high levels of s and will be represented by -1 and 1 respectively. In this case, there are 2^3 combinations of the parameter values studied. These combinations are shown in Table 3. This method can also be used to check or highlight interactions between the various parameters.

Run	A: Kp = Proportional gain	B: Ki = Integral gain	C: s = Weighting factor	AB	BC	AC	ABC
1	-1	-1	-1	1	1	1	-1
2	1	-1	-1	-1	1	-1	1
3	-1	1	-1	-1	-1	1	1
4	1	1	-1	1	-1	-1	-1
5	-1	-1	1	1	-1	-1	1
6	1	-1	1	-1	-1	1	-1

7	-1	1	1	-1	1	-1	-1
8	1	1	1	1	1	1	1

Table 3 Design of experiments for the ECMS calibration

This experimental plan was applied in two types of situations: a "liaison"-type situation in which maintaining the charge is the priority, and a combat-type situation in which performance takes the priority and therefore charging the battery is not a main priority.

Interpretation of the results for the "liaison" type situation

Run	A: Kp = Proportional gain	B: Ki = Integral gain	C: s = Weighting factor	AB	BC	AC	ABC	dSOC
1	-1	-1	-1	1	1	1	-1	y_1
2	1	-1	-1	-1	1	-1	1	y_2
3	-1	1	-1	-1	-1	1	1	y_3
4	1	1	-1	1	-1	-1	-1	y_4
5	-1	-1	1	1	-1	-1	1	y_5
6	1	-1	1	-1	-1	1	-1	y_6
7	-1	1	1	-1	1	-1	-1	y_7
8	1	1	1	1	1	1	1	y_8
	a_1	a_2	a_3	a_4	a_5	a_6	a_7	

The constants a_i are obtained as follows:

$$a_1 = \frac{y_1 - y_2 + y_3 - y_4 + y_5 - y_6 + y_7 - y_8}{8}$$

$$a_2 = \frac{-y_1 - y_2 + y_3 + y_4 - y_5 - y_6 + y_7 + y_8}{8}$$

$$a_i = \frac{1}{8} * \sum_{1}^{8} sign(column_i) * y_i$$

The ANOVA method was used to study the different repetitions of this experimentation design. In order to respect the rules of the experimental methods, each combination/experiment was repeated three times. In addition, these experiments were carried out randomly. Based on the a_i factors, the effects and interactions of the various parameters were investigated.

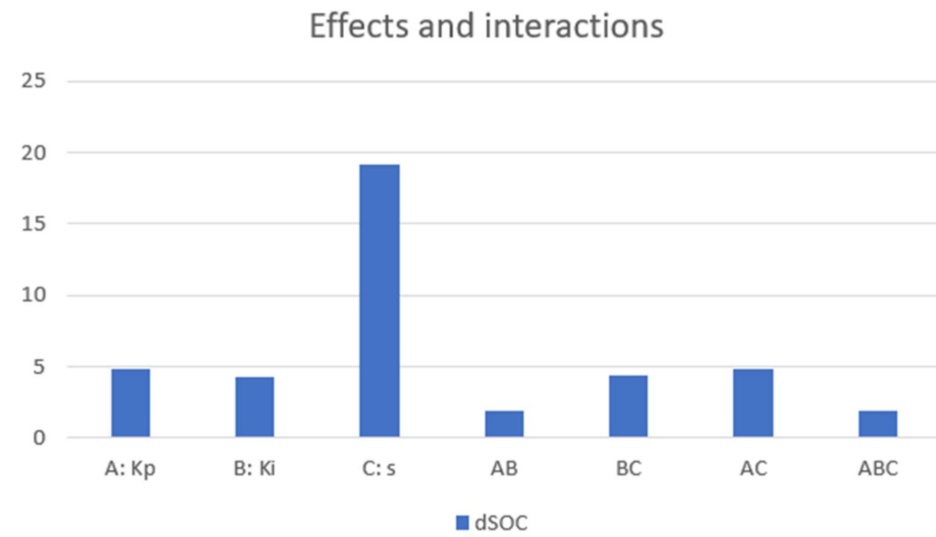


Figure 14 Effects and interactions of the studied parameters

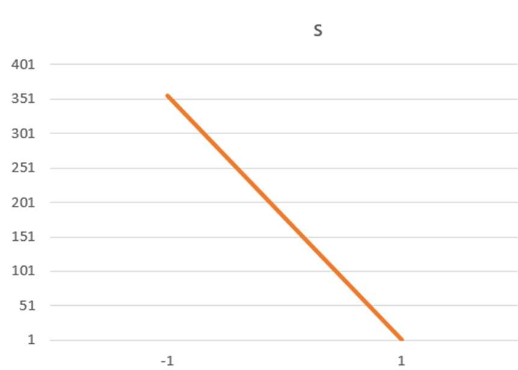
We can observe that the initial value of the weighting factor has the greatest influence on the obtained results. We also note that the interactions between the different parameters are weak. This implies that the choice of one parameter has little to no impact on the others, which could be useful later on.

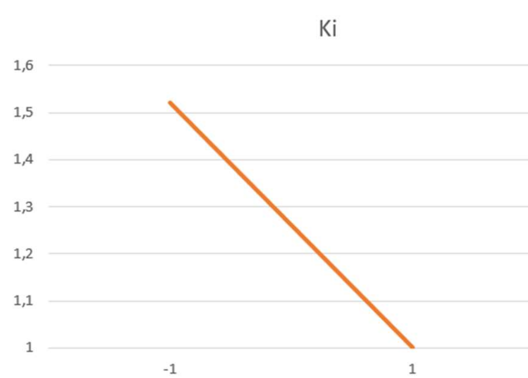
After this step, it is possible to study the impact of the value of each parameter on the studied element. For every parameter, the variation of SOC as a function of the parameter value is calculated as follows:

$$A(-1) = \frac{y_1 + y_3 + y_5 + y_7}{4}$$

$$A(1) = \frac{y_2 + y_4 + y_6 + y_8}{4}$$

The values corresponding to the high level (+1) and the low level (-1) were normalized by the minimum value in order to study the influence of each value. The results obtained for the study of the variation in the state of charge are as follows:





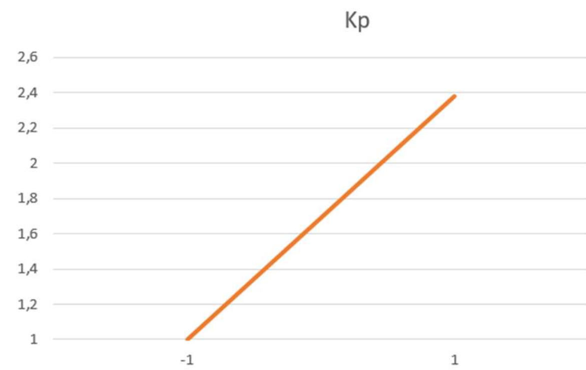


Figure 15 Principal effects of the studied parameters

To obtain a more precise result than reading these graphs, a MATLAB optimization program was created to obtain the parameters needed to minimize fuel consumption, the variation in the state of charge and to reduce the difference between simulation time and real time.

This method minimizes the following function:

$$f = a_1 * x_1 + a_2 * x_2 + a_3 * x_3 + a_4 * x_1 * x_2 + a_5 * x_2 * x_3 + a_6 * x_1 * x_3 + a_7 * x_1 * x_2 * x_3$$

The a_i are the parameters obtained above, and the x_i are the parameters we are seeking to optimize.

As the set of optimization parameters is different for each criterion, it has been decided that for the “road” mode the priority criterion is to maintain the battery's state of charge and therefore minimize the variation of the SOC.

The program used to find the parameters minimizing the variation in the battery's state of charge gives the following levels: $\mathrm{s} = 0.95$; $\mathrm{K_p} = 0.75$; $\mathrm{K_i} = -1$.

Results for the combat type situation

In a battle situation, the battery can be used over a wider range of state of charge values. Consequently, in this situation, minimizing fuel consumption is a priority.

As Figure 16 shows, the effects and interactions of the different parameters are similar. However, Figure 17 shows that for each parameter the values used to minimize fuel consumption are not the same.

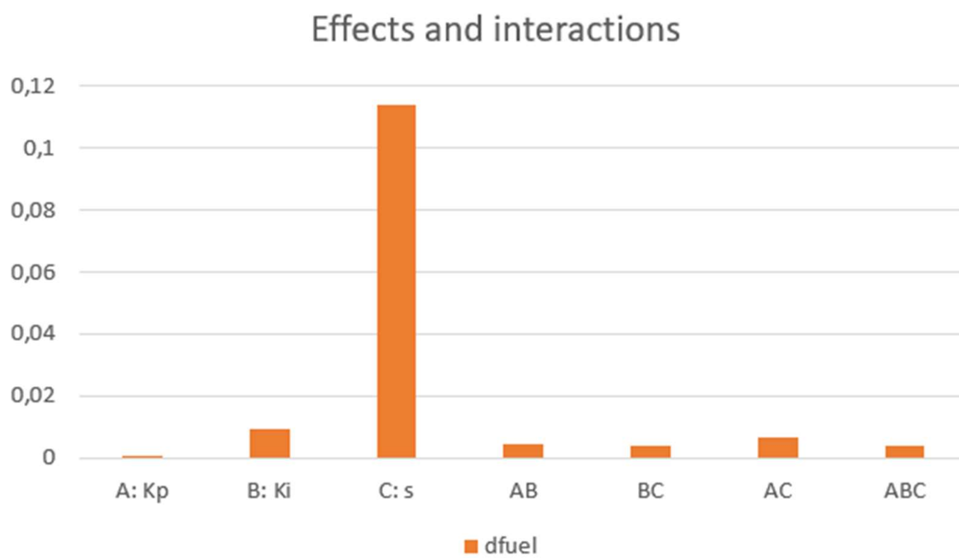


Figure 16 Effects and interactions of the studied parameters in combat mode

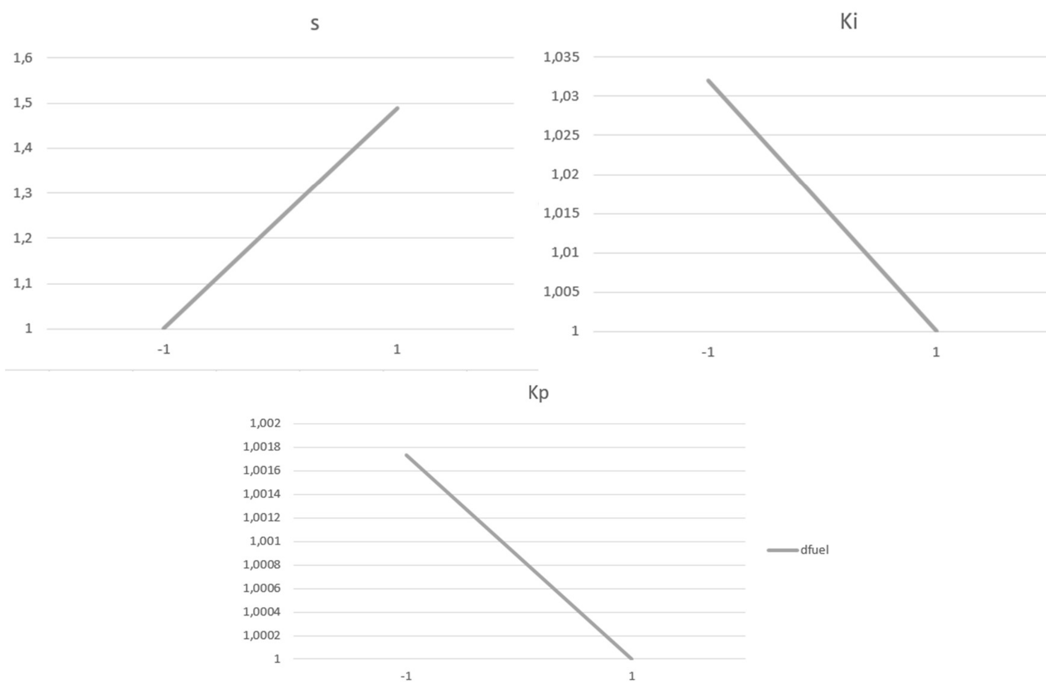


Figure 17 Principal effects of the studied parameters in combat mode

The program used to find the parameters that minimize fuel consumption gives the following normalized levels: $s = 0.7$; $K_p = -1$; $K_i = 1$.

As the results used to optimize the strategy were different for liaison mode and combat mode, the strategy block was modified to change the parameters according to the mode of use given as a setpoint in the mission profile.

5.5. Other parts

In the MATLAB block corresponding to the hybridization strategy, in addition to the ECMS block itself, we find upstream the regenerative braking management block and the block for the conversion of the accelerator pedal control signal into control torque for the ECMS.

There is also a block for the power calculation for each auxiliary and the extraction of a power command for the batteries. This block calculates the priority and non-priority power required for the high voltage and low voltage batteries as a function of the mode reference and the prioritization, network information and percentage of use corresponding to each mode. All the auxiliaries have a constant consumption, except for air conditioning, whose percentage of use depends on the mode. In addition, for the firing function, the power is constant during the usage phase, which is of short duration.

Generally speaking, the goal is to anticipate future needs and improve the model in the years to come. An event command is transmitted from the mission profile in order to take into account auxiliaries that operate in a similar way to the firing function. This setpoint sends a strictly positive value power for a predetermined duration when a particular event is required. This power is considered to be a priority power. The addition of UGV recharge power has also been handled in this way.

6. Batteries

As Arquus had already worked on the development of a battery pack for the hybridization of the Griffon [9], it was specified that in the case of tank hybridization the same pack should be used. A compliance table and technical data were provided by a supplier (pack maker). In addition, data for one cell was provided by Arquus.

6.1. Evolution of the project from the last version

In the work carried out prior to this internship, the choice was made to use three batteries. The High voltage battery was sized with seven packs to power the two electric motors and the following auxiliaries: Air conditioning, firing function, turret mobility and gun stabilization.

The low voltage battery was used to power the remaining auxiliaries (on-board electronics, communication, observation, passive protection, active protection, drones, etc.). Finally, the 48V battery powered the e-turbo and was used to meet peak power requirements during start-up.

The aim of this year's project was to refine the sizing of these batteries. However, during the course of the project it was decided to choose an e-turbo that could be powered by the high voltage battery. This decision was taken in order to be able to remove the 48V battery, which would reduce the overall dimensions and also reduce losses. In fact, in the last year project configuration, power was exchanged between the different batteries via three DCDC converters, which enabled them to maintain their state of charge.

Following this decision, we had to resize the high voltage and low voltage batteries so that they could meet the power demands of the various auxiliaries, supply the motors and handle power peaks.

As far as the auxiliaries are concerned, in addition to those considered in the previous work, it was decided to add an induction recharging plate enabling UGVs to be recharged.

In the PFE 2022, the architecture was built up as follows: firstly, a calculation of the power required by the auxiliary devices, the calculation of the power required by the batteries, DCDC management, then a high voltage battery model in parallel with the low voltage and 48V battery model, and finally power redistribution.

For this updated version, the power calculation for the auxiliary devices and the calculation of the power required from the batteries have been transferred to the strategy section. The architecture chosen for the new model is shown in Figure 18. DCDC management and power distribution upstream of the high voltage and low voltage batteries are included, followed by a power redistribution block.

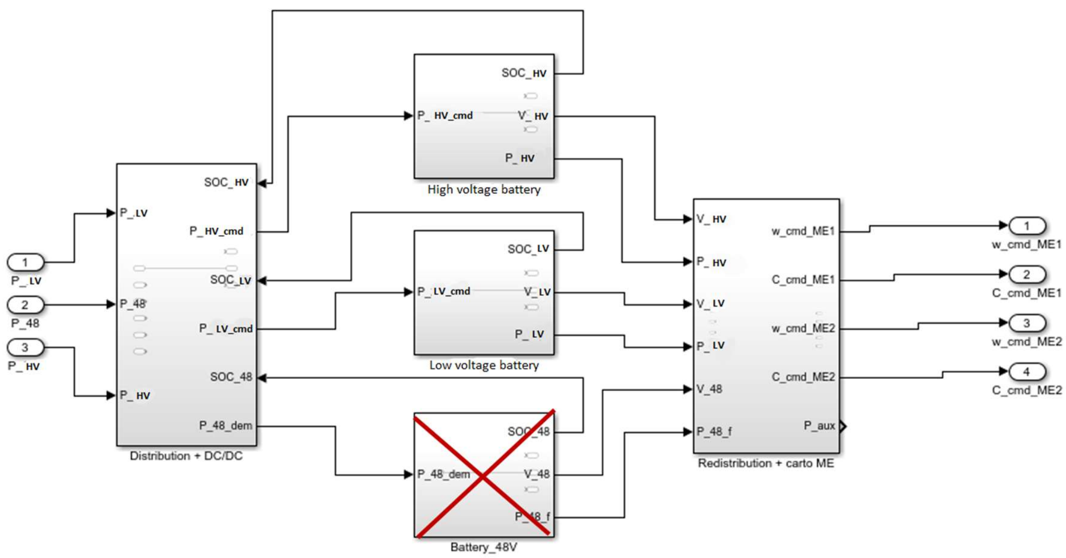


Figure 18 Diagram of the new batteries block in MATLAB Simulink

In Table 4 the network used by the auxiliaries are listed. The list of auxiliaries and the electrical grid used for each of them were determined based on what is currently present in tanks.

Auxiliaries	Grid
On-board electronics	LV
Climatization	HV
Communication	LV
Observation	LV
UGV	HV
Firring function	HV
Turret mobility	HV
Gun stabilization	HV
Passive protection	LV
Active protection	LV
Drones	LV

Others	LV

Table 4 Network for the use of the auxiliaries

6.2. Sizing and modeling of the High Voltage battery

6.2.1 Sizing

An important refine of the sizing and the modelling of the high voltage battery was necessary in order to improve the knowledge of the model and to gain in accuracy in the results of the simulation.

To achieve this purpose, the battery cell was modelized by a RC circuit more complex than the one used in the previous internship [29], [30] and with the following form:

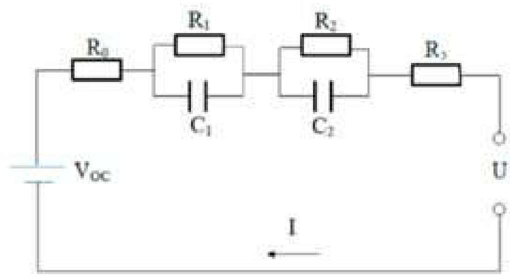


Figure 19 Schematic diagram of a battery cell

The formulas for the current and the voltage of the cell are:

$$I_{cell} = \frac{U_n}{R_n} + C_n \frac{dU_n}{dt}$$

$$\frac{dU_n}{dt} = \frac{I_{cell}}{C_n} - \frac{U_n}{R_n C_n}$$

$$U_n = \int_0^t \left[\frac{I_{cell}}{C_n} - \frac{U_n}{R_n C_n}\right] dt$$

$$U_{cell} = V_{oc} - I_{cell} R_0 - \sum_{n=1}^{2} U_n - I_{cell} R_3$$

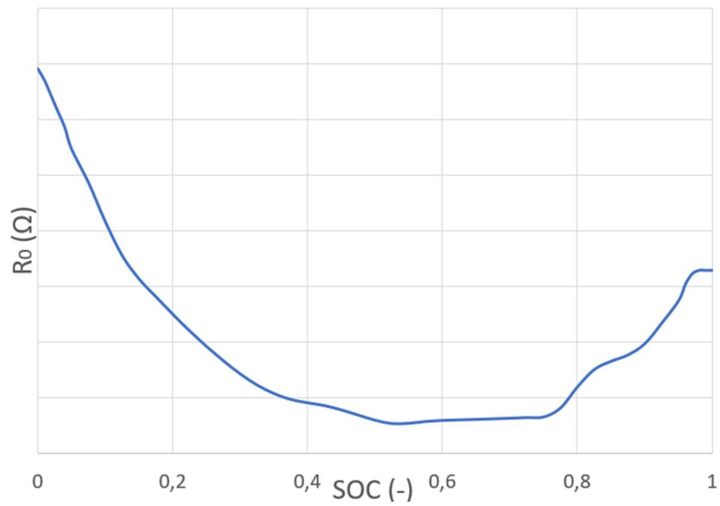


Figure 20 Battery internal resistance as a function of SOC (at 23°C)

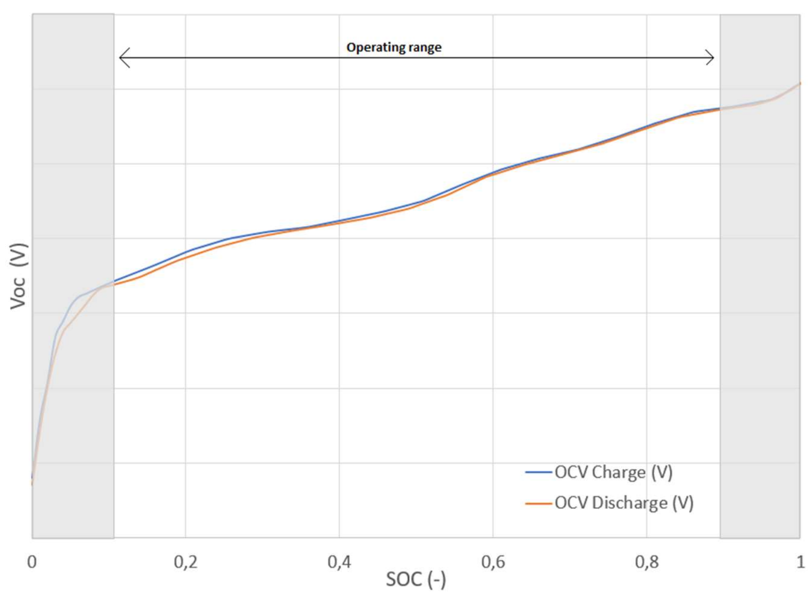


Figure 21 Battery open circuit voltage as a function of SOC and operating range (at 23°C)

The battery pack voltage is obtained by multiplying the cell voltage (Figure 21) by the number of cells in series, n_{cs} and the number of modules in series, n_{ms}. The value of the current is obtained by multiplying the cell current by the number of cells in parallel n_{cp}.

$$U_{HV} = U_{cell} * n_{cs} * n_{ms}$$

$$I_{HV} = I_{cell} * n_{cp}$$

If the resistances, other than R_0 (Figure 20), are neglected, the battery resistance is:

$$R_{HV} = n_{ms} * \frac{1}{n_{cp} * \frac{1}{n_{cs} * R_0}}$$

In order to calculate the evolution of the state of charge, the capacity is used and calculated with the following formula:

$$Capacity(t_n) = Capacity(t_0) + \int_{t_0}^{t_n} I_{HV} dt$$

$$SOC(t_n) = \frac{Capacity(t_n)}{Capacity_{total}}$$

Resistance and capacitance values were obtained from "lookup tables" providing these values from linear interpolations as a function of current, temperature and state of charge. The data tables feeding these modules were supplied by Arquus. To scale back to the sub-module or module level, the current and voltage are multiplied by a factor corresponding to the number of cells in parallel or series and the number of sub-modules in series. The SOC is then recalculated at module level.

CC-CV (constant current, constant voltage) charging has been implemented at module level to optimize battery charging while respecting the battery's voltage limitations.

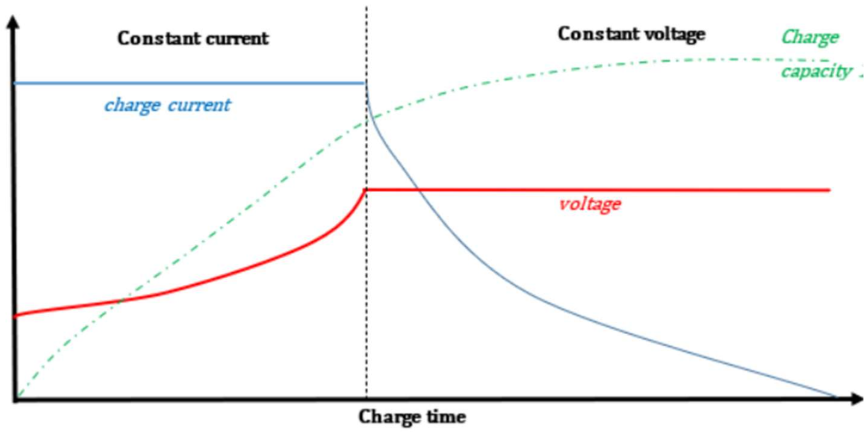


Figure 22 Charge of the battery at constant current followed by a charge at constant voltage (CC-CV)

Regarding the sizing of the battery, the addition of the e-turbo and the new auxiliaries had to be taken into account. A validation of energetic criteria and power criteria were done in order to determine the number of battery pack necessary for the good operation of the vehicle.

The battery had to verify two criteria. The first one is regarding energy. The HV battery has to power some auxiliaries (on-board electronic, climatization, communication and passive protection) during a four-hour silent watch.

$$C_{batt\_HV} = \frac{T_{autonomy} * P_{aux}}{(SOC_{max} - SOC_{\min}) * \eta_{inverter}} - C_{LV}$$

With C_{LV}, the capacity that can be transfer from the LV battery thanks to the converter DC/DC.

$$C_{LV} = C_{battLV} * DOD_{LV} * \eta_{DCDC}$$

With DOD_{LV} the depth of discharge ($SOC_{max} - SOC_{min}$)

The number of battery packs can be calculated as the capacity of a pack is provided by the manufacturer's data.

$$n_{pack} = \frac{C_{battHV}}{C_{pack}}$$

$$n_{pack} = 4$$

The second criteria for battery sizing is in terms of power. The battery must be able to power the two electric motors as well as the auxiliaries, whether in continuous or peak mode. In order to achieve a wide power sizing, we consider that the battery should supply the peak power of the motors while supplying the maximum power to all the auxiliaries at the same instant. In this case, the number of battery packs required is calculated using the following formula:

$$n_{pack} = \frac{n_{ME} * P_{\max\_ME} + P_{\max\_aux}}{\eta_{inverter} * P_{\max\_pack}}$$

$$n_{pack} = 5\ (for\ continuous\ power)$$

$$n_{pack} = 4\ (for\ peak\ power)$$

To meet all these criteria, the HV battery is made up of five elementary battery packs.

6.2.2 Modeling

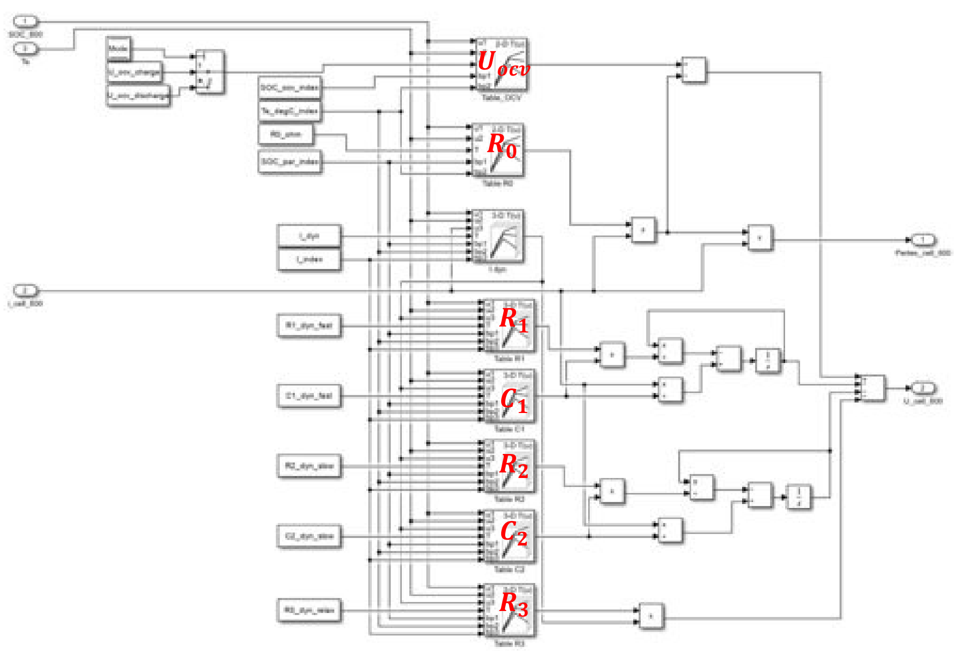


Figure 23 Modeling of a battery pack cell under MATLAB Simulink

A battery pack is modelled by the model of a cell to which the gains corresponding to the number of cells in series, in parallel and the number of modules is added in order to obtain the voltage and current of a pack from the voltage and current of a cell.

The cell model is shown in Figure 23. As mentioned previously, the cell voltage is calculated from matrices that provide resistances and capacitances as a function of current, SOC and temperature. Joule effect losses are also calculated to give an estimate of the battery's efficiency.

Upstream of the battery packs, a power limiter (representing the BMS) is modelled using a MATLAB function.

6.3. Sizing and modeling of the Low Voltage battery

To model the LV battery, which is a conventional battery, it was decided to use the MATLAB/Simulink "Battery datasheet" module. A power limiter was added upstream to limit the use of the battery to the predefined SOC range (i.e., 15-85%).

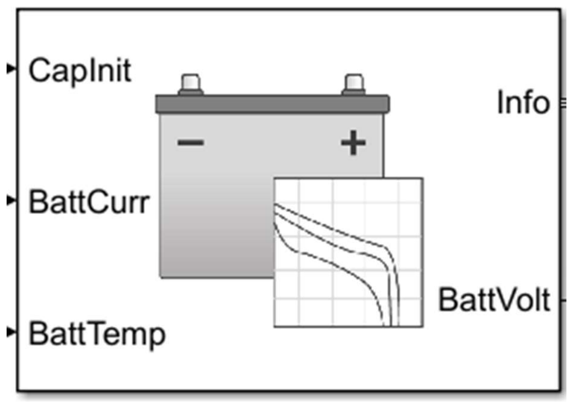


Figure 24 Block MATLAB "Datasheet Battery"

The LV battery was sized to meet a power performance requirement. The LV battery must be capable of simultaneously supplying power to the auxiliaries on this network with the associated level of prioritization.

This leads to the following sizing:

$$C_{batt\_LV} = \frac{P_{max}}{\tau_{decharge} * \eta_{onduleur}}$$

6.4. Power management

6.4.1 DC/DC convertor

The design of the DC/DC convertor is quite simple. It is modelized by a state of chart and a MATLAB function.

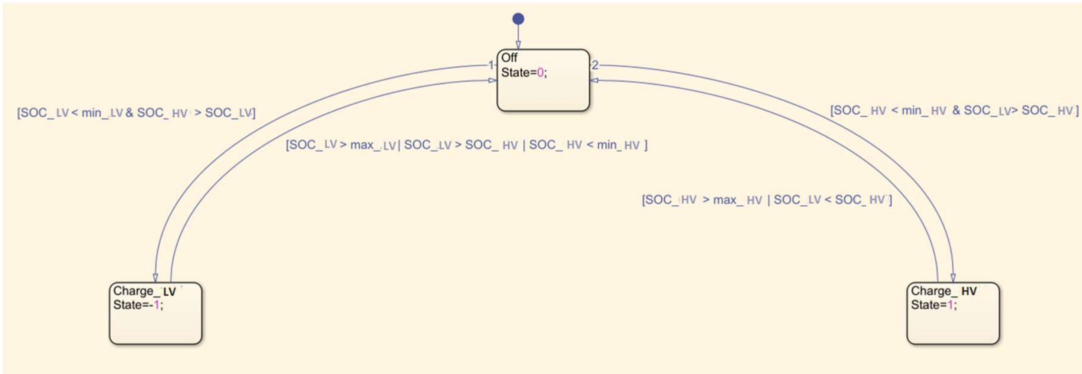


Figure 25 State chart of the LV/HV DCDC convertor

The DCDC transfer power between batteries if the following conditions are satisfied:

$$Charge\ of\ the\ LV\ battery: \begin{cases} SOC_{HV} > SOC_{LV} \\ SOC_{LV} < SOC_{\text{minLV}} \end{cases}$$

$$Charge\ of\ the\ HV\ battery: \begin{cases} SOC_{LV} > SOC_{HV} \\ SOC_{HV} < SOC_{\text{min}HV} \end{cases}$$

The DCDC is off if one of the following requirements is satisfied:

$$End\ of\ the\ HV\ battery\ charging: \begin{cases} SOC_{HV} > SOC_{maxHV} \\ SOC_{LV} < SOC_{HV} \end{cases}$$

$$End\ of\ the\ LV\ battery\ charging: \begin{cases} SOC_{LV} > SOC_{maxLV} \\ SOC_{HV} < SOC_{LV} \\ SOC_{HV} < SOC_{minHV} \end{cases}$$

In the charging situation the transfer of power is calculated as follow:

$$Charge\ HV: \begin{cases} P_{LVtoHV} = -Capa_{LV} * \tau_{CD\_LV} \\ P_{HVtoLV} = -\eta_{DCDC} * P_{LVtoHV} \end{cases}$$

$$Charge\ LV: \begin{cases} P_{LVtoHV} = -\eta_{DCDC} * P_{HVtoLV} \\ P_{HVtoLV} = -\ Capa_{LV} * \tau_{CD_{LV}} \end{cases}$$

In Figure 26 we can observe the DCDC convertor use over a portion of the mission. The DCDC convertor is only used to recharge the LV battery.

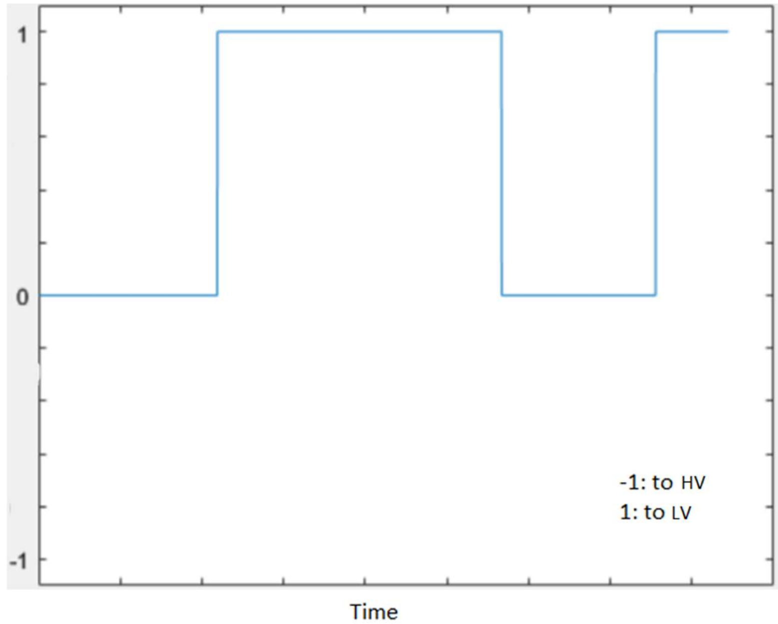


Figure 26 DCDC convertor utilization over time

6.4.2 Power limitation

Each battery has a power limiter which acts like a BMS and enables the value and duration of power peaks in particular to be controlled. According to the data supplied by the HV battery suppliers, the battery can supply power P_i for a period t_i. The Limiter upstream of the battery is used to control these power peaks and also to check that the battery's state of charge remains within the predefined limits (10-90%).

The limiter was validated using a simple script and the following results were obtained:

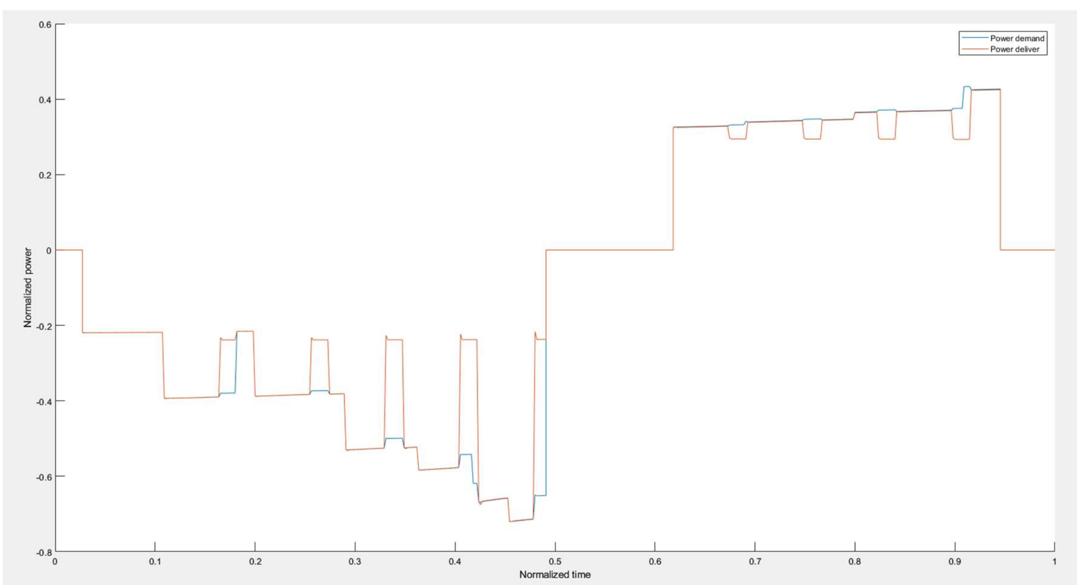


Figure 27 Comparison of the power required, and the power delivered by the battery

We can see that the limiter manages to control the power demanded from the batteries in order to comply with the peak power limits for both charging and discharging. The time between two peaks is set at a fixed duration.

6.4.3 Distribution of the power

A power distribution unit is placed downstream of the batteries, enabling the power to be redistributed to the auxiliaries and the torque commands for the electric motors to be calculated from the power supplied by the batteries. If power is limited, the difference between the power required from the batteries and the power supplied by them is calculated. The power is then distributed according to the following priorities:

- Priority 1: priority auxiliaries (like protection or on-board electronics)
- Priority 2: the e-turbo, then the electric motors
- Priority 3: non-priority auxiliaries (like observation or communication)

In the event of a power limitation, redistribution begins by restricting the power supplied to non-priority auxiliaries. The other auxiliaries have priority over the electric motors, as there is always the possibility of switching to purely internal combustion propulsion in a critical situation.

6.5. Validation of the model by comparing with analytical results

6.5.1 Silence Watch

The energy sizing requirement based on the autonomy during silent watch was verified. The model was subjected to a power demand corresponding to that required for silent watch, for a predefined period. Figure 28 shows that at the end of this watch, the battery's state of charge was still within the authorized range. The HV battery was used to recharge the LV battery via the DC/DC converter.

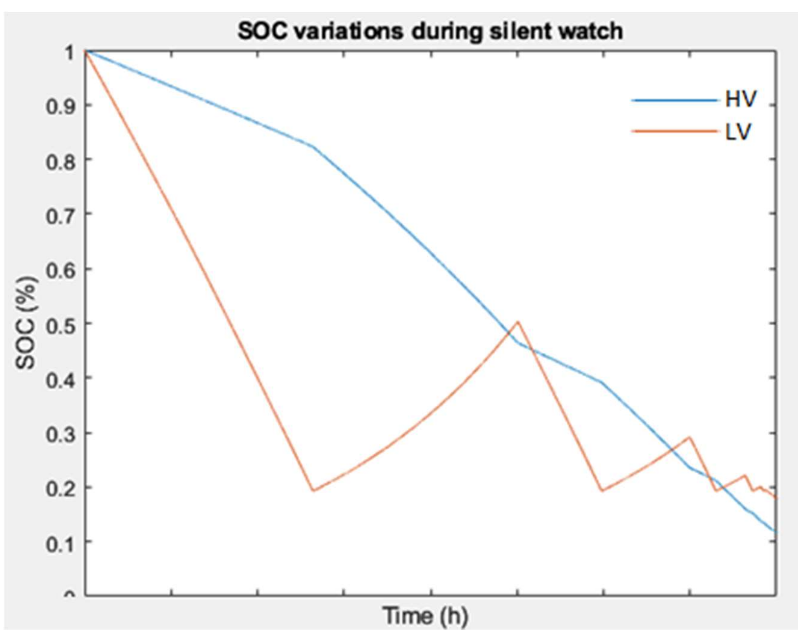


Figure 28 Evolution of the SOC during silent watch

6.5.2 Charge and discharge

In order to verify that the model matches the analytical results, charge and discharge tests with different constant currents were carried out. This was done to check that the charging and discharging times were close to those calculated analytically using the following formula:

$$\Delta T = \frac{C_{bat}}{I * (SOC_{max} - SOC_{min})}$$

With ΔT the duration of charge or discharge, C_{bat} the capacity of the HV battery and I the current.

	Discharge	Charge
I(A)	Error (%)	Error (%)
5	2,5E-03	2,5E-03
10	-1,8E-03	-1,8E-03
15	7,4E-04	-1,4E-14
20	-1,8E-14	-1,8E-14
25	1,1E-14	1,2E-03
30	-1,4E-14	1,5E-03
40	2,0E-03	2,0E-03
50	1,1E-14	2,5E-03
60	-1,4E-14	-1,4E-14
80	4,0E-03	4,0E-03
100	5,0E-04	5,0E-04
150	7,4E-04	7,4E-04
200	1,1E-14	1,1E-14
300	0,0E+00	0,0E+00
400	2,0E-03	2,0E-03

Table 5 Relative error between analytical and simulation results for charging and discharging

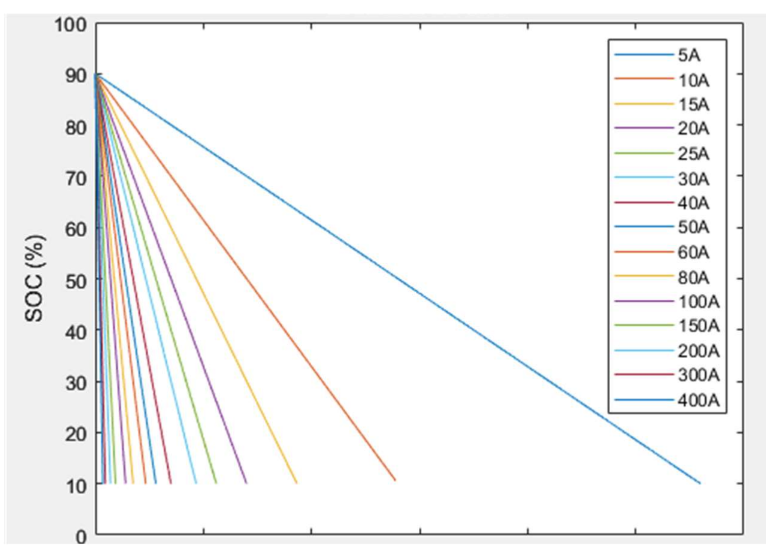


Figure 29 Evolution of the SOC during discharging as a function of entry current

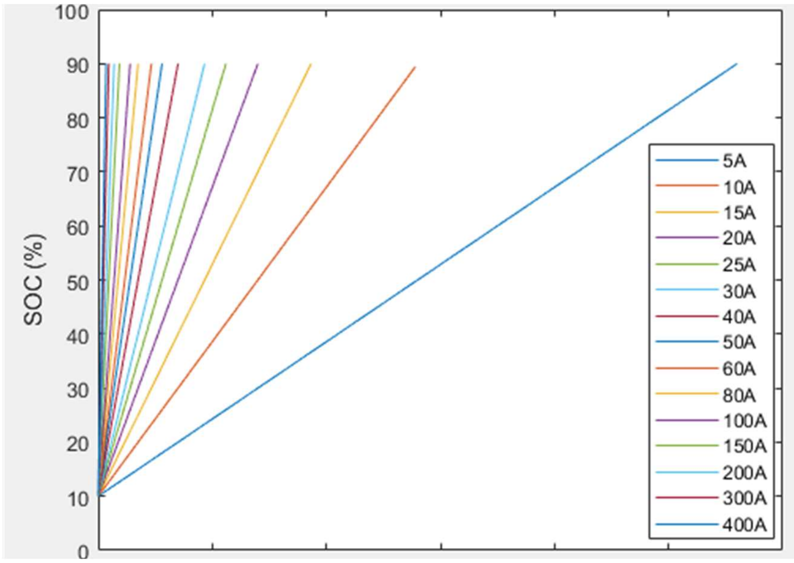


Figure 30 Evolution of the SOC during charging as a function of current

Either for the charge or the discharge the resulting errors between the times of the simulation and the analytically calculated times are low and sometimes even zero.

7. Simulation

7.1. Simulation parameters

Considering the complexity of the model, the calculation time and also the storage requirements for the various simulations, the mission path had to be shortened in three parts. The first phase corresponds to a liaison situation of several hundred kilometers. The second phase is a combat phase, also covering several hundred kilometers. Finally, the last phase is a liaison phase similar to the first one. Each of these stages is carried out with the hybrid model and also with the thermal model.

To do this, as explained in Mission profile, two different Excel spreadsheets were created to define all the parameters for these different phases, including position and speed setpoints, ground type and mode, stopping times and events, etc...

Before starting the simulation of the various Simulink models. An initialization file is launched in MATLAB. This includes the following information

- General vehicle data
- Terrain data
- Batteries data
- Auxiliary equipment data
- Gearbox data
- Turntable data
- Engine data (ICE and electric motors)
- Braking data
- eTurbo data
- Hybridization strategy parameters data
- Initialization of control and dynamic data

- Load mission data (from Excel file)

7.2. Performances and requirements validation

Performances	Error (%)
0-30 km/h [s]	20
0-40 km/h [s]	-20
0-60 km/h [s]	-40
0-400 m [s]	-10
Max speed [km/h]	6

Table 6 Relative error between the simulation performances and the reference ones

An initial performance validation was carried out by comparing the performance of the hybrid model designed with those of the tank used as a reference for this project. The validations were carried out on the road.

Although there is a noticeable difference between the reference criteria and the results obtained, it is important to note that the hybrid vehicle achieves better performance in all criteria except the initial one. However, it was specified at the start of the project that the vehicle should have at least the same performance as the internal combustion vehicle, but that any improvement would be even better. In addition, these validations were carried out with dynamics that were not yet optimal (specifically during gear change transitions). After correction of this point, the hybrid vehicle should gain in performance and therefore also validate the first criterion. As the dynamic is the same for the thermal model and the hybrid one, this did not cause any problem for the energetic comparison of the two versions.

We can therefore conclude that the vehicle's performance satisfies the established requirements.

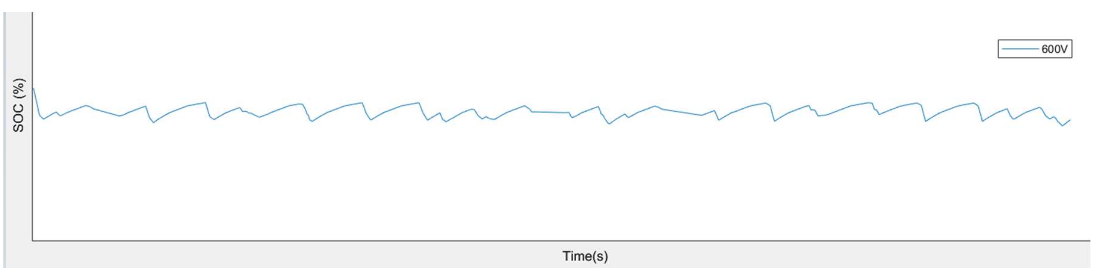


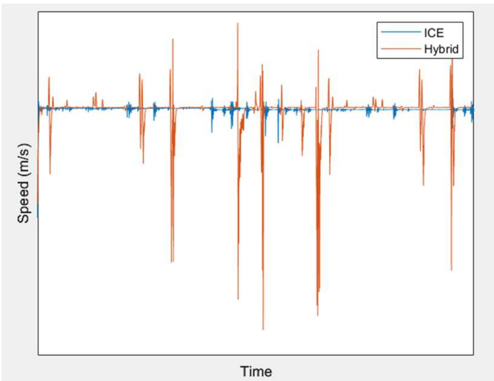
Figure 31 SOC evolution during the first phase of the mission ("road" mode)

The Figure 31 shows that during the first phase (and the last one) the behavior of the energy management strategy is correct. We can clearly observe a charge sustaining behavior around the define target state of charge, as the state of charge varies within a range of 5% near the target SOC.

8. Results

8.1. Thermal and hybrid models comparison

This section presents the results of the comparison between the thermic model and the hybrid model developed during this project.



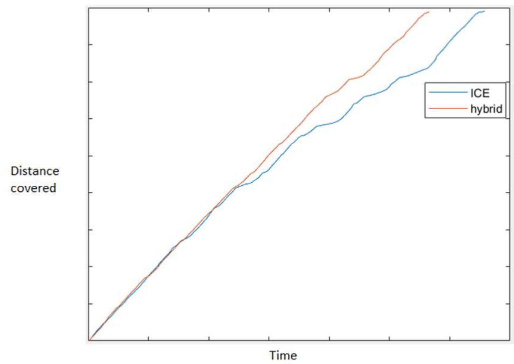


Figure 32 (left) Speed evolution over time, (right) distance covered over time for ICE only and hybrid mode

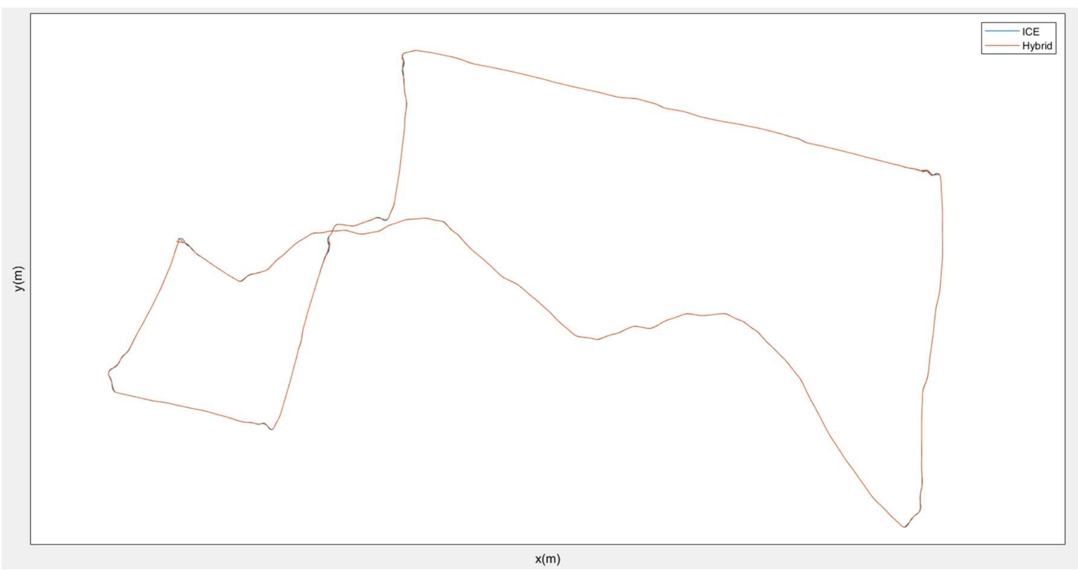


Figure 33 Trajectory of the tank in ICE only and hybrid mode

Figure 32 and Figure 33 show that ICE only and hybrid model both follow the set trajectory quite well. Moreover, they both achieve to follow the speed command. Finally, the hybrid shows a better performance in achieving the trajectory, indeed it covers the distance quicker than the ICE only model.

Figure 34 shows the fuel consumption of the different models over a part of the mission profile defined in section 4.3. We can observe with the hybridization a gain in fuel consumption varying between 10 and 20% depending on the mode and terrain used.

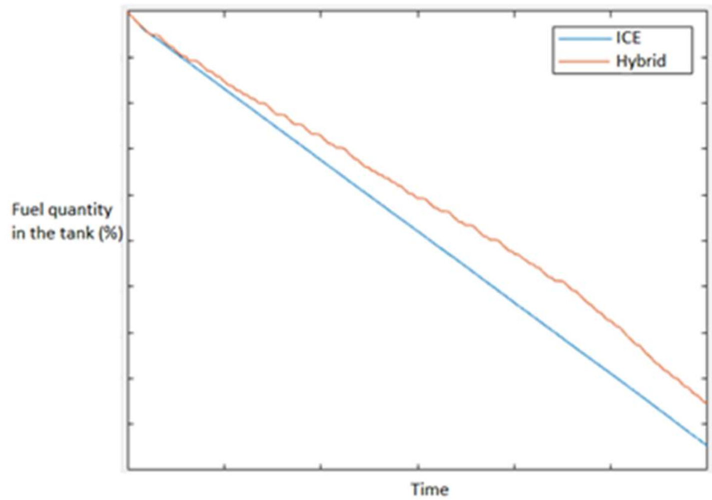


Figure 34 Comparison of the fuel consumption of the combustion model and the hybrid model

To further study the behavior of the hybrid model compared with the purely thermal model, other comparisons and results were analyzed.

The Figure 35 shows the charging and discharging distribution during the "road" mode. We can observe that the proportion are close to 50% each, which is representative of the sustaining phase.

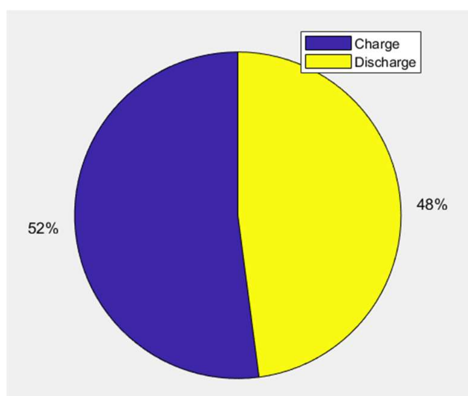


Figure 35 HV battery charging and discharging distribution

The different distributions of electrical and thermal energy are shown in the Figure 36 and the Figure 37.

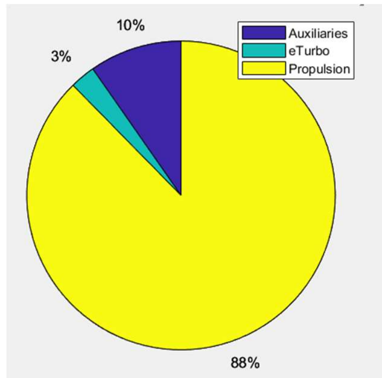


Figure 36 Electrical energy distribution

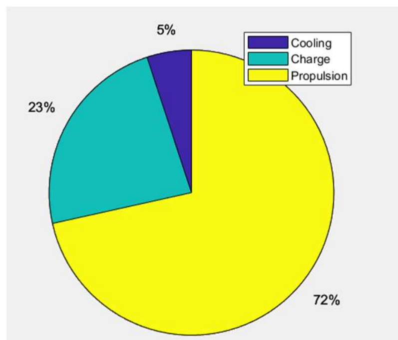


Figure 37 Thermal energy distribution

We can see that recharging the batteries accounts for 23% of the thermal energy. The auxiliaries account for 10% of the electrical energy. In comparison with the previous project, a greater proportion of electrical energy is used for propulsion in "combat" mode in the new model.

Details of the origin of the recharging of the HV battery are shown in Figure 38. Most of the charge comes from the combustion engine, 67%. 28% comes from regenerative braking and 5% from the e-turbo.

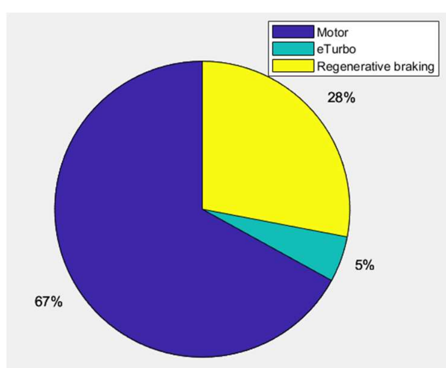


Figure 38 Origin of regenerated electrical energy

The Figure 39 shows the distribution of propulsion over time through the torque command repartition. And the Figure 40 shows the torque command in ICE only mode.

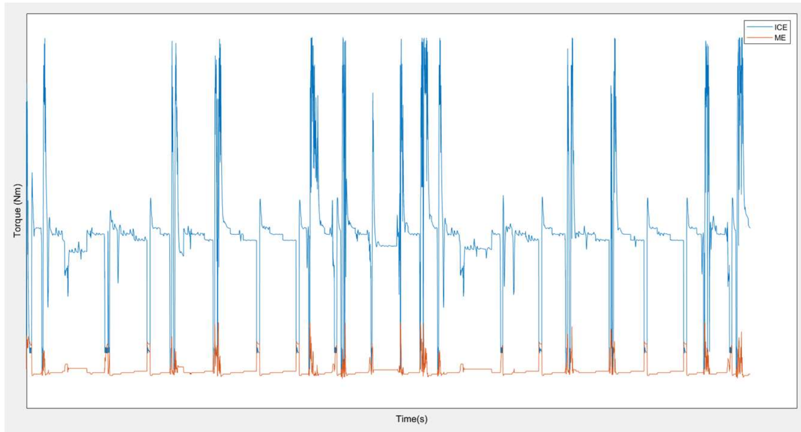


Figure 39 Torque commands over time for hybrid model

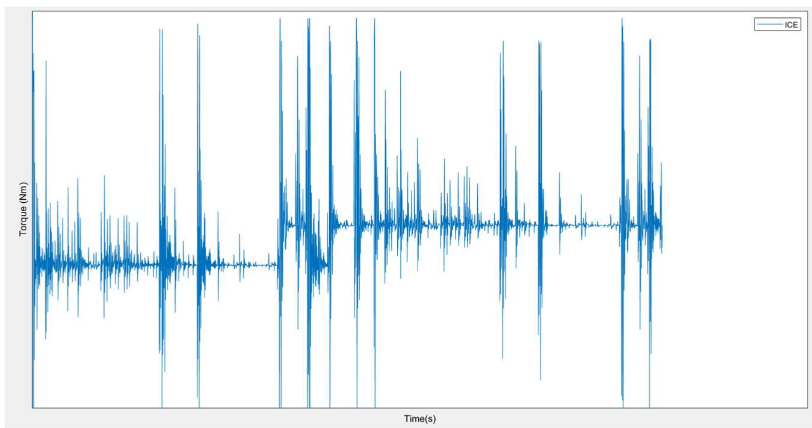


Figure 40 Torque command over time for thermal model

As we can observe from these last two figures, there are still some issues with the control of the dynamics in particular - but also with other parts which do not concern the subject of this report either - which leads to a lot of oscillations. The results presented in this section therefore provide an initial estimation of the behavior of the hybrid vehicle and the associated gains, but it will be necessary to wait for these issues to be resolved to obtain more accurate results and to be able to draw definite conclusions about the use of hybridization in this type of vehicle.

8.2. Improvements

Several points have been improved in the model or the simulation, but there are still others that need to be developed further.

To begin with, the simulation calculation time quickly turned out to be an obstacle. As the model is very complex, the simulation time was excessively long when the mission studied was being conducted. By refining the various calculation functions, particularly in the hybridization strategy block (Figure 41), and fine-tuning the MATLAB simulation parameters, we were able to reduce the simulation time by a factor of four. To this day, the simulation time is only between 2 and 3 times longer than the set time.

(a)

(b)

Figure 41 Simulation real time duration for a set duration of 30s before improvements (a) and after (b)

Another point that still needs to be improved is the files sizes. After running the model on one phase of the simulation (the mission being divided into three phases), the data obtained generated a file size between 50 and 100 GB. The number of signals studied therefore had to be reduced, and by adjusting the parameters of the MATLAB blocks we were able to reduce the size of the vectors corresponding to each signal. The resulting files were between 5 and 15 GB in size, which is still substantial but can be used via MATLAB or Excel. In the future, if there is a need to study a larger number of signals and data, we will have to try to reduce the size of the vectors even further or use tools that can process files of this size.

Some points, that did not fall within the scope of this thesis because they were dealt with by other collaborators on the project, did not allow us to obtain certain results. Indeed, the parts concerning the dynamics linked to the gearbox and the driver and control command are still being studied in greater depth. The assumptions made at the start of the training course have faced a number of limitations and need to be redefined. However, as explained earlier, these parts did not have too much impact on the results we were interested in in this report, as they are common to both models and are not the subject of this internship. Once these points have been tackled, the results obtained will be more accurate and closer to the behavior that can be expected from a hybrid vehicle of this type.

Regarding the parts of the model studied in this report, there are some points that could be further developed. Firstly, the vehicle's thermal behavior could be implemented in the future. This year, the temperature is set to be constant, but in reality, the values of the battery and engine components depend greatly on the temperature. Furthermore, this vehicle is likely to be used in extreme temperature conditions. It would therefore be important to rework this aspect in the future, as performance could be affected. Secondly, the BMS was simplified by a power limiter upstream of the batteries. To further refine the behavior of the batteries, it would be interesting to develop a realistic BMS block.

Conclusion

The purpose of this internship was to study the potential gains offered by reengining a battle tank with a hybrid powertrain. To do this, the tank with hybrid propulsion was modelled from the pedal command to the interaction between the track and the ground, including the hybridization strategy and the electrical components (batteries, motors, etc) in MATLAB Simulink. The part presented in this report focused mainly on the hybridization strategy and the electrical components. The strategy, based on the Pontryagin's principle of cost minimization, was modelled in MATLAB Simulink, taking into account the specific features of this project. The sizing and modelling of the batteries also depended heavily on the specific features of this kind of application.

This project aimed to improve an existing project, the updates were focused on refining the models (e.g. batteries) or optimizing the methods used (e.g. strategy). The battery model has gone from a simple equation used to calculate the evolution of the SOC based on an RC model to a more complex RC model, in which each element has been represented by matrices, allowing temperature and state of charge to be considered in the interpolation of the resistances and capacitances values. The strategy has moved from a rule-based method to a model-based method, making it possible to refine the vehicle's behavior and improve its performance, while also improving fuel consumption.

These improvements have enabled the system to meet the requirements of this internship, which called for the battery sizing to be refined, new auxiliaries to be taken into account, and a control strategy to be developed that is more advanced than the previous one, as well as an overall energy review that includes the return to operational condition at the end of the mission.

However, several limitations were encountered that prevented us from providing results and analyses on a situation corresponding to the mission profile used in real situations. The parts handled by the other collaborators had not yet been completed, so the overall behavior of the vehicle was not yet in line with expectations (dynamic feedback problem at the gearbox output, driver and controller problem). As this project is likely to be taken further by other students in future years, it would be interesting to develop a new control and driver tool that is better suited to this type of vehicle. This year, a pre-existing MATLAB block was used for this part of the project, but it was not entirely compatible with the way it was used.

Although, once these points are corrected, this MATLAB Simulink model offers a major asset for future projects. It has been designed to be modular: the physical blocks (engine, gearbox, etc.) and the vehicle parameters can be modified easily to obtain a different powertrain configuration or to study another vehicle. This will provide a wide range of information on the performance and benefits of hybridization for different powertrains or different vehicles. A guide is also planned to facilitate the use of this project for future users.

Finally, this model lays a solid, in-depth foundation for getting as close as possible to real vehicle behavior and optimizing the use of hybridization and will provide the necessary information on the contribution of hybridization in a wide range of configurations.

Bibliography

[1] Military planning law 2024-2030. https://www.defense.gouv.fr/actualites/livret-presentation-loi-programmation-militaire-2024-2030

[2] MGCS. https://fr.wikipedia.org/wiki/MGCS

[3] Technodays 2023 summary. http://mars-attaque.blogspot.com/2023/05/conference-et-autres-innovation-et.html

[4] Arquus website. https://www.arquus-defense.com

[5] Arquus a key player for scorpion program. https://www.arquus-defense.com/scorpion-program/arquus-key-player-scorpion-program

[6] Cerovsky, Z. (2022) Hybrid electric vehicle. Course of CVUT

[7] (2022) Advanced Propulsion Systems. Course of ENSTA Bretagne

[8] Morkus, J. (2022) Hybrid and electric powertrains. Course of CVUT

[9] Arquus PR - Arquus launches the Scarabee.pdf. (s. d.).

[10] Thompson. (s. d.). Oshkosh Unveils Hybrid-Electric Joint Light Tactical Vehicle That Matches/Surpasses Performance Of Original. Oshkosh Unveils Hybrid-Electric Joint Light Tactical Vehicle That Matches/Surpasses Performance Of Original

[11] SEP Modular Armoured Tactical System. (s. d.). https://www.army-technology.com/projects/sep/

[12] Randive, V., Subramanian, S. C., & Thondiyath, A. (2021). Design and analysis of

a hybrid electric powertrain for military tracked vehicles. Energy, 229, 120768. https://doi.org/10.1016/j.energy.2021.120768

[13] Lee, S., & Kim, J. (2017). Implementation methodology of powertrain for series-hybrid military vehicles applications equipped with hybrid energy storage. Energy, 120, 229-240. https://doi.org/10.1016/j.energy.2016.11.109

[14] NATO, (2021). Guidance for standards applicable to the development of next generation NATO reference Mobility Models (NG-NRMM)

[15] Piotr, A. (2021). A method for predicting the internal motion resistance of rubber-tracked undercarriage, Pt. 1. A review of the state-of-the-art methods for modeling the internal resistance of tracked vehicles.

[16] Wong, J.Y. (1978). Theory of Ground Vehicles

[17] Wong, J.Y. (1989) Terramechanics and Off-Road Vehicle Engineering

[18] Wong, J.Y. (2009) Terramechanics and Off-Road Vehicle Engineering: Terrain Behaviour, Off-Road Vehicle Performance and Design.

[19] Onori, S. Serrao, L., Rizzoni. (2016). Hybrid Electric Vehicles Energy Management Strategies https://link.springer.com/book/10.1007/978-1-4471-6781-5

[20] Silvas, E., Hofman, T., Murgovski, N., Etman, L. F. P., Steinbuch, M. (2016). Review of optimization strategies for system-level design in hybrid electric vehicles. https://ieeexplore.ieee.org/document/7442900

[21] Peng, J., He, H., Xiong, R. (2017). Rule based energy management strategy for a series-parallel plug-in hybrid electric bus optimized by dynamic programming. https://doi.org/10.1016/j.apenergy.2015.12.031

[22] Wang, H., Song, Q., Wang, S., Zeng, P. (2015). Dynamic modeling and control strategy optimization for a hybrid electric tracked vehicle. https://www.researchgate.net/publication/284113295_Dynamic_Modeling_and_Control_Strategy_Optimization_for_a_Hybrid_Electric_Tracked_Vehicle

[23] Musardo, C., Rizzoni, G., Guezennec, Y., Staccia, B. (2005). A-ECMS: an adaptive algorithm for hybrid electric vehicle energy management. https://doi.org/10.3166/ejc.11.509-524

[24] Yang, C., Du, S., Li, L., You, S., Yang, Y., Zhao, Y. (2017). Adaptive real-time optimal energy management strategy based on equivalent factors optimization for plug-in hybrid electric vehicle. https://doi.org/10.1016/j.apenergy.2017.06.106

[25] Trivic, I. (2012). Comparative Analysis of alternative hybrid systems for automotive applications. http://amsdottorato.unibo.it/4592/1/Trivic_Igor_tesi.pdf

[26] Alegre, S., Miguer, J. V., Carpio, J. (2017). Modelling of electric and parallel-hybrid electric vehicle using MATLAB/Simulink environment and planning of charging stations through a geographic information system and genetic algorithms. https://doi.org/10.1016/j.rser.2017.03.041

[27] Antony, J. (2014). Fundamentals of Design of Experiments. In Design of Experiments for Engineers and Scientists (p. 7-17). Elsevier. https://doi.org/10.1016/B978-0-08-099417-8.00002-X

[28] Antony, J. (2014). A Systematic Methodology for Design of Experiments. In Design of Experiments for Engineers and Scientists (p. 33-50). Elsevier. https://doi.org/10.1016/B978-0-08-099417-8.00004-3

[29] Morel, A. (2022). Battery Pack Design. Course of ENSTA Bretagne

[30] Schweighofer, B., Wegleiter, H., Recheis, M., Fulmek, P. (2012). Fast and accurate battery model applicable for EV and HEV simulation. https://ieeexplore.ieee.org/document/6229525

[31] Chan, C. C., Bouscayrol, A., Chen, K. (2009). Electric, Hybrid, and Fuel-Cell Vehicles: Architectures and Modeling. https://ieeexplore.ieee.org/document/5276874

[32] Hannan, M.A., Azidin, F.A., Mohamed, A. (2014) Hybrid electric vehicles and their challenges: A review. https://doi.org/10.1016/j.rser.2013.08.097

[33] Hohl, G. H. (2007). Military terrain vehicles. Journal of Terramechanics, 44(1), 23-34. https://doi.org/10.1016/j.jterra.2006.01.003

[34] Kim, D.-M., Lee, S.-G., Kim, D.-K., Park, M.-R., & Lim, M.-S. (2022). Sizing and optimization process of hybrid electric propulsion system for heavy-duty vehicle based on Gaussian process modeling considering traction motor characteristics. Renewable and Sustainable Energy Reviews, 161, 112286. https://doi.org/10.1016/j.rser.2022.112286

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Annexe 1

Mode / Auxiliaries	M1			M2			M3			M4			M5			M6			M7			M8			M9			M10		
On-board electronics	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Climatization	0.85	1	1	0	0	1	1.04	1	1	0.76	1	1	1	1	1	1.14	1	1	1.18	1	1	1.1	1	1	1.23	1	1	1.25	1	1
Communication	1	1	0	0	0	0	1	1	1	1	1	0	1	1	0	1	1	0	1	1	0	1	1	0	1	1	0	1	1	0
Observation	1	1	0	0	0	0	1	1	1	0	0	1	1	1	0	1	1	0	1	1	0	1	1	0	1	1	0	1	1	0
UGV	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0
Firring function	0	1	1	0	0	1	0	1	0	0	0	0	0	1	1	0	1	1	0	1	1	0	0	1	0	1	1	0	1	1
Turret mobility	1	1	1	0	0	1	1	1	1	0	0	1	0	0	1	0	0	1	1	1	1	0	0	1	0	0	1	0	0	1
Gun stabilization	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0
Passive protection	1	1	1	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Active protection	1	1	1	0	0	1	1	1	1	1	0	1	1	1	1	0	0	1	1	1	1	0	0	1	1	1	1	1	1	1
Drones	0	0	0	0	0	0	1	1	0	1	0	0	0	0	0	0	0	0	1	1	0	0	0	0	1	1	0	1	1	0

First column: Percentage of use

Second column: indication of use

Third column: Prioritization of the auxiliaries