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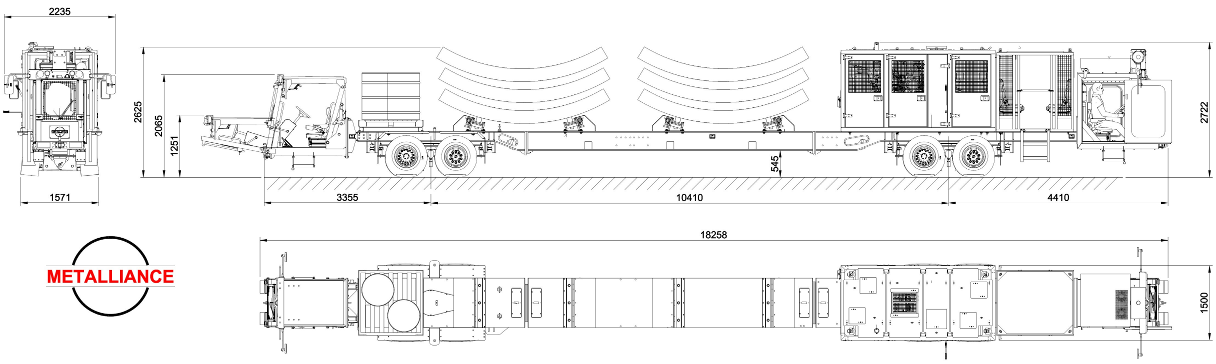


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Article

# Electrical-hydraulic Modeling and Simulation in MATLAB/Simulink of an Industrial Multi-service Vehicle for Tunneling

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**Abstract** The land transport sector has gone through multiple phases of evolution in vehicle design, development, and manufacturing. In particular, the construction sector continues to move towards autonomous vehicles, which have been one of the major trends and have become a hot topic in the industrial and academic world. With this new technology of assistance systems, which control the hydraulic actuators of a car (steering wheel, accelerator, and brake), humans are freed from driving tasks and the number of traffic accidents will be reduced. The modeling and simulation phases play a major role in the development of the construction machine in order to simulate the dynamic behavior of the vehicle and adjust all the parameters beforehand, so that the automated functionality will be easy to realize, and safety will be improved with high accuracy. The objective of this paper is to design a hydro-electric industrial vehicle model for the company METALLIANCE using MATLAB/Simulink environment and compare its simulation with experimental tests. The study addresses the modeling of industrial machines based on the mathematical description of the vehicle dynamics by defining for real-time evaluation of the different vehicle parameters, verifying, and validating the simulation model by comparison with real recorded data.

**Keywords** vehicle system modeling; vehicle dynamics; construction machinery; simulation; tunnel environment; traction and suspension control; electrical-hydraulic modeling

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## 1. Introduction

This work represents the first step of our project research, which is a part of the Autonomous Vehicle Simulation project "SIMVA-2" funded by France relaunch (plan measures to preserve jobs in research and development). SIMVA-2 is a bipartite project between the DRIVE laboratory from the University of Burgundy and the METALLIANCE company, which aims to develop an autonomous vehicle simulator with an application to the confined industrial environment in which the company's construction machinery operates. This simulator will reproduce the dynamic behavior of METALLIANCE's machines in their real environment (with a large number of scenarios, system configurations, and driver characteristics). It requires the modeling of the physical behavior (electrical, thermal, etc.) of the various parts of the vehicle (engine, battery, perception/vision systems, etc.) and constitutes the goal of this paper: modeling the electrical and hydraulic part of METALLIANCE's vehicles using MATLAB/Simulink.

The automotive and ground transportation sectors are constantly moving towards vehicle automation, also known as autonomous driving. This is an important future technology that will change the mobility paradigm [1], especially the operations of the construction industry. With the help of assistance systems, construction vehicles are continuously progressing towards the implementation of fully automated vehicles, known as autonomous vehicles (AVs). These are systems capable of performing maneuvers and driving tasks on their own, without human intervention, and of communicating with their occupants and with external elements. The main benefits of these new technologies are therefore the reduction of energy consumption, $CO_2$ and pollutant emissions and environmental impact, as well as the improvement of safety by minimizing and preventing as much as possible the number of road accidents caused by driver carelessness (the main cause of accidents depends on the reaction of the vehicle driver). These autonomous driving technologies are being combined with "Autonomous Electric Vehicle" (AEV) technologies that automatically facilitate charging when the battery's state of charge is low and that demonstrate the best analysis of the environment by their artificial intelligence system in order to avoid any type of collision with static or dynamic objects.

In this context, METALLIANCE, which specializes in the design of mobile machines for tunnel construction, has recently been interested in the full automation of its machines. The development of AEVs requires several tests of the vehicle's operation in real-time in certain driving scenarios to determine whether the requirements are met for the design. This development process justifies the high cost and long lead-time of the final product. Therefore, modeling and simulation have become important tools to solve this type of problem and are considered the best solution to dimension all components and control the vehicle actuators. Vehicle modelling was invented to facilitate any kind of parameter change and to analyze several control actuator configurations in a computer model before building the vehicle prototype. Thus, it can allow the final product to be well-built and faster while reducing costs. Modeling and simulation are therefore essential for METALLIANCE to design, characterize and simulate the behavior of its mobile machines on an industrial site, while reducing the costs of the development phase. With these modes of transport, a better analysis of the environment will be performed by the Artificial Intelligence system in order to avoid any type of collision with static or dynamic objects. A literature review of all the steps taken to describe and model the dynamic behavior of any type of system is discussed in [2].

This work provides a review of existing models for the industrial environment and makes a comparison of the modeling of METALLIANCE's industrial vehicles. The remainder of the paper is arranged as follows. Section 2 presents some existing construction vehicle models in the literature and a literature review of all the steps taken to describe the dynamic behavior of a system in the form of a model. Section 3 presents the industrial environment of our case study: the characteristics of the METALLIANCE mobile machines and their Operational Design Domains (ODDs) as well as a method used for the extraction of road profile data. The mathematical description of the vehicle dynamics and the value of all vehicle parameters used for both experimentation and simulation are addressed in Section 4. Section 5 highlights an overview of the MATLAB/Simulink-based vehicle model, the simulation results with validation on a real road profile, and the behavior analysis. The present work ends with a conclusion and perspectives.

## 2. Literature Review on Industrial Vehicle Models

In the literature, there is a large number of papers dealing with the modeling of construction vehicles to assess energy consumption, examine the impact of different factors influencing energy consumption, study the impact of different factors influencing actuator control, and improve vehicle efficiency (actuator control) [3,4], where most of them were numerical models used.

In [5], a dynamic model of the industrial tractor-trailer vehicle, consisting of a tractor and a complete trailer, was developed based on certain assumptions and simplifications (the kinematic and dynamic parameters of the trailer). By instantaneously controlling the forces acting on the tractor, which are measured by the load cell, and by neglecting all trailer parameters with low accuracy and variable configurations, the dynamic vehicle was separated into subsystems, and the dynamic modeling was simplified. A practical implementation of the simplified model was applied to a full-scale tractor and trailer based on different analysis performances but the whole vehicle model is not investigated. A path-following control approach for an industrial vehicle consisting of a tractor and a trailer that deals with a pure problem has been proposed considering the implementation of a dynamic model [6]. A force sensor is installed to monitor and measure all the forces exerted on the tractor and the dynamic model evaluates in real time these measured forces for a proposed trajectory. The performance of the model is validated by fitting all parameters with experimental data and the accuracy of the variables is verified.

In [7], a lateral control approach for a trailer-tow vehicle was proposed to drive the truck, which required mathematical modeling based on the steering input. Only the values of the steering axle are simulated, and the simulation of the lateral dynamic model shows that the dynamic behavior of the vehicle is approximately identical to the experimental data. In [8], a vehicle dynamics model of the heavy tractor-trailer was developed for use in the National Advanced Driving Simulator. In this work, the tractor and trailer chassis, suspension, and steering mechanisms are taken into account and the modeling is based on a multi-body dynamics description. The estimated parameters are compared with the measured parameters. In [9], a self-driving tractor-trailer vehicle was studied based on autonomous driving technologies to improve efficiency and solve labor problems. A tractor-trailer vehicle controller with full autonomy was implemented and simulated in a real industrial environment. Under certain assumptions, the dynamic model is simplified and simulated using extensive experiments.

Some studies, in the first phase of the vehicle design, have been proposed for the modeling of electric construction machines in order to evaluate all the parameters affecting the energy requirements on the basis of a sensitivity analysis. In [10], a model-based optimization of an electric vehicle was developed in the Simulink environment. It was used to determine a driving optimization strategy to reduce energy consumption while driving (prototype electric car designed for the Shell Eco-marathon). In this case, the genetic optimization algorithm was used. The model includes the vehicle, the electric motor, and the motor controller. The simulation was compared with real measurements and the results showed that the optimized model was similar to the experiment. In this study, the total efficiency of the electromechanical power system is treated. However, every change, such as modeling of the route or driving conditions, applied to one of the electromechanical power subsystems has to be evaluated experimentally. This model also takes into account the driver control system, using the reference speed of the vehicle or the activation of the accelerator as inputs. In [11], a powertrain design optimization model was developed. The system was applied to the development of fuel cell electric vehicles using a carbon fiber monocoque powered by a hydrogen fuel cell with an electric motor. In the model, the vehicle and its subsystems (fuel cell, hill climbing, electric motor, tire rolling resistance, aerodynamic drag, etc.) are simulated in AMESim and the vehicle's dynamic behavior is analyzed. An optimization algorithm was used to find the optimal driving strategy leading to the lowest fuel consumption. Noting that the modeling is applied to a vehicle prototype with three wheels which was a basic system.

In [12], a numerical model of the powertrain of a vehicle participating in the Shell Ecomarathon competition is described. The model includes vehicle motion and fuel consumption and has been validated using real measurements. An optimization strategy was used to reduce fuel consumption. Previous studies, which modeled industrial vehicles, did not consider the whole dynamic system, but only the kinematic dynamics.

To conclude, these aforementioned works model simple vehicles, i.e., having few parts or only vehicle module. However, in this work we study the modeling of industrial vehicles which are more complex (two or three vehicle modules: leading vehicle, trailing vehicle, and intermediate module). In addition, the industrial environment where the modeling system vehicle was applied is very different.

The modeling of any system requires the knowledge of developing a model and designing a powerful simulation [13], which are described below.

- **Identify the problem:** Before proceeding with the modeling of a proposed vehicle system, it is necessary to define the inputs, the corresponding outputs, the temporal and spatial constraints, the traffic conditions, the stochastic elements, the study objectives, etc.
- **Formulate the problem:** Select the bounds of the system, the traffic conditions, the environment conditions, the control rules, and the security constraints. The purpose of this step is to define performance measures and quantitative criteria based on different system configurations. At this stage, formulate brief hypotheses about system performance. Hence, problems must be formulated as precisely as possible, and specific outputs are defined for each problem.
- **Collect and process real system data:** Collect data on system specified input variables. Generally, sensors are installed on the system and permanently record information about its environment, and perception and data fusion algorithms are then used to extract useful information.
- **Formulate and develop model:** Develop a network diagram of the system based on the relationships that connect the different outputs to the different inputs. Develop the model using simulation software.
- **Simulate and validate model:** Once the previous steps are checked and validated, all that remains is the simulation of the model from the real data and ensures that the model achieves the expected results. At this level, it is required to vary different input parameters over their acceptable range and check the output in order to verify that the simulation

model executes as intended by comparing its performance to the performance of the real system.

In the physical sciences, models are defined from mathematical tools (differential equations, recurrent equations, or partial differential equations), physical tools (generally used for vehicle systems), or computer tools (tools derived from the formalisms of Artificial Intelligence (AI). In the case of our study, the model was developed with extreme accuracy for every element based on different physical tools (mechanical block, thermal block, power electronic, electrochemical block, and electric energy storage).

## 3. Industrial Environment and Operational Design Domain System

In this study, the modeling is applied to an industrial environment: machines developed by the company METALLIANCE which were used for underground, rail works and track laying, road works, and vibrating and aeronautical equipment. Two types of machines were designed: Multi-service Vehicles (MSV), which were intended for various loads (rails, skips, racks, drums, etc.), and Rubber-tyred Trains (RTT), carried voussoirs, mortar tubs, and various components required for the construction of tunnels. These vehicles comprise axles with four wheels and axles with two wheels with rubber tires. A single non-articulated vehicle can comprise eight or more wheels based on the load that has to be supported. The combination of rubber tires and an innovative suspension system allows the vehicles to operate on any kind of terrain without the need for the installation of rails.

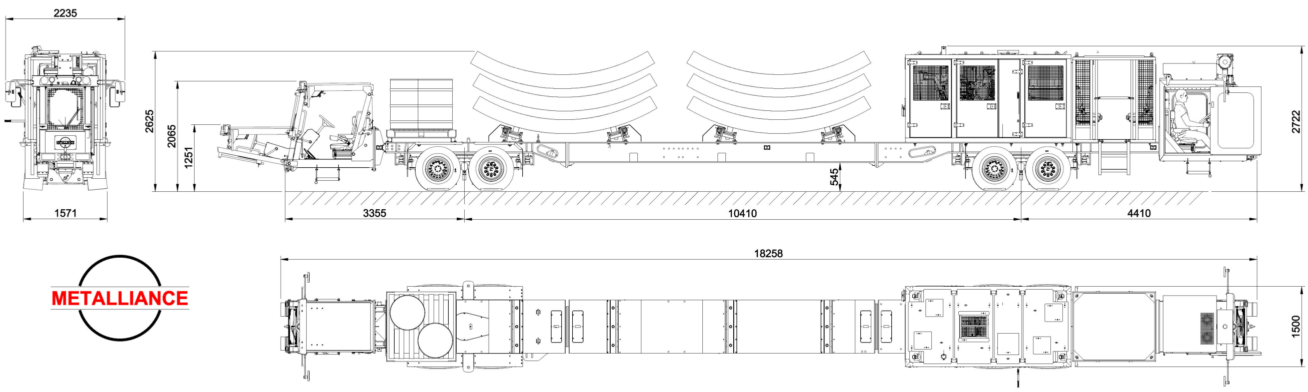
### 3.1. METALLIANCE's Vehicles

The RTT consists of a leading vehicle and a trailing vehicle, each with a driver's cab to facilitate reversible operation without having to turn around in a confined space. The lead and trailing vehicles are self-propelled and can be operated simultaneously in the desired direction. However, the MSV is a non-articulated vehicle with only one vehicle. Like the wheeled train, the MSV is also designed to allow reversible operation. The vehicles currently used by the company are available in three variants regarding the energy source used by the vehicles. The vehicles can be powered by a diesel engine, a hybrid propulsion (diesel engine and electric motor), or a fully electric motor. They are therefore equipped with wheels, which allows them to travel on flat terrain and even on concave surfaces inside tunnels, without the need to build rails inside the tunnel.

The lead and trailing vehicles are self-propelled and can be used simultaneously depending on the direction of travel required. The vehicle comprises a longitudinal chassis and each of the vehicles has at least two axles and a platform to support the material to be transported. The chassis of the leading and trailing vehicles each have two axles and both vehicles have at least one drive axle. Power may be supplied to one or both drive wheels of the axle by means of an electric or hydraulic motor powered by a hydraulic pump. The power supplied to the drive wheels may vary depending on the capacity of the hydraulic pump. Under normal operating conditions, power is transmitted to the wheels of the leading vehicle and the driving wheels of the trailing vehicle, but in the event of a malfunction, the drive to specific wheels or wheels of an axle can be disengaged and the axle can turn freely.

The driving axle is thus transformed into a steering axle. This function can be useful in the event of a breakdown of one of the vehicles. The operation of the vehicle axles is independent of each other, which is advantageous in areas with high space constraints. Both MSV and RTT are equipped with a traction control system. The traction control system is particularly useful on uneven roads. If one of the wheels is not in contact with the ground due to the unevenness of the surface, this wheel will turn faster than the others. To avoid loss of power and traction, the system interrupts the transmission of power to the wheel that is not in contact with the ground. This power is supplied to the other wheels that are in contact with the ground surface, to ensure optimal traction. The steering of both vehicles is limited to 15°. This is to ensure the safe operation of the vehicles. In the case of a two-wheeled axle, the width of the vehicle's track decreases as the steering angle increases. The vehicle can then wobble or fall on its side due to the heavy load. METALLIANCE is currently developing Automated Guided Vehicles (AGVs) to assist the driver in driving the vehicle and to facilitate indoor and outdoor logistics and storage operations. Figure 1 illustrates one of the real MSV developed by METALLIANCE, and its layouts and dimensions.

(**a**)




(**b**)

**Figure 1.** (**a**) A real METALLIANCE's multi-service vehicle (MSV); (**b**) Schematic Diagram of the METALLIANCE's MSV.

### 3.2. Extraction of the Road Profile Data (METALLIANCE Test Site)

Many previous research works, especially in social science, study the impact of roadway elevation changes on vehicle performance [14]. The traffic data has an important role in network analysis transportation (obstacle detection, performing location, infrastructure construction, improving safety), which is why the environmental constraints (road data) are one of the automated driving functions [15]. Generally, to achieve a fully autonomous vehicle, the system simulation is necessary with the dynamics model; it requires information about the road environment to generate the motion planning and control the dynamics behavior of the vehicle. In this section, a method for extracting road data (vehicle distance, road slope) using road Global Positioning System (GPS) data from different road shapes and diverse locations is presented. The GPS describes precise geographic location on the earth by longitude, latitude, altitude, and the time of transmission, and in this work the software Google Earth (GE) (which was used for various transportation applications) is chosen to extract the roadway data.

#### 3.2.1. GE Data Extraction Method

To extract data from any location or area on the planet, GE software has been developed with a road data extraction system at Keyhole, Inc., a software development company in Mountain View, California, where Google's base of operations is also located. The GE software is a worldwide known platform that allows the user to view any city or area in 3D (from different angles) and to specify the longitude, latitude, altitude, distance, and elevation of any point in the location or route planning.

The distance is shown on the X-axis and the altitude on the Y-axis. The measurement can be saved in a Keyhole Markup Language (KML) file (*.kml).

#### 3.2.2. Data Conversion Using GPS Visualizer

The saved file (*.kml) can only be used with the GE application. It is necessary to explore these geographical data (profiles) with a file table format (for example, an Excel file). To perform this conversion, it is necessary to go through the GPS data. As an online utility, the GPS visualizer can generate map data with GPX (an XML file format for storing GPS data, which has been used for interchanging coordinate data between applications and web services) format from many different sources. First, access the GPS visualizer, and then click on the elevation data from the New DEM files tab, from where the exported KML file can be uploaded for conversion and elevation can be added. After this, the converted GPS file will be presented for download.

#### 3.2.3. Convert GPS File to CSV File Using TCX Converter

The last step is to explore the Road data (distance, elevation, and slope), which is saved in an Excel file. It is required to convert the GPS file to a CSV file. We used the TCX converter to achieve this conversion. With this application, the saved GPS file can be easily loaded and converted to the desired CVS file.

## 4. Description System, Simulation and Validation on a Real Road Profile

Based on the fourth model development step and in order to proceed with modeling the electrical and hydraulic part of the METLLINCNCE's vehicles, it was required to define the model inputs and outputs and their relationship. In this work, we took the road profile and the vehicle speed as inputs and the different electrical and hydraulic vehicle variables as outputs for the model. The mathematical equations that describe the dynamic behavior of the vehicle and connect these inputs to the different outputs are presented in the following sections. The modeling has been carried out in the MATLAB/Simulink environment based on the mathematical system description and the simulation was compared to real data measured during the vehicle operation. The purpose of this modeling is to combine the present electrical and hydraulic models with a thermal vehicle model in order to model all parts of the machine and create a full vehicle model. The complete vehicle model will be exploited to create the autonomous vehicle simulator.

### 4.1. Electrical Modeling Vehicle

The modeling of the vehicle's electrical system is based on studying the vehicle's dynamic behavior (motion of vehicle), defining what element provides this motion, and the energy supplier. In the case of METALLIANCE's machines, the vehicle dynamics described the external forces and the interaction with the environment, the motor was providing the motion, and the battery was supplying the energy.

#### 4.1.1. Fundamental and Mathematical Description of Electrical Vehicle Dynamics

The electrical drive system is based on two modes: forward and reverse mode. The forward mode is defined when the accelerator pedal is pressed (the vehicle starts rolling), sufficient electrical power is provided by a pack of batteries, and an inverter (an essential component that controls the motor and determines driving behavior) is used to convert the high-voltage battery into alternating voltage (AC). The motor was supplied by this three-phase AC supply (Inverter Output) and will control the rotation of the vehicle wheel. However, during the braking phase (when the machine is decelerating), the motor becomes an alternator and produces power, which is sent back to the battery based on the inverter. This is defined as the reverse mode. Figure 2 depicts a schematic of the vehicle drive system and external forces acting on the vehicle moving.

Electrical modeling vehicle allows the evaluation of all different electric parameters acting on the system at a time to determine the electrical power needed for moving the vehicle forward. It constitutes the system of electrical equations associated with the power supply circuit. The electrical vehicle environment is modeled through the resistant torque applied to the electric motor. Therefore, the proposed electric model receives as input the drive cycle that the vehicle should execute (the given speed and road profile). The wheel torque depends on the forces acting on the vehicle moving [16]. Four forces are acting on vehicle moving: rolling friction force, aerodynamic force, acceleration force, and the downhill slope force. rolling friction force $F_r$, which represents the force that resists the motion of the vehicle rolling on a surface, is defined by the following equation:

$$HF_r(N) = C_r * m(kg) * g(m/s^2) \tag{1}$$

where $C_r$, $m$ and $g$ represent respectively the rolling resistance coefficient (defined as the ratio of the force of the rolling friction to the total weight of the vehicle), vehicle mass (loaded and unloaded vehicle), and gravitational acceleration (the acceleration of an object in free fall within a vacuum which has an approximate value of 9.81 $m/s^2$). The law states that the acceleration force $F_{acc}(N)$, which causes the acceleration motion, is given by the multiplication of the vehicle acceleration a by the mass of the vehicle $m$.

$$F_{acc}(N) = m(kg) * a(m/s^2) \tag{2}$$

The force exerted by the air on the vehicle constitutes the aerodynamic force in which the machine is immersed.

$$F_{aero}(N) = 0.5 * S_{vehicle}(m^2) * \rho(kg/m^3) * C_x * [V^2(m/s)] \tag{3}$$

where $\rho$ represents the air density (characterizes the mass of air contained in a cubic meter, the pure air has approximately 1.2 $kg/m^3$), $S_{vehicle}$ constitutes the section area of the vehicle, $C_x$ is the aerodynamic coefficient (represents the air penetration coefficient), and $V$ is defined as the vehicle speed in $m/s$. Given that the maximum speed is 20 $km/h$, the vehicle is moving at a low speed so we can neglect the aerodynamic force. Therefore, the resultant force down the slope (downhill-slope force) is given by this equation.

$$F_{slope}(N) = m(kg) * g(m/s^2) * sin(\alpha) \tag{4}$$

where $\alpha$ is the slope angle (refers to the angle of an inclined road). The sum of all these forces multiplied by the wheel radius results in the resistant wheel torque (the torque opposing the rotary motion), which is given by this equation.

$$T_{Wheel}(Nm) = \sum Forces(N) * R_r(m) \tag{5}$$

As the vehicle's dynamic behavior has been described, it is necessary to study the connection with the motor. By the value of the resistant wheel torque and the reduction wheel ratio (refers to the ratio between the turn of the steering wheel and the turn of the wheels), the motor torque, which represents its amount of rotational force, is defined as below.

$$T_{Motor}(Nm) = T_{Wheel}(Nm) * R_{ratio} \tag{6}$$

The motor speed is defined by the vehicle speed.

$$N_{Motor}(rev/min) = V(m/s) * \frac{60}{2 * \pi * R_{ratio}} \tag{7}$$

Thus, the torque and speed relationship of the motor is defined by the mechanical power as below.

$$P_{mecha}(kW) = T_{Motor}(Nm) * N_{Motor}(rev/min) \tag{8}$$

For an electrically driven motor, the mechanical power $P_{mecha}$ is converted to electrical $P_{elec}$ by a power efficiency $\eta_{power}$ (defined as the ratio of the mechanical power divided by the electrical power).

$$P_{elec}(kW) = \frac{P_{mecha}(kW)}{\eta_{power}} \tag{9}$$

As the vehicle dynamics and the source of motion have been highlighted, it is time to define the connection to the battery (energy supplier). The power $P$ is the product of the voltage $U$ (potential difference expressed in volts) and current $I$ (the rate at which electric charge flows past a point in a circuit). Indeed, the current $I$ is directly proportional to the voltage by the resistance $R$ which is given by Ohm's Law.

$$P(W) = U(V) * I(A) = U(V) * \frac{U(V)}{R(ohms)} = \frac{U^2(V^2)}{R(ohms)} \tag{10}$$

From the technical characteristics of the battery used in the METALLIANCE's machines, the range of the battery voltage is between 300 $V$ and 400 $V$ and the electrical power has a maximum of 60 $kW$. The value of ohmic resistance is fixed to 2.916 $ohms$ for maintaining the battery voltage within the desired range and the electrical power value not exceeding its maximum. According to Equation (10), the voltage and the current can be determined by these formulas.

$$U(V) = \sqrt{P(W) * R(A)} \tag{11}$$

$$I(A) = \frac{U(V)}{R(ohms)} \tag{12}$$

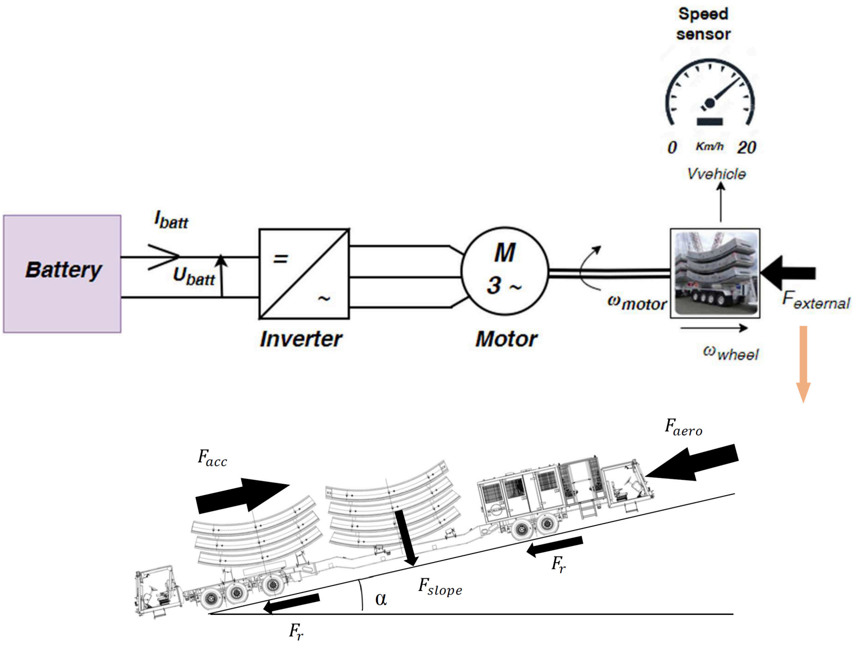



**Figure 2.** Schematic of the vehicle drive system and external forces acting on the vehicle moving.

#### 4.1.2. Reference to the METALLIANCE's Electric Vehicle Data

The vehicle parameters and configurations used for both simulation and experimental recording are presented in the Table 1 below (electric vehicle parameter).

**Table 1.** Reference to the electric vehicle data.

| Parameter | Symbol | Value |
|---|---|---|
| Maximum vehicle speed $(km/h)$ | $V_{max}$ | 18 |
| Wheel radius $(mm)$ | $R_r$ | 485 |
| Rolling resistance coefficient | $C_r$ | 0.02 |
| Unloaded vehicle mass $(kg)$ | $M_{unloaded}$ | 20,590 |
| Loaded vehicle mass $(kg)$ | $M_{loaded}$ | 44,590 |
| Aerodynamic Coefficient | $C_x$ | 1 |
| Air Density $(kg/m^3)$ | $P$ | 1.2 |
| Maximum slope (%) | $a_{max}$ | 13 |
| Section area of the vehicle $(m^2)$ | $S_{vehicle}$ | 6 |
| Gravitational acceleration $(m/s^2)$ | $G$ | 9.81 |
| Reduction Wheel ratio | $R_{ratio}$ | 35.83 |
| Power efficiency | $\eta_{power}$ | 0.95 |
| Maximum battery voltage $(V)$ | $U_{max}$ | 350 |
| Maximum battery current $(A)$ | $I_{max}$ | 120 |
| Maximum electrical power $(kW)$ | $P_{max}$ | 60 |
| Operating motor speed $(rpm)$ | $N_{Motor}$ | 0–7700 |
| Maximum motor torque $(Nm)$ | $T_{max}$ | 320 |
| Peak efficiency | $\eta_{motor}$ | 0.95 |
| Operating voltage $(V)$ | $V$ | 270–425 |

4.1.3. Simulation Results of the Electric Vehicle Model

The final step of the development is to simulate the model in a simulating environment. In our case, the vehicle model is implemented in MATLAB/Simulink based on the electric and hydraulic vehicle description.

Using the GE data extraction method (presented in Section 2), road data from the METALLIANCE test site is collected and used for the simulation, as shown in Figure 3. The modeling is applied to the operation of a METALLIANCE MSV vehicle at the company's test site where the actual machine operation measurements are recorded and shared with an Excel file, receiving the desired vehicle speed and road profile as input data and estimating all the electrical and hydraulic elements of the machine. The results of the simulation are compared to the actual data recorded while driving the MSV. The maximum elevation is approximately 275 $m$ over a distance of 350 $m$ with a maximum gradient of 13%.

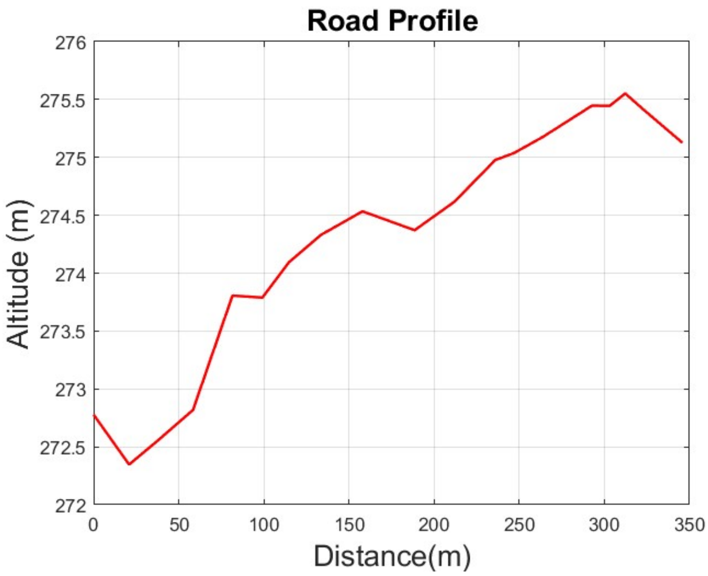



**Figure 3.** Road profile of the METALLIANCE test site (altitude vs distance).

An overview of the electrical modeling part of the MSV vehicle, implemented in MATLAB/Simulink is depicted in Figure 4 below.

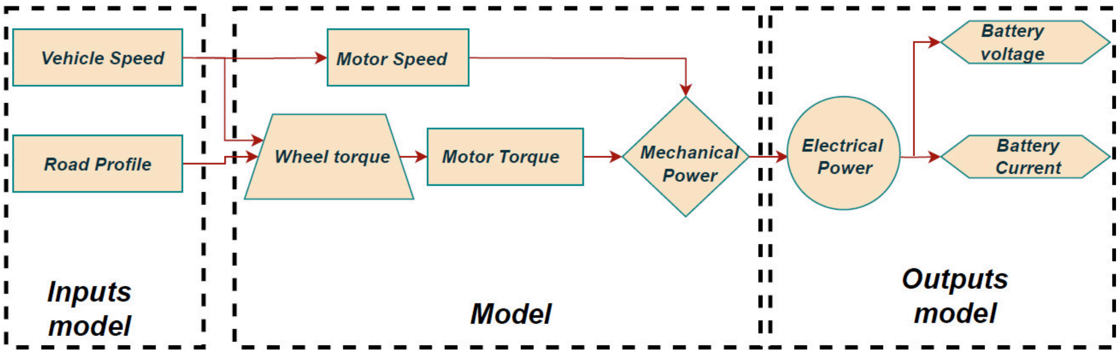



**Figure 4.** Electric model of METALLIANCE's MSV machine.

The control method used for the electric vehicles is a torque control method that controls the torque of three-phase AC electric motors based on variable-frequency drives. The method estimates the motor's magnetic flux and torque based on the measured voltage and current of the motor. The current control is adjusted according to the available generation and torque capacity of the electric motors.

From the road profile presented in Figure 3, the system model estimates the electric vehicle behavior. The vehicle speed has a maximum of 20 $km/h$, which is a driving task with low speed. It is divided into two phases driving: acceleration and braking. The simulation results of the proposed electrical model with a comparison to the recorded data are presented in Figures 5 and 6.

In Figure 5, the upper left plot shows the vehicle speed profile, the upper right, lower left and lower right plots present respectively the comparison of the simulation results to their corresponding signals that are recorded during the driving machine operation: signals of acceleration vehicle, motor, and wheel torque. Moreover, in Figure 6 the upper right, upper left, lower left and lower right plots depict respectively the simulated and corresponding experimental data of motor speed, electrical power, battery voltage, and current. The two signals from the simulation model and the measured data of the vehicle speed and acceleration are superimposed.

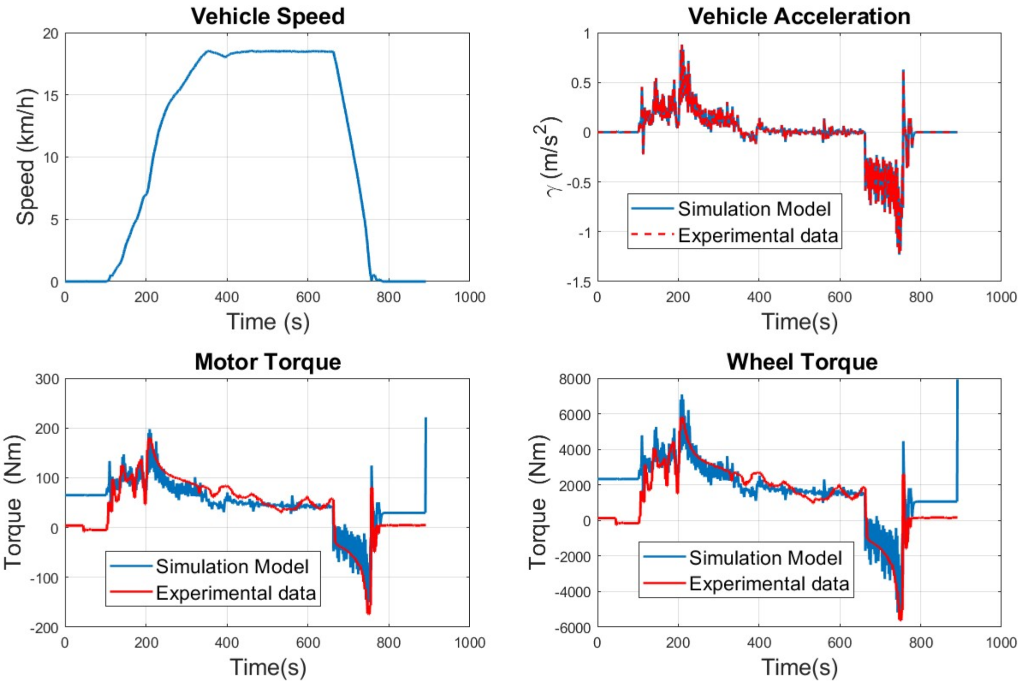



**Figure 5.** Vehicle speed profile, comparison of simulation results with recorded data of vehicle acceleration, motor, and wheel torque.

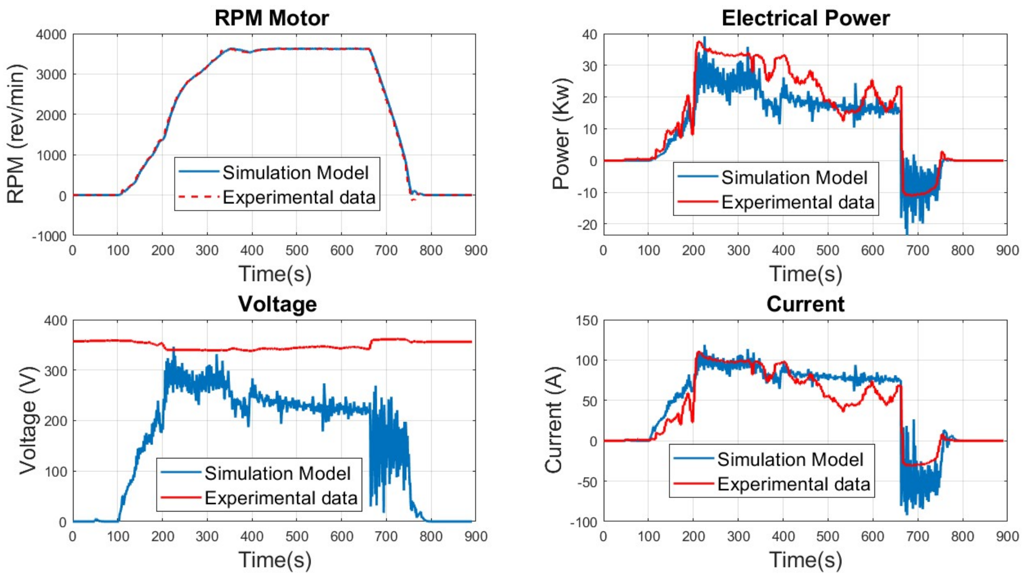



**Figure 6.** Comparison of simulation results with recorded data of motor speed, electrical power, battery voltage, and current.

As we see, the two curves of the simulation model and the measured data of vehicle speed, and vehicle acceleration are superimposed, and these results are expected. While the diagrams resulting from the simulation and experimental data of the motor and wheel torque are substantially identical, the only difference is when the vehicle speed is void, the measured signal is null while the simulated signal is different to zeros. This is due to the model inputs which are the vehicle speed and the calculation of the wheel torque including the rolling friction force which is independent of vehicle speed and has a constant value depending on the vehicle mass. This simulation demonstrates the same curve of motor speed as the real measurements.

The curve of the battery voltage from the recorded data is almost constant during the recording with a weak variation. However, the corresponding signal from the simulation model is dependent on the model input, grows during the acceleration phase, and decreases during the braking phase. This is because the model does not consider the presence of a voltage, instead it considers an open circuit at the beginning, so the voltage value starts with zeros. But for the driving task of the MSV vehicle, a voltage is always present and has a constant value. Since we consider this work to be a preliminary study, the complete work will be enhanced and the performance and accuracy can be improved by introducing and implementing a battery model, an electrical motor model, etc. The signal of the battery current is related to the electrical power signal, as shown in the plot, their curves from the simulation and the experimental test of MSV vehicle operation are approximately superimposed.

The simulation results demonstrates that the electric model is highly close to the real world. This allows us to conclude that the performance and high accuracy of the proposed model are validated. This work is applied to METALLIANCE's industrial vehicles, but it can also be used for other types of industrial vehicles. The electrical vehicle model will be used after the hydraulic model and thermal model to create a complete vehicle model.

### 4.2. Hydraulic Modeling Vehicle

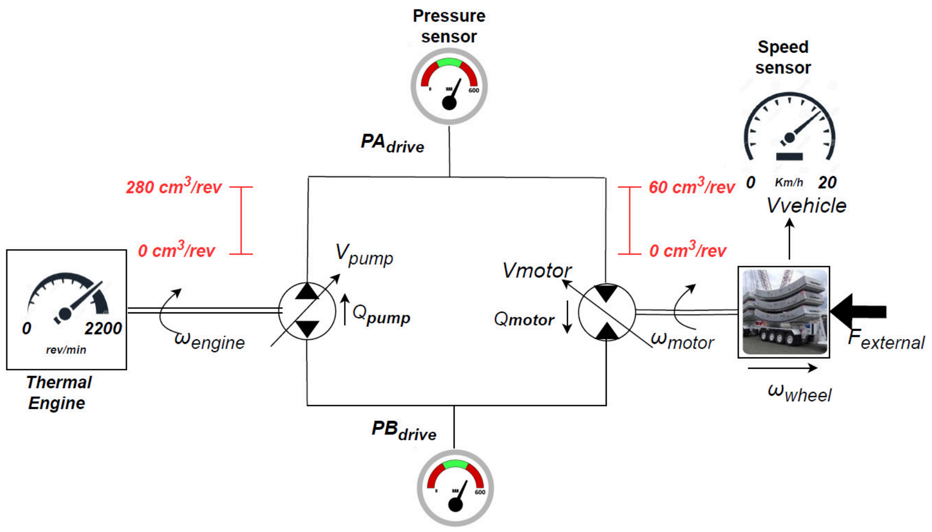
Each machine developed by METALLIANCE was equipped with hydraulic systems to control its movement by generating a lot of force based on small amounts of hydraulic fluid moving through a closed pipe. The systems installed on vehicles are beneficial for the company and provide many advantages such as easy control of speed, position, movements directions, power, an accumulation of energy, and an improvement of safety mechanism. The hydraulic unit of METALLIANCE's machine hydraulic systems consists mainly of hydraulic pumps for the conversion of the mechanical energy (from thermal or electrical motor) to hydraulic energy (pressure energy), hydraulic motors for the conversion of the received pressure energy to mechanical force that controls the vehicle motion, directional valve for the control of the energy distribution (control the direction of the fluid), for the protection of hydraulic elements from excessive pressure by maintaining the pressure within a range of value (sets by the manufacturer), distributing block for the distribution of energy to each of the various axles, speed sensors for the control of the wheel speed. Indeed, the fluid circulates in a closed pipe from the pump to the hydraulic motor and from there returns directly to pump's the suction line. Auxiliary pumps and flushing valves are used for the fluid circulation and preventing the car's engine from overheating and the flashing of the hydraulic fluid from the closed circuit, they are not considered in the hydraulic transmission circuit.

#### 4.2.1. Fundamental and Mathematical Description of Hydraulic Vehicle Dynamics

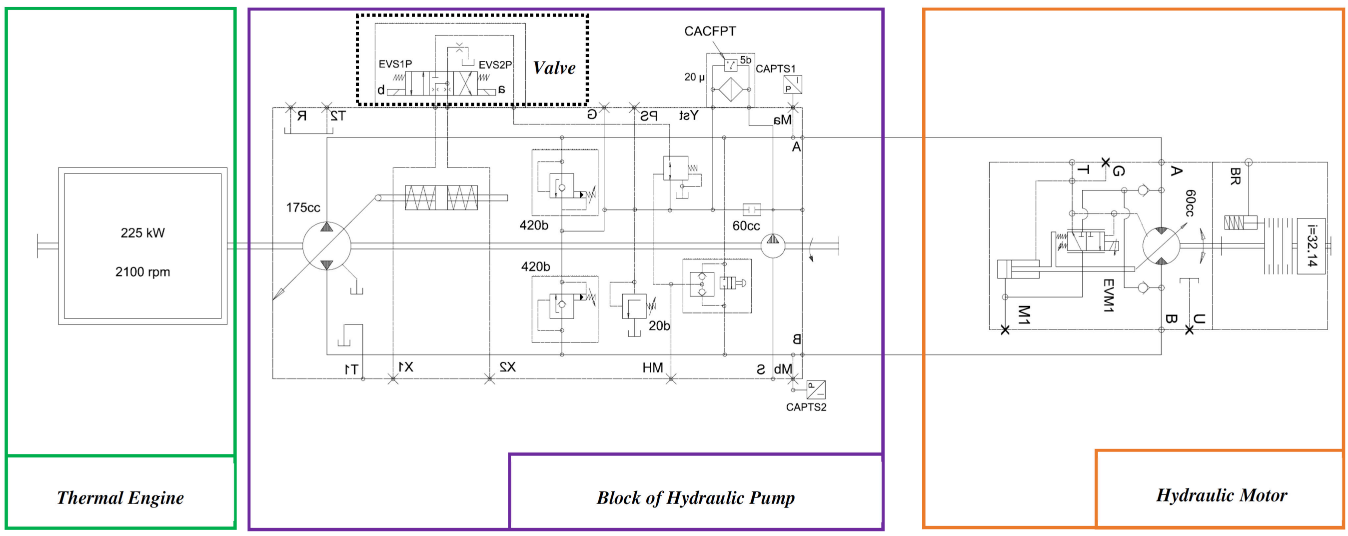
The design and modeling of the dynamic vehicle, that METALLIANCE' manufactured, required the description of its hydraulic system functionality considering the hydrostatic transmission from the engine to the driver shaft. Therefore, hydraulic modeling describes the control of the hydraulic actuators which are considered the hydraulic transmission from the engine of a vehicle to its axle. In this modeling, the evaluation of the wheel torque and the mechanical power is addressed in order to define the limits values needed for moving vehicles and not to be exceeded. The control of the hydraulic actuators of construction vehicles is defined from the hydraulic source, which was a thermal engine, to the drive shaft incorporating subsystems that make connections between them and transmit energy through the circulation of hydraulic fluid. The hydrostatic transmission structure is shown in Figure 7.

The hydraulic pumps used in METALLIANCE's machines, pumps with fixed displacement or variable displacement, are turned by a thermal engine, that transforms thermal energy into mechanical energy (results in engine speed $RPM$. A fluid is created by the transmission of this mechanical energy, in the form of flow (kinetic energy) and pressure (potential energy). These fluid energies are converted into mechanical energy by the hydraulic motor, which can also be variable displacement or fixed displacement. This results in a rotational movement making it possible to turn the wheels and therefore to move the vehicle forward. All these energies are exchanged and consumed in the movement and installation circuits.

The engine speed of the engine at which the machine speed reaches 20 $kmp$ has a value of 2200 $RPM$ $(rev/min)$. The hydraulic pump is controlled by a proportional and Integral Pulse Width Modulation (PWMI) current from 200 $mA$ to 600 $mA$: 200 $mA$ corresponds to 0 $cm^3/rev$ displacement while 600 $mA$ corresponds to 280 $cm^3/rev$ displacement. Also, the hydraulic motor is controlled by a PWMI signal between 200 $mA$ and 600 $mA$ where 200 $mA$ corresponds to 60 $cm^3/rev$ displacement while 600 $mA$ corresponds to 0 $cm^3/rev$ displacement. These commands determine the pump and motor cylinder. Wherever, the pressure sensors are controlled by Linear Proportional Current from 4 $mA$ to 20 $mA$, the desired range of pressure was between 0 $bars$ (4 $mA$) and 600 $bars$ (20 $mA$). The speed sensors used to measure and control the wheel speed received a frequency pulse signal with 54 impulsions per wheel revolution.

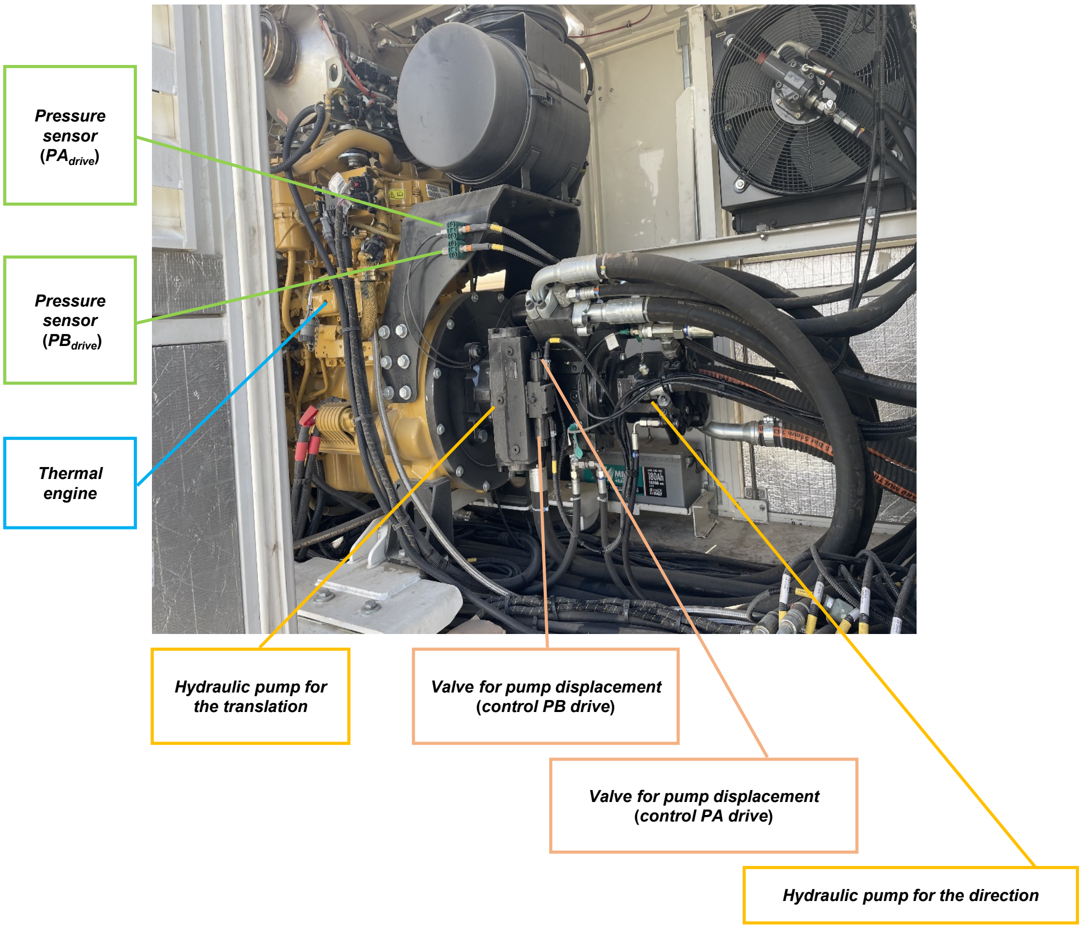



(a)




(b)

**Figure 7.** (**a**) General hydrostatic transmission structure (from the engine to drive wheels); (**b**) schematic of hydrostatic transmission with ISO symbol; (**c**) real hydrostatic transmission circuit for METALLIANCE's machine.




(c)

**Figure 7.** (*Continued*)

The volume of fluid delivered by the pump $Q_{pump}$ or the motors $Q_{motor}$ per unit time which represents the volumetric flow in which the fluid passes through a given surface per unit time. It results from displacement $V_{pump}$ or displacement $V_{motor}$ (the measure of the cylinder volume swept by all of the pistons of a piston pump or a piston engine, respectively). The flow rate and the rotational speed are given by these formulas.

$$Q_{pump}(l/min) = \eta_{V\_pump} * V_{pump}(cm^3/rev) * \frac{RPM(rev/min)}{1000} \tag{13}$$

$$N(rev/min) = Q_{motor}(l/min) * \frac{1000 * \eta_{v_{motor}}}{V_{motor}(cm^3/rev)} \tag{14}$$

where $\eta_{V\_pump}$ and $\eta_{v_{motor}}$ represents respectively the volumetric efficiency of the drive pump and the hydraulic motors (defined as the ratio of the volume of fluid delivered to the piston displacement). Contrary to the pump which converts the rotational mechanical power from the thermal motor into hydraulic power (flow and pressure), the hydraulic motors are turned by the volumetric flow rate that passes through the hydraulic circuit. The pressure difference (in lines forward and backward of the hydraulic transmission circuit), $\Delta_p = P_{A_{drive}} - P_{B_{drive}}$, depends on the flow rates of the fluid and the available transmission power.

$$P_{hyd}(kW) = \Delta_p(bars) * \frac{Q_{pump}(l/min)}{600} \tag{15}$$

This equation was used for the modeling of the drive pressure line $P_{A_{drive}}$ and $P_{B_{drive}}$.

$$\Delta_p(bars) = P_{hyd}(kW) * \frac{600}{Q_{pump(l/min)}} \tag{16}$$

The multiplication of the pressure difference by the displacement motors results in the motor torque based on the motion of the hydraulic motor.

$$T_{motor}(Nm) = \Delta_p(bars) * \frac{V_{motor}(cm^3/rev\ )}{20 * \pi} * \eta_{hyd_{mecha}} \tag{17}$$

where $\eta_{hyd_{mecha}}$ represents the hydro-mechanical efficiency which is calculated from the division of the effective torque by the ideal torque ($\eta_{hyd_{mecha}} = T_{ideal}/T_{effective}$). The mechanical power delivered by the driver staff is defined with the following formula:

$$P_{mecha} = \frac{Q_{pump}(l/min) * \Delta_p(bars)}{600} * \eta_{total} \tag{18}$$

where $\eta_{total}$ represents the total efficiency of the drive pump which is composed of the hydro-mechanical efficiency and the volumetric efficiency. It is also defined as the ratio of useful hydraulic power delivered to the fluid to the mechanical power: $\eta_{total} = \frac{P_{mech}}{P_{hyd}} = \eta_{hyd}{}_{mecha} * \eta_{V_{pump}}$. The mechanical power supplied by the pump staff is calculated from the following formula:

$$P_{mecha} = \frac{T(Nm) * N(rev/min)}{30000} * \pi \tag{19}$$

The proposed model was implemented based on both electric and hydraulic descriptions of METALLIANCE's MSV vehicle.

#### 4.2.2. Hydraulic Transmission Parameters

The vehicle parameters and configurations used for both simulation and experimental recording are illustrated in Table 2 below (hydraulic transmission vehicle parameters).

**Table 2.** Hydraulic transmission parameters.

| Parameter | Symbol | Value |
|---|---|---|
| Maximum vehicle speed ($km/h$) | $V_{max}$ | 18 |
| Wheel radius ($mm$) | $R_r$ | 485 |
| Unloaded vehicle mass ($kg$) | $m$ | 20,590 |
| Loaded vehicle mass ($kg$) | $m$ | 44,590 |
| Reduction Wheel ratio | $R_{ratio}$ | 35.83 |
| power efficiency | $\eta_{power}$ | 0.95 |
| Maximum difference pressure ($bars$) | $\Delta_{pmax}$ | 600 |
| Maximum displacement pump ($cc$) | $V_{pumpMax}$ | 280 |
| Maximum displacement motor ($cc$) | $V_{pumpMax}$ | 60 |
| Volumetric efficiency pump | $\eta_{vpump}$ | 0.93 |
| Volumetric efficiency motor | $\eta_{vmotr}$ | 0.97 |
| Hydro-mechanical efficiency | $\eta_{hyd_{mecha}}$ | 0.94 |
| Maximum power ($kW$) | $P_{max}$ | 350 |

#### 4.2.3. Simulation Results of Hydraulic Vehicle Model

An overview of the hydraulic modeling part of the MSV machine, developed in the MATLAB/Simulink environment, is shown in Figure 8. Using the same road profile used in the electrical modeling and a speed profile, the system calculates and evaluates the power required to move the machine forward, including the torque of the hydraulic motors and other elements of the hydraulic drive, such as volume flow, pressure difference, corresponding pump displacement, and hydraulic motors. As with the electrical modeling, the vehicle speed profile is divided into two phases: the acceleration phase and the braking phase. The driving tasks of the METALLIANCE machine are always performed at a low speed (maximum 20 $km/h$).

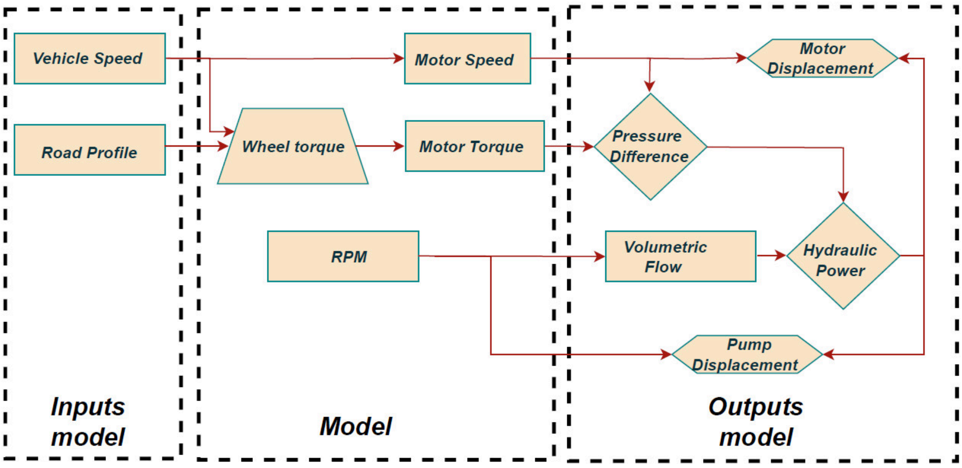



**Figure 8.** Simulink hydraulic model of METALLIANCE's MSV machine.

A speed control method was used with a ramp of acceleration and deceleration to control the vehicle speed according to a smooth and controlled change in motor speed. A hydraulic mechanism-based power regulation was also used to control the hydraulic transmission. The displacement of the pump and motors is adjusted according to the power consumed by the hydraulic circuit and the power available from the thermal engine.

The comparison of the simulation results with the corresponding experimental data is presented in Figures 9–11. The plot at upper left in Figure 9 shows the vehicle speed profile, and the comparison of simulation results to their corresponding recorded signals: vehicle acceleration at upper right, motor speed at lower left, and motor torque at lower right. In Figure 10, the plots display the comparison between the simulation results and the experimental data of pump and motor displacement respectively at upper left and lower left, volumetric flow at upper right, and pressure difference at lower right. And, Figure 11 depicts the simulation result of the hydraulic power and its experimental curve.

As shown in the upper left curve of Figure 9, the simulation model and the measured data of vehicle speed are superimposed. During the acceleration phase, the curve of vehicle speed increases progressively and does not exceed 20 $km/h$, while the curve of vehicle acceleration oscillates around zeros. The simulation result of the motor speed is confused with the corresponding measured speed. This justifies the fidelity and high accuracy of the proposed vehicle model compared to reality. The engine torque simulation is approximately identical to its experimental data. It shows some variations from reality during the acceleration and braking phases and a non-zero value when the vehicle speed is zero. Based on the model inputs, the driving torque is defined from the forces acting on the vehicle motion, while the rolling friction force is independent of the inputs and has a constant value throughout the simulation. Then, this discrepancy is propagated to the pressure difference and the hydraulic power because they are calculated from the engine torque. The curves of pump displacement, and motor displacement, derived from simulation results and experimental measurements are identical regarding the curved shapes, and maximum values did not exceed as indicated in Table 2. The pump acts as a motor at the beginning of the simulation (acceleration phase) and as a pump at the end (braking phase).

From these simulation results, we can conclude that the proposed hydraulic model is very close to reality. The most of curves from the simulation and the experimental measurements are superimposed, which attests to the high accuracy of the proposed model. Note that the discrepancy between the simulation result and the experimental data is due firstly to the difference in the sampling period where the experimental data were recorded every 300 $ms$ and the simulation data were simulated each 100 $ms$, and secondly to the constant efficiency. Indeed, the sampling period was fixed between 200 $ms$ and 300 $ms$, and because of this fix, the MATLAB simulation did not fetch all the data; however, it has been the highest accuracy in this range of values. The real efficiencies of METALLIANCE's machines varied depending on the vehicle speed, the pressure, and the oil temperature, however, the company had no more details on these technical characteristics. Based on vehicles tests to ensure the expected behavior, these efficiencies are fixed and allocated to their average. As mentioned for the electric vehicle model, this work can be used for other industrial vehicles. The hydraulic vehicle model will be used after the electrical model and thermal model to create a complete vehicle model.

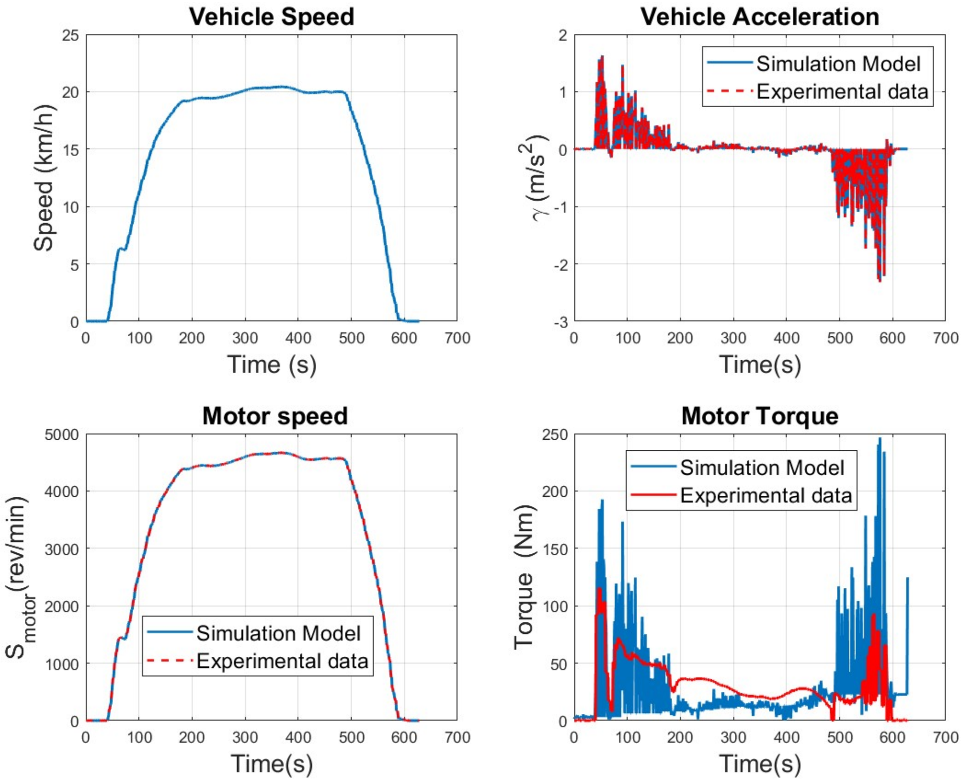



**Figure 9.** Comparison of simulation results with recorded data of vehicle speed and acceleration, motor torque, and speed.

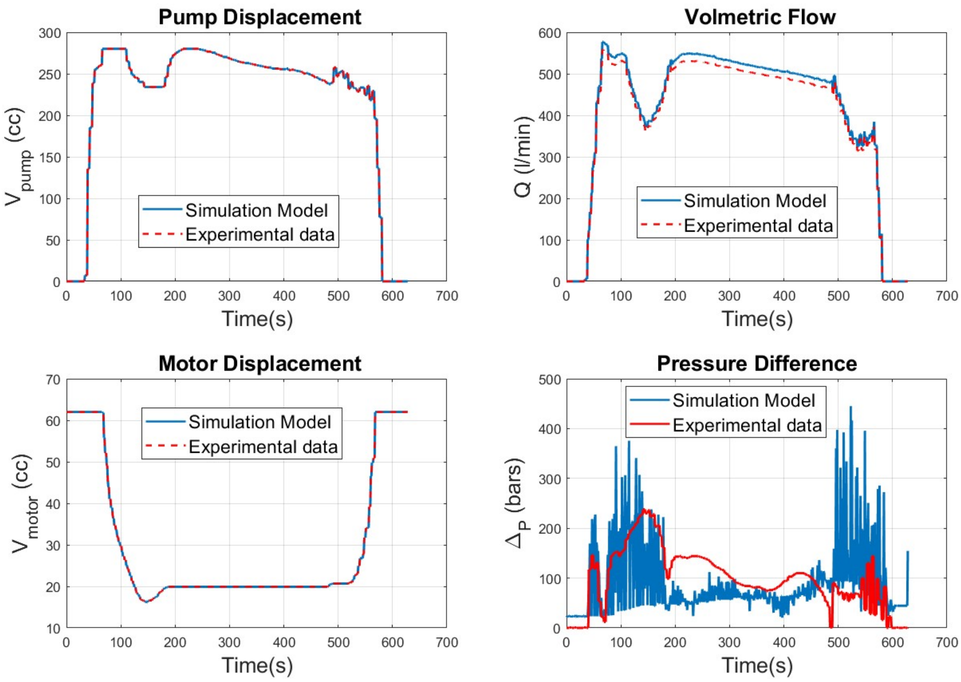



**Figure 10.** Comparison of simulation results with recorded data of pump and motor displacement, volumetric flow, and pressure difference.

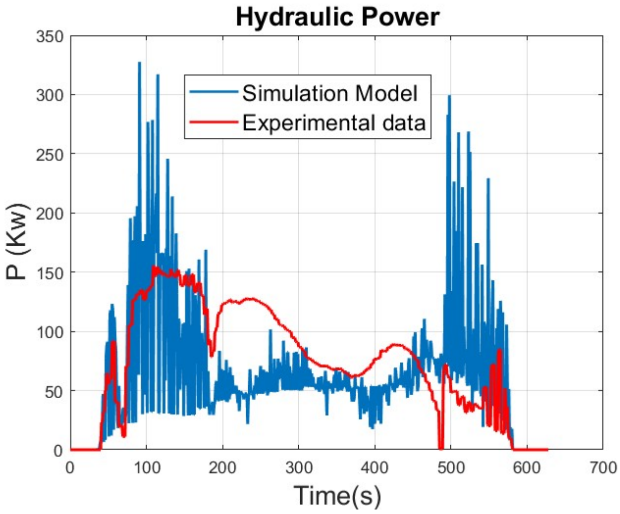



**Figure 11.** Comparison of simulation results with recorded data of hydraulic power.

## 5. Conclusion

This paper presents an appropriate process to implement a dynamic model of the hydraulic and electrical part of METALLIANCE multi-service vehicle (MSV) in the MATLAB/Simulink environment, based on the steps proposed in the literature for the development of a system model. It will be operated with the use of autonomous functionalities, as the METALLIANCE machines are being empowered. Therefore, the methods and steps for the development of the model have been outlined and it remains to investigate the operational design domain of the system used: environmental information, vehicle system characteristics, and operation (METALLIANCE test site). The proposed model evaluates the hydraulic and electrical behavior of the real system based on a mathematical description of the vehicle dynamics. The high accuracy and robustness of the model were validated by real measurements, recorded from the operating system at the METALLIANCE test site. These two models will be combined into a thermal model in order to model the full dynamics of METALLIANCE's vehicles, to develop a complete vehicle model.

As a result, exploiting this complete vehicle model will allow to develop an autonomous vehicle simulator that represents a virtual prototype of the actual behavior of METALLIANCE's machines. Future work will focus on the design of a complete simulator, which reliably reproduces the dynamic behavior of METALLIANCE construction vehicles. Ultimately, the use of the proposed full model to simulate the dynamic behavior of the vehicle is still considered the main step in the process of full automation of construction vehicles.

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## Author Contributions

Conceptualization: M.S., & E.-H.A.; Methodology: M.S., & E.-H.A.; Validation: X.D., & E.-H.A.; Formal analysis: M.S.; Investigation: M.S.; Supervision: E.-H.A., X.D., & P.D.; Writing – original draft preparation: M.S.; Writing – review and editing: E.-H.A., X.D., & P.D. All authors have read and agreed to the published version of the manuscript.

## Conflicts of Interest

The authors have no conflict of interest to declare.

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