

Mechanical Systems from Automotive Industry: Modelling and Simulation of Trailer Systems

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Abstract: This paper presents the modelling of car trailer systems through the analytical method, using the mathematical equations of the laws of physics which describe the process behavior. The simulation of the system was done using MATLAB/Simulink and dSPACE hardware interfaces for real-time environment.

Keywords: car-trailer system, speed, acceleration, mathematical modelling, real-time simulation

1. INTRODUCTION

The dynamic modelling and real-time simulation of the mechanical systems from automotive industry are contemporary engineering topics, having a great impact in the design and validation of control algorithms. Mathematical models are very useful for providers of control solutions from automotive industry.

One of these mechanical systems is the trailer system, which should fulfill many functional safety goals in the car driving process.

Trailer interface modules are designed to control the brake system, hitch and lights from the trailer. Afterwards these hardware and software interfaces are real-time simulated by using the electrical emulation of sensors and actuators which operates as an interface between the simulated process and the embedded system under testing.

In a "Hardware-in-the-loop" (HIL) simulator, a real-time processor executes mathematical models which refer to different behaviors (e.g. motors dynamics, trailer brake dynamics).

A brake controller is usually a device or module installed by the OEM (Original Equipment Manufacturer) or aftermarket. This is mounted on the driver side dashboard area and it operates the electrical brake system of the trailer either with a time delay or proportional to the vehicle's brake when the car decelerates or it has to stop.

There are different types of trailers and brake systems. Small trailers may not contain a dedicated brake system, but when the trailer's weight is over some thousands of kilograms it is recommended to equip the system with a brake controller for the trailer.

The article is structured as follows: Section 2 briefly presents a review of previous trailer system studies. Section 3 provides an overview of the environment used. Section 4 presents the mathematical modelling of a car-

trailer system and simulation with MATLAB/Simulink. Section 5 describes the real-time simulation of the model obtained using dSPACE. Section 6 presents conclusions of the study.

2. RELATED WORK

The inventors T. Brunson and T. McKenzie (2001) created a trailer brake system which involves a controller that supplies pressurized air or hydraulic fluid to an actuator that powers a brake cylinder on the trailer. A pressure sensor provides feedback to the controller. This system includes an indicator that allows the driver to see the status of the trailer braking system.

The industry's first integrated trailer brake controller (2009) was released by K. Englert at Ford Motor company. He also launched the first application of trailer sway control on Ford vehicles and he supported roll stability control on multiple programs.

Z. Kaminski (2014) studied the mathematical modelling of the trailer brake control valve for the tractors equipped with hydraulically actuated brakes and he performed the modelling and simulation in MATLAB/Simulink.

The study done by R.W. Murphy, R. Limpert and L. Segel (1971) presents results and recommendations from a research program of the University of Michigan related to the bus, truck, tractor-trailer braking system performance. The objectives of this study were the implementation of technics and standards for the brake systems of commercial vehicles.

Many studies have been done on car-trailer brake system. MATLAB/Simulink environment contains a complete modelling and simulation of the car, taking into consideration the simulation of wheel slip and motor speed. dSPACE ASM provides models and simulations for cars and trailers. ASM Trailer is an extension of the ASM Vehicle Dynamics Simulation Package and it is

based on a trailer system with up to 4 axles. Trailer and axles can be connected or disconnected during simulation.

3. OVERVIEW

This paper presents in the beginning the modelling of the car-trailer system using the analytical method. Most of the basic principles of the laws of physics have been covered, resulting an approximated mathematical model of a car. This model has also been used to approximate the trailer.

Based on the obtained model, a simulation of the car-trailer system inside MATLAB/Simulink has been done by implementing the systems and subsystems which are involved in the process.

The real-time simulation was done using a dSPACE environment which is composed of hardware and software tools.

The main hardware component which offers real-time simulation is the DS1103 controller board, seen in Fig. 1. The board acquires and generates data at high speed and for this reason it is usually used for applications that have a high number of sensors and actuators. The board is programmable using MATLAB/Simulink via Real Time Interface (RTI). The RTI is a Simulink library which contains input/output resources for the board.

Besides MATLAB/Simulink, dSPACE ControlDesk seen in Fig. 2 has been used which represents the interface between the DS1103 board and the user. Through this tool applications can be downloaded on the board and it provides a way to create virtual instruments to control, monitor or automate experiments.

Based on the same MATLAB/Simulink model but with inputs and outputs acquired and generated by DS1103 board, the model was simulated again.



Fig. 1: DS1103 controller board

4. CAR-TRAILER SYSTEM MODEL

4.1. Mathematical modelling

The vehicle motion can be fully determined by analyzing the forces influencing it, as seen in Fig. 3.

The tractive force (F_t) in the contact area between the wheels and the road surface propels the vehicle forward, which respects the second motion law of Newton:

$$\frac{dV}{dt} = \frac{\sum F_t - \sum F_{resistance}}{\delta \cdot M} \quad (1)$$

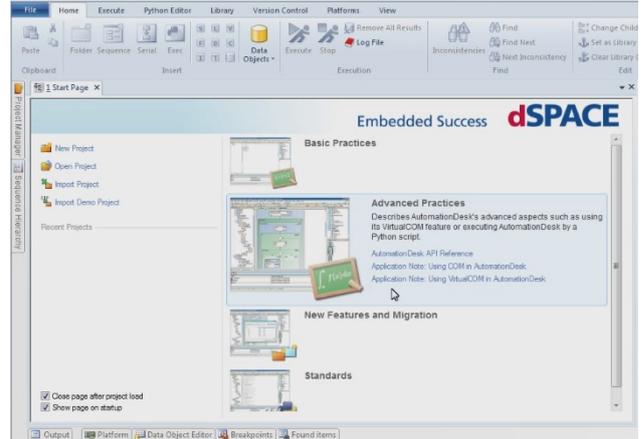


Fig. 2: dSPACE ControlDesk

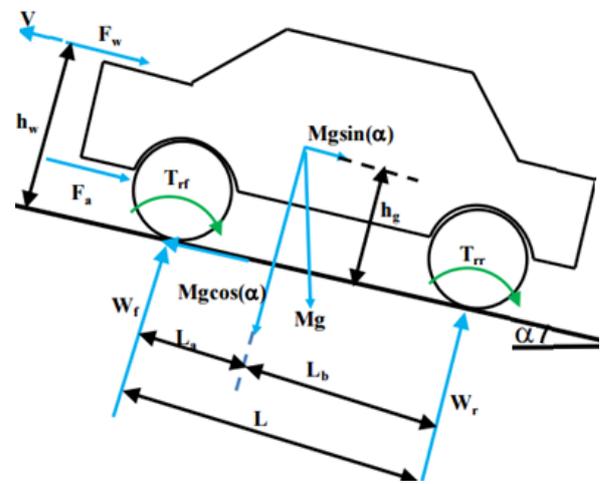


Fig. 3: Forces in the vehicle motion (nptel.ac.in)

The vehicle encounters different resistive forces:

- Rolling resistance appears due to hysteresis in the material of the tire.

$$F_r = \frac{T_r}{r_{dyn}} = \frac{N \cdot \Delta y}{r_{dyn}} = N \cdot f_r \quad (2)$$

$$T_r = N \cdot \Delta y = M \cdot g \cdot \Delta y; f_r \approx 0.01 \cdot \left(1 + \frac{V_x}{160}\right) \quad (3)$$

- Aerodynamic drag appears due to the resistance of the air to the motion of the car.

$$F_w = \frac{1}{2} \cdot \rho \cdot A_f \cdot C_D \cdot V^2 \quad (4)$$

- Uphill (grading) resistance appears when a vehicle goes up or down a slope.

$$F_g = M \cdot g \cdot \sin \alpha \quad (5)$$

- Acceleration resistance appears due to inertial forces which manifest during acceleration and braking.

$$F_a = \left(M + \frac{\sum J_{rot}}{r_{dyn}^2}\right) \cdot \frac{dV_x}{dt}; V_x = \frac{2\pi \cdot r \cdot n_e \cdot (1 - \lambda)}{\varepsilon_0} \quad (6)$$

$$\varepsilon_0 = \frac{N_k \text{ teeth}}{N_1 \text{ teeth}}; \left(M + \frac{\sum J_{rot}}{r_{dyn}^2} \right) = \gamma_m \cdot M \quad (7)$$

On the longitudinal direction, the external forces appearing on a two-axle vehicle are described in Fig. 4.

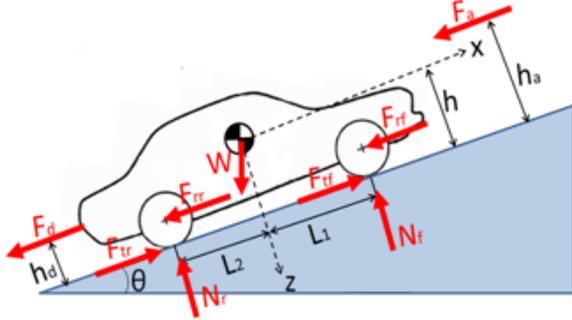


Fig. 4: Forces for longitudinal motion (ni.com)

The tractive force required is summed up from the motion resistance of the vehicle:

$$F_{resistance} = F_r + F_w + F_g + F_a \quad (8)$$

$$\gamma_m \cdot M \cdot \dot{V}_x = F_t + M \cdot g \cdot f_r \cdot \cos \alpha + \frac{1}{2} \cdot \rho \cdot A_f \cdot C_D \cdot V_x^2 + M \cdot g \cdot \sin \alpha \quad (9)$$

Total tractive effort is defined by the following formula:

$$F_t = \mu(\lambda) \cdot M \cdot g; \mu(\lambda) = 2 \cdot \mu_0 \cdot \frac{\lambda \cdot \lambda_0}{\lambda^2 + \lambda_0^2} \quad (10)$$

$$\lambda = \begin{cases} 1 - \frac{V_x}{\omega_w \cdot r_{dyn}}, V_x < \omega_w \cdot r_{dyn} \text{ (acceleration)} \\ 1 - \frac{\omega_w \cdot r_{dyn}}{V_x}, V_x \geq \omega_w \cdot r_{dyn} \text{ (braking)} \end{cases}$$

List of abbreviations:

- $\sum F_{resistance}$ → total resistance.
- $\sum F_t$ → total tractive effort.
- A_f → vehicle frontal area.
- C_D → drag coefficient.
- J_{rot} → inertia of rotational components.
- T_r → rolling resistance.
- V_x → component of vehicle speed on x axis.
- f_r → rolling resistance coefficient.
- n_e → crankshaft.
- r_{dyn} → dynamic radius of the tire.
- $\gamma_m = 1.04 + 0.0025 \cdot \varepsilon_0^2$ → mass factor which explains the inertia of the rotational components.
- ε_0 → gear reduction ratio.
- λ_0 → optimal slip ratio.
- ω_w → wheel angular speed.
- Δy → deformation of the tire.
- g → acceleration constant.
- M → total mass of vehicle.
- V → vehicle speed.

- α → road angle.
- N → normal load acting on the center of the wheel.
- k → number of pinion teeth.
- r → wheel radius.
- δ → mass factor for converting the rotational inertias of rotating components into translation mass.
- λ → driveline slippage.
- $\mu(\lambda)$ → adhesion coefficient.
- ρ → density of air.

4.2. MATLAB/Simulink simulation

The car-trailer system has been simulated using the Simulink implementation, seen in Fig. 5, based on the determined mathematical relations.

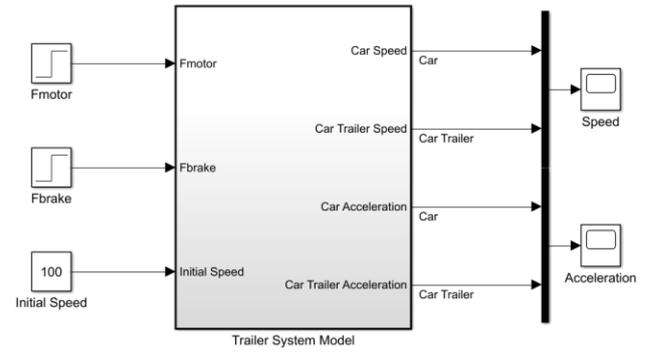


Fig. 5: Block diagram of the trailer system model

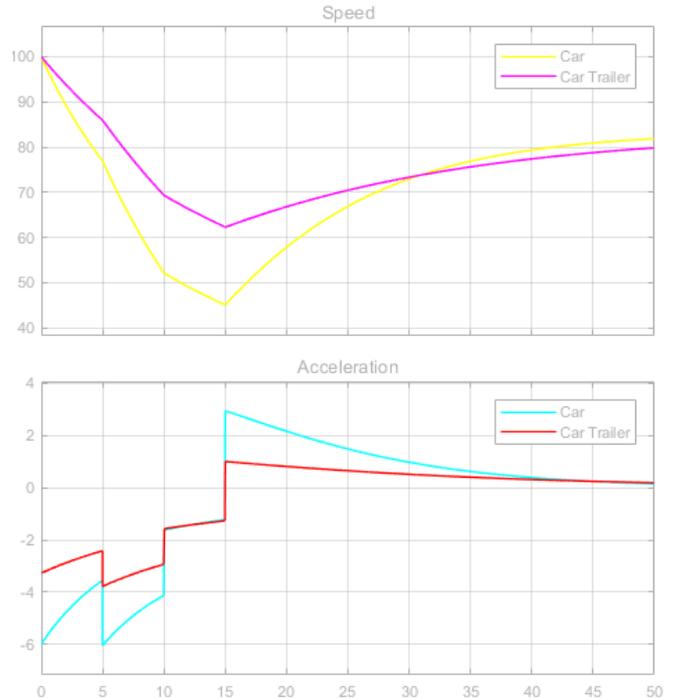


Fig. 6: Speed and acceleration simulation of the system

Fig. 6 shows the response of the car-trailer system when the initial speed is 100 km/h. At the beginning of the simulation there is no acceleration and no braking. At simulation time 5 seconds the brake is activated, at

simulation time 10 seconds the brake is deactivated and at simulation time 15 the acceleration is activated. The speed and acceleration of the trailer follow the speed and acceleration of the vehicle but with a time delay because of the mass difference of the two vehicles.

5. REAL-TIME SIMULATION

Mathematical models of large mechanical systems from automotive industry can be real-time simulated in order to obtain efficient control algorithms. For this purpose, the trailer system model from the previous section was implemented as a block diagram in Simulink.

Following model inputs were considered:

- Driving force (corresponding to pressing the accelerator pedal of the vehicle with trailer).
- Braking force (corresponding to pressing the brake pedal of the vehicle with trailer).

Following model outputs were considered:

- Vehicle's speed.
- Trailer's speed.
- Vehicle's acceleration.
- Trailer's acceleration.

The model inputs were represented by voltages between the range $[-10V, 10V]$ generated through DS1103 controller board.

To generate the voltage corresponding to the driving force, a signal was applied on the analogical channel DACH6, pin 10 of port P1A. This was connected to the pin 23 of port P1B, channel ADCH17.

To generate the voltage corresponding to the brake force, a signal was applied on the analogical channel DACH2, pin 25 of port P1A. This was connected to the pin 40 of port P1B, channel ADC19.

The block diagram for real-time simulation of the trailer system can be seen in Fig. 7.

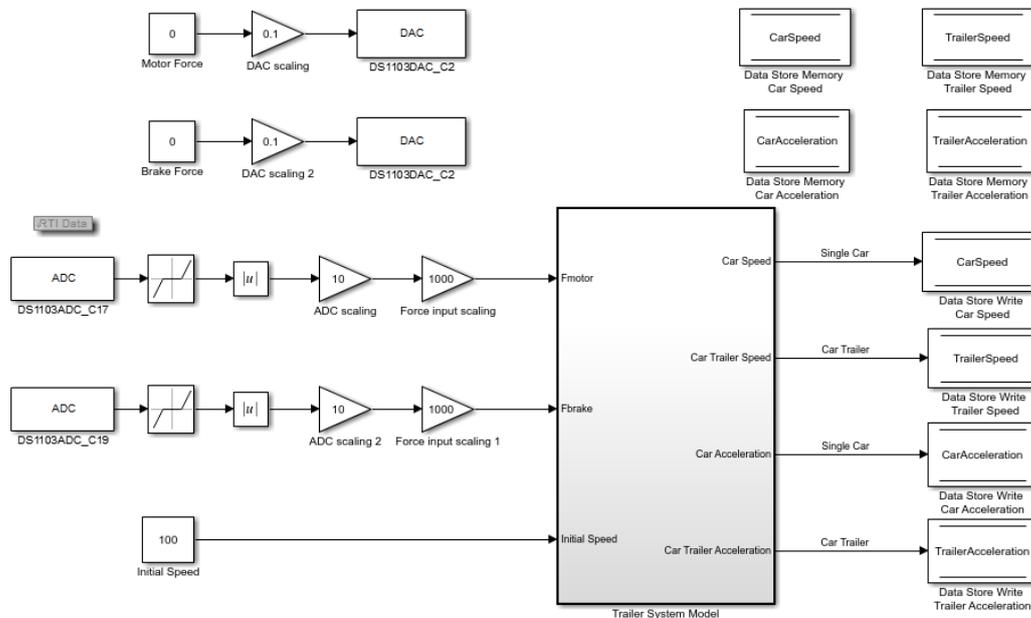


Fig. 7: Trailer system testing – Simulink block diagram

The voltage applied on the analogical channel is converted into a number between $[-10, 10]$. Due to the fact that the model's inputs are forces, this number has to be scaled accordingly. So, for a value 10 of the ADC the input force will be 10000 N.

The initial speed of the vehicle is set in the Constant block and it has the value 100 km/h.

When the Simulink model is compiled, the code generated is stored in a *.sdf* file, which can be downloaded on DS1103 controller board. After this file is loaded in dSPACE ControlDesk the variables for the real-time hardware can be manipulated in the simulation.

In the trailer system simulation, the outputs were followed on the same axis system using *Plotter* indicators which

had assigned corresponding *Data Store Memory* variables.

It can be seen in Fig. 8 the simulation results when a driving force of 5000N is applied, corresponding to the pressing of the accelerator pedal. Therefore, the car speed increases and the trailer speed follows the same behavior with a certain delay due to the mass difference of the two vehicles. The acceleration has the same behavior, with some delay on trailer side.

When a voltage equal to 8V corresponding to a braking force of 8000N is applied, then the speed of the car-trailer system decreases till the value 0. At this point the car and the trailer have constant motion. If a driving force equal to 8000N is applied, then the speed and acceleration begin to increase, which means that the trailer system can be

considered a tracking system of the vehicle. This behavior can be seen in Fig. 9.

The settling time of the trailer system, represented by its mathematical model, can be improved by implementing numerical control algorithms on a microcontroller.

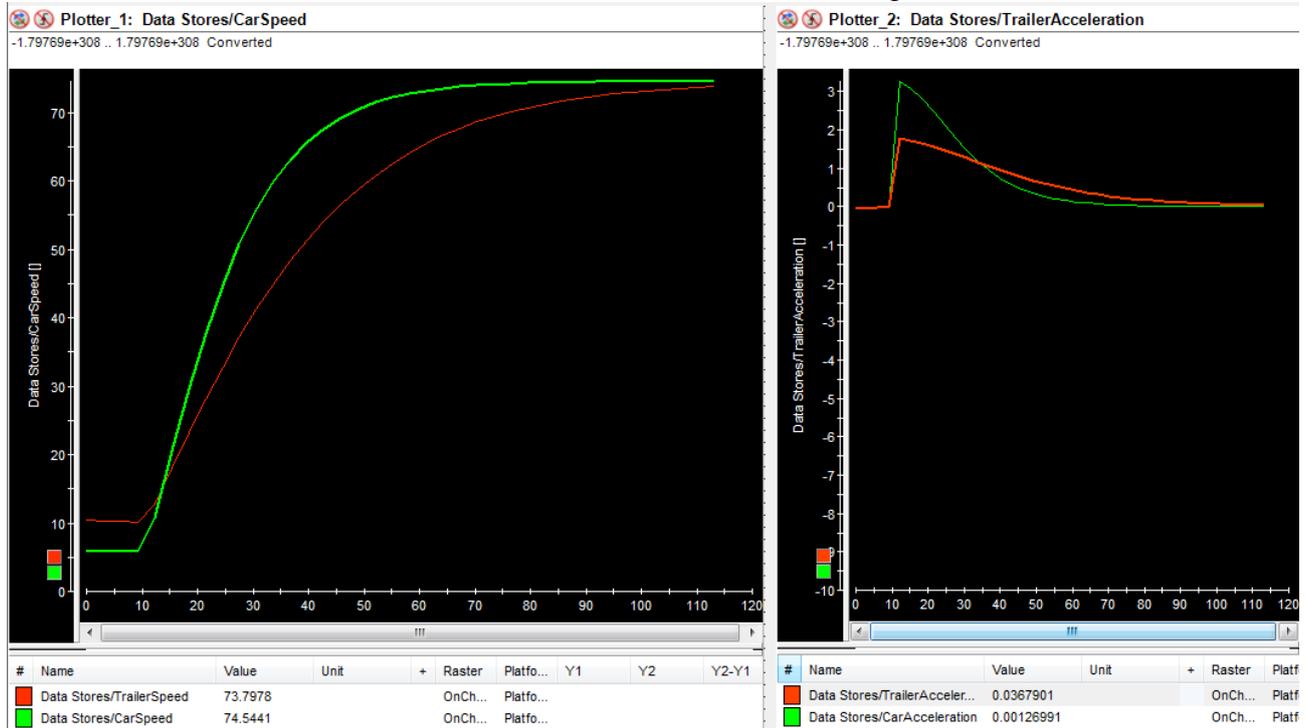


Fig. 8: Speed and acceleration simulation in dSPACE

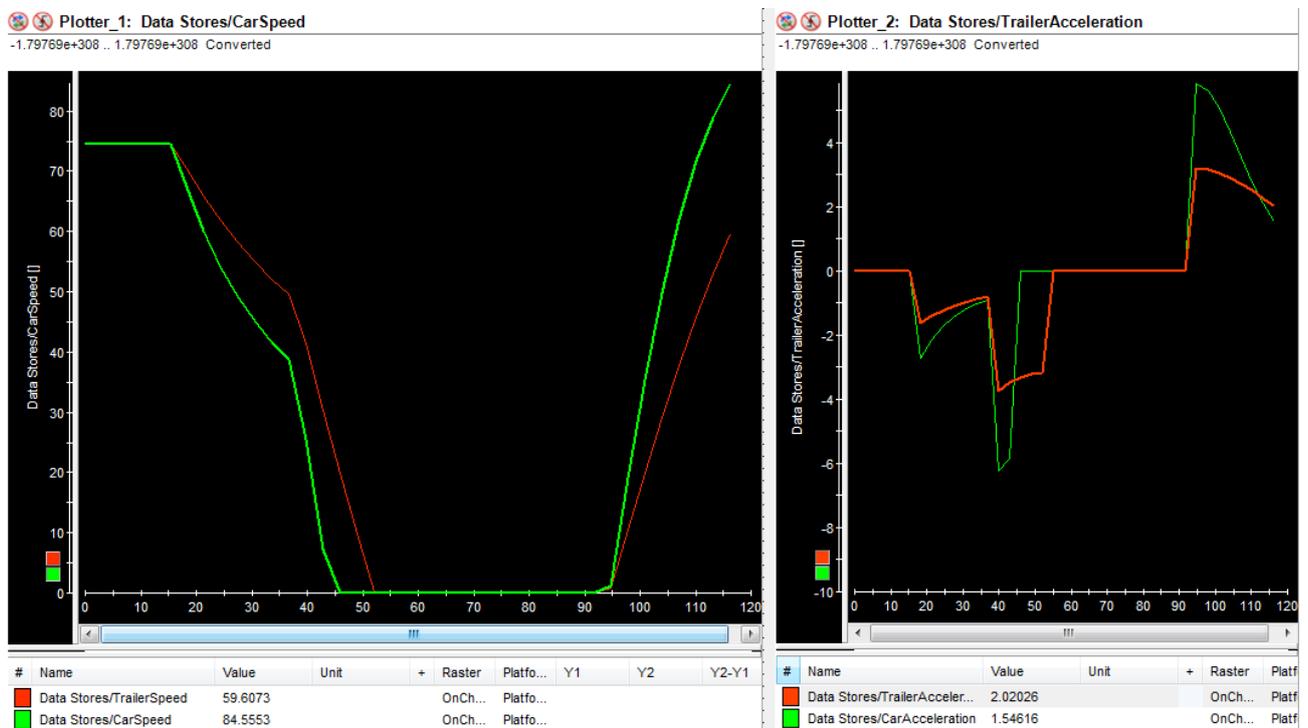


Fig. 9: Speed and acceleration simulation in dSPACE

6. CONCLUSIONS

Mathematical modelling of different components of a technological process is the first step in controlling automated systems. Knowing the approximate

mathematical expression of a process can help to create a series of simulations to determine optimal parameters. Mathematical modelling involves the development of a suitable model representing the physical model.

The car-trailer system modelling was done by covering the topics related to the general description of vehicle motion, vehicle resistance and dynamic equations. This implied studying the forces which influence the vehicle.

In automated systems engineering, mathematical models play a very important role. After obtaining the model, these systems are represented within a simulation environment such as MATLAB/Simulink and different libraries are created. By adding a hardware component that can simulate real-time, the model can be treated as a real system.

One technique to develop and test complex embedded systems in real-time is the Hardware-in-the-Loop (HIL) simulation. This integrates in the testing platform the complexity of the system that is desired to be controlled by using the mathematical models of each subsystem.

With a simulated system, tests can be executed to determine the possible problems which might appear and which might destroy the system or which could be harmful for the environment. This is the reason for which HIL simulation can greatly improve the car operation.

HIL simulation of the car-trailer system was done by covering the dSPACE TargetLink testing environment solutions, analyzing and interpreting the results obtained based on the MATLAB/Simulink mathematical model. The analysis of the system response was done in order to validate the model.

In automotive industry, HIL simulation makes possible the creation of a virtual vehicle for validation and verification of the systems with tests that evaluate the performance and diagnostic functionalities of the car. HIL simulators allow developers to validate hardware and software solutions that fulfill quality and time requirements.

Therefore, if a real-time simulation is integrated in the process design based on a model, this can be used starting with the first phase of development. The simulation is extended together with applications and it is used by engineers to continuously test their control systems. These tests can detect problems early in the development process, which reduce the risk of high costs later in the project.

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