CAPABILITIES AND LIMITATIONS OF A 4-DOF CAR SIMULATOR

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Abstract: *4-DOF car simulators are effective platforms that help analyze vehicle behavior under different dynamic conditions. The 4-DOF movements are pitch, roll, yaw, and heave. The car simulator described in the paper is an AUTO ROMOTION 4-DOF simulator dedicated to learn how to drive a vehicle, but also for entertainment. A 4-DOF simulator offers a balance between complexity and practical applicability. The equations used in the paper are specific to the 4-DOF model, utilizing Lagrange's equation. The paper describes how MATLAB/Simulink works, from the input variable data and the software's fixed data for executing a command, to the obtained trajectory, and finally to the resulting graphs, activating command blocks. Modelling in MATLAB/Simulink allows for an accurate representation of vehicle movements, facilitating virtual testing of behavior in controlled environments.*

Keywords: *4-DOF, MATLAB/Simulink, Simulator, Plots*

1. Introduction

The significant progress made in the automotive industry over the last decades, as well as the development of advanced monitoring and control systems, has led to the emergence and widespread adoption of driving simulators. These platforms allow for the analysis of driver behavior [Houda, 2020], [Zhang, 2025] in various conditions. Such evaluations can be conducted in controlled laboratory environments, without involving the risks and costs associated with the test carried out in real traffic conditions.

The first motion simulators appeared in the early 1910s, in France and England. These were for flight training [Bruck, 2021]. The origin of the first driving simulator is unclear [Bruck, 2021], but a system from 1934 is often mentioned; its simplicity leads many authors to consider later appearances as the real beginning of relevant development in the field.

In the 1970s was developed several 3-degree-of-freedom (3-DOF) driving simulators (yaw, roll, and pitch) were developed by developers and research institutes, calling here the devices developed by Volkswagen and the Swedish Road and Traffic Research Institute [Bruck, 2021]. This simulator in 3-DOF can demonstrate motion in three planes: x-axis, y-axis, and z-axis [Kondyli, 2021]. In 1985, Mazda developed a 4-DOF [Yoshimoto, 2008] vehicle (yaw, roll, pitch, and surge) system [Capustiac, 2011]. Around the time, Daimler-Benz developed a 6-DOF system with a 180-degree range. In 1994, Ford introduced their 6-DOF simulator, having, in addition to the 3 standard grades, another 3: sway, heave, and surge [Kondyli, 2021]. After that, they continued with the development of the Renault car simulators in 2004 [Kondyli, 2021].

At the end of the 1990s and the beginning of the 2000s, the rapid development of digital (3D) plots, the increase in screen resolutions, and the advancement of real-time plots processing significantly expanded the capabilities of car simulators.

Building on these developments, the AUTO ROMOTION 4-DOF [Simulator 4-DOF, 2025] simulator integrates modern motion-control systems, precise actuators, and real-time feedback to deliver high-fidelity motion cues. Its configuration provides a robust platform for studying driver responses, human–machine interaction, and the performance of advanced vehicle systems under safe and controlled laboratory conditions.

This paper is organized like this:

Section 2 Simulator 4-DOF - Description of AUTO ROMOTION Simulator 4-DOF. Functioning of the AUTO ROMOTION Simulator's 4-DOF.

Section 3 Mathematical modelling - Kinetics and dynamics models. Simulink modelling

Section 4 - Conclusions

2. Simulator 4-DOF

2.1 Description of AUTO ROMOTION Simulator 4DOF

The AUTO ROMOTION 4-DOF simulator is a device designed for driving simulation, offering a high degree of flexibility and the capability to replicate specific real-world traffic conditions. It is intended both for the preliminary training of driving school students and for entertainment purposes [Simulator 4-DOF, 2025].

Figure 1: *AUTO ROMOTION 4DOF Simulator*

The simulator is powered by single-phase, 4,5kW/230V/50Hz.

The simulator has the following main structural parts [Simulator 4-DOF, 2025]:

1 – Monitor 40", 4K;

2 – Wheel Thrustmaster;

3 – Chair RS;

4 – Platform;

5 – Mounted circular platform;

6 – Thrustmaster gear;

7 – Pedals;

8 – Keyboard and remotes, for TV and sound;

The simulator's computer supports virtual reality and has the following technical specifications: Intel I7 12700K processor, Z790 motherboard, 32 GB 6000 MHz DDR5 memory, 750W Gold power supply, 360 liquid cooling cooler, RTX 4070 Super graphics card, 1TB M.2 SSD. The type of audio system is 2.1.

Figure 2: *The platform T300 RS*

The platform shown in Figure 2 includes the elements [Simulator 4-DOF, 2025] presented below:

9 – 3 servo motors M1, M2, M3;

10 – Servo motor with drive belt M4;

11 – 4 frequency converters V1, V2, V3, V4;

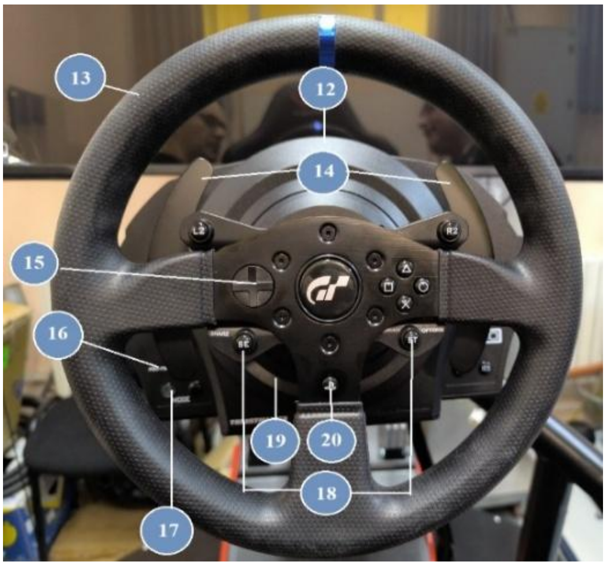

Figure 3: *The wheel T300 (front side view)*

Figure 3: *The wheel T300 (back side view)*

The wheel T300, from Fig. 3, includes the following elements [Thrustmaster, 2025]:
12 – T300 base;
13 – T300 wheel;
14 – 2 sequential paddle shifters (up & down)
15 – Directional buttons;
16 – Built-in USB sliding switch for PS5™ consoles, PS4™ consoles, and PC;
17 - Button + red/orange/green indicator light;
18 – Share/Options buttons on PS4™ consoles and create/options on PS5™ consoles;
19 – PS buttons;
20 – Large threaded hole (for attachment system and fastening screw);
21 – Power supply connector (type A or B) (varies from one country to another);
22 – Raing wheel USB cable and connector;
23 – Gearbox connector;
24 – Pedal set connector;

2.2 Functioning of the AUTO ROMOTION Simulator's 4-DOF

The connection–disconnection of the power supply can be done through the contactor C, controlled by 2 switchable buttons, placed on the simulator's pedestal. A STOP power button is provided on the simulator for safety reasons. From this contactor, power will be supplied through circuit breakers Q1, Q2, Q3, and Q4 to 4 frequency converters V1, V2, V3, and V4, which will in turn supply, at variable frequency, the motors M1, M2, M3, and M4, which operate the simulation of various movements. The speed control is done with a 0-10 VDC voltage, provided by the PLC equipment.

A voltage stabilizer (VS) will provide a stabilized voltage to the DC power supply 230 V/24 VDC and to the sockets P1, P2, P3, P4, P5, and P6, which power various consumers. The computer, as the central unit powered from one of the sockets, receives specific information (steering movement, acceleration, braking, gear shift, etc.), processes it according to specific software, and sends signals to the monitor, speakers, and PLC interface [Simulator 4-DOF, 2025].

3. Mathematical modelling

Vehicle models can exhibit varying levels of complexity, depending on the phenomena they are intended to capture.

A model with four degrees of freedom-longitudinal, lateral, yaw, and roll [Yoshimoto, 2008]—can demonstrate that longitudinal dynamics are often negligible in pseudo-random steering tests, primarily because the longitudinal velocity remains approximately constant throughout the maneuver.

3.1 Kinetics and dynamics models

Kinetics models describe vehicle motion under applied forces and moments, while dynamics models comprehensively include inertia, mass, force interaction influencing stability and performance. Figure 4, according to [Kelkar, 2021], shows the coordinate system that will be used in this study.

Using this system, the forward movement of the vehicle is described in the positive ***X*** axis, the lateral movement is described by the ***Y*** axis, being positive when oriented to the left, from the driver position, and the vertical movement is represented in the ***Z*** axis.

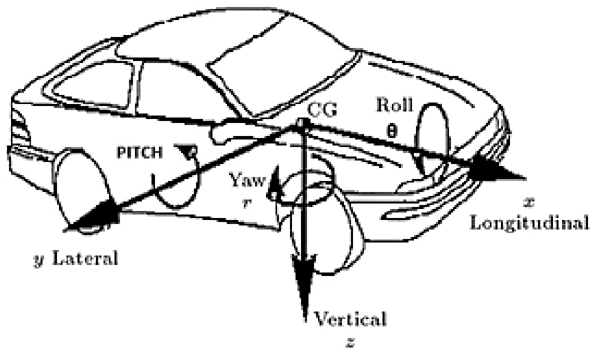

Figure 4: *System of coordinates* [Kelkar, 2021]

Figure 5 represents a schematic vehicle model, with 4-DOF: longitudinal velocity ***n***, lateral velocity ***t***, yaw velocity ***w***, and roll angle ***τ***, [Pardele, 2004], [Xu, 2012].

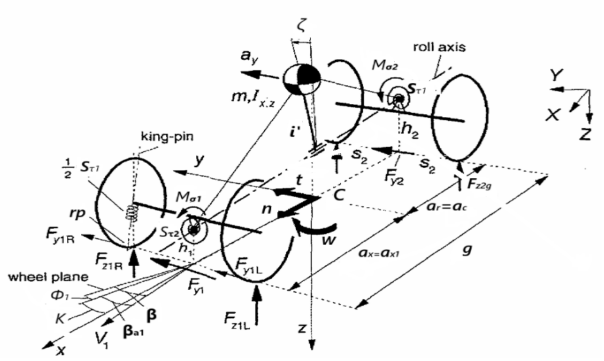

Figure 5*: Vehicle model with 4-DOF*

The equations of motion can be obtained using the equation of Lagrange [Pardele, 2004]:

$$\frac{d}{dt}\frac{\nu E}{\nu \dot{q}_i} - \frac{\nu E}{\nu q_i} + \frac{\nu P}{\nu q_i} = Q_i \qquad (1)$$

Where:
E: kinetic energy;
P: potential energy;
Q_i *:* generalized forces;
q_i *:* generalized coordinates.

Taking into consideration the vehicle model, the generalized coordinates can be used [Patil, 2017]:

- Global Cartesian coordinates ***X*** of the center of gravity (CG);
- Global Cartesian coordinate ***Y*** of the CG;
- Yaw angle ***χ*** between the moving x-axis and the global X-axis in the CG;
- Roll angle ***ω*** around the roll axis of the vehicle.
- Another set of variables, according to Fig. 5:
- Longitudinal velocity, ***n***;
- Lateral velocity, ***j***;
- Yaw velocity, ***w***;
- Roll angle ***ω***, around the roll axis of the vehicle.

Taking into consideration *Tire and vehicle dynamics* [Pardele, 2004], [Nguyen, 2021], the relation for kinetic energy *E* and potential energy *P* can be written with the new variables. Also, considering a small roll angle and a flat level road, these relations become [Pardele, 2004]:

$$E = \frac{1}{2} m \{(n - i'\omega w)^2 + (j + i'\dot{\omega})^2\} + \frac{1}{2}R_x\dot{\omega}^2 + \frac{1}{2}R_y(\omega w)^2 + \frac{1}{2}R_z(w^2 - \omega^2 w^2 + 2\theta_r w\dot{\omega}) - R_{xz}w\dot{\omega} \qquad (2)$$

Where:
m: vehicle mass;
i': CG height according to the roll axis.
R_x: roll moment of inertia (about vehicle (*x*-axis).
R_y: pitch moment of inertia (about vehicle *y*-axis).
R_z: yaw moment of inertia (about vehicle z-axis).
R_{xz}: roll-yaw product of inertia.
θ_r: inclination angle of roll axis according to the horizontal plane.
ω: roll angle, around the roll axis of the vehicle.

n: longitudinal velocity.
j: lateral velocity.
w: yaw velocity.

The kinetic energy [Pardele, 2004] is:

$$E = \frac{1}{2} mn^2 + \frac{1}{2} mj^2 + \frac{1}{2} R_z w^2 + \frac{1}{2} \left(m_\omega i'^2 + \right.$$
$$\left. + R_{x,\omega}\right) \dot{\omega}^2 - m_\omega i' n \omega w + m_\omega i' j \dot{\omega} +$$
$$+ \frac{1}{2} \left(m_\omega i'^2 + R_{y,\omega} - R_{z,\omega}\right) w^2 \omega^2 +$$
$$+ \left(R_{z,\omega} \theta_r - R_{xz,\omega}\right) w \dot{\omega} \qquad (3)$$

With Eq. (3), it reformulated Eq. (1), using the equation of Langrage [Pardele, 2004]:

$$\frac{d}{dt} \frac{\nu E}{\nu n} - w \frac{\nu E}{\nu j} = Q_n$$
$$\frac{d}{dt} \frac{\nu E}{\nu w} + w \frac{\nu E}{\nu w} = Q_j \qquad (4)$$
$$\frac{d}{dt} \frac{\nu E}{\nu w} - t \frac{\nu E}{\nu n} + n \frac{\nu E}{\nu j} = Q_w$$
$$\frac{d}{dt} \frac{\nu E}{\nu \dot{\omega}} - \frac{\nu E}{\nu \omega} + \frac{\nu P}{\nu \omega} = Q_\omega$$

The generalized forces [Pardele, 2004] are:

$$Q_n = F_{x1} - F_{y1}(K + \Phi_1) + F_{x2} - F_{y2}\Phi_2;$$
$$Q_j = F_{x1}(K + \Phi_1) + F_{y1} + F_{x2}\Phi_2 + F_{y2};$$
$$\Phi_w = fF_{x1}(K + \Phi_1) + fF_{y1} + M_{z1} -$$
$$dF_{x2}\omega_2 - dF_{y2} + M_{z2}; \qquad (5)$$
$$Q_\omega = -K_\omega \dot{\omega};$$

Where:

K: applied steer angle at wheels, result of input on steering wheel;
Φ: additional steer angle, result of compliance and roll steer;
f: distance between vehicle CG and front axle;
d: distance between vehicle CG and rear axle;
F_x: longitudinal tire force;
F_y: lateral tire force;
M_z: tire self-aligning moment (about the vehicle z-axis)

2.3 Simulink Modelling

Simulink is a software program that helps in understanding dynamic system behavior, modelling, and simulating. This software offers a visual modelling environment, numerical results, and flexible block databases for making and simulating dynamic systems models.

Simulink is integrated with MATLAB [Ma, 2023], [Patel, 2010], allowing users to put together MATLAB algorithm models and export the results obtained from simulations to MATLAB for further analysis [Matlab/Simulink], [Meiners, 2025].

A Simulink model [Țurcanu, 2020] is composed of blocks, connections, subsystems, parameters, numerical solver parameters, and variables from the workspace.

In Fig. 6, it's presented a simulation model for a vehicle is presented [Matlab/Simulink]. The application offers a customizable vehicle-dynamics model for progressive steering movements, enabling assessment of design compliance, ride, handling, and lateral dynamics, supporting advanced chassis-control development.

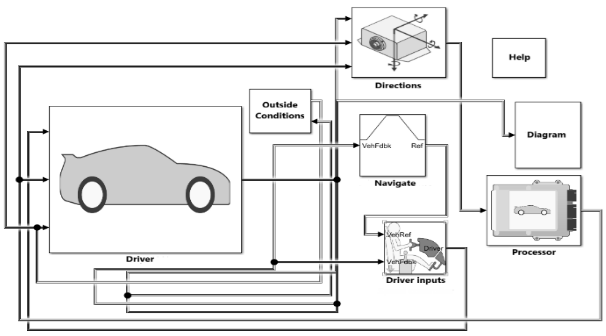

Figure 6: *The simulation model*

The main subsystems, for this Simulink model, are:

- Driver;
- Outside conditions;
- Directions;
- Navigate;
- Driver inputs;
- Diagram;
- Processor;

The test analyzes vehicle lateral dynamics through gradual steering maneuvers, supporting ride, handling, and chassis control development.

The driver does:

- Accelerates until it's obtained the desired velocity;
- Keeps the velocity, for a certain time;
- Keeps the steering wheel [Gerber, 2019] angle for a certain time;
- The steering wheel angle linearly decreases, from the maximum angle to 0 degrees.

  This Simulink model runs, depending on the parameters set, either variable or fixed. Variable parameters have been modified [Matlab/Simulink]:

- *Maneuver start time, t start* – **2s**
- *Longitudinal speed setpoint, xdot_r [xdotUnit]* – **50 mph**
- *Handwheel rate, omega_hw* – **5deg/s**
- Maximum absolute handwheel angle, theta_max – **500deg**
- *Steering hold time after max angle reached, t_stop* – **5s**

Fixed parameters [Matlab/Simulink] are:

- *Steady-state solution to start from, ssVar* – **50mph**
- *Lateral acceleration absolute threshold, ay_max* – **0.5g**
- *Initial longitudinal position X_0* – **0m**
- *Initial lateral position, Y_0* – **0m**
- *Initial heading (yaw) angle, psi_0* – **0rad**
- *Steady-state solver tolerance, ssTol[xdotUnit]* – **0.1**
- *Maximum simulated time to reach steady-state, ssMaxTime* – **30s**
- *Workspace variable name to generate, ssWSName* – **is50mph**

After running the [Matlab/Simulink] program, it was possible to obtain the graph with the path shown in Figure 7, where the x and y coordinate values are available, using a speed of 19 m/s.

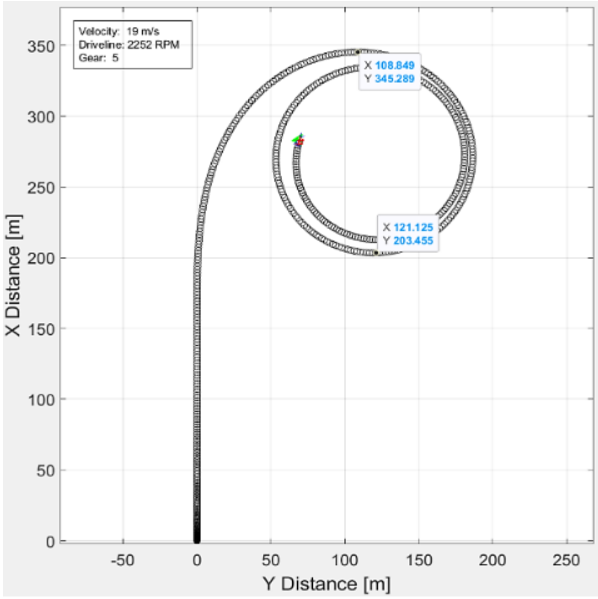

Figure 7: *The path of the vehicle*

Running the simulation, the "*Diagram*" subsystem [Matlab/Simulink] provides information about the driver, vehicle, and response information. The reference application logs vehicle signals—steering [Zhou, 2025], speed, and lateral acceleration—for analysis using the Simulation Data Inspector to examine dynamics.

In this way, one graphic [Alqudsi, 2025] is obtained with *YAW rate* and *STEER Angle (*Fig. 8*)* [Matlab/Simulink], and one graphic with *Steer angle, Longitudinal vehicle velocity* versus *time* (xdot), *Lateral acceleration* versus *time* (ay), Fig. 9 [Matlab/Simulink], and *Engine* versus *time*, Fig. 10 [Zhou, 2025] [Matlab/Simulink]:

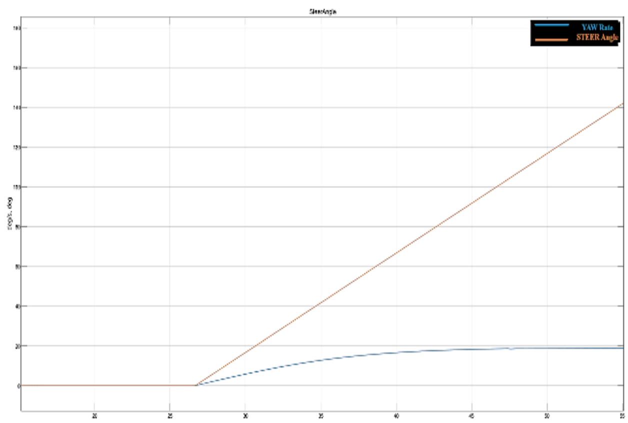

Figure 8: *Yaw rate and Steer*

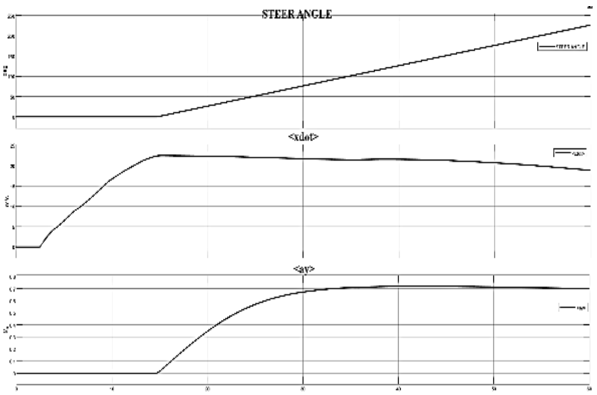

Figure 9: *Steer angle, Longitudinal vehicle velocity, and Lateral acceleration*

Also, with the help of "*Data inspector*", from "*Diagram*" subsystem, it can be observed how the *engine* (rpm) versus *time* (Fig. 10) [Matlab/Simulink].

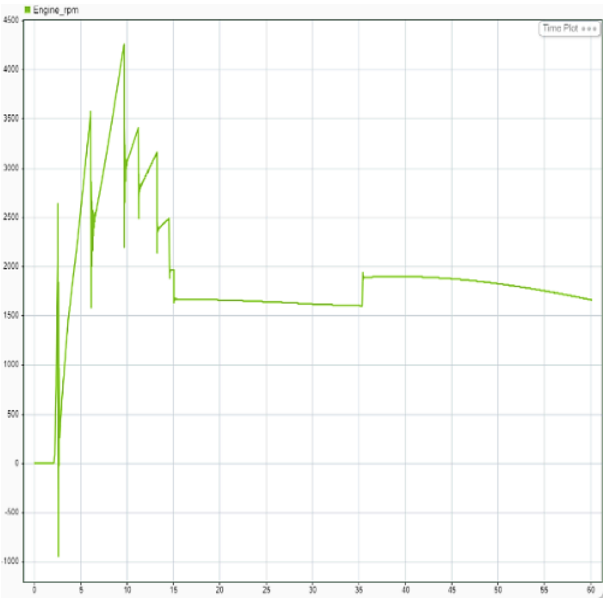

Figure 10: *Engine (rpm) versus time*

3. Conclusions

The AUTO ROMOTION 4-DOF simulator provides a realistic and flexible environment for driving instruction and entertainment by replicating real-world vehicle behavior through hardware and control systems.

Separately, MATLAB/Simulink enables detailed simulation and analysis of vehicle dynamics, supporting virtual testing and control development.

Used together, these tools offer complementary insights: the simulator focuses on practical, hands-on experience, while MATLAB/Simulink delivers precise modeling for research and design, advancing both automotive education and engineering.

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