

# **CAN-Based Digital Twin of Electric Vehicle ECU System**

**Platform:** MATLAB/Simulink

**Subsystems:** ECU Stateflow Controller, PID Speed Control, CAN Communication, Vehicle Dynamics

**Method:** Stateflow Logic and CAN-Based System Integration

**Writer:** Mehmet Karagülle

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# 1. Introduction and Objectives

This project extends the previously developed Electric Vehicle Powertrain Model by introducing a CAN-based digital twin of the Electronic Control Unit (ECU). The aim is to simulate a real-time communication and control environment where the ECU manages vehicle modes and torque commands through the CAN protocol.

## Main objectives:

- Develop a Stateflow-based ECU control structure with operational modes (Idle, Accel, Cruise, Decel).
- Integrate a PID controller to generate torque demand (Torque\_Req) through CAN messages.
- Establish CAN Pack/Unpack communication between control and physical layers.
- Analyze the effect of communication scaling and parameter tuning on system stability.

# 2. System Architecture

The overall model consists of two main layers:

Layer	Description
Physical Layer	Simulates the EV Powertrain including dynamics and torque response.
Control Layer (ECU)	Stateflow manages driving modes and PID-based throttle control. Communication is with CAN messages.

The electric vehicle ECU system integrated with EV powertrain system is given below(Fig. 1):

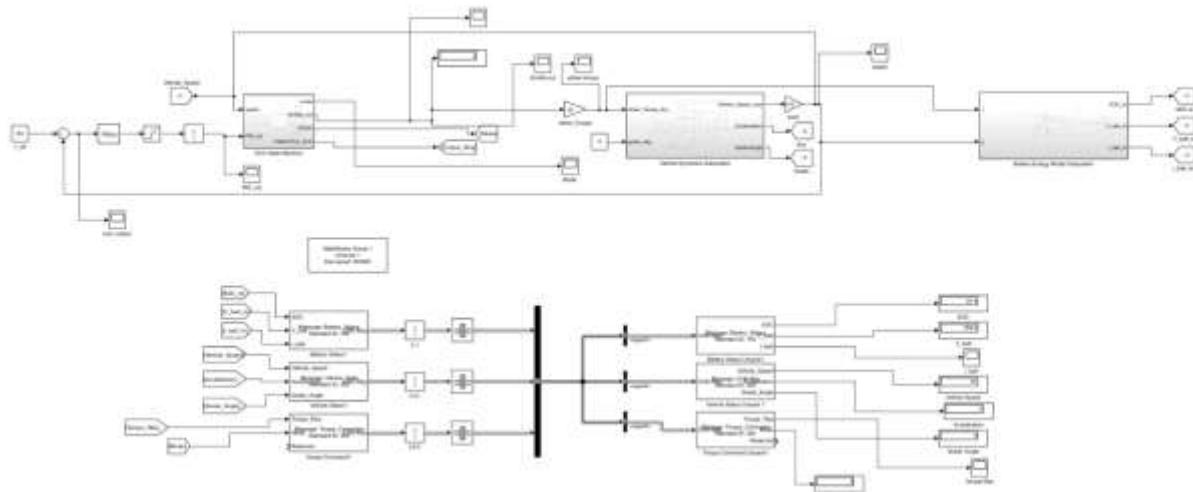


Figure 1: The electric vehicle ECU system with EV powertrain

### 3. ECU Stateflow Design (System Core)

The core of this project is the ECU State Machine (Stateflow) architecture. The ECU determines the vehicle's driving mode and generates throttle commands (Throttle\_out) based on speed feedback, PID control and CAN communication.

#### 3.1 Core Logic

The ECU is implemented as a finite state machine (FSM) with four operational modes, representing real vehicle behavior(Table 1):

State	Description	Output (Throttle_out)	CAN Signal
<b>Idle</b>	Vehicle is stationary, throttle disabled	0	Mode = 1
<b>Acceleration</b>	PID controller active, vehicle accelerates	PID_out	Mode = 2
<b>Cruise</b>	Speed maintained near target value	PID_out (steady)	Mode = 3
<b>Deceleration</b>	Throttle decreases smoothly	Decreasing throttle	Mode = 4

Table 1: Operational modes in Stateflow

The state transitions emulate a driver's natural input behavior under throttle control, mapped directly into ECU logic.

#### 3.2 Input and Outputs

The following signals and symbols are defined at the Stateflow interface to connect the ECU with the vehicle dynamics and control system(Table 2)(Table 3):

Signal	Type	Source / Destination	Description
speed	Input	Vehicle Dynamics	Actual vehicle speed (km/h)
V_ref	Input	Step / Constant block	Target reference speed
PID_out	Input	PID Controller	PID-calculated throttle value
Throttle_out	Output	Powertrain subsystem	ECU throttle command
Mode	Output	CAN Pack block	ECU operating mode

Table 2: Signals at the Stateflow

This structure allows the ECU to function independently while communicating with CAN.

Symbol	Meaning	Typical Value	Purpose
V_CRUISE	Reference (target) speed	80 km/h	Defines steady-state target
H	Hysteresis margin	0.5–1.0 km/h	Smooths state transitions and prevents chatter

Table 2: Symbols at the Stateflow

### 3.3 Transition Conditions (Mode Logic)

State transitions are driven by vehicle speed comparisons and PID behavior(Fig. 2):

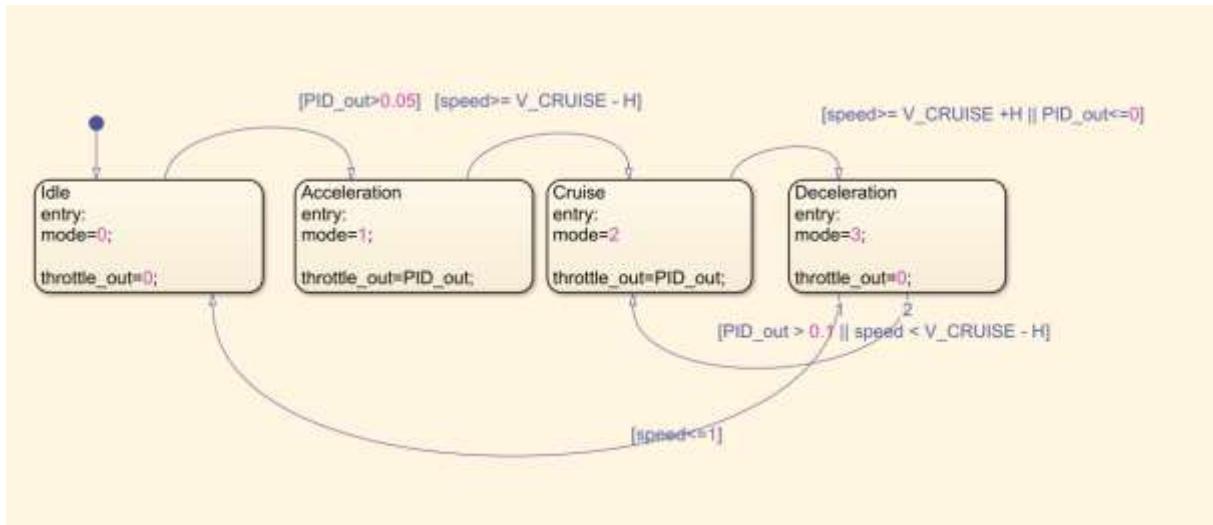


Figure 2: Stateflow chart at the ECU

### 3.4 PID Integration

The PID controller operates externally from the Stateflow chart to preserve timing accuracy. Its output (PID\_out) is used as the ECU's throttle reference, processed based on mode logic(Fig. 3):

- Acceleration / Cruise: Throttle\_out = PID\_out
- Deceleration / Idle: Throttle\_out = 0 or a decreasing value

This separation of control and state logic improves modularity — allowing PID tuning without altering the ECU logic itself.

The Throttle\_out signal is then sent to the CAN communication block.

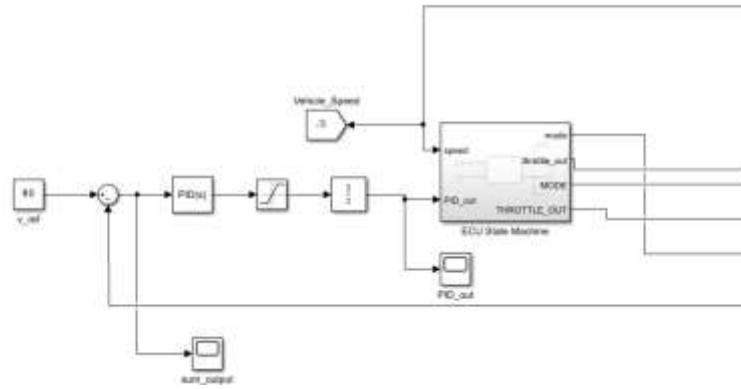


Figure 3: PID integration on ECU state machine

### 3.5 Delay Synchronization (Time Alignment)

During early testing, an algebraic loop occurs because the ECU computes outputs and feedback simultaneously.

To solve this, a Unit Delay (sample time = 0.01 s) or Transport Delay is added before the CAN transmission stage(Fig. 4).

This ensures:

- Deterministic (stable) simulation,
- Throttle values updated every 0.01 s,
- CAN transmission executed at 0.1 s intervals.

The result is synchronized real-time control and message timing consistency.

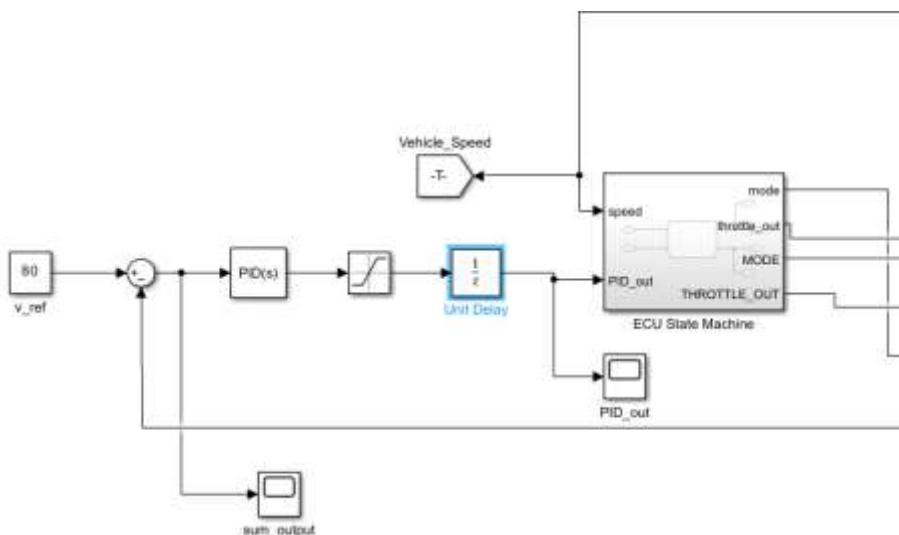


Figure 4: Unit delay block

### 3.6 CAN Transmission (Torque Command Frame)

The ECU transmits the throttle command and operating mode through the CAN network. The message structure follows Message ID 300 – “Torque\_Command”(Table 4)(Table 5):

Signal	Start Bit	Length (bit)	Data Type	Factor	Description
Torque_Req	0	32	single	1000	PID-generated throttle demand
Mode	32	8	uint8	1	Active ECU mode
Reserved	40	8	uint8	1	Reserved for future signals

Table 4: Torque Command Pack parameters

Signal	Start Bit	Length (bit)	Data Type	Factor	Description
Torque_Req	0	32	single	0.001	PID-generated throttle demand
Mode	32	8	uint8	1	Active ECU mode
Reserved	40	8	uint8	1	Reserved for future signals

Table 5: Torque Command Unpack parameters

This ensures that both PID control output and state information are transmitted simultaneously, mirroring how a real ECU communicates with the powertrain controller.

### 3.7 Why It's the heart of the system

This ECU Stateflow structure is the control core of the entire model because it integrates:

1. Dynamic decision logic — determines what mode the vehicle is in.
2. PID-based control — computes throttle and torque commands.
3. CAN communication — transmits real-time data between controller and plant.

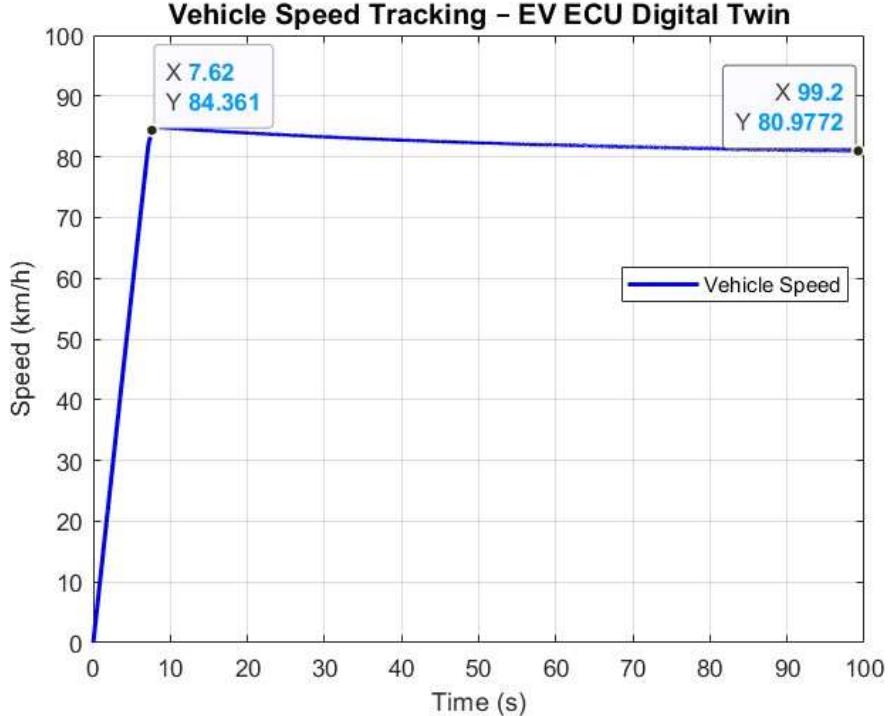
Together, these make the ECU both the “brain” (control intelligence) and the “nervous system” (communication pathway) of the digital twin model.

## 4.Simulation Results

The plot illustrates the response of the vehicle speed (blue line) over a 100-second simulation period. The controller successfully tracks the desired speed profile generated by the ECU(Graph 1).

- The vehicle accelerates rapidly from rest, reaching approximately 84.8 km/h at around 7.8 seconds.
- After the initial acceleration, the system stabilizes near the reference value of 80 km/h, showing a small steady-state deviation of less than 5%.
- The rise time is short, indicating a fast response of the control system.
- The small overshoot (~5 km/h) demonstrates a slightly aggressive but acceptable tuning of the PID controller.
- The settling behavior confirms that the ECU control logic maintains speed stability with minimal oscillation.

This result verifies that the PID parameters, tuned using the Ziegler–Nichols method, achieve a well-balanced dynamic performance—fast transient response with stable steady-state behavior. The CAN-based ECU structure effectively transmits control commands and feedback signals, enabling real-time speed tracking consistent with digital twin validation objectives.



Graph 1: Vehicle speed tracking

## 5. Common Issues and Fixes

Issue	Cause	Solution
“Signal overlap in CAN Pack”	Bit range conflict	Reassigned bits (0–31, 32–39, 40–47)
Wrong scaling of Torque_Req	Mismatch between Pack/Unpack factor	Set consistent scaling (1000 ↔ 0.001)
CAN data not updating	Virtual bus mismatch	Added “To Nonvirtual Bus” before CAN Pack
Unstable PID torque curve	Unsynchronized sample times	Aligned CAN and simulation step size

Table 6: Common issues and fixes

After these corrections, the system achieved accurate data transfer and torque stability across all states.

## 6. Conclusion

This study successfully demonstrates a CAN-based digital twin of an electric vehicle ECU system.

The integrated approach allows real-time simulation of communication, control, and dynamics in MATLAB/Simulink.

Key Achievements:

- Fully functional ECU with mode-based logic and PID control
- Reliable CAN message structure for torque and mode signals
- Improved system stability and synchronization across subsystems

This framework is ready for HIL testing and further development with real ECU hardware.

## 7. References

- [1] MathWorks, “Vehicle Network Toolbox – CAN Communication Interface,” Documentation, 2024.
- [2] MathWorks, “Simulink Control Design – PID Tuning Methods,” Documentation, 2024.
- [3] ISO 11898-1:2015 – Road Vehicles – Controller Area Network (CAN).
- [4] R. Rajamani, Vehicle Dynamics and Control, Springer, 2012.
- [5] Gao, D. W., “Modeling and Simulation of Electric and Hybrid Vehicles,” Proc. IEEE, 2008.

## 8.Appendix A – MATLAB Code for ECU System

```
clear; clc; close all;

% --- Get simulation output structure ---

out = sim('ECU_Durum_Makinesi'); % replace with your model name

if evalin('base','exist('''out''',''var''))'

    out = evalin('base','out');

else

    error('Simulation output variable ''out'' not found in workspace. Run the
simulation first.');

end

% --- Extract signals from the Simulink.SimulationOutput object ---

try

    Vehicle_Speed = out.Vehicle_Speed;

catch

    error('Vehicle_Speed or Speed_ref not found inside the simulation output
(out).');

end

% --- Extract time and data vectors ---

tV = Vehicle_Speed.Time;

v = Vehicle_Speed.Data;

% --- Plot ---

figure('Color','w');

hold on;

grid on; box on;
```

```
% Vehicle speed (blue solid)

plot(tV, v, 'b', 'LineWidth', 1.8);

xlabel('Time (s)', 'FontSize', 11);

ylabel('Speed (km/h)', 'FontSize', 11);

title('Vehicle Speed Tracking - EV ECU Digital Twin', ...
      'FontWeight', 'bold', 'FontSize', 12);

legend('Vehicle Speed', 'Location', 'best');

ylim([0 100]);
```