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Implementation of Simulink model for On-Board Diagnosis of an automotive system—TPMS

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Abstract:

Automotive systems consist of mechanical, hydraulic and hardware components that implement specific vehicle functions. The increasing applications in high-end vehicles require tracking and control of each individual parameter. This paper involves the diagnosis of multiple ECUs interconnected by a message-based protocol called CAN bus. The research presents the mathematical model for advanced Tire Pressure Monitoring System by displaying the tire pressure and controlling the hazard breaking system. The paper exclusively focuses on the implementation of TPMS using graphical modeling. The main purpose of the paper is designing a diagnostic model using Simulink, which provides simulated data consistent with real-time parameters.

Keywords: *ABS, CAN bus, ECU, On Board Diagnosis, Simulink, TPMS*

1. INTRODUCTION

The escalation in a number of functionalities in new high-end cars makes it difficult to determine the fault in the system in real time. On-board diagnosis for any vehicle is necessary. OBD is a set of self-testing and diagnostic instructions programmed into vehicle's control unit. The system directly allows the driver to check the status of vehicle's various subsystems [7]-[9]. The status is determined by displaying the fault on dashboards such as MIL (Malfunction Indicator Lamp) or TPMS indicator [10] or engine check light etc. Tire pressure monitoring system alarms the car with early signaling of the hazardous state of tires. The monitoring system is developed for measuring both the tire pressure as well as temperature in real time. Furthermore, in this programming, the system is equipped with an Anti-lock braking system in order to modulate brake and speed of the car. A study by European Union states that an average under-inflation of 5Psi results rise in fuel consumption by 2% and reduces the lifespan of the tire by 25%. Therefore they made it mandatory to install TPMS in every vehicle, worldwide, as it has a great advantage in fuel saving, extending the life of tires, minimizes the risk of accidents [11].

Engineers and programmers are instructed to interface the control unit with OBD system. Few protocols, a dozen modes, hundreds of parameters, thousands of trouble codes are involved to identify the fault in the control unit. Hence to figure them all we need OBD interface, some simulations, and coding. The main objective of the research is to program the diagnostic system in Matlab-Simulink. Simulink, developed by the MathWorks, is a mathematical and graphical programming environment. It helps in simulating and analyzing the multi-domain dynamical system by interfacing with visual modeling and customizable set of block libraries. Simulink generates C source code automatically for real-time application of systems. Also, for embedded systems embedded coders generates [12] an efficient code. Hence, Simulink models are compatible with any kind of system and are flexible for code generation.

2. ON-BOARD DIAGNOSIS

OBD is a complete electronic system, which detects exhaust emission related failure in vehicles. It is a computer-based system which is designed for monitoring the performance of major engine components. An OBD system includes Engine Control Unit (ECU), Sensors, Actuators, protocols and display units. Earlier OBD would simply illuminate a malfunction indicator light as the fault was detected in the control unit but could not provide information regarding the malfunctioning. Today advanced OBD system provides real-time data along with standardized series of diagnostic trouble codes. Modern OBD uses digital communication to provide real-time data.

A systematic understanding of an integrated engine system level is essential for designing a monitoring strategy. The development work for the project begins with Simulink model designing for monitoring the condition of tires on the desktop with analysis and optimization. However, without collecting the data from ECU it is not possible to produce accurate results as required. Thus a closed-loop communication between ECU and TPMS model was established.

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2.1 ECU –Engine Control Unit or Electronic Control Unit

ECU is considered as the crucial part of the Vehicle Management System. ECU, also known as an electronic control unit, controls the set of sensor data transmitted from each sensor present in the electric system to warrant ideal performance. This embedded electronic device reads the signals coming from sensors, positioned at various parts, and other parameters of different components of the vehicle. ECUs are the Programmable control unit [13]. On a multi-layered circuit board, the processor is enclosed with several components and peripherals. Some of the components are ADC and DAC converters, signal conditioners, controllers and processors, Frequency inputs and outputs, Switch outputs, Analog inputs, PWM output. The serial bus communication protocols such as CAN, LIN, etc. are used to have mutual communication between all the ECUs.

2.2 SENSORS

The whole working of an ECU is controlled by the sensors and actuators. Automotive sensors include Air fuel ratio meter, temperature sensor, speed sensor, throttle position sensor, wheel speed sensor and Tire pressure monitoring sensor. TPMS sensors are used to warn the driver when air pressure drops below the expected levels. These sensors detect the exact pressure of each tire; in addition, it also detects the temperature and motion of the tire [14]. The RF signal transmitted from the sensor carries data to ECU.

2.3 CAN- Serial BUS Communication

As the functionalities increase the number of ECU's increases and therefore it may lead to a haphazard arrangement of the system. In order to communicate ECU and other devices with each other without a host system Control Area Network protocol are used. CAN bus deals with collisions where multiple devices need to send data at a time [16]. In this protocol data transmission uses a lossless bit-wise arbitration technique. CAN bus is virtuous at fault tolerant/handling system design. The maximum transmission rate is 1Mbits (up to 50m) and maximum bus length is 1600m (at 50kbps).

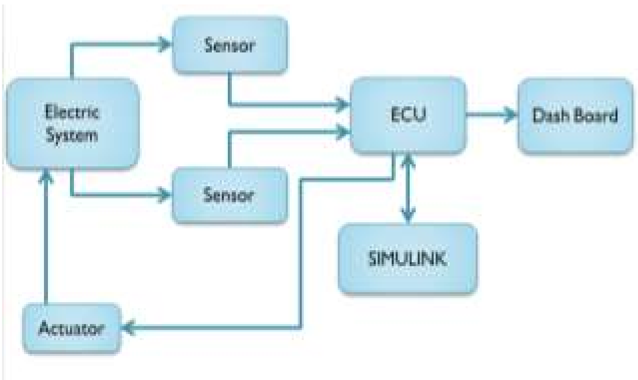

Figure.1 On board diagnosis block diagram

3. TIRE PRESSURE MONITORING SYSTEM

Since 2008, vehicles have been equipped with a Tire pressure monitoring system also known as TPMS. It is designed to alert the driver, of significantly low pressure in one or more tires. In every TPMS vehicle, the sensors are mounted inside the wheels to determine if the tires are inflated to proper specification. When air pressure drops certain amount below required specification an indicator is illuminated on the vehicle instrument panel. Fixed radio antennas are used to extract the unique Sensor ID of each TPM sensor associated with the wheels and ECU can be programmed with this data.

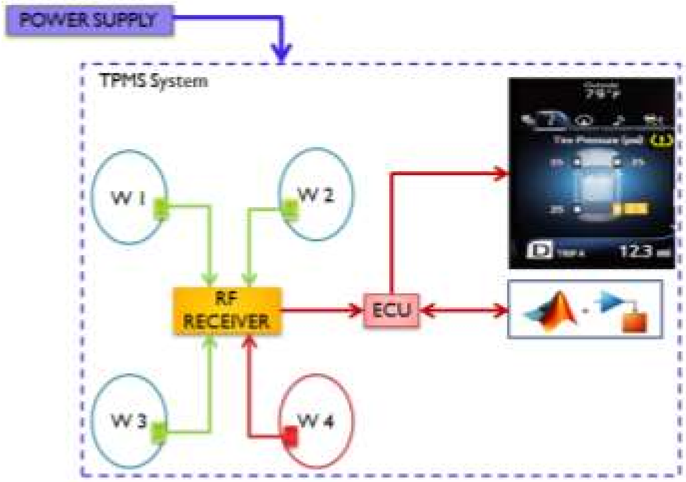

Figure.2 Direct TPMS software design

In this monitoring system, the data transmission will be in the form of analog signals which are received by the control unit from each individual sensors associated with every single tire. Each sensor signal is converted into digital data in ECU (controller); this digital binary data is called as Sensor ID. These sensor ids include the calculated data of each parameter i.e. Motion of wheels, the temperature of the tire and air pressure in the tire. RF Transmitter and Receivers are used for desirable wireless data transfer.

4. METHODOLOGY

4.1 DESIGN CONSIDERATION

There are two types of TPMS – Indirect TPMS and Direct TPMS. In an Indirect TPMS, the RF receiver identifies the positioning of each sensor with the aid of information from ABS control unit and runs it automatically with just one receiver. The tire pressure is calculated based on the wheel rotation, and thus when the car is stopped we cannot calculate the pressure. Also, if all the four tires are equally low in pressure it will not trigger the warning. Once the fault is triggered the indirect TPMS system has to be reset manually.

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Direct TPMS has TPM sensors mounted inside each wheel. It measures the accurate pressure and temperature of each wheel and displays the result on the dashboard. An advanced TPMS requires only a single antenna which is integrated directly into the TPMS control unit. It automatically identifies the position of sensors in the wheel and also able to train the new sensors using automatic sensor recognition.

Each wheel sensor transmits the pressure data using a unique ID number at a certain frequency (433 MHz). This results in delivery of wheel specific transmission profile. The receiver uses this profile to converge the signals with the ABS impulses and assigns the sensor id to the correct wheel position. Change of tires will not affect the TPMS system, so summer tires once replaced it will recognize the pressure of one wheel and set for the others. When pressure is constant the data is transmitted and received every one minute, whereas if the system detects an abnormality it switches to a faster mode. The sample rate will increase, and pressure will be calculated several times and the pressure loss can be detected in 10seconds. TPMS calculates the pressure even when the car is in standby mode, but at a low frequency. Once the car is turned on it attains its usual pressure in few minutes, unlike indirect TPMS.

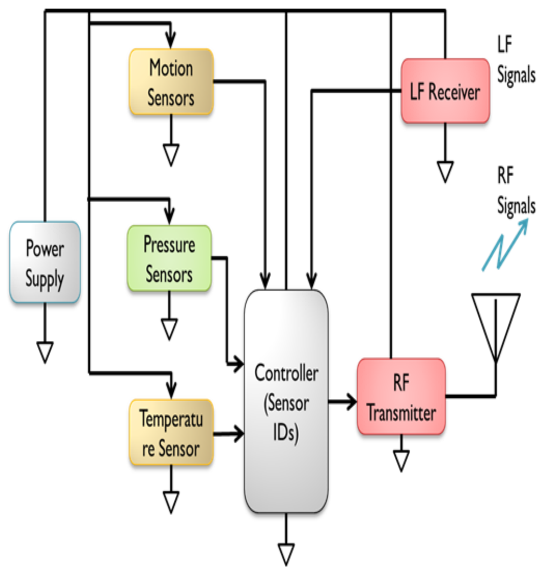

Figure.3 Top level TPMS model

4.2 WORKING ANALYSIS

The flowchart realized in the process to monitor the tire pressure is shown in the Fig. 4. Initially when the car is turned on it will display the pressure of each tire when the car was on standby. Once the ignition is on, TPMS system will display the pressure data stored in the memory. As the processing of data initializes it starts receiving pressure and temperature signals from the sensor. The received data signals will be transmitted to the control unit and expected pressure is calculated considering the ambient temperature. The calculated data is displayed on the dashboard. This measuring of temperature and pressure is a continuous process till the ignition is on [17].

For the better performance pressure of each tire is set between 24psi to 36psi (approx.). If the pressure varies from the expected pressure i.e. if the pressure of any tire goes below 25% of its actual pressure (24psi), hazard system will be activated by generating an alarm as well as the suspected wheel position along with the updated pressure will be displayed. Once the suspected wheel is replaced TPMS system will reset automatically.

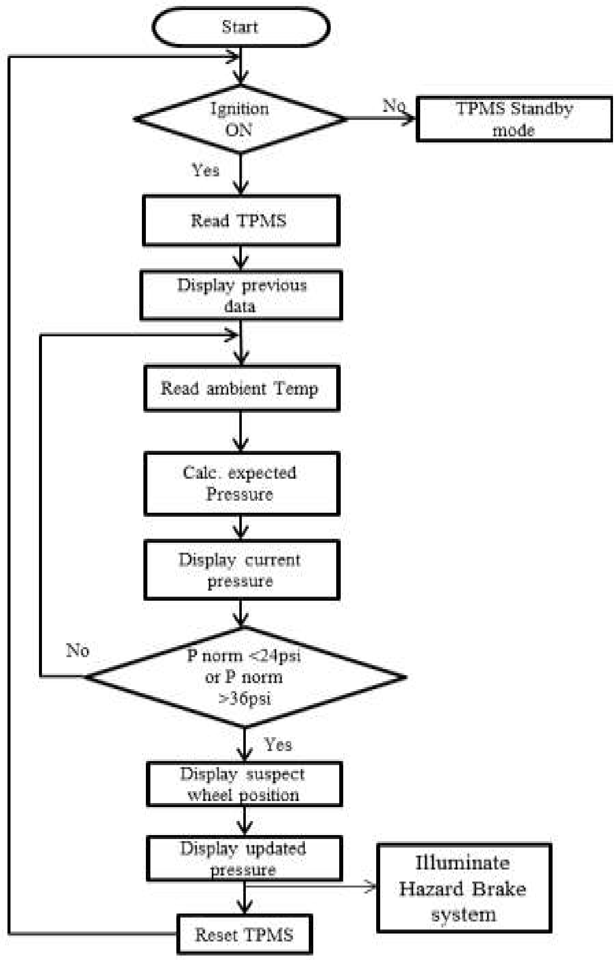

Figure.4 Flowchart of TPMS

4.3 ALGORITHM

Change in tire pressure with respect to Temperature:

It is always advised to change the tires every season, as internal volume of tire changes with the change of climate. Summer tires are highly agile and built for good speed. They have a good grip on roads. Whereas all-season tires provide traction in winters. According to the kinetic theory, Gay-Lussac's law states that Pressure (P) is directly proportional to Temperature (T).

$$P / T = R$$

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R=constant

Let us consider pressure from sensor as P′ and relative temperature as T′, and convert them to absolute units. Converting PSI sensor value to PSI absolute consider standard sea level value as 14.7 PSI.

$$P=P'+14.7$$

According to the Rankine scale,

$$T=T'+459.7$$

Considering the scalar factor

$$(nR/V)=P/T$$

n= amount of air in the tire
V= internal volume of the tire

Calculating the average values we result in
P′= 0.96*(T'+459.7)-14.7 at 70 degree F and 36psi for 225/40-18
P′= 0.11*(T'+459.7)-14.7 at 70 degree F and 46psi for 265/35-18

Further, dropping the pressure by 4psi less than the standard pressure results in the following equation,
P′= 0.088*(T'+459.7)-14.7 at 70 degree F and 36psi for 225/40-18
P′= 0.104*(T'+459.7)-14.7 at 70 degree F and 46psi for 265/35-18
Hence it is observed that change in 1psi changes the scalar factor by 0.002 at 225/40-18 and 0.00175 at 265/35-18. Thus implementing the equations following graph has been created.

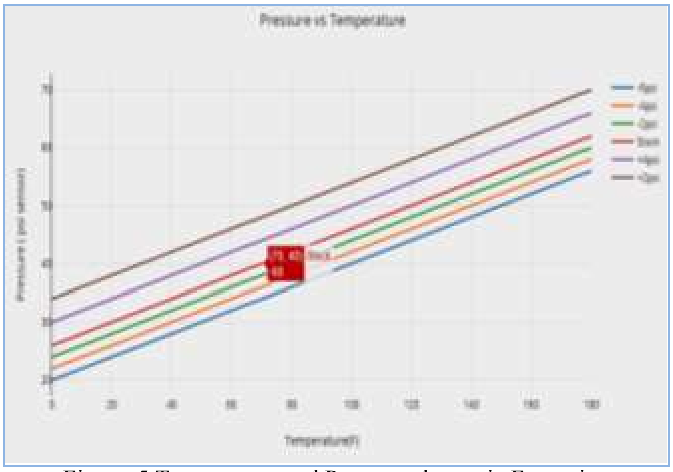

Figure. 5 Temperature and Pressure change in Front tires

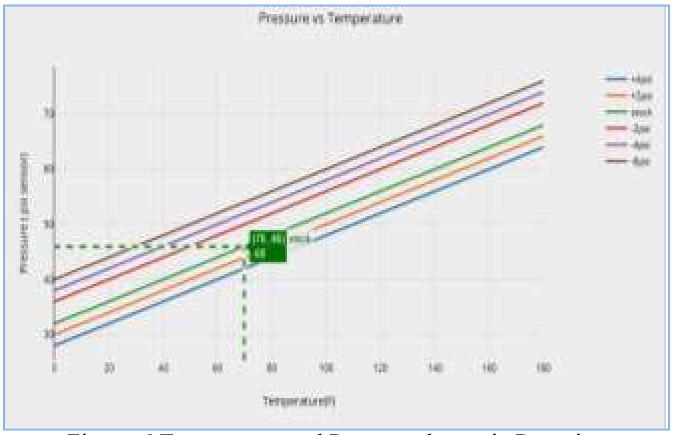

Figure. 6 Temperature and Pressure change in Rare tires

Hence from the above charts, we can conclude that an approximate change in 10 degrees F, temperature, results in the change in air pressure in the tire by 1psi. For example, if the absolute pressure value for the tire is given as 44psi at 65degrees, but if the sensor detects the pressure as 48psi it states the temperature outside is 80degrees (approx.). Similarly, if ambient temperature drops to 20degrees sensors will update the pressure as 14psi (approx.).

Change in tire pressure with respect to Speed and Load on the vehicle:

Driving at a high speed can minimize the distance from the destiny but also leads to bursting of tires because of high air pressure. Increase in speed will create a difference between an unloaded radius and loaded radius of the tire which causes deflection. To make the vehicle move in a specific way certain forces will be acting on the tires such as circumferential force F_U, Vertical tire force F_N and lateral force F_S. Circumferential force is produced due to power transmission or braking. This force acts on the lane surface as the linear force in a straight path along with the longitudinal axis of the vehicle and enables the driver to accelerate or decelerates the speed of the vehicle. The vertical force is the downward force between the tire and the lane surface. The lateral force causes the vehicle to change the direction.

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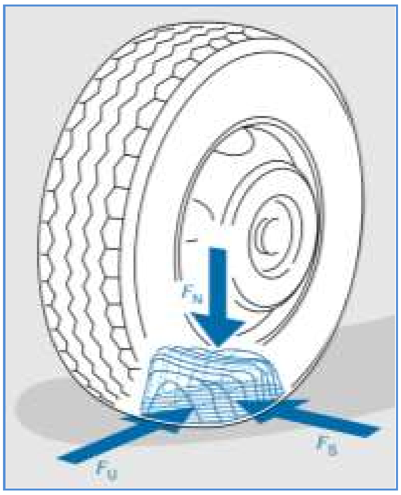

Figure.7 Components of tire force and pressure distribution over the track of radial tire

Law of motion states

Force= mass x acceleration

This indicates that change in speed will affect the force applied on tires along with the load on the vehicle. This force which acts between two bodies at a surface contact dissipates some energy which is determined by the friction force.

$$F_R=\mu_{HF}.F_N$$

The factor μ_{HF} is the coefficient of friction.

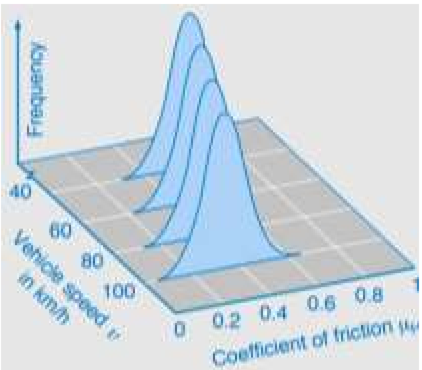

Figure.8 Frequency distribution at various road speeds

It is assumed that energy dissipated in the form of heat on the sliding surfaces within the area of contact, then the rate of heat generated per unit area of contact is

$$q_{area}=\mu_{HF} P| V_2-V_1|$$

P is contact pressure
$| V_2-V_1|$ is sliding velocity

Fourier law of heat condition for any moving body is

$$\nabla.k\nabla T +Q=\rho C(dT/dt)$$

Where Q is the internal heat generation rate per unit volume,ρ is the density, C is the specific heat and v is the velocity of isotropic solid.

Thus when internal heat is generated we get,

$$k \nabla^2 T=\rho C(\partial T/\partial t +v. \nabla T)$$

If there is no internal heat generation,

$$\nabla^2 T=\rho C(\partial T/\partial t +v. \nabla T)$$

This analytical method is used to solve the surface temperatures resulting due to frictional heat.

This frictional heat will cause heat in the tires and hence it is already observed that change in temperature in the tires results in the change in pressure.

4.4 SOFTWARE IMPLEMENTATION

Simulink, developed by MathWorks, is a graphical programming environment for modelling, simulating and analysing multi-domain dynamic systems. Its primary interface is a graphical block diagramming tool and a customized set of block libraries. Many customized and integrated blocks are present in the library and are used for designing of any nonlinear system. It integrates Matlab algorithms into models and export simulation results.

Based on the requirement specification an algorithm will be developed and designed. From the algorithm the logic design will be implemented in Simulink using different blocksets which are readily available in the library. The data range and precision will be mapped to each block according to the requirement specification. The blocks will be arranged in subsystems logically to follow hierarchy of the dynamic system. The model is simulated by setting preferences based on behaviour of the system and code will be generated based on hardware using ideal tool and compiler. Automatic code generation is the main advantage of this software. For each model, the generated code is always a platform independent and language independent. The generated code of any Simulink model can be traced back and can be redesigned even after the verification and validation process. Any embedded system can be designed and coded using Simulink Code generation.

The tire pressure monitoring system is designed using the logic blocks. Each subsystem in the model consists of different stages of the algorithm. Fig.5 describes the main model of pressure monitoring system. It includes some subsystems designed using the logic blocks. Each subsystem is having different functionalities such as

- Mode of TPMS, which determines the state of the monitoring system.
- Sensor data management receives the vehicle data as input including all the circumstances of the wheel and sensor.

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- RF data block, it processes the continuous data flow from the sensors.
- Pressure data, designed to calculate the pressure of wheel at each state.
- Hazard request, designed to alert the hazard breaking system.

The following model (Figure 9) includes some of the customized library blocks such as relational operator which results in the rational array indicating the location where the relation is true. This block helps in comparing the sensor values with the absolute values i.e. less than, greater than, equal to or not equal by comparing arrays. Secondly multiport switch block, it includes two data ports (u1& u3) and one control port(u2). The criteria for u2 is u2>= threshold, u2> threshold and u2~= threshold. In this model for passing the first input u2>= threshold is taken in reference. Display and Scope blocks are used to show the simulated value of its input. Some subsystems include a Stateflow setting for modelling and simulating combinational and sequential decision logic. All the above subsystems together form the TPMS model.

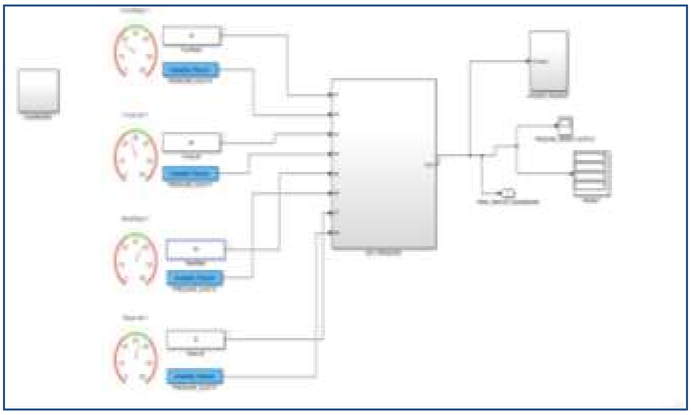

Figure.9 Mathematical model of advanced TPMS using simulink

The model focuses on determining the pressure range as expected from the algorithm. The model also includes hazard request block in order to alert the driver. It consists of the dashboard which displays the value of pressure in each wheel.

5. OBSERVATION

A low-pressure indication on the dashboard of the vehicle is observed from all the tires. The Pressure in the model is calculated considering the required parameters such as temperature and speed. Effect on the pressure with respect to these parameters has been simulated. Each pressure value is displayed in the binary form, if 0=false or 1=true. This output helps in determining the deflection in the tires, if 0ह Tire needs to be replaced, else 1ह Tire is in working condition. The information provided by monitoring system will differ depending on the brand and category of the vehicles.

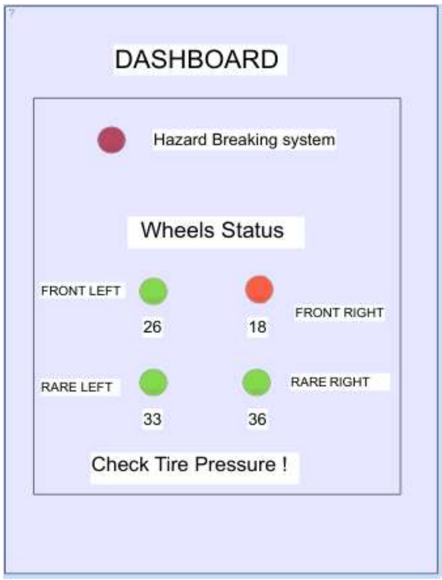

Figure.10 Dashboard display

In the above dashboard, it is observed that when pressure changes beyond or below its set point there will be an alert on the dashboard to check the tire condition. This outcome can be observed graphically.

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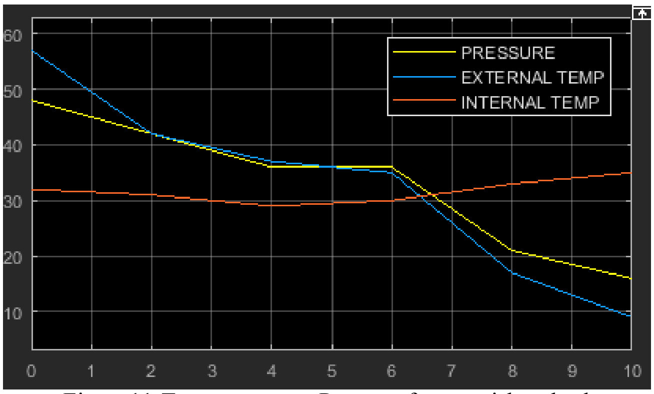

Figure.11 Temperature vs Pressure for rare right wheel

Above graph displays the change in pressure with respect to the temperature of the wheel. Consider a constant temperature inside the wheel and ambient temperature outside, it is observed that as ambient temperature decreases the air pressure in the wheel also decreases.

6. CONCLUSION

Modelling, analysing and simulating the dynamic system have been performed using graphical programming. Implementation of direct TPMS system was demonstrated using Simulink, which do not require a real vehicle for verification and validation.

Ambient temperature, the speed of the car and load on the wheels is taken into consideration to design the model. In the model, at the output display binary values are generated which represents the pressure values of each tire. After simulating the model required code is generated.

Diagnosis of tire pressure is performed in this system this notifies the condition of the tires in the car. It is always recommended to maintain a proper pressure in the tires as instructed by the manufacturers. A small negligence in pressure maintenance may lead to either complete wear n tear of tire or bursting of the tire. This occurs because tires are having too much of surface contact which affects the thread separation in the tires and may cause heavy accident. The pressure drops (more than 6psi) could also reduce the total fuel economy up to 5% [20]. Consequently, installation of TPMS in every vehicle is mandatory all over the world.

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