Tires Automatic real-time Safety System (TASS)

Thesis

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BY

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Master of Science in Mechatronics

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Declaration of Authorship

I, Hugo Martínez Paredes, declare that this thesis, "Tires Automatic real-time Safety System (TASS)", is the result of my own work. Any part of this dissertation has not been previously submitted, in part or whole, to any university or institution for a degree or other qualification.

I confirm that all consulted work for others is attributed and the source is always given. Where the work is done with the help of others, these sources of help have been acknowledged.

Sign: ____

Date: ____

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Last but not least, to my family: my mother, my father, my brother and my sister for supporting me to achieve my goals and never give up. The good example I observed every day in your actions and decisions always motivated me to try to improve myself and be worthy of your pride, thanks to that I have become the person I am today.

Dedicated to the memory of my grandparents. Thanks for everything

ABSTRACT

Road traffic injuries are one of the principal causes of death all around the globe, One of the main mechanical-causes for traffic crashes are tire problems. As a proposal to a safety system focused in the monitoring of the tires tread temperature, the definition, and conceptual design of the “Tires Automatic real-time Safety System (TASS)" are presented in this thesis.

The methodology used for the creation of the system concept is based on the V-Model for development of projects. As a first approach, the system definition is disclosed, comprehending the Concepts of Operations (ConOps) giving the user point of view and the High Level Requirements (HLR) that need to be accomplished. The “functional safety" concept, nowadays implemented in safety-related systems is reviewed because its consideration for the conceptualization and design of the system is important. The system concept is described, taken into account three general components: the monitoring subsystem comprehending the senors to measure the tire tread temperature sensors and the roadway sensor, the Electronic Control Unit (ECU) to control the whole system and the Human-Machine Interface (HMI) designed to show the information about abnormalities and the hints to solve the problem in the car. For each component defined, a trade-off-analysis were executed to select critical components as part of the design of the system.

The presented system development concluded on the beginning of the preliminary design of the engineering model. The simulation of a Human-Machine Interface (HMI) obtaining data and showing it graphically and clear to the user showed that the correct monitoring of the tire tread temperature distribution and the clear and opportune advising can help driver inexpert in the automotive-mechanical topics to act precisely and rapidly against some tire abnormality. For further work the list of identifiable symptoms of the tires abnormally behavior are planned to been improved and increased, and continue with the further steps of the V-Model to accomplish a fully operational system.

KURZFASSUNG

Verkehrsunfälle sind eine der Haupttodesursachen weltweit. Reifenprobleme sind eine der Hauptursachen für Verkehrsunfälle. In dieser Arbeit wird ein Sicherheitssystem vorgeschlagen welches sich auf die Überwachung der Reifenprofil Temperatur konzentriert. Vorgestellt wird die Definition und Konzeption des System “Tires Automatic real-time Safety System"(TASS).

Die Methodik für die Erstellung des Systemkonzept basiert auf dem V-Modell für die Entwicklung von Projekten. Als ein erster Ansatz wird die Systemdefinition präsentiert welche die Konzepte der Operationen (ConOps) umfasst, die die Benutzeranforderungen und die High-Level-Anforderungen (HLR) erfüllen. Das Konzept der funktionalen Sicherheit, das heutzutage in sicherheitsrelevanten Systemen implementiert ist, wird überprüft, da seine Berücksichtigung für die Konzeptualisierung und den Entwurf des Systems wichtig ist. Das Systemkonzept wird beschrieben, wobei die allgemeinen Komponenten berücksichtigt werden: das Überwachungs Subsystem, welches die Sensoren für Reifenprofil Temperatur und den Fahrbahnsensor umfasst, die elektronische Steuereinheit (ECU) zur Steuerung des gesamten Systems und die Mensch-Maschine-Schnittstelle (HMI), welche die Informationen zu Anomalien und Hinweise zur Lösung des Problems im Auto anzeigen. Für jede definierte Komponente wurde eine Abwägungsanalyse durchgeführt, um kritische Komponenten im Rahmen des System Designs auszuwählen.

Die vorgestellte Systementwicklung wurde zu Beginn des Vorentwurfs des Engineering-Modells abgeschlossen. Die Simulation einer Mensch-Maschine-Schnittstelle (HMI), bei der Daten erfasst und dem Benutzer grafisch übersichtlich angezeigt wurden, hat gezeigt, dass die korrekte Überwachung der Reifentemperaturverteilung und die klare und zweckmäßige Information dem Fahrer dabei helfen können, welche sich in den automobilmechanischen Themen nicht auskennen präzise und schnell vor einer Reifenanomalie warnen. Für die weitere Arbeit ist geplant, die Liste der identifizierbaren Symptome des anormalen Verhaltens der Reifen zu verbessern und zu erhöhen und mit den weiteren Schritten des V-Modells fortzufahren, um ein voll funktionsfähiges System zu entwickeln.

RESUMEN

Los accidentes automovilísticos son una de las principales causas de muerte en todo el mundo, una de las principales causas mecánicas para choques automovilísticos son problemas relacionados con el buen funcionamiento de las llantas. Como una propuesta a un sistema de seguridad enfocado en el monitoreo de la temperatura de la suela del neumático, la definición, y diseño conceptual del "Tires Automatic real-time Safety System (TASS)"son presentados en esta tesis.

La metodología usada para la creación del concepto del sistema está basado en el V-Model para el desarrollo de proyectos. Como primer acercamiento, la definición del sistema es desarrollado, generando los "Concepts of Operations (ConOps)"dando el punto de vista del usuario y el "High Level Requirements (HLR)"que necesitan ser cumplidas. El concepto de seguridad funcional, hoy en día implementado en sistemas relacionados con la seguridad es revisado porque su consideración para la conceptualización y diseño del sistema es importante. El concepto del sistema es descrito, tomando en cuenta tres componentes generales: el subsistema de monitoreo que comprende los sensores para medir la temperatura en la suela de la llanta y el sensor que mide la temperatura del camino, el "Electronic Control Unit (ECU)"para controlar todo el sistema y el "Human-Machine Interface (HMI)"diseñado para mostrar la información acerca anormalidades y los consejos para resolver el problema presentado por el carro. Para cada componente definido, un "Trade-off-analysis"fue ejecutado para seleccionar componentes críticos como parte del diseño del sistema.

El presente desarrollo de sistema concluye en el inicio del diseño preliminar del modelo de ingeniería. La simulación de la interfaz Humano-Máquina obteniendo datos y mostrándolo gráficamente y de una manera clara al usuario demuestra que el correcto monitoreo de la distribución de la temperatura en la suela de la llanta y la clara y oportuna advertencia puede ayudar a los conductores inexpertos en temas mecánico-automotrices para actuar precisa y rápidamente en contra de alguna anormalidad en la llanta. Como futuro trabajo, la lista de los síntomas identificables para las condiciones anormales de las llantas está planeada para ser mejorada y aumentada, y continuar con los siguientes pasos del V-Model para conseguir un sistema completamente operacional.

Contents

1 Introduction

In the last years the statistics around the world position road traffic tragedies in the top of leading causes of deaths, the most of the registered accidents derive from drivers negligence, but for the crashes due to vehicle factors, tire abnormality on the pre-crash phase is a very common situation.

Since the moment the car was designed and commercialized the automobiles industries have been searching for the way to make them safer and safer, from the Seatbelts and the Airbags to the Anti-lock Braking System (ABS), Electronic Stability Control system (ESC) and the principal antecedent of this work, the Tire Pressure Monitoring System (TPMS), the implemented safety systems have increased the safety in cars nowadays. This work propose a system, widely used nowadays in the automotive racing performance environment, that monitors the temperature distribution on the tires to be tread as a complementary safety system, improving that way the behavior of the tires while in contact with the road and reduce tire-related accidents, leading to material and human looses. The system, based on non-contact temperature measure sensors (infrared (IR) sensors), will provide information about the real-time temperature distribution on tires surface and then it will be displayed to the driver through a Human-Machine Interface (HMI) to alert about abnormalities in the normal performance and some hints about the problem. The present master thesis for the German-Mexican master program is focused in the definition and conceptual design of an automotive system.

The “Tires Automatic real-time Safety System (TASS)" is a system capable to measure the temperature distribution in each of the tires and notify in real-time through the HMI these measurements and any abnormality in the functionality of the tire related to this phenomenon; the inferring of the abnormality cause and some hints about the possible solution are displayed as well, the use of an understandable language is another objective of the system in order to make it understandable to the widest range of possible users.

The biggest contribution to the art is the real-time information provided to the user through the

HMI so this element of the system is emphasize in the following chapters.

Right after, the motivation and the justification on the development of the system are disclosed, exposing the impact of the tires malfunctions in the deaths around the world. The hypothesis, the objectives, the scope and the methodology of the thesis are discussed and these are the principal indicators of the work to be done during the development of the thesis.

1.1 Motivation

The World Health Organization (WHO) published in the Global Status Report on Road Safety 2018 that Road traffic injuries are the eighth leading cause of death for all age groups, even over, HIV/AIDS, tuberculosis or diarrhoeal diseases for example, and it was the leading cause of death for children and young adults aged 5–29 years according to a study done in 2016, shown graphically in Figure 1-1 [WHO18b].

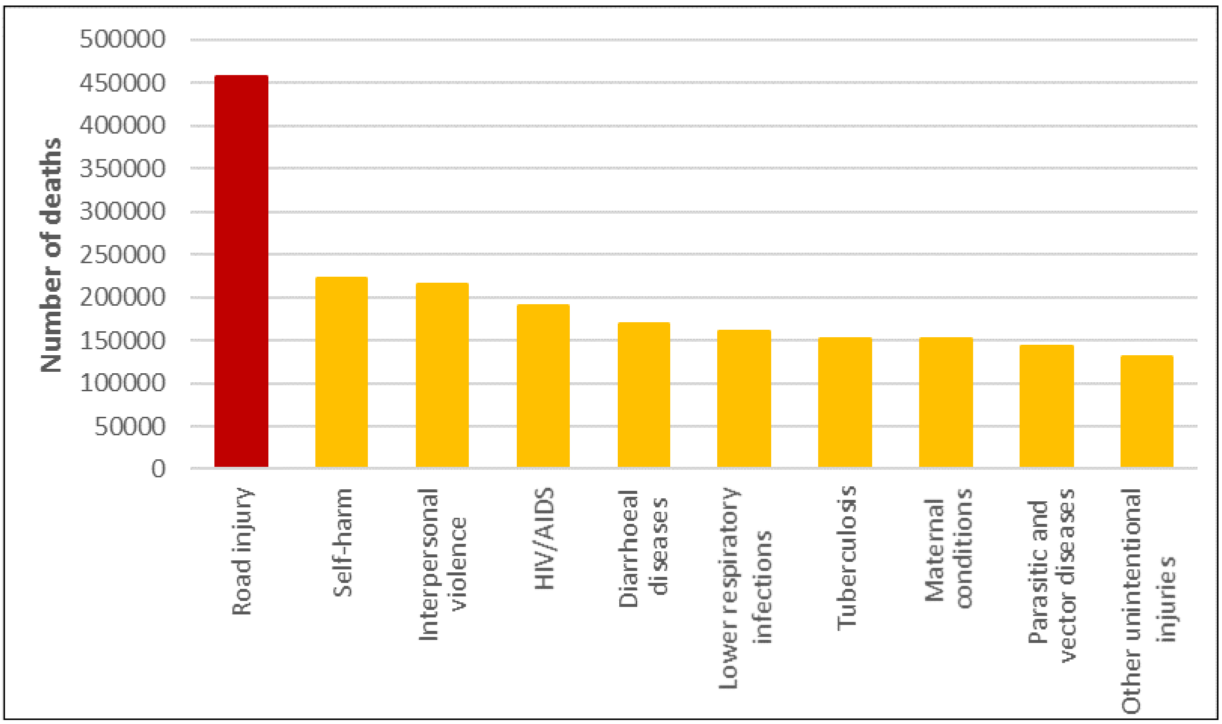


Figure 1-1: Top ten causes of death worldwide among people aged 5 - 29 years, 2016 [WHO18a]

In the U.S.A., the National Center for Health Statistics (NCHS) pointed, in the 2015 "annual report on mortality", motor vehicle traffic as the 13th leading cause of death overall among all causes. When the aforementioned list is ranked by specific ages & gender, vehicle traffic crashes were the leading cause of death among males for ages 10, 11 and 17 to 23, among females for ages 9 and 16 to 23 [Web18], in Figure 1-2 it is exposed the changes within the top ten leading causes grouped by “stages of life" (the vehicle traffic crashes is highlighted in black squares) and it is evident how it rise up to the top in the Children (8-15), Youth (16-20) & Young Adults (21-24) stages.

RANK	Cause and Number of Deaths										
	Infants Under 1	Toddlers 1–3	Young Children 4–7	Children 8–15	Youth 16–20	Young Adults 21–24	Other Adults 25–34	Other Adults 35–44	Other Adults 45–64	Elderly 65+	All Ages
1	Perinatal Period 11,613	Congenital Anomalies 389	Malignant Neoplasms 360	**MV Traffic Crashes 744**	**MV Traffic Crashes 3,114**	**MV Traffic Crashes 3,415**	Accidental Poisoning 11,231	Malignant Neoplasms 10,909	Malignant Neoplasms 159,176	Heart Disease 507,138	Heart Disease 633,842
2	Congenital Anomalies 4,825	Homicide 329	**MV Traffic Crashes 279**	Malignant Neoplasms 694	Suicide 2,441	Accidental Poisoning 2,820	Suicide 6,947	Accidental Poisoning 10,580	Heart Disease 111,120	Malignant Neoplasms 419,389	Malignant Neoplasms 595,930
3	Heart Disease 292	Accidental Drowning 316	Congenital Anomalies 168	Suicide 663	Homicide 2,027	Suicide 2,798	**MV Traffic Crashes 6,281**	Heart Disease 10,387	Chronic Liver Disease 22,152	CLRD[5] 131,804	CLRD[5] 155,041
4	Homicide 263	Malignant Neoplasms 273	Accidental Drowning 163	Homicide 307	Accidental Poisoning 1,075	Homicide 2,601	Homicide 4,863	Suicide 6,936	CLRD[5] 131,804	Stroke 120,156	Stroke 140,323
5	Septicemia 180	**MV Traffic Crashes 249**	Homicide 136	Congenital Anomalies 261	Malignant Neoplasms 614	Malignant Neoplasms 747	Malignant Neoplasms 3,704	**MV Traffic Crashes 4,652**	Diabetes 20,378	Alzheimer's 109,495	Alzheimer's 110,561
6	Influenza/ Pneumonia 174	Heart Disease 132	Exposure to Smoke/Fire 70	Heart Disease 202	Heart Disease 352	Heart Disease 607	Heart Disease 3,522	Homicide 2,895	Accidental Poisoning 19,452	Diabetes 56,142	Diabetes 79,535
7	Stroke 89	MV Nontraffic Crashes[4] 88	Heart Disease 61	Accidental Drowning 160	Accidental Drowning 261	Accidental Drowning 210	Chronic Liver Disease 844	Chronic Liver Disease 2,861	Stroke 17,423	Influenza/ Pneumonia 48,774	Influenza/ Pneumonia 57,062
8	Nephritis/ Nephrosis 85	Influenza/ Pneumonia 76	CLRD[5] 55	CLRD[5] 135	Congenital Anomalies 181	Congenital Anomalies 159	Diabetes 798	Diabetes 1,986	Suicide 16,490	Nephritis/ Nephrosis 41,258	Nephritis/ Nephrosis 49,959
9	**MV Traffic Crashes 57**	Exposure to Smoke/Fire 73	MV Other/ Nontraffic Crashes[4] 43	MV Other/ Nontraffic Crashes[4] 91	MV Other/ Nontraffic Crashes[4] 101	MV Other/ Nontraffic Crashes[4] 129	Stroke 567	Stroke 1,788	**MV Traffic Crashes 10,043**	Septicemia 30,817	Accidental Poisoning 47,478
10	Malignant Neoplasms 53	Perinatal Period[6] 45	Influenza/ Pneumonia 41	Exposure to Smoke/Fire 69	Accidental Falls 83	Accidental Falls 128	HIV 529	HIV 1,055	Septicemia 8,316	Accidental Falls 28,486	Suicide 44,193
ALL[3]	23,455	3,376	2,096	4,995	12,461	16,942	51,517	73,088	532,279	1,992,283	2,712,630

Figure 1-2: Top ten leading causes of death in USA in 2015, by age group [Web18]. In black: Deaths caused by traffic crashes

The data collected through the National Motor Vehicle Crash Causation Survey (NMVCCS) from 2005 to 2007 is a sample of 5,470 crashes, representing 2,188,970 crashes at the national level in U.S.A., in 9 percent of these crashes, one or more vehicles experienced tire problems in the pre-crash phase [Cho12].

In Mexico, the “Instituto Mexicano del Transporte (IMT)” published in “Anuario estadístico de accidentes en carreteras federales (2017)” that the causes of automobiles accidents in federal highways due to vehicles malfunctions are the 6.98% (1,092) of the 15,644 car crashes, and from this factor, 43.2% are due to tire problems, the main cause, in Figure 1-3 a graphic showing the data collected in 2016 about collision causes is shown [CMM18].

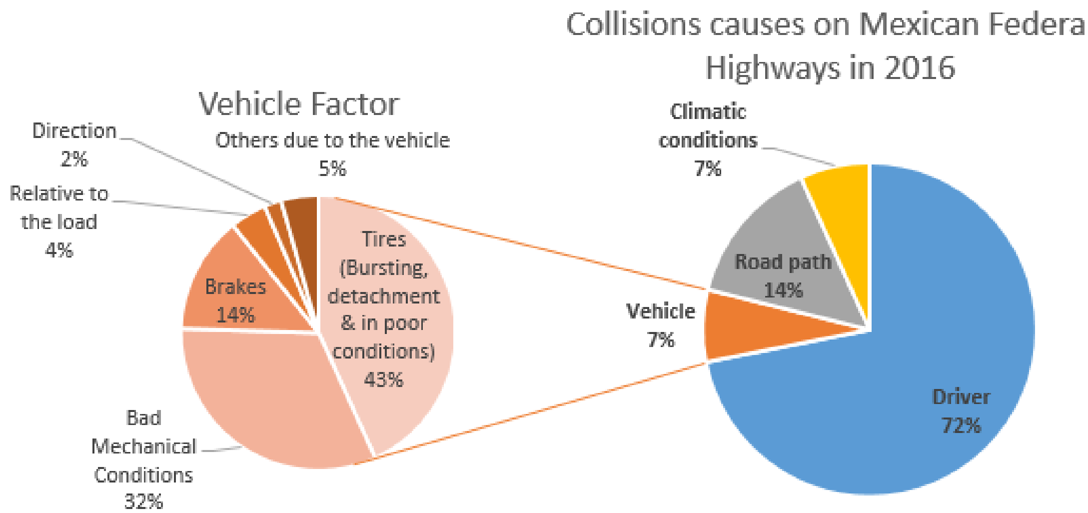


Figure 1-3: Collision causes on Mexican Federal Highways in 2016, due to the vehicle factor [CMM18]

The next section gives the justification of the present work. The “why?" the system proposal therein should be done and the impact it could have if it is developed.

1.2 Justification

The intention of the proposed system is to monitor tires temperature in real-time to prevent car accidents, the safety systems nowadays are not good enough to prevent all the accidents due to tire problems, the cars could be safer with the implementation of this safety system, that measure the temperature in real-time and warning you about some irregularity with a tire, this could be the difference between a car crash occur or not.

In Mexico, the main factor of automobile accidents attributed to the vehicle corresponds to the poor condition of the tires due to continuous overheating, unfortunately this has been verified after the mishaps occurred, since although progress has been made in the field of safety with the measurement of the tire pressure in real time, there is no table of relationship between the increase in tire temperature and the increase in tire pressure as well as the premature and disproportionate wear of the tire tread.

The Tires Automatic real-time Safety System (TASS), as the proposed system was named, will provide sufficient and necessary information to determine the temperature range and its optimal distribution in the tire, preventing different levels of damages that may lead to the bursting of it and cause accidents in which the material losses are too many, and there are several numerous of deaths.

The next section is the hypothesis, the tentative statement searching to be proven in the development of the thesis work.

1.3 Hypothesis

“The implementation of a Human-Machine interface to the race cars tuning technology based on tire tread temperature monitoring makes feasible the implementation of a safety system for commercial vehicles based on this same technology"

In the following section, the system and the objectives that are pretended to be achieved in the development of the thesis will be briefly explained.

1.4 Objectives

In this section the main and specific objectives are established. The main objective will be long-term fulfilled and the specific objectives are designed as short-term tasks. The fulfillment of them help to follow a defined path and to being focused in a step-by-step development of the thesis. The specific objectives are chronological ordered.

1.4.1 General objective

The general objective of this work is to develop, from its definition to its conceptualization a system that measures in real time the temperature distribution in the tire tread, process these data and programmatically give warnings of detected problems along with clear and understandable hints so that any user, even those who do not have technical knowledge at all about cars, can react correctly and in time to avoid a car accident; the conceptual development includes concept proposal, system architecture and preliminary associated studies and tests design.

1.4.2 Specific objectives

The specific objectives in a chronological order are listed below. The time bounded criteria for each of these objectives is shown in the chronogram of activities in Appendix A.

1. State of the art & concept exploration.
2. Concepts of operations & High-level requirements.
3. Considerations of Functional Safety.
4. System concept.
5. Concept Design.
6. User Interface Design.
7. Thesis final draft delivery.
8. Thesis dissertation.

The self defined objectives to accomplish a satisfactory thesis development for the engineering system works as basis for the selected methodology, which is reviewed below, but in the following section, the infrastructure available for the fulfillment of these objectives is pointed.

1.5 Infrastructure

In this section, available resources are divided in four main categories: human resources, equipment and materials, financial resources, and available information and knowledge

1.5.1 Human resources

- Thesis main executor: Eng. Hugo Martínez-Paredes.

  Bachelor's degree in Mechatronics engineering by the Universidad Politécnica de Chiapas (UPCH), in 2017; currently Master's student in a double degree program in science in Mechatronics at Center for Industrial Engineering and Development (CIDESI), Mexico and the University of Applied Sciences of Aachen (FH-Aachen), Germany

- Thesis director: Dr. Eng. Gengis Kanhg Toledo-Ramírez.

Gengis K. Toledo-Ramirez, Dr.Ing.,2008 UNAM-Mx, M. Sc.,2002 CINVESTAV-MX, starts his research career working at the Mechatronics and Micromechanics Lab at UNAM in 2004. He worked as a fellow research scientist at the Institute for Industrial Automation and Software Engineering of the Stuttgart, University, Germany. Since 2012 he was worked at the Center for Engineering and Industrial Development - CONACYT, México. Working in fields such as industrial automation, mechatronics, artificial intelligence, automotive, railways and ground based telescopes related projects. He has been reviewer of the Computer Integrated Manufacturing Journal of Thompson and for several projects and studies of Mexico, as well. He has participated in several research papers. His current interests are real-time complex systems, intelligent mechatronics systems and robotics.

1.5.2 Equipment and materials

For research, simulation and thesis writing a laptop from the brand HP and an Operative Systems Windows 10 is going to be used, the software used for the development of the thesis work is: LabVIEW with a license provided by the FH-Aachen, TexStudio, ProjectLibre and Autodesk Sketchbook.

1.5.3 Financial resources

For this thesis project the monetary part was limited to a scholarship from Consejo Nacional de Ciencia y Tecnología (CONACyT) that supports the student program.

1.5.4 Available information and knowledge

For the development of the thesis the state of the art is crucial, this work pretends to innovate the safety systems already existing in the cars somehow, so it is necessary to deploy a very complete actual-market study and patents already registered, the books and the scientific papers of temperature-related effects on the tires will be used as basis for the investigation.

For the proposal, all the articles, journals, scientific researches and former works used for this project are obtained thanks to the subscription-based access of the FH Aachen and CIDESI. Also, the opensource community and international organizations free-to-public works.

The infrastructure is important in the planification of any project, the knowledge of the available resources (human or material) help to define the scope of the work. The next section describes the scope and contribution of the present thesis.

1.6 Scope

The aim of the thesis work is to research and conceptualize a mechatronic system to improve the safeness of the nowadays commercial cars. By sensing the tire tread temperature distribution; following the V-model for system engineering, shown in Figure 5-2, a very general and raw preliminary design will be reach in this work and the design of the system interface will be discussed and developed. For being used in future work before the implementation in a real automotive system.

As it has been disclosed, the scope of the thesis is based on the V-model for systems engineering, the same model that defines the methodology to follow, explained in the next section. The selected methodology is essential in a good project planification, this defines the path to follow and break down the work that must be done, the next section describes the methodology developed to be followed throughout the writing of the thesis and the development of the system.

1.7 Methodology

The methodology to be followed is based in the V-model, the principal characteristic and the reason why this model is chosen is because it gives relationship between each development stages and testing stages, this particular model, shown in Figure 1-4, adapted by the Center for Engineering and Industrial Development (CIDESI) for its necessities in the development of engineering systems, contemplates the complete procedure for the development of a system, but in the particular case of the thesis, the system will be developed until the definition subphase of the development phase, going from the Problem/Necessity/Motivation to the System concept.

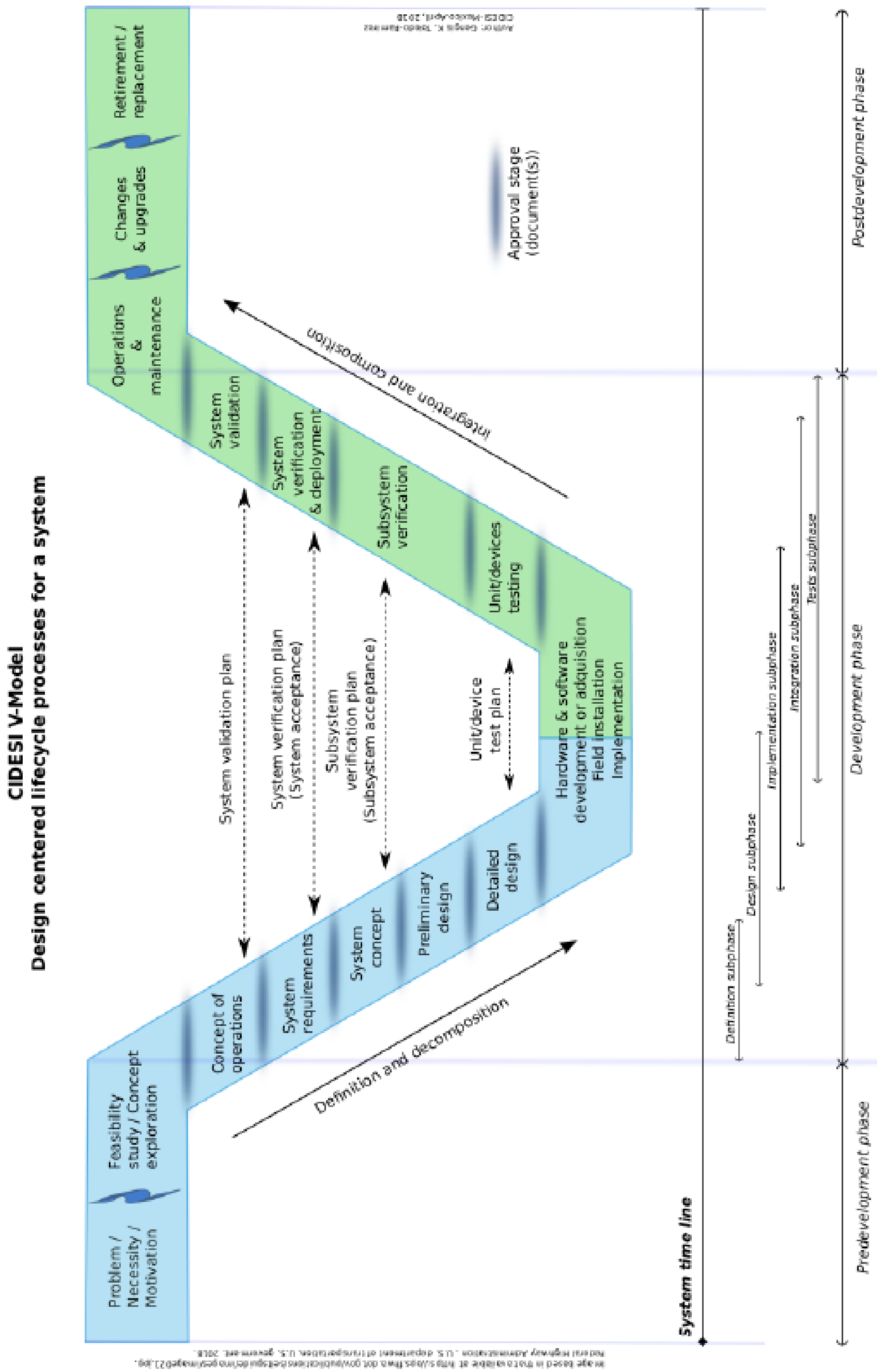


Figure 1-4: CIDESI V-Model [Tol18]

The elements to delimit the methodology to follow are listed below.

1. Identification, clarification and delimitation of the problem, necessity or motivation.
2. Study and review of the State of the Art.
3. Definition of the system characteristics, delimit the potential application and focus the system on it.
4. Development of the High-level requirements & ConOps of the system.
5. Exploration of the functional safety concept for the implementation in the system.
6. Definition of preliminary test cases for system concept validation.
7. System concept development.
8. System architecture analysis.
9. Development of the Concept design of the system.
10. Analysis of the obtained results.
11. Establish conclusions.

In the following chapter, some technical key concepts, fundamental for the correct development and understanding of the thesis work are described. That includes, the pneumatic tire construction, the functional principle of the infrared sensors and the Real-Time Systems.

2 Technical concepts

For the better understanding of the proposed system, important technical concepts are introduced, the composition of the pneumatic tires, the IR-basis for contactless temperature measuring technology, the technology proposed to use for the proposed system and the real-time automotive systems.

2.1 Most common tire construction

The construction of the pneumatic tire (shown in Figure 2-1) consist of different materials carrying the load, maintaining the shape and sealing the tire, the components can be divided into four sections: bead, sidewall, shoulder and tread.

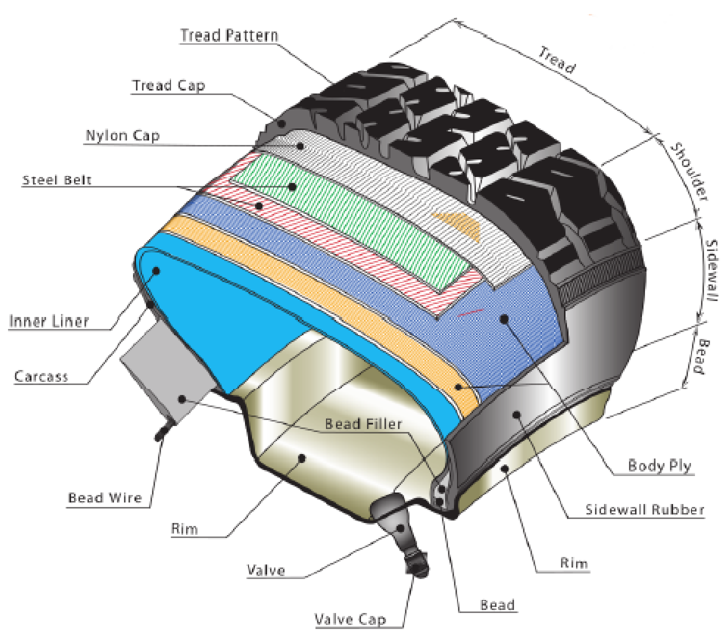


Figure 2-1: Radial tire construction [Mar15]

The Body Ply is the main load carrier of the tire and typically consists of rubber-coated fabric, like polyester or nylon, it runs from bead to bead in a radial direction. Body plies hold the shape of the tire while it is inflated and absorb the impact and forces from the road. The number of body plies can vary from tire to tire, depending on the load-carrying capability of the tire [Mar15].

Two steel belt plies are located under the tread area, at opposite angles to one another and on top of the body plies. These plies consist of rubber-laminated steel wire sheets. They provide stiffness in the tread area and protect the body plies from damage [Mar15].

A nylon cap ply is used in some tires, it wrapped circumferentially on top of the steel belt plies. The cap ply reinforces the tire further as it prevents expansion due to centrifugal forces [Mar15].

The inner liner is a rubber layer consisting of low permeable rubber, its function is to retain air when the tire is inflated [Mar15].

The bead is the part of the tire in contact with the rim and is fabricated from a bead wire, an abrasion gum strip and bead filler. The bead wire secures the tire to the rim and maintains the shape of the tire. The abrasion gum strip is a rubber layer between the body plies and the rim, where the body plies turn-up around the bead wire. This provides an airtight seal between the tire and the rim. The bead filler consists of stiff rubber and fills the void between the inner body plies and the turned-up body plies. It assists in handling and stability characteristics of the tire [Mar15], It is the main interface that transfers the normal load from the contact patch to the rim. Hence it should be able to support the load [RD14].

The sidewall is the most flexible part of the tire and consists of flexible rubber and the body plies. The sidewall protects the body plies from abrasion and impact as well as flex fatigue and also serves as the information placement area, there the enterprises print the tire specifications.

The tire shoulder is the thickest part of the tire and consists of rubber and body plies, as well as steel belt plies, which end at the shoulder. It forms the transition from the flexible sidewall to the stiffer tread. The shoulder protects the body plies from external shocks and damage.

The tread is the component that comes in contact with the road. It provides traction and durability, defines tire life and protects the body plies. The tread is fabricated from durable rubber that is formulated to provide a balance between wear, traction, handling and rolling resistance. Tires designed for different conditions have different tread patterns to provide better traction, better durability and reduce pattern noise. Pattern noise is the noise generated by the tire pattern while it is rolling [RD14].

2.2 Infrared sensors

Any object with a temperature above absolute zero ($-273.15\,°C$) generates IR radiation, which has a frequency range from 3×10^{11} Hz to 4×10^{14} Hz and a wavelength from $0.75\,\mu m$ to $1000\,\mu m$ shown in Figure 2-2. IR spectrum (i.e., wavelength range) and energy density (i.e., intensity of radiation) depend on object type, surface temperature, surface shape, and other factors [XWXL17].

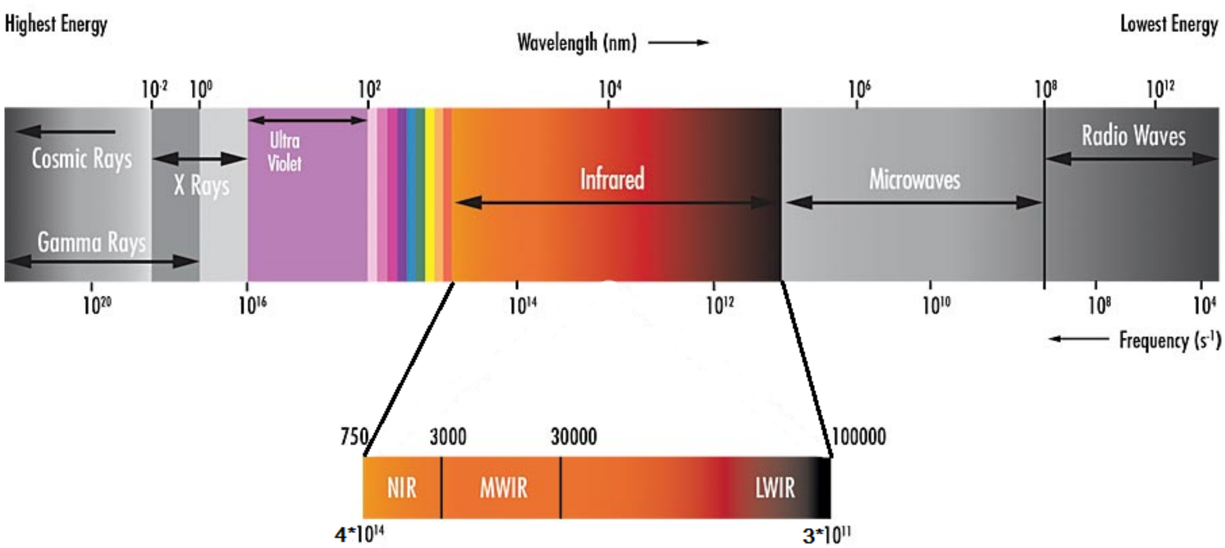


Figure 2-2: Electromagnetic spectrum ilustrating the Wavelength(nm) & Frequency(Hz) [Boo17]

An IR sensor is a light sensor that can respond to external IR radiation. IR sensors can be divided, according to the detection mechanism into [Rog02]:

- Thermal IR sensor

These sensors absorb the radiation and converts it into thermal energy and consequently, the temperature of sensitive components increase, the IR radiation magnitude measurement principle of this sensor type is based on measuring the increase in temperature of this sensitive components.

- Photon IR sensor

  For these sensors the electronic state of the semiconductor materials changes when the detector absorbs photons, and this change results in photovoltaic or other phenomena.

Thermal IR sensors are classified according to their working principle [XWXL17]:

- Thermoelectric

  The temperature change is measured by Seebeck effect.

- Pyroelectric

  The charge acumulation in the heated objects.

- Bolometer

  The electrical resistance of the sensor.

The system to be developed in this thesis is think to use a Thermopile IR Array sensor, a Thermal IR sensor by its detection mechanism and a Thermoelectric by its working principle, because they are the cheapest technology for the application in the market and fulfill perfectly the necessities of the system.

2.3 Real-Time Automotive Systems

For safety critical cyber-physical systems such as automotive systems, absolute guarantee of timely behaviors are crucial. In fact, an extensive amount of work in the real-time system research community have been motivated by applications in automotive systems.

In modern automotive systems that support real-time applications, distributed architectures are commonly used, where several buses (e.g., Controller Area Network (CAN)) and tens of computation units (e.g., Electronic Control Unit (ECU)) are connected in a complex network system.

This complex network system normally have the characteristics:

- Functions are often distributed across the system and may involve several ECU, sensors, actuators and communication busses for their execution.

- Each ECU may be involved in the realization of many different functions. This leads to a mutual influence of the functions on each ECU.
- Subsystems are often developed by different teams and suppliers and have to be integrated by the car manufacturer (OEM).
- The ECUs realize an increasing number of functions. This leads to a higher degree of integration on each ECU.
- The distributed functions often have to fulfill stringent timing constraints to function properly.

AUTOSAR is a development partnership founded by the major automotive Original Equipment Manufacturers (OEMs) and tier-1 suppliers. And the initiative define common development methodology nad standarized software architecture for ECUs with well defined module interfaces. As a basis for this, a comprehensive structural system model comprising software components, their communication, basic software, software mapping to ECUs etc. can be described in a standardized formal way. This information can then be exchanged across car manufacturer and suppliers if necessary, i.e. across different development teams. With the version 4.0 of AUTOSAR also the required timing behaviour of the system is addressed.

Then when an automotive real-time system is gonna be develop, the AUTOSAR approach is the most common guideline and standard.

In the following chapter, the state of the art is presented showing the advances that have been made in topics related to the system through scientific research, the products currently on the market and an overview of inventions' patents.

3 State of the Art & Concept exploration

In this chapter an overview about literature concerning tires temperature monitoring, tire problems and the topic “smart tires" is given. Some scientific research work done until today around these topics, the most used temperature monitoring systems nowadays and an U.S. patents overview.

3.1 Scientific research

The scientific community have been working in topics as “smart tires" or “autonomous vehicles" that are related to the system to be developed, below there are, a scientific article about the consequences of high-temperatures in rubber tires and a proposal of an indirect real-time monitoring strategy, combining analysis of tire vibration with effective radius, to indicate that a blowout has occurred.

3.1.1 Processes in the tire due to temperature increase

The tire temperature increase, due to a directly or indirectly factor, generates three different processes in the tire: air expansion, loss of structural mechanical resistance and chemical degradation [DNA+08].

3.1.1.1 Expansion of the air inside the tire

When air contained in an enclosed chamber such as a tire is subjected to a temperature increase, its volume increases. In the case of tires, such a volume increase is constrained by the low deformability of the rubber/reinforcement cable composite structure, leading to an increase in the pressure in the tire. For a new tire, since a safety factor of 3–8 is usually included by manufacturers, the risk of tire blowout is limited under the sole effect of thermal expansion of the air. However, if the tire has a structural defect or has suffered prior damage that have weakened its mechanical resistance, the maximum pressure it can sustain without blowing out can be significantly reduced [DNA+08].

3.1.1.2 Thermal weakening of the tire mechanical structure

Since a tire is a composite structure, the change in its mechanical resistance due to an increase in temperature may arise both from changes affecting the individual components themselves or the links between them.

Temperature changes also physically affect the rubber constituting the tire matrix. For example, between 25 °C and 100 °C, a temperature range within the normal operating conditions of tires, it has been shown that rubber undergoes a slight thermal softening, translating into a decrease in the storage modulus measured by dynamical mechanical analysis [Bur04]. Between 95 °C and 125 °C, microstructural changes within vulcanized rubber may create substantial stress relaxation, material softening, permanent set, and creep [WJS03], which affect the rubber's mechanical behavior.

3.1.1.3 Thermo-chemical degradation of rubber

When the polymer matrix is subjected to high temperatures, various chemical reactions may occur, leading to the thermo-chemical degradation of the material. Pyrolysis takes place in the absence of oxygen under the sole action of heat. Thermogravimetric analyses of truck tire materials have measured initial degradation temperatures by pyrolysis as low as 185 °C, three types of products are obtained from the degradation of tires: solid matter (35–40% excluding textile and cable reinforcement material), oils (38–55%), and gas (10–30%) [DNA+08].

Thermo-oxidation takes place when oxygen is present but not in sufficient quantity for complete combustion, reactions may also occur on the inner surface of the tire if the tires are inflated with air (high concentration of oxygen). It has been shown that the presence of oxygen leads to a decrease in the degradation temperature as compared to inert gas. As for pyrolysis, the thermo-oxidation products consist of solids, oils and gases, with similar highly combustible properties [DNA+08].

Finally, combustion takes place when enough oxygen is available to fully oxidize the species it proceeds through four stages, between 200 °C and 480 °C, a first decomposition can be observed, next the carbonaceous residues of the first reaction are oxidized between 480 °C and 500 °C, During the third step between 600 °C and 650 °C, the inorganic fraction of the tire material, such as calcium carbonate and zinc oxide, are decomposed. Finally, combustion of solid carbon takes place above 800 °C. Unlike pyrolysis and thermo-oxidation, combustion residues include only solids and gases [DNA+08].

One of the common characteristics of all three reactions (air expansion, loss of structural mechanical resistance and chemical degradation) is that they produce flammable gases. In the first place, when the thermo-chemical reactions take place on the inner surface of the tire, the gases they produce add to the increase in pressure inside the tire due to thermal expansion of the air. It has been calculated that the chemical degradation of only 20 g of rubber produces enough gas to reach the standard blowout pressure of tires. In addition, with an auto-ignition temperature situated around 430 °C, these flammable gases can generate an explosion at high temperature if their concentration inside the tire is above 1–8% while the oxygen concentration is above 5.5%. Among the other products of the chemical degradation of tires, sulfur and carbon black particles may also produce explosions, with auto-ignition temperatures of 200 °C for carbon and 190 °C for sulfur [DNA+08].

3.1.2 Real-time system to identify tire failure

This system is based in real-time effective radius & tire vibration analysis, to identify tires blowouts or severe leakage. Through experimentation is proved that this system can identify a blowout condition within approximately 0.6 Seconds, far less than the 2 to 3 second typical driver response time, demonstrating that the tire failure identification system can save time for relative emergency braking system to carry out braking and stability controlling [CWX14].

The principle of the system is the use of the wheel speed signal to determine the resonance frequency and calculate the effective tire radius. If the characteristic of the tire frequency or radius is in the range of the established criteria (determined through an empirical formula and experiments), then a weighted factor analysis is used to determine if the target tire has experienced a blowout or severe leakage. In Figure 3-1, a schematic of the system is shown [CWX14].

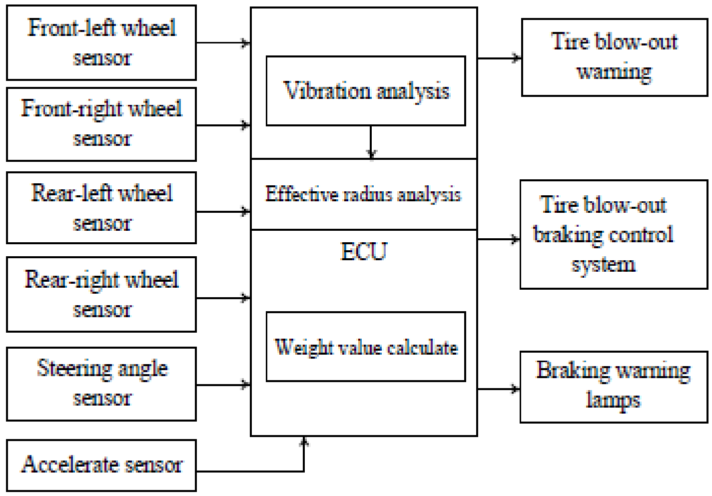


Figure 3-1: Schematic of Real-time system to identify tire failure by Chen [CWX14]

In Figure 3-2 the system software process is described graphically by a flowchart and the steps followed in the system to determine a tire blowout or severe leakage are the following:

1. the thresholds defined to determine a tire blowout or severe leakage are:

   - Tire resonance frequency ($f_{resonance-min}$)

     $$f_{resonance-min} = \frac{1}{2\pi}\sqrt{\frac{2k_0}{G}}$$

     Where k_0 is the torsional elastic stiffness under normal tire pressure (measured by static measurement) and G is the vehicle weight.

   - Change rate of wheel speed (ω'_{j-max})

     $$\omega'_{j-max} = \frac{h_{tire}}{2r - h_{tire}}$$

     Where h_{tire} is tire height and r is the wheel radius when the tire is at normal pressure.

   - Ratio between the product of diagonal wheels radius (η_{max})

     $$\eta_{max} = \frac{r}{r - 0.5h_{tire}}$$

2. The wheel speed signal is obtained from car ECU.

3. This wheel speed time domain signal is transformed into frequency domain with Fast Fourier Transform (FFT) to get the corresponding real-time resonance frequency, named $f_{resonance-real}$.

4. Test if $f_{resonance-real} \leq f_{resonance-min}$ in a tire.
5. If it is true, then the real-time resonance frequency is corrected by a weight value t_i, relating to steering direction, turning radius, severity of braking, and acceleration. To simplify algorithm, the weight value is defined as t_i when the vertical load is increasing on the detected abnormal wheel due to steering, braking and accelerating is less than $0.25G$ (which is approximately 1 time of original load), and if the load increase is greater than $0.25G$, then $t_i = 0.8$.
6. Previous comparison is tested again, considering the weight value, $t_i f_{resonance-real} \leq f_{resonance-min}$. If it is true, the other two analyses (based on effective radius) are carried out to minimize the possibility of a false positive (indicating a blowout or excessive leakage has occurred when it has not).
7. $\omega^{'}_{j-max} \geq \omega^{'}_{j-max}$
8. $\eta \geq \eta_{max}$
9. If this three conditions are true then almost irrefutably the tire is suffering, or has already suffered, a blowout or severe leakage.

Once a tire blowout or severe leakage is determined, the emergency braking system is driven to carry out braking and stability control to slow down the vehicle steadily.

Experimentally it have been proven that this system is efficient to detect tire blowout and severe leakage with vehicle speed from 50 km/h to 90 km/h and ineffective for speeds 20 km/h & 30 km/h (speeds at which these tests were carried out), averaging a detecting time delay of around 0.60 seconds [CWX14].

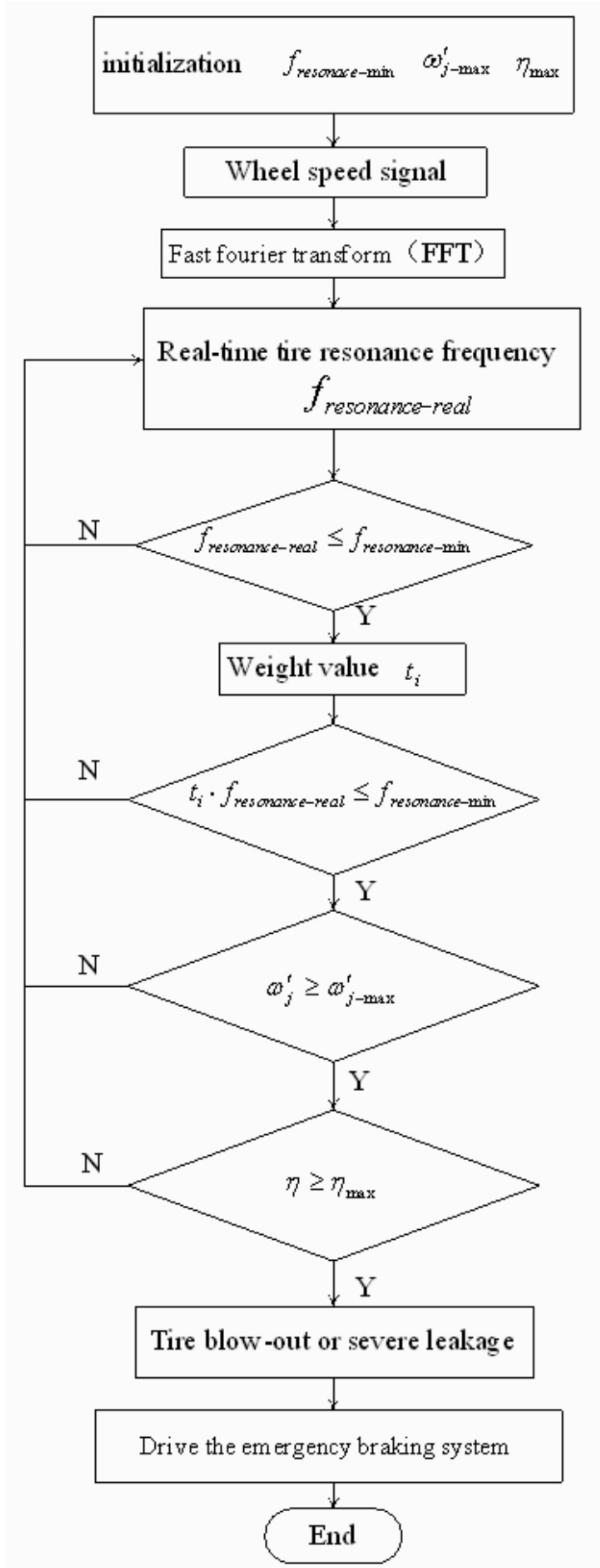


Figure 3-2: Software process of Real-time system to identify tire failure by Chen [CWX14]

The next section explore the patents databases to describe the most similar invention patents related to the proposed system in this thesis.

3.2 Patent overview

Below some U.S. patents for devices, methods, and systems that are aimed at detecting, correcting, and/or preventing event sequences that can potentially lead to tire blowout are listed. They are exposed as referenced systems and ordered based on the publication year. The inventions are described by their inventor own words with the abstract presented to the patents office, the cover image of the patent for graphical representation and some key characteristics of interest are disclosed, like: **publication year, status, abstract, tire temperature measurement method, Communication method, methodology to detect a problem, extra considerations, HMI & Singularity over the other patents reviewed**, all of these characteristics based on the description of preferred embodiments (Pointed to be considered in all respects as illustrative and not restrictive by the inventors). The scope of the inventions are indicated by the appended claims rather than by the illustrative description and all changes which come within the meaning and range of equivalency of the claims are therefore intended to be embraced therein. Refer to the specific patent for specific claims.

3.2.1 Method and apparatus for monitoring tires

- **Patent number** US 6,748,797 B2 to Breed et al.
- **Publication year** 2004.
- **Assignee** Automotive Technologies International Inc., US.
- **Status** Expired in 2016.
- **Abstract** Arrangement and method for monitoring tires mounted to the vehicle in which thermal radiation detecting devices are arranged external of and apart from the tires for detecting the temperature of the tires. The detected temperature of the tires is analyzed, e.g., relative to a threshold or as to the magnitude of a difference between mated tires, and an action is effected in response to the analysis. The thermal radiation detecting devices are preferably supplied with power wirelessly, e.g., through an inductive system, a capacitive system or a radio frequency energy transfer system.

The Figure 3-3 is the cover image of the patent document and it is the most representative of the preferred embodiment of the patented invention.

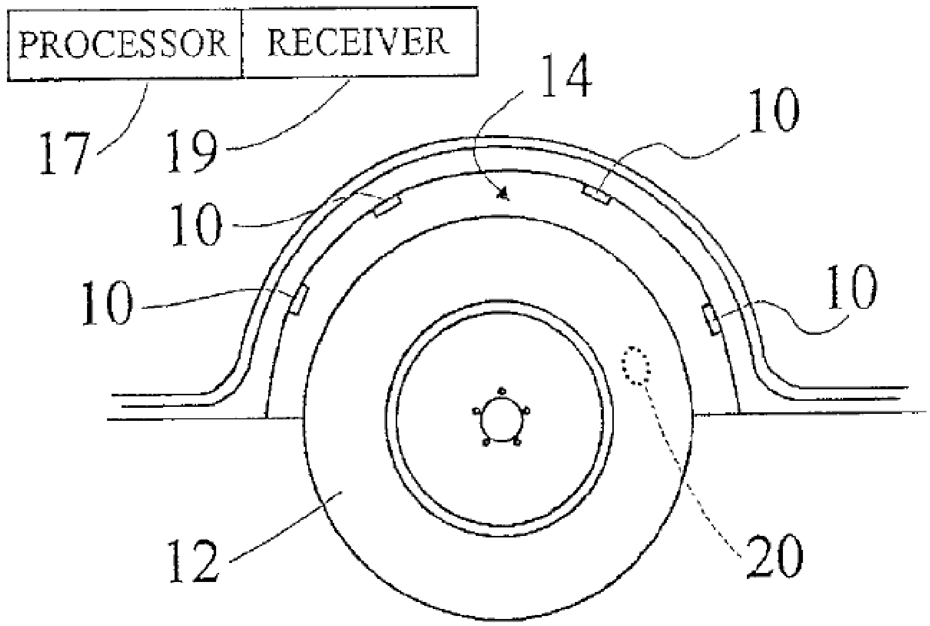


Figure 3-3: Cover image of the patent US6748797

- **Tire temperature measurement method** Contactless tires temperatures.
- **Communication method** Wireless.
- **Methodology to detect a problem** Comparing tire temperature measurement with an adaptable threshold.
- **Extra considerations** Threshold based on the environment and the load of the vehicle.
- **Human-Machine Interface (HMI)**
  - Alarm for emitting noise into the passenger compartment.
  - Display an indication or representation of the determined difference in thermal radiation between mated tires.
  - Warning light.
- **Singularity over the other patents reviewed**
  - Claims to supply power for the sensors wirelessly.
  - Considering mated tires.

- Telecommunication unit to send signal to a remote vehicle service facility.

3.2.2 Thermal monitoring system for a tire

- **Patent number** US 6,963,273 B2 to O'Brien et al.
- **Publication year** 2005.
- **Assignee** Michelin Recherche et Technique S.A., CH.
- **Status** Active.
- **Abstract** A Thermal monitoring system for use with a tire. The system includes one or more thermal sensors that are carried by a vehicle. One of the thermal sensors may produce a first sensor output signal that is representative of the temperature of a first location on the tire. Additionally, a second sensor output signal may be produced that is representative of the temperature of a second location on the tire. A signal processing device is included that receives the first and second sensor output signals. The signal processing device produces a processing device output signal that is representative of a potential damage condition of the tire. This signal is produced in response to a particular temperature difference between the first and second locations as indicated by the first and second sensor output signals. An indication device receives the processing device signal and indicates to a user of the vehicle that the tire is experiencing a potential damage condition.

  The Figure 3-4 is the cover image of the patent document and it is the most representative of the preferred embodiment of the patented invention.

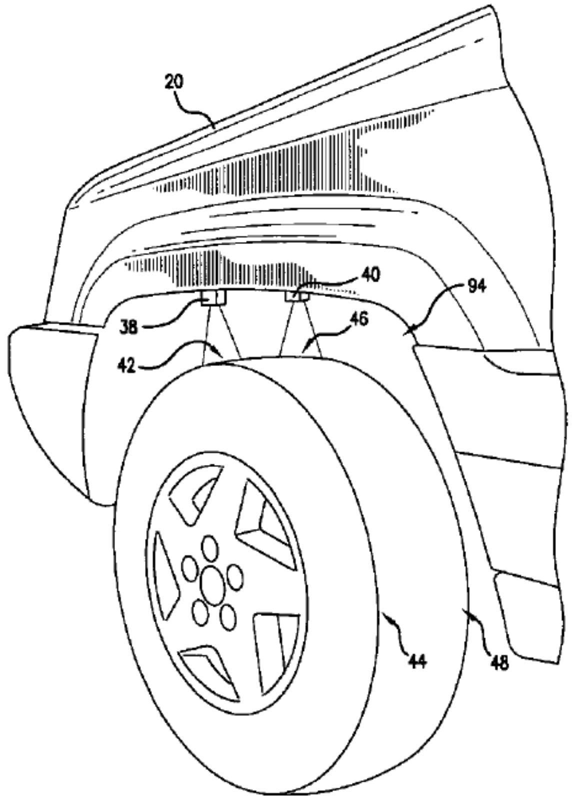


Figure 3-4: Cover image of the patent US6963273

- **Tire temperature measurement method** Contactless (IR sensors or array sensor) condition of the tire (through temperature).
- **Communication method** Wireless/Wired.
- **Methodology to detect a problem**
  Comparison of tire temperatures:
  - Two locations in a single tire.
  - Between two different measurements in the same tire and location but in different time.
  - Between the two front tires.
  - Between the two back tires.
- **Extra considerations**
  - The system uses the tire temperature to determine the condition of it.

  - Consider specific points of interest, that are key to evaluate if there are undesired conditions like tread belt separation.

- **Human-Machine Interface (HMI)**
  The indication device may be:
  - a lamp,
  - a light emitting diode,
  - a gage, or
  - an audio indicator

  indicating to the user that the tire is experiencing a potential damage condition.

- **Singularity over the other patents reviewed**
  - Propose to measure the sidewall of the tire.
  - Its principal aim is to monitor the condition of the tires, detecting undesired conditions like tread belt separation.
  - Consider filtering false alarms readings.

3.2.3 Tire temperature and pressure monitoring sensors and systems

- **Patent number** US 7,075,421 B1 to Tuttle
- **Publication year** 2006.
- **Assignee** None.
- **Status** Expired in 2010.
- **Abstract** A tire monitoring system providing tire status and notifying or warning the vehicle operator of early detection of imminent tire failure and performance degradation; thus improving safety by preventing blowouts from occurring, lengthening tire life by encouraging preventive maintenance, and improving fuel mileage by encouraging the operator to fill the tire to its proper pressure or repair it. The system monitors temperature of the rim of the wheel to which the tire is attached, such temperature being transmitted to the vehicle operator or other interested parties via means such as radio frequency.

  The Figure 3-5 is the cover image of the patent document and it is the most representative of the preferred embodiment of the patented invention.

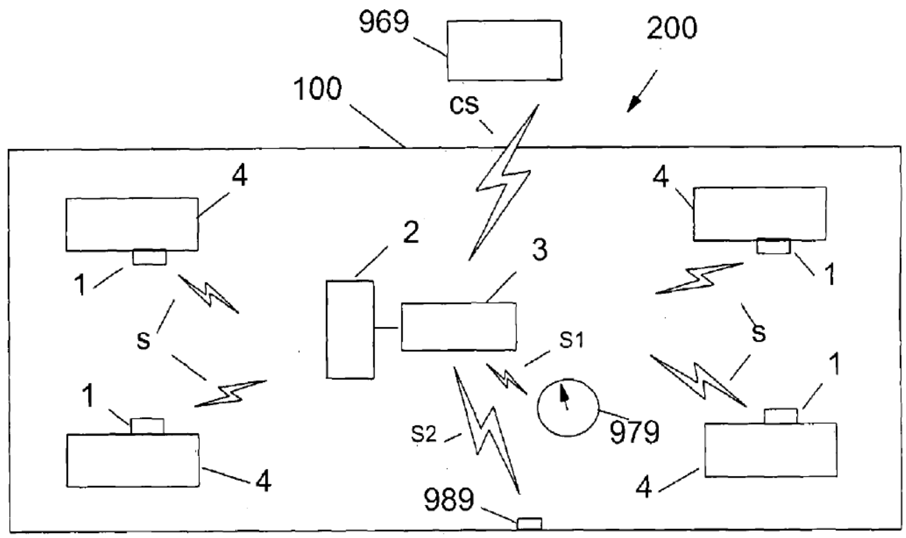


Figure 3-5: Cover image of the patent US7075421

- **Tire temperature measurement method**
  - Contact tire rim temperature.
  - Contact tire internal air temperature.
- **Communication method** Wireless.
- **Methodology to detect a problem** Based on the fact that all tire problems of interest generate heat when the tire is in motion; and heat can be measured by a device attached to the tire rim instead of to the tire itself or to the valve stem, because being a good conductor of heat, will then have virtually the same temperature on its outside surface as it has on its inside surface and the high rim temperature can correlate inversely with tire health.
- **Extra considerations**
  - Tire pressure measurement.
  - Tire rim temperature, tire internal air temperature and tire pressure factors measured together.
  - Compensation of measured parameters due to other effects such as braking, external temperature, road conditions, etc.
  - Ambient temperature sensor.
  - Vehicle speed data from car speedometer.

- **Human-Machine Interface (HMI)**
  A whole display sub-system with:
  - Power on/off switch and its respective Light Emitting Diode (LED) indicator
  - Temperature display window
  - Mode display window
  - Up toggle
  - Down toggle
  - Alarm visual indicator
  - Alarm speaker
  - Mode button
  - Auto-LED indicator
  - Manual-LED indicator
  - Pushing mode button
- **Singularity over the other patents reviewed**
  - Measure the temperature in the rim of the tires.
  - Ambient temperature sensor.
  - Vehicle speed data from the car speedometer.
  - Consideration of battery saver with power on/off function.
  - Various alarm levels.
  - Description of a display modulus with several indicators and controllers.
  - Consideration of different modes for the system.

3.2.4 Tire breakdown warning device and pneumatic tire

- **Patent number** US 7,316,251 B2 to Kogure et al.
- **Publication year** 2008.
- **Assignee** The Yokohama Rubber Co., Ltd., JP.

- **Status** Expired in 2016.
- **Abstract** A tire breakdown warning device includes at least one temperature sensor for detection of temperature of a pneumatic tire, and provides a warning when a breakdown of the tire is found on the basis of detection signals detected by the at least one temperature sensor. The at least one temperature sensor is embedded in the vicinity of at least one end of at least one tire constituent component which is placed in the pneumatic tire and which is vulnerable to break down.

  The Figure 3-6 is the cover image of the patent document and it is the most representative of the preferred embodiment of the patented invention.

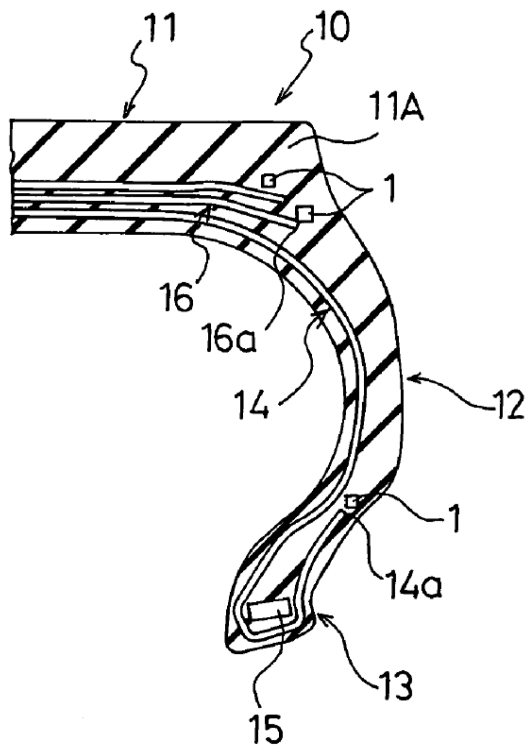


Figure 3-6: Cover image of the patent US7316251

- **Tire temperature measurement method** Contact internal tire temperature (rubber) in key places (ends of carcass ply, belt ply and shoulder areas of the tread).
- **Communication method** Wireless.
- **Methodology to detect a problem**
  Temperature sensing on the vicinity of detected highest stress concentration into the tire

(end of carcass ply, belt ply and shoulder areas of the tread), the comparison with thresholds (adjustable by the ambient or road temperature) generates two different kind of signals based on the danger of a tire breakdown:

- Precautionary signal:
  - Inform that a tire temperature is close to a breakdown temperature.
  - Comparing the lecture with a preset precautionary temperature threshold value.
  - Calculates a value of each temperature rise amount in a unit of time and determine if this value exceed the precautionary temperature rises amount threshold value.
- Warning signal:
  - Inform that a tire temperature reached a breakdown temperature.
  - Comparing the lecture with a preset breakdown temperature threshold value.
  - Calculates a value of each temperature rise amount in a unit of time and determine if this value exceed the breakdown temperature rises amount threshold value.

- **Extra considerations**
  - Temperature sensor for detecting an ambient temperature or a road surface temperature.
  - Consider specific points of interest at ends of a tire constituent component (into the tire), like belt ply, carcass ply and shoulder area of the tire tread.
- **Human-Machine Interface (HMI)**
  - For a precautionary signal, turning on a yellow lamp or by giving a precautionary warning sound.
  - For a Warning signal, a red lamp or a warning sound other than the above precautionary sound.
- **Singularity over the other patents reviewed**
  - Consideration of precautionary and warning thresholds based on the hazardousness of the tire to break down.
  - Ambient or road temperature sensor to adjust the thresholds.

  - Its principal aim is the prevention of tire breakdown.
  - Consideration of points of interest into the tire (Internal contact sensors).

3.2.5 Wireless tire pressure and temperature detecting system

- **Patent number** US 7,541,919 B1 to Huang
- **Publication year** 2009.
- **Assignee** Mobiletron Electronics Co., Ltd., TW.
- **Status** Expired in 2017.
- **Abstract** The present invention provides a wireless tire pressure and tire temperature detecting system, using a wireless monitoring and transmission device with a centrifugal switch. When the tire rotational speed of the car reaches a certain speed, it turns on the centrifugal switch. The centrifugal switch is used to turn on the entire wireless monitoring and transmission device to detect, process signal, and transmit. The wireless monitoring and transmission device is not working, until the tire rotational speed of the car reaches a certain speed before it is initiated and causes power consumption. The invention saves more power consumption than the conventional structure, which extends the shelf life of the wireless tire pressure and temperature detecting system as well as time involved to change the battery, which is practical and convenient.

  The Figure 3-7 is the cover image of the patent document and it is the most representative of the preferred embodiment of the patented invention.

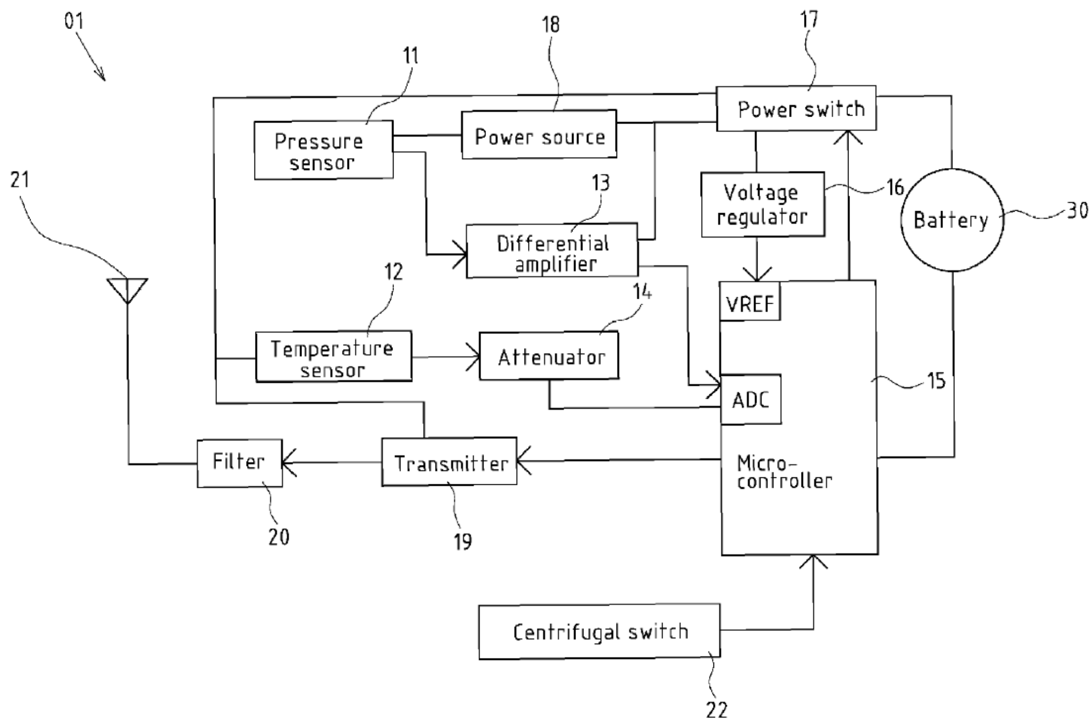


Figure 3-7: Cover image of the patent US7541919

- **Tire temperature measurement method** Contact internal tire (air) temperature.
- **Communication method** Wireless.
- **Methodology to detect a problem** Compare the pressure and temperature measurements with predetermined thresholds.
- **Extra considerations**
  - Tire pressure measurement.
  - Battery saver with a centrifugal activation switch.
- **Human-Machine Interface (HMI)**
  Digital reception display device comprising:
  - Display panel
  - Temperature display button
  - Pressure display button
  - Setting button

  - Alarm indicator

- **Singularity over the other patents reviewed** Centrifugal switch to turn on/off the monitoring and transmitting system based on the vehicle speed to save energy when the monitoring is not necessary.

3.2.6 Tire temperature measurement system

- **Patent number** US 8,547,216B2 to Cao
- **Publication year** 2013.
- **Assignee** Honda Motor Co., Ltd., JP.
- **Status** Expired in 2017.
- **Abstract** A system and method for a tire temperature measurement system. An instantaneous temperature value of a tire may be requested through an input device. At the time of a temperature measurement request a control unit may retrieve tire temperature from a sensor and determine an instantaneous temperature value of a tire. The instantaneous temperature value of a tire may be displayed, stored and transmitted to a remote device.

  The Figure 3-8 is the cover image of the patent document and it is the most representative of the preferred embodiment of the patented invention.

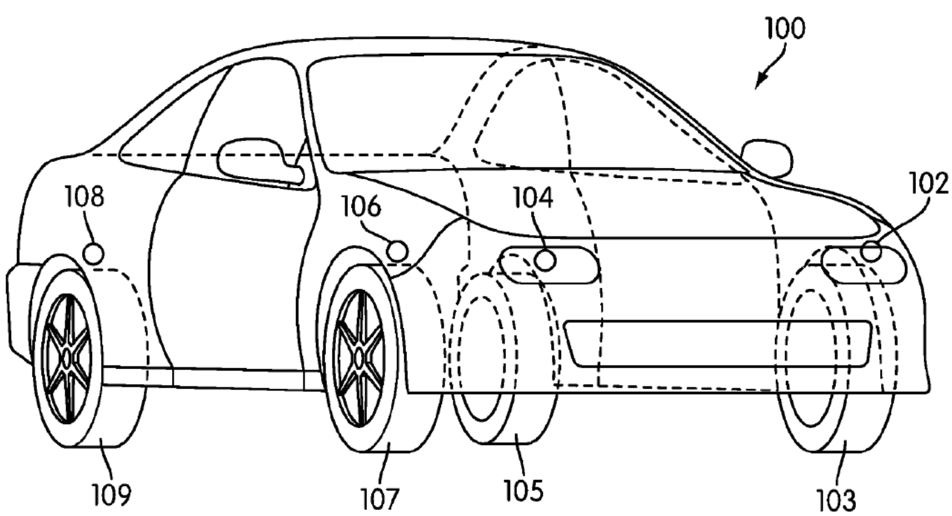


Figure 3-8: Cover image of the patent US8547216

- **Tire temperature measurement method** Contactless tire temperature.

- **Communication method** Wireless/Wired.
- **Methodology to detect a problem** Just measures the temperature in the tires and then the information is storage to been read in the future by an expert in the art who analyzed it and determine if there is a problem or not.
- **Extra considerations** Just measure the tire temperature and a team of experts in the art interprets that measurements.
- **Human-Machine Interface (HMI)**
  - Display device into the car with car schematic and temperature for each tire.
  - An input device where you have the possibility to request actions to the controller.
- **Singularity over the other patents reviewed**
  - Input from the car.
  - Data stored.
  - Data transmitted to a remote device.
  - Store and display temperature value for a selected interval of time.

3.2.7 Vehicle using tire temperature to adjust active chassis systems

- **Patent number** US 8,718,868 to Petrucci
- **Publication year** 2014.
- **Assignee** GM Global Technology Operations LLC, US.
- **Status** Active.
- **Abstract** A system and method for using tire temperature for dynamically adjusting active chassis systems of a vehicle. The method comprises determining a tire temperature value for at least one tire of a vehicle using at least one sensor and adjusting at least one active chassis system of the vehicle responsive to the tire temperature value. The system comprises a chassis having an engine providing power to tires to propel the vehicle. At least one active chassis system is configured to control braking, power applied or control inputs to the tires, and a controller is configured to determine a tire temperature value for adjusting the at least one active chassis system. The at least one active chassis system

are adjusted responsive to the tire temperature value provided by the controller to control braking, power applied or control inputs to the tires.

The Figure 3-9 is the cover image of the patent document and it is the most representative of the preferred embodiment of the patented invention.

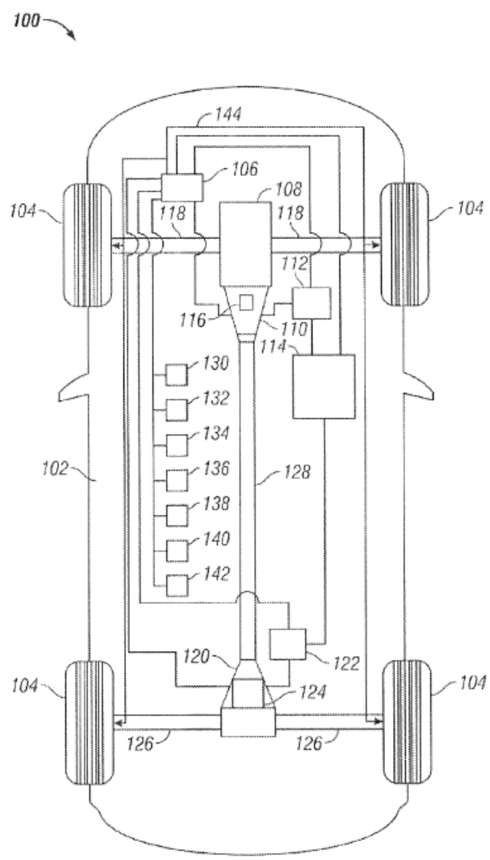


Figure 3-9: Cover image of the patent US8718868

- **Tire temperature measurement method** Contact internal tire (air) temperature.
- **Communication method** Wireless.
- **Methodology to detect a problem**
    1. Determine an initial tire temperature estimate using operating parameters of a vehicle.
    2. Measure an initial tire temperature value.
    3. Determine validity of the initial tire temperature estimate and initial tire temperature value.

4. Classify the initial tire temperature estimate and the initial tire temperature value into one of a plurality of predetermined temperature ranges and determine a tire temperature state.
5. Select a default value for the tire temperature state when tire temperature value and estimated validity are not determined.
6. Change the tire temperature state responsive to the electronic control system detecting aggressive driving of the vehicle based upon monitoring vehicle speed and lateral acceleration.

- **Extra considerations**
  - Tire pressure measurement.
  - Estimate a tire initial (at start up) temperature by using vehicle operating parameters:
    - Intake
    - air temperature sensors
    - Coolant temperature sensors
    - Elapsed time since the engine was last turned OFF (Key Down) from an engine OFF timer
  - Detect aggressive driving of the vehicle based upon monitoring vehicle speed and lateral acceleration.
  - Adjustment, responsive to the tire temperature state, of an active chassis system, like:
    - Antilock braking system
    - Traction control system
    - Electronic stability control
    - Electronic all-wheel drive system
    - Electronically controlled front, center and rear driveline coupling
    - Electronic power steering system
    - Electronic suspension system
  - Ambient air temperature obtained from filtering (averaging) intake air temperature measurement.

  - Plurality of temperature states to classify the tire temperature values varied according to vehicle type or the environment.

- **Human-Machine Interface (HMI)** None.

- **Singularity over the other patents reviewed**

  - It does not have warning method.

  - The system use the information from the tire temperature measurement, tire temperature estimation (by vehicle operating parameters, foregoing pointed) and detection of vehicle aggressive driving (based upon monitoring vehicle speed and lateral acceleration) to actively improve the safety of the car by the adjustment of at least one active chassis system of the vehicle.

  - Use of redundant system, with the tire temperature actual value and the tire temperature estimation (by vehicle operating parameters, foregoing pointed), increasing the reliability of the measurement system.

3.2.8 Tire tread temperature sensor and diagnostics for In-Vehicle display

- **Patent number** US 9,085,205 B2 to Son

- **Publication year** 2015.

- **Assignee** Continental Automotive System, Inc., US.

- **Status** Active.

- **Abstract** A tire tread temperature sensing and display apparatus, system and method are disclosed. The apparatus comprises a temperature sensor, a controller and a display. The sensor is configured to be mounted to a vehicle and to sense tire tread temperature. The controller is configured to receive and process temperature measurements and to communicate to a display, the display configured to display temperature information in response to communication from the controller.

  The Figure 3-10 is the cover image of the patent document and it is the most representative of the preferred embodiment of the patented invention.

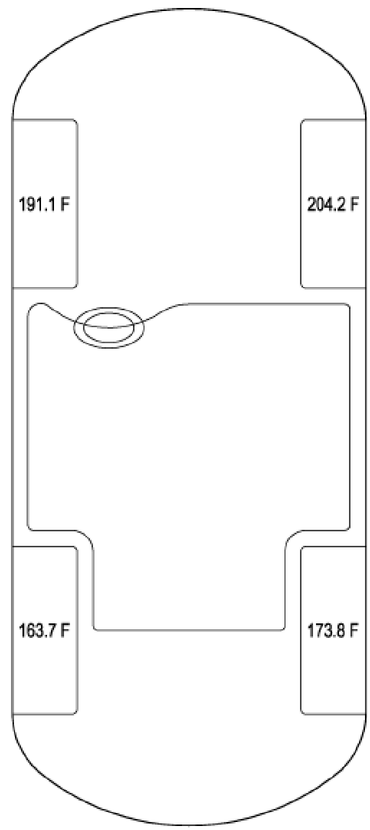


Figure 3-10: Cover image of the patent US9085205

- **Tire temperature measurement method** Contactless/Contact tire tread temperature.
- **Communication method** Wireless/Wired.
- **Methodology to detect a problem**
  - Map the whole tire tread temperature measurement and analyze the data differences in three delimitated zones (the inside tread, the center tread and the outside tread).
  - Determine if the tire temperatures are too hot or too cold for the optimum use using thresholds with recommended temperatures for the specific mounted tire type.
- **Extra considerations**
  - Driving surface temperature.
  - Specific characteristics of the mounted tires.
- **Human-Machine Interface (HMI)** Display device into the car with indication of individual tire's tread temperature of at least three areas of the tire's tread as a color, possible

corrective action and percentage of maximum traction.

- **Singularity over the other patents reviewed**
  - Sensing the driving surface temperature.
  - Display indicating a possible corrective action and percentage of maximum traction based on the tread temperature.

The comprehensive review of each patent is done to emphasize the similarities with the proposed system and the contributions to the art this thesis work could do, The Table 3-1 enclosed the comparative of the identified principal characteristic that defines the inventions, all of these systems search for the timely alert of a tire malfunction to avoid an accident and/or the efficient configuration for the car to obtain the best performance. Later on this work the conceptualization of the proposed system will be disclosed and the similarities and contributions from the proposed system to the art will be explored in detail.

The next section encloses a research for commercial products and services related to the temperature monitoring in the tires and the non-commercially-included safety systems related to the tires malfunctions detection.

Table 3-1: Inventions preferred embodiments main characteristics.

Characteristics	US 674797 B2	US 6963273 B2	US 7075421 B1	US 7316251 B2	US 7541919 B1	US 8547216 B2	US 8718868 B2	US 9085205 B2
Tire temperature measurement method	Contactless	Contactless	Contact	Contact	Contact	Contactless	Contact	Contactless / Contact
Communication method	Wireless	Wireless/Wired	Wireless	Wireless	Wireless	Wireless/Wired	Wireless	Wireless/Wired
Methodology to detect a problem	Adaptable Threshold	Tires temperatures comparison	Relates the temperature of the tire rim with the tire health	Adjustable threshold	Predetermined thresholds for tire pressure and temperature	An expert in the art analyze the temperature data and detects a problem	Temperature stages related to predefined temperature ranges	Map the temperature of the entire width of the tire tread in a strip shape, use a threshold depended of the mounted tire
Extra considerations [1]	Environment & load of the vehicle	Condition of the tire & Specific point of interest to evaluate	Tire pressure, Compensation due to external effects & Vehicle speed from speedometer	Ambient and/or driving surface temperature & specific point of interest to evaluate	Tire pressure	-	Tire pressure, vehicle speed, lateral acceleration & intake air and coolant temperature	Driving surface temperature, specific characteristics of the mounted tires
Human-Machine Interface (HMI)	Output device: Visual & audible	Output device: Visual & audible	Output & Input device: Console with plurality of buttons and indicators	Output device: Visual & audible	Output & Input device: Console with plurality of buttons and indicators	Output & Input device: Display with car and each tire temperature schematic and a button to request the measurement	-	Output device: Display with each tires tread temperature, possible corrective action & percentage of maximum traction
Singularity over the other patents	Power suply wirelessly, mated tires & send signal to a remote vehicle service facility	Detects undesired conditions like tread belt separation, filter false alarms readings & Propose to measure the sidewall of the tire	Measure the tire temperature in the rim of it, battery saver, various alarm levels & different modes	Contact sensors inside the inner layers of the tire & prevention of tire breakdown	Centrifugal switch based on the velocity of the car to turn on/off the monitoring system	Interval of time to measure selected by the user, transmission to a remote device & necessity of an expert in the art	Adjustment, responsive to the tire temperature state, of an active chassis system, detection of aggressive driving based on speed and lateral acceleration & Redundant system	Temperature measurement of the complete width of the tire tread & possible corrective action and percentage of maximum traction

[1] Apart of the tire temperature measurement.

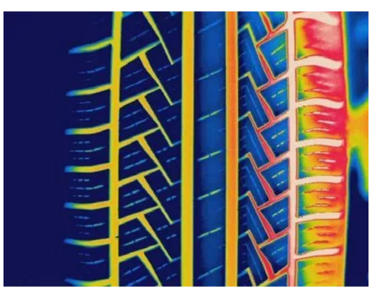
3.3 Commercial products & thermal inspection services

Nowadays the thermal analysis laboratories have found a niche market using their equipment to analyze the behavior of the tires under different tests using a test bench; some analyzes published in their web pages are taken as a reference to exemplify an application for the analysis of the temperature distribution in a tire and the data that can be obtained from it.

The temperature measurement in the tires is taken into account for several users, out there exist many products which main task is to measure the tire pressure and complementary the temperature in it as well, one example of these devices will be listed first just to have a little bit knowledge of the most used devices in commercial automobiles and trucks but the ones of our real concern are the devices used primarily in race ambit, the tires' heat distribution monitoring, these devices are similar to the desired system to been develop, the car receive this information and it is analyzed by expert in the topic to find some irregularity or mechanical problem with the car.

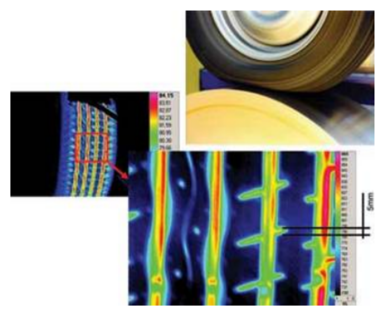
3.3.1 Tires Thermal analyses nowadays

In the present, a few enterprises are using thermographic cameras to analyze the behavior of the temperature in the tires, subjected to laboratory tests that simulate normal conditions of use.



(a) Detection of an alignment problem (overheat right edge) [IIS18]

(b) Detection of a bubble caused by delamination in the sidewall of the tire [IIS18]



(c) Simulating turning and braking loads [Wil06]

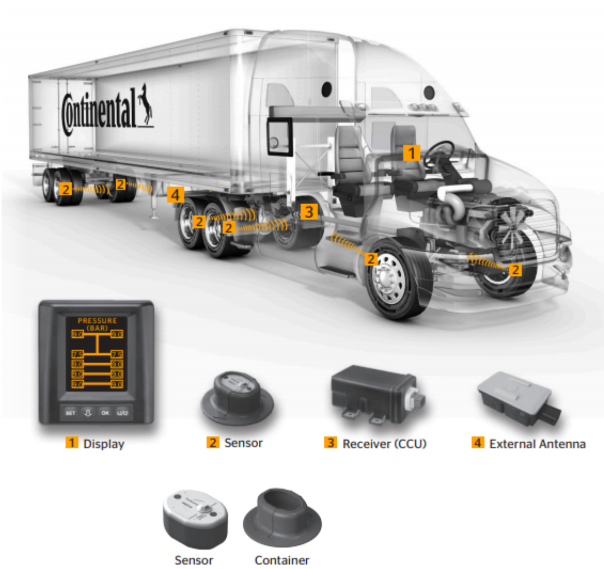
Figure 3-11: Tire applications of IR technologies

Figure 3-11a and Figure 3-11b are some of the tire IR inspections an American enterprise named “Infrared Imaging Services LLC" have made, this enterprise is dedicated to do thermal imaging, IR consulting and have a certificated training on it. Using a high-resolution camera, they were able to detect that the heat buildup along the right edge of the wheel (Figure 3-11a) was caused by an alignment problem, and they detected it long before the tire started to show traditional signs of uneven wear. Infrared thermal imaging reveals differences within materials, as shown in Figure 3-11b, this method detects a bubble caused by delamination, the density of material changes when layers separate conducting heat at different rates and this is detectable by the thermal imaging.

In Figure 3-11c we can see a laboratory test, simulating normal on-road tire conditions, the IR camera could observe tires running at speeds in excess of 150 mph and capture detailed temperature data during dynamic testing to simulate turning and braking loads.

3.3.2 ContiPressureCheck by Continental

In this TPMS developed by Continental specially for trucks, they measure tires' temperature as an extra task from the sensor but the main scope is the pressure, Continental ensure this system helps to save fuel, increase mileage, significantly reduces the risk of tire failure, whilst maintaining the value of the casing, and thus the retreadability and you can actively reduce operating costs by up to $1,750.55 per vehicle a year while improving driver and vehicle safety [Con15].



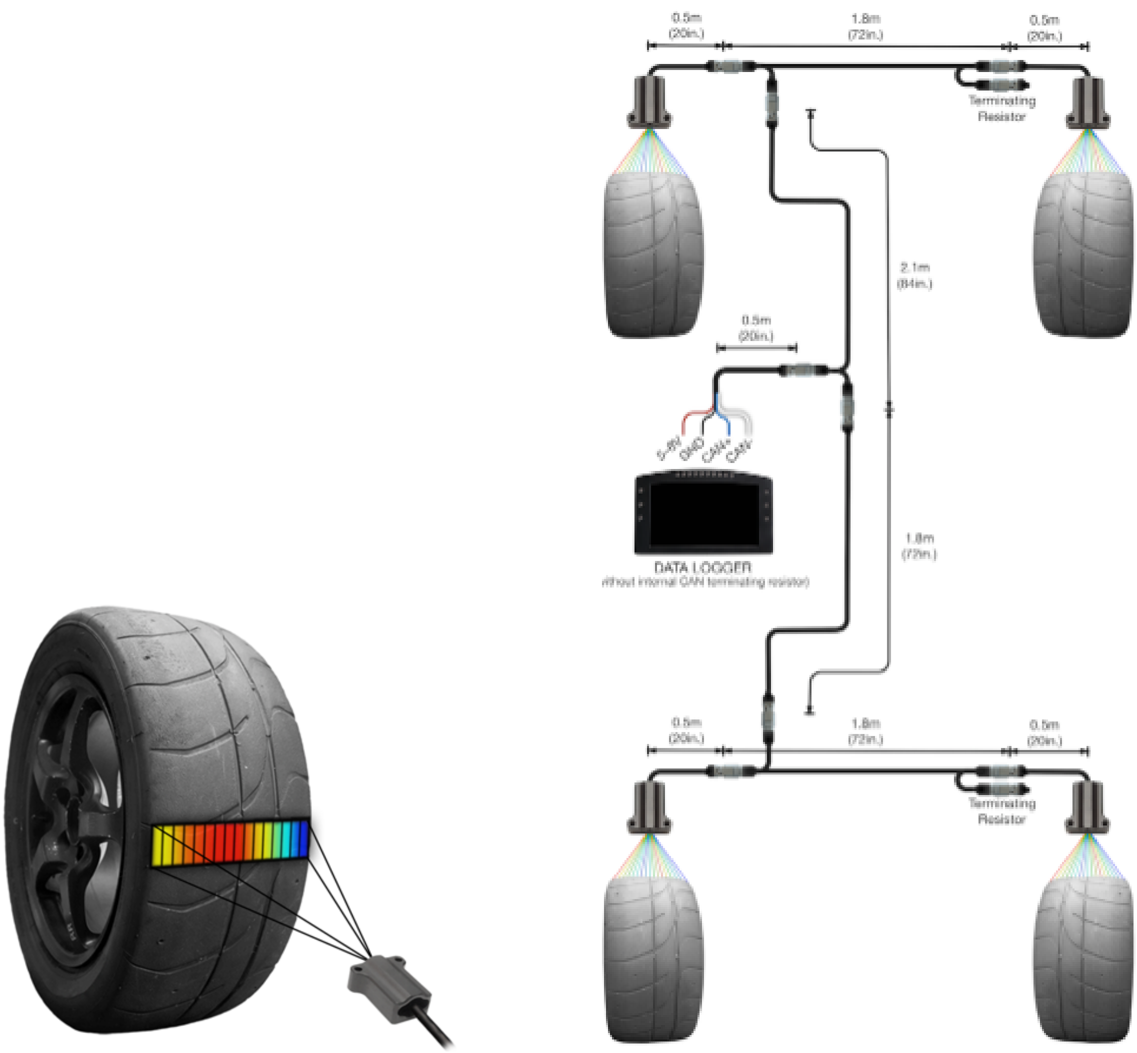
(a) Components of the system [Con17]

(b) The sensor mounted in the tire [Con06]

Figure 3-12: ContiPressureCheck sensor by Continental

3.3.3 Tire temperature sensor by Izze-Racing

Izze-Racing is an American company dedicated to motorsport electronics design and manufacture, this temperature sensor is specifically designed to measure the highly transient surface temperature of a tire with spatial fidelity, providing invaluable information for chassis tuning, tire exploitation, compound selection, and driver development. This sensor is based in IR technology and as is shown in Figure 3-13a the idea is to cover the complete width of the tire, and for that you have two field-of-views: ultra-wide (120°) or wide (60°) at 16, 8 or 4 laterally-spaced points and the temperature range is between −20 °C and 300 °C [IR18a], in Figure 3-14 its shown the readings of this sensor when a driver is turning to the right in a driving test done by the company Izze Racing itself.



(a) Functionality of the sensor

(b) simplified system layout

Figure 3-13: Tire temperature sensor by Izze-Racing [IR18a]

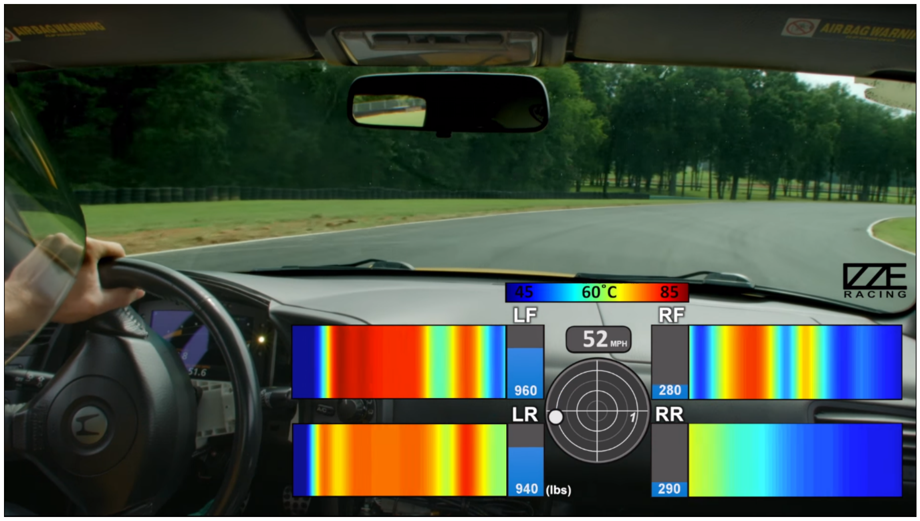
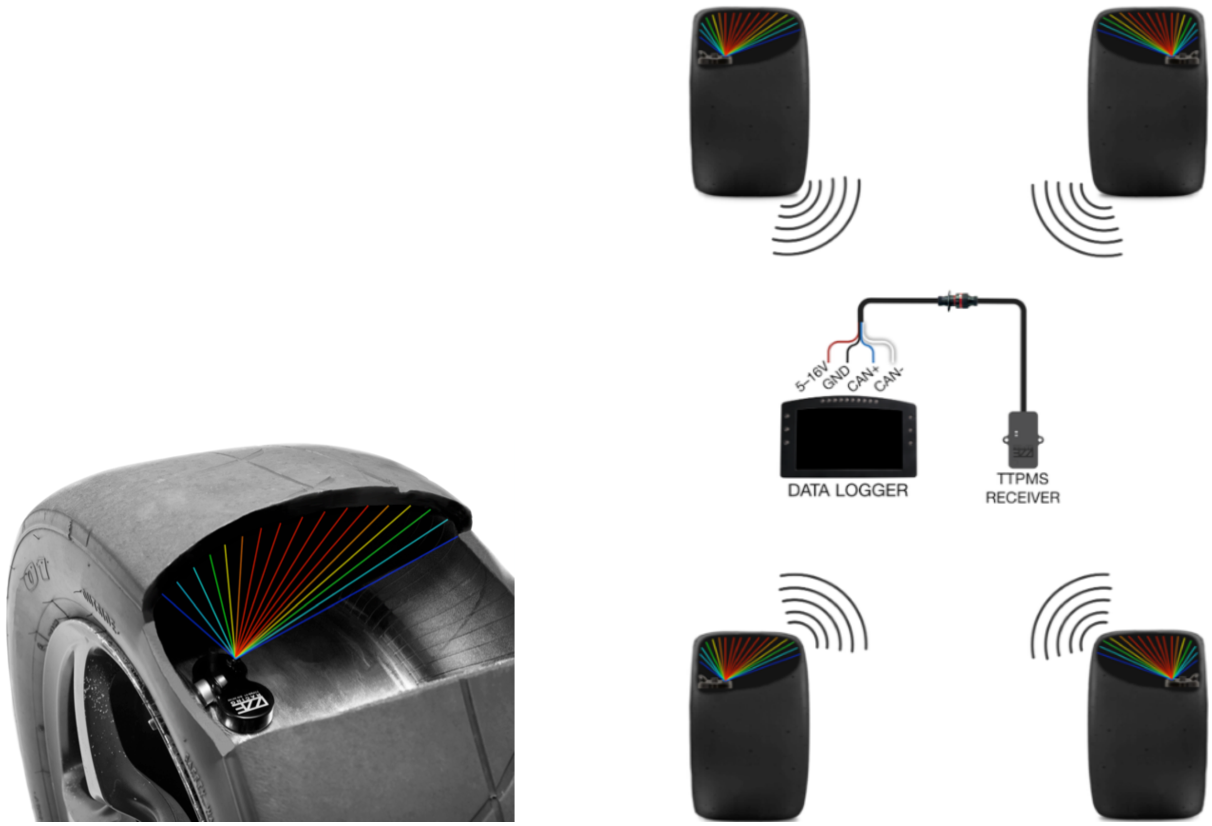


Figure 3-14: Driving test realized by the own company Izze Racing, with the “tire temperature sensor" [IR16]

3.3.4 TTPMS by Izze-Racing

This version of a temperature monitoring system from the same company is designed to measure the internal temperature and pressure of the tire, but as counter part of the first sensor (ContiPressureCheck), this one prioritizes the temperature using a very similar methodology as the previous IR sensor, the wireless sensor measures the lateral temperature distribution of the inner tire carcass with an ultra-wide 16-channel IR sensor and pressure with a precision 24-bit pressure transducer. The temperature threshold goes from ambient temperatures up to 130 °C and the pressure sensor have ±1 mbar resolution [IR19].



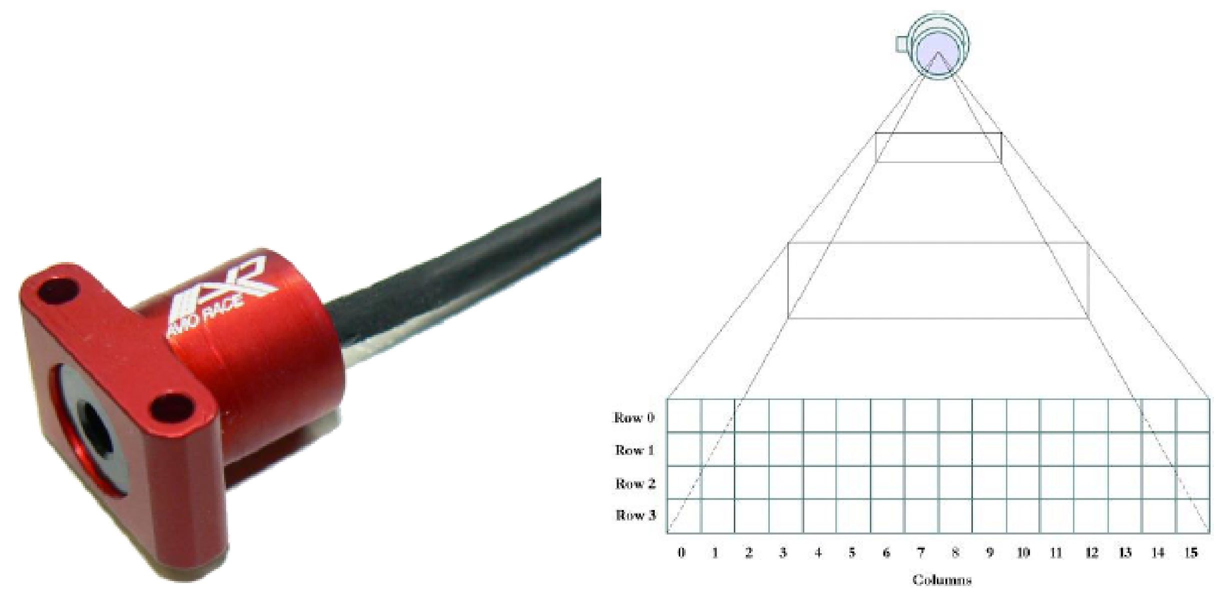
(a) Functionality of the sensor (b) simplified system layout

Figure 3-15: Tire Temperature & Pressure Monitoring System (TTPMS) by Izze-Racing [IR19]

Figure 3-16: Driving test made by the own company Izze Racing, with the “tire temperature sensor" (Outer Surface) & the “Tire Temperature & Pressure Monitoring System (TTPMS)" (Inner Surface) simultaneously [IR18b]

3.3.5 Infrared tyre temperature sensor by Avio Race

Avio Race is an Italian company, provider of electrical and electronic solutions for customers in the Motorsport, Automotive, Aerospace and Marine Industries [Raca]. This IR sensor is designed for contact less temperature measurement as the previous IR products, but this one differs in the quantity of temperature points detectable, this one reach 64 points on 4 rows ×16 columns (4 ×16) distribution, while the previous ones do not distributes the temperature points in a matrix, this arrangement can work to make the lecture more reliable comparing the rows between themselves and founding an average to reduce the misreadings or some issues like these. The Sensor is available in three versions each with different field of view: 40°, 60° and 120° [Racb].



(a) IR sensor

(b) Temperature points matrix

Figure 3-17: IR tyre temperature sensor by Avio Race [Racb]

As it has been reviewed, the commercial products currently on the market that focus on the temperature distribution in the tires are aimed to racing performance automobiles and do not show the data in real-time to the driver, their purpose is to been analyzed by the mechanical expert afterwards; the idea of this work is to propose a system with the same objective of the reviewed commercial products, obtain the temperature distribution in the tires, but aimed to a more commercial market and providing to drivers, without any mechanical knowledge, an interpretation of the data and warning of any temperature-evident abnormality with the tire.

The state-of-the-art study put on the table that the tire tread temperature distribution is a topic that has been of interest as a research topic, for the development of inventions and even, nowadays there are few systems already developed and on the market to be purchased. The principal difference in the systems proposed and developed in all these areas of technology development contrasting the proposed Tires Automatic real-time Safety System (TASS) is the approach and aim of the system, the proposed system is focused in the implementation of the day-by-day car and not for race cars, and the objective is to be implemented as a safety system.

In the next section the system is technically described as an engineering system concept developing the ConOps and the High-Level requirements.

4 System definition

This section aims to describe the Concepts of Operations (ConOps) of the “Tires Automatic real-time Safety System (TASS)" and point the High Level Requirements (HLR) to been accomplished.

The ConOps and the High-level requirements are part of a series of technical documents aiming to describe an engineering system concept in the pre-development phase, the aims and objectives of the system in this section are intended to be fulfilled through the development of the complete system phases, and as it was mentioned before in the section 1.7 the thesis project aim is to reach the system concept stage of the entire lifecycle described through the V-model in the Figure 1-4, so the aims and objectives from the thesis project does not fulfilled the ones from the proposed system and they are pointed in the chapter 1.

4.1 Concept of Operations for the system to be developed

A ConOps is a document describing the characteristics of a system to be developed from the viewpoint of its future users. It is used to communicate system characteristics to all stakeholders and serve as a basis for stakeholder discussions [KZB19], in this work the ConOps is divided in two sections, Required systems concepts and Requirements.

4.1.1 Current system status

Commercially one can find few systems on charge to measure the tire tread temperature distribution, they are focused in the racing-cars market because their principal aim is to help the mechanics to chassis tuning and obtain the best performance possible during a career based on their expertise knowledge, they are not focused in the safety of the driver and do not contemplate the intervention of amateurs drivers with any mechanical knowledge with the information obtained; the proposed system aims to reach the passenger cars drivers interested in obtain a better performance for fuel consumption efficiency and a safer performance of the tires while in drive thanks to the real-time temperature distribution monitoring even when their mechanical knowledge is very basic.

The system proposed is made up of three principal subsystems, the monitoring subsystem, the control subsystem and the On-board subsystem.

4.1.2 “Stakeholders"

The “Stakeholders" are all the people, institutions or entities that one way or another are affected by the implementation of the system and may be potentially interested in the project because of that. The knowledge and analysis of the “stakeholders" give to the “systems engineering" an important power of decision and fundamental that can not been bypassed.

The “stakeholder" taken into account for the present project are listed below:

- Drivers & Passengers

  The automobiles principal consumers are the drivers and passengers of them, as customers they always search for the best quality, power and of course safety when purchasing a car; the TASS, which aim is to improve the safety should be one of the determining factors in the decision of selecting a car over another one.

- Motor vehicle safety standards regulatory agencies.

  Worldwide the United Nations (UN) through the Economic Commission for Europe (ECE) created an international working party called The World Forum for Harmonization of Vehicle Regulations (WP.29) and they develop the UN regulations, among other things, regulations on vehicle safety to been adopted voluntarily by the nations members of the UN [UE99]. Some counterparts of these international regulations are national standards as the U.S. counterpart called the Federal Motor Vehicle Safety Standards (FMVSS) developed and enforced by the National Highway Traffic Safety Administration (NHTSA), or the Canadian Motor Vehicle Safety Act (CMVSA) containing the Canadian Motor Vehicle Safety Regulations (CMVSR) and the Canadian Motor Vehicle Safety Standards (CMVSS) [MoJ19]; between others national regulations.

- Companies selling very similar products.

Nowadays there are some companies that sell IR sensors to analyze the distribution of the heat in the tires, but, all of them are focused to racing cars and not commercial ones, so they might be interested on the focus on this market.

- Commercial vehicles manufacturers.

  Even if at the beginning this idea could sound a little useless for commercial cars, nowadays we are living in a transformation era where the cars are turning smarter and smarter every day, in the search of the autonomously, but to achieve it, tons of new safety systems have been taken into account to reach the safest version of a car possible, this system can be helpful to achieve that.

- Researchers.

  Primarily focused in research topics as “Smart Tires", “Smart car" or even “crash avoidance systems", this topic (even if it is already implemented in commercial products) does not have a lot of public research work, the most of the work was “closed door" research.

In Table 4-1 the “stakeholders" are cataloged by their interest in the project and the power of influence, both in percentage.

Table 4-1: “Stakeholders"

Stakeholder	Interest %	Power %
Drivers & Passengers	100	70
Motor vehicle safety standards regulatory agencies	85	80
Companies selling very similar products	80	40
Researchers	70	30
Commercial vehicles manufacturers	60	60

The “Stakeholders" investigation worked to realize (as it was expected) that the users are the most interested in the development of a system of this kind because it could help to make their day-by-day safer, but they do not have much influence power for the system development, the “Motor vehicle safety standards regulatory agencies" is the principal stakeholder to have present because even if it does not have as much interest as the users, they have a good percentage of interest and they are the ones with more influence power.

4.1.3 Required systems concepts

This section is dedicated to describe the general concepts of the required system. Even if the topic have been introduced in a general way and their antecedents have been mentioned, this section is focused in the required system from the point of view of a user and not from the developer.

Below the operation policies and the expected restrictions for the system are pointed, description of the system, its operational concepts and the expected final users classes.

4.1.3.1 Operation policies

The monitoring subsystem is intended to be mounted in the under part of the chassis in moving automobiles, in front of the tires tread, this leads to a very chaotic environmental, where it will be exposed to water, dust, mud, debris, stone impacts, very high temperatures due to the road vape and the heat dissipated by the tire and the automotive, it should be used in highways, where the temperature of the tires achieve their critical conditions so the time periods of use can reach several hours of use, even entire days.

The control subsystem is intended to be enclosed in an controlled area, protected from the weathering.

The HMI subsystem is intended to be on-board the vehicle and that means the conditions are not of special attention due to the controlled environment inside the automobile.

4.1.3.2 Required system description

In this section it is described in detail the required system starting with the necessity introduction, the system objective, the uses that it should been developed for, its limits, interfaces and its relevance as well.

Introduction

A system to measure the distribution of the temperature on the tires is required, it is intended to be implemented in commercial passenger cars so it should be done the cheapest way possible and it should be done to been used by every kind of user, that means with few technical knowledge on the field or even any knowledge on it.

Objective

The objective of the development from the user point of view is to create a system capable of monitor the tire heat distribution while on use in real-time and use that information to reliably identify the most possible mechanical problems that are evidently reflected in the tire temperature, then with that information show the user some hints about the possible problem and an advice to solve it in a non-technical language that every user understands, very intuitive.

Uses

1. The system will be mounted on particular's vehicles in movement, obtaining the tire temperature distribution for prevent accidents due to the increase on tire temperatures.
2. It will be used to impulse the "smart tire" investigation and the influences of the heat generated by the friction on the tire tread when the automobile is in movement.
3. The system development and improvement should work as well, to win knowledge and experience in automobile-related systems through the experimentation and tests for further development of more advanced systems by students, researchers or private industries.

4.1.3.3 Operational concepts

An operative monitoring, post-processing and displaying data system is the aim of the development, the cheapest and robustest possible to make feasible the implementation in commercial cars without having such a significant impact on the price of the vehicle.

One characteristic the system should have is, been implemented to the root programming of the car, using CAN bus, add a new Electronic Control Unit (ECU) capable of have communication with the others components of the car, the display is planned to been external and independent but doing the system this way is much simple give maintenance or repair if necessary the system.

4.1.3.4 Users clases

There are three types of end users: Drivers, developers and technicians. Which are describe below.

- Drivers The principal directly users of the system; they will be the most benefited by the system, visualizing the hints and warnings from it, increasing their safety when they drive the car, they do not need any technical knowledge about the system to make good use of it.

- Developers They manipulate the sensors because they are on charge of the installation or any software update, they mount the sensors in their right places to obtain the best temperature lectures, implement the system to the car ECU and calibrate the sensors, these users have more expertise and technical knowledge of the system functionality than the others.
- Technicians They are able to give maintenance to the system, maybe some system update, if is necessary, repair it and mount it or dismount it if is required. They should have very good knowledge of the system functionality and the technical phases of it.

The next section is about operation procedures, the steps to operate the system are described, from its implementation to its maintenance.

4.1.4 Operation procedures

This section is dedicated to describe the minimum that is required between the different procedures of the system: Mount & implementation to car ECU arrangement, turning off, calibration, diagnosis procedure and maintenance.

4.1.4.1 Mount & implementation to car Electronics control units arrangement

The physical mounting of the sensors should be done taking care for the position of these and a “base" is installed to speed up future dismounting and mounting, then the system should be integrate with the existing ECU of the car to couple the safety system with the rest of the electronic.

4.1.4.2 Calibration

Once the sensors are mounted, the developers need to calibrate them to obtain reliable measures, guaranteeing the precision specified for the system and other parameters if they are considered.

4.1.4.3 Turning off

The system need to be externally powered, that electrical supply is obtained from the car battery so when the car is switched off the system can not been functional.

4.1.4.4 System in operation

While the system is operational, the readings from the sensors measuring the temperature of the tires will be post processing and at the end the user will visualize in a panel if there are any problem on the tires or everything is in order, these indication needs to been compressible for every kind of user, even without any knowledge of mechanical topics.

4.1.4.5 Diagnosis procedure

There should be diverse diagnosis procedures regularly in every system stage to alert of a misreading or failure, in this respect, the user should be advice about it as soon as possible and in the case is in one of the sensors deactivate it to avoid more misreadings and confusion with the element.

4.1.4.6 Maintenance

The maintenance required will be specified by the developer in an users manual after the system is mounted and operational, the user will be able to follow the most of them but for others a technician, with more electro-mechanical knowledge should be necessary.

Once the ConOps has been presented, in the next section the high-level requirements are discussed which are essentials to clarify the users necessities and demands to be fulfilled in the system development, the requirements are the principal guidelines for the system developer.

4.2 High-level requirements to the system to be develop

The system requirements are formal statements that establish the characteristics from the users point of view, about what the systems should accomplish. In this case, talking about a preliminary prototype the testers and system approvers are considered to be the users. The requirements can be functional or not, but they always must be clear, verifiable and without ambiguities.

The functional requirements define specific behavior or functions, more focused in the system design. The non-functional requirements specifies criteria that can be used to judge the operation of a system, rather than specific behaviors and is more focused on the system architecture.

4.2.1 Brief description of the required system

As system that measures in real-time and reliably the temperature distribution in the tire, process these data and programmatically give warnings of detected problems along with clear and understandable hints so that any user, even those who do not have technical knowledge at all about cars, can react correctly and in time to avoid a car accident; the development includes concept proposal, system architecture and preliminary associated studies and tests design.

The functional and non-functional requirements are organized by the mentioned subsystems, the monitoring subsystem, the ECU and the HMI.

4.2.2 Functional Requirements

1. **General**

   FR 1.1 The system should work in real time and guarantee the reliable functionality.

   FR 1.2 Once the system is installed it should not be intrusive into the vehicle electronics or modify internal parameters of it.

   FR 1.3 The electrical power supply of the system will be provided by the car.

   FR 1.4 The communication between subsystems should be based on the same protocol.

   FR 1.5 The system should respond against a tire problem faster than the typical driver response time.

2. **Monitoring subsystem**

   FR 2.1 The subsystem should measure the temperature distribution in each tire tread contactless.

   FR 2.2 The subsystem should measure the roadway temperature contactless.

   FR 2.3 The sensors should be waterproof, dustproof and shockproof.

   FR 2.4 The sensors should be mounted in the car under-body.

3. **ECU**

   FR 3.1 The ECU should process the data from the monitoring subsystem and present the determine action in the HMI.

   FR 3.2 The ECU should work in real-time.

FR 3.3 The ECU should be reliable and robust.

4. **HMI**

FR 4.1 The system should give warnings of detected problems along with clear and understandable hints.

FR 4.2 The interaction with the system must be as intuitive as possible for the user.

FR 4.3 The messages should be easy to read and comprehend.

FR 4.4 The system should not distract the driver creating a hazard situation.

4.2.3 Non-Functional Requirements

1. **General**

NFR 1.1 The communication protocol must be Controller Area Network (CAN) 2.0 because it is the principal communication protocol used in the environmental this project will be developed, the automotive industry.

NFR 1.2 The life cycle of the system development should follow and be based on the functional safety for automotive equipment of the ISO 26262.

2. **Monitoring subsystem**

NFR 2.1 Based on the ISO 16750-4:2010 the operational temperature range should be from $-40\,°C$ to $90\,°C$.

NFR 2.2 The system should measures tire temperatures from $-20\,°C$ to at least $100\,°C$, preferably up to $300\,°C$.

NFR 2.3 Sensor temperature measurement accuracy of $\pm 1.5\,°C$.

NFR 2.4 Sensor field of view (FOV) minimum of 60° fro the linear array sensor.

NFR 2.5 Based on the ISO 20653:2013 The sensors enclosure should have the IP6K9K certification.

NFR 2.6 Based on the IEC 62262 the sensors should have the IK10 certification.

NFR 2.7 The power stage of the system must be designed for 12 V, which is the vehicle connector power supply.

3. **ECU**

NFR 3.1 The electronic control unit should meet the ISO 26262-functional safety standard for minimum ASIL-B.

NFR 3.2 The ECU should be able to handle CAN 2.0 communication protocol.

NFR 3.3 The software should fit the AUTOSAR approach to real-time automotive systems.

4. HMI

NFR 4.1 The design of the HMI should meet the ISO standards of ergonomics aspects for the Transport Information and Control Systems (TICS) for road vehicles.

NFR 4.2 The performance of the HMI should meet the ISO standards of ergonomics aspects for the TICS for road vehicles.

5 Automotive Functional Safety

5.1 Introduction

Functional safety is a concept that we could find in the standard series from the International Electrotechnical Commission (IEC), the IEC-61508, for Electrical, Electronic and Programmable Electronic (E/E/PE) safety related systems. It supports the assessment of risks to minimize the failures in all E/E/PE safety-related systems, irrespective of where and how they are used. This standard defines functional safety as: "part of the overall safety that depends on a system or equipment operating correctly in response to its inputs. Functional safety is achieved when every specified safety function is carried out and the level of performance required of each safety function is met". Functional safety relies on active systems and the safety achieved by measures that rely on passive systems is not functional safety.

There are plenty several functional safety standards for each industry or markets, but they are intended to encourage machine designers and manufacturers to focus more on functions that are necessary to reduce each individual risk and improve the performance required for each function. These standards make it possible to achieve greater levels of safety throughout the life cycle of the machine. [Sha17] In Figure 5-1 are exposed examples of some functional safety standards derived from the general IEC-61508, each of them have their own definitions and set their own terminology and guidance for engineering developments including target metrics, based on the target market and the specific requirements and principles the systems need to accomplished.

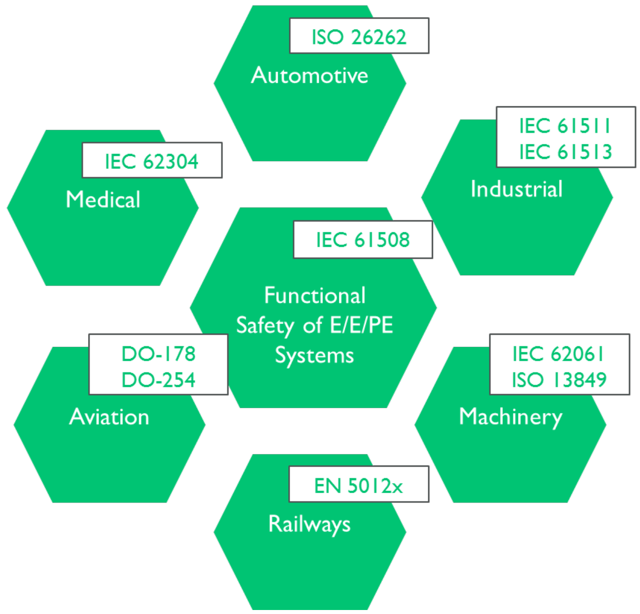


Figure 5-1: Functional safety standards applicable for different markets, derived from the IEC-61508 [IR18b]

5.2 Automotive safety-critical electronic control systems

As it is shown, the standard ISO 26262, developed by the International Organization for Standardization (ISO) is the most relevant automotive electronic systems safety standard, but a study developed from 2012 to 2016 by the John A. Volpe National Transportation Systems Center (Volpe Center) and the NHTSA about the safety and reliability of automotive safety-critical electronic control systems, take into account another four relevant safety standards (not just in the automotive industry) to been compare and asses:

- ISO 26262: Road Vehicles - Functional Safety
- MIL-STD-882E: Department of Defense Standard Practice - System Safety
- DO-178C: Software Considerations in Airborne Systems and Equipment Certification
- AUTOSAR: Automotive Open System Architecture
- MISRA C: Guidelines for the Use of the C Language in Critical Systems

Table 5-1 is a tabulated summary of the assessment results of this study.

Table 5-1: Summary of assessment results in a study done by NHTSA & Volpe center about five relevant automotive safety standards.

Factors	ISO 26262	MIL-STD-882E	DO-178C	AUTOSAR	MISRA C
Type of Standard	Process and method	Process	Process	Design (architecture)	Design (coding)
Definition of safety	Absence of unreasonable risk.	Freedom from conditions that can cause death, injury, occupational illness, damage to or loss of equipment or property, or damage to the environment.	No clear definition provided. Based on Failure Condition Category, the definition is similar to MIL-STD-882E.	Same as ISO 26262.	No explicit definition.
Definition of Hazard	Potential source of harm caused by malfunctioning behavior of the item. Malfunctioning Behavior: failure or unintended behavior of an item with respect to its design intent.	A real or potential condition that could lead to an unplanned event or series of events (i.e., mishap) resulting in death, injury, occupational illness, damage to or loss of equipment or property, or damage to the environment.	No definition provided.	Same as ISO 26262.	No explicit definition.
Identification of Safety Requirements	At high level of the system, use hazard analysis method. At lower levels of the system, use safety analysis methods.	Functional hazard analysis on predefined nominal system functions is used to identify safety hazards.	Assumes software requirements are flowed down from system-level activities, and provides no guidance on how to further decompose the requirements and identify additional safety-critical requirements at each level of the system decomposition hierarchy.	Focused on architecture design requirements. Depend on ISO 26262 to identify safety requirements.	Focused on coding standard.
Management of Safety Requirements	Safety requirements and regular system requirements are managed together.	Hazard Tracking System used separately from other requirements management system.	Safety requirements and regular system requirements are managed together.	Not discussed.	Not discussed.
Design for Safety Approach	No explicit discussion. Focus on *safety mechanism*.	Thoroughly discussed starting with prevention and elimination.	Not explicitly discussed.	Good architecture may prevent hazards.	Good coding practice will reduce errors in software.

Table 5-1: (continued)

Factors	ISO 26262	MIL-STD-882E	DO-178C	AUTOSAR	MISRA C
Hazard and Safety Analysis Methods	Hazard Analysis includes: brainstorming, checklists, quality history, Failure Models and Effects Analysis, and field studies. Safety Analysis include: Failure Modes and Effects Analysis, Fault Tree Analysis, Event Tree Analysis, and Hazard and Operability Analysis, Markov Model, Reliability Block Diagram, etc.	Functional hazard analysis on predefined nominal system functions is used to identify safety hazards.	Not discussed.	Not discussed.	Not discussed.
Risk Assessment	Uses three dimensions—Severity, Exposure, and Controllability to generate ASILs. Uses the term of "acceptable risk," without sufficiently precise definition. Accepts both qualitative and quantitative probability assessment. Suggests ASILs decomposition for all hardware and software.	For general system: Severity and Probability of occurrence. For software: Severity and Software Control Category (no probability). Uses the term of "acceptable risk," but mentions user involvement in decision. Accepts both qualitative and quantitative probability assessment.	Only considers severity, no probability assessment. Hazards are considered to be caused by software behavior inconsistent with specified requirements, assuming all safety requirements are identified already.	Not applicable.	Not applicable.
Software Safety	Follows the systems engineering process. Uses the concept of *Software Fault*.	Same as Hardware Development Process, following the systems engineering process.	Follows the systems engineering process. Uses the concept of *Software Anomaly*.	Not applicable.	Coding standards
Human Factor Considerations	Not emphasized. Only controllability assessment in ASILs relates to human factors.	Emphasized throughout the standard.	Not discussed.	Not discussed.	Not discussed.

Table 5-1: (continued)

Factors	ISO 26262	MIL-STD-882E	DO-178C	AUTOSAR	MISRA C
System Lifecycle Consideration	Considers lifecycle of the system, including manufacturing, but does not explicitly discuss the safety of human operators and maintainers, and the environmental hazard.	Prompts considerations for various aspects after system is in operation, but does not mention safety considerations for the manufacturing process.	Focuses on software lifecycle considerations such as coding, configuration management, etc.	Focuses on reusability, modifiability.	Not applicable.
Review, Audit & Certification	Independent confirmation reviews, safety audits, and safety assessments are required for various ASILs. No safety certification requirement.	Supports government reviews, audits, and boards, but details to be specified in Request for Proposal and Statement or Work for each project. Specifics are left up to the program manager and contractor.	The certification authorities consider the software as part of the airborne system or equipment installed on the certified product, and do not certify the software as a unique, stand-alone product. Systems and equipment, including embedded software, should be "approved" and then accepted as a part of a certification. Approval is given dependent upon successful demonstration or review of products of the software lifecycle.	Not for safety approval or certification.	Supports software quality system by contributing to the documentation; but, not used for software safety certification.

Volpe made the following observations based on the comparative assessment of the five relevant standards:

- Existing process standards could be enhanced by providing a precise definition of "unreasonable risk" within the context of automotive safety.
- Hazard definitions vary across different standards.
- Severity alone can be used as the risk measure for software, similar to the approach outlined in DO-178C. Further, in cases when statistically valid failure probability or the probability of the occurrence of a mishap is not available, severity could be used as the only

measure.

- Exposure and controllability assessment used by the industry, as defined in the ISO 26262 standard, could be enhanced with the collection of additional data through design of specific experiments.
- Existing process standards for software design could be enhanced with consideration for the overall safety of the control systems and software safety certification, in addition to the focus on specific aspects of the design solution (i.e., good architecture and coding standard).
- Design-for-safety approach as specified in MIL-STD-882E provides a framework that could be leveraged for separate management of hazard tracking/safety requirements from regular system requirements, simpler risk assessment, and more emphasis on human factors.
- The topic of health hazard analysis for drivers and service technicians could be further assessed for the appropriateness of including this topic in a process standard.
- Existing process standards do not explicitly address environmental impacts on a vehicle throughout its lifecycle, including testing, manufacturing, operation, maintenance, etc.
- Human factors studies could be better integrated into a comprehensive functional safety approach.

After the review of the study realized by the NHTSA & the Volpe National Transportation Systems Center (Volpe) the ISO 26262 standard suits better with the intentions and scope of this work, encompasses process and method, the identification of system requirements occur at high level, with *hazard analysis method* and at low level with *safety analysis method* and both are discussed through the standard; and the risk assessment is based on the ASILs for hardware and software that help the developer to define the safety requirements necessary.

Once, the definition and importance of functional safety have been exposed, and that the ISO 26262 have been pointed as the standard to follow in the implementation of functional safety to the system proposed, the next section is centralized in that standard and the application of it in the conceptualization of the system proposed in this work.

5.3 ISO 26262

The development and integration of automotive functionalities strengthen the need for functional safety and the need to provide evidence that functional safety objectives are satisfied. With the trend of increasing technological complexity, software content and mechatronic implementation, there are increasing risks from systematic failures and random hardware failures, these being considered within the scope of functional safety. Here is where the ISO 26262 series of standards surge, including guidance to mitigate these risks by providing appropriate requirements and processes.

To achieve functional safety, the ISO 26262 series of standards:

a) provides a reference for the automotive safety lifecycle and supports the tailoring of the activities to be performed during the lifecycle phases, i.e., development, production, operation, service and decommissioning;

b) provides an automotive-specific risk-based approach to determine integrity levels [ASILs];

c) uses ASILs to specify which of the requirements of ISO 26262 are applicable to avoid unreasonable residual risk;

d) provides requirements for functional safety management, design, implementation, verification, validation and confirmation measures; and

e) provides requirements for relations between customers and suppliers.

The ISO 26262 series of standards is comprised by twelve parts and is based upon a V-model as a reference process model for the different phases of product development, as shown in the Figure 5-2, whithin the figure:

- The principal shaded ”V" represent the interconnection among ISO 26262-3, ISO 26262-4, ISO 26262-5, ISO 26262-6 and ISO 26262-7;
- the ISO 26262-5 and ISO 26262-6 comprises product development, in the hardware and software level, respectively, and have their own v-model reference process model between the ”principal V-model";
- for the adaptation to motorcycles (part 12):
  - ISO 26262-12:2018, Clause 8 supports ISO 26262-3;
  - ISO 26262-12:2018, Clauses 9 and 10 support ISO 26262-4;

- the specific clauses are indicated in the following manner: “m-n”, where “m” represents the number of the particular part and “n” indicates the number of the clause within that part (Example: ”2-6” represents ISO 26262-2:2018, Clause 6.).

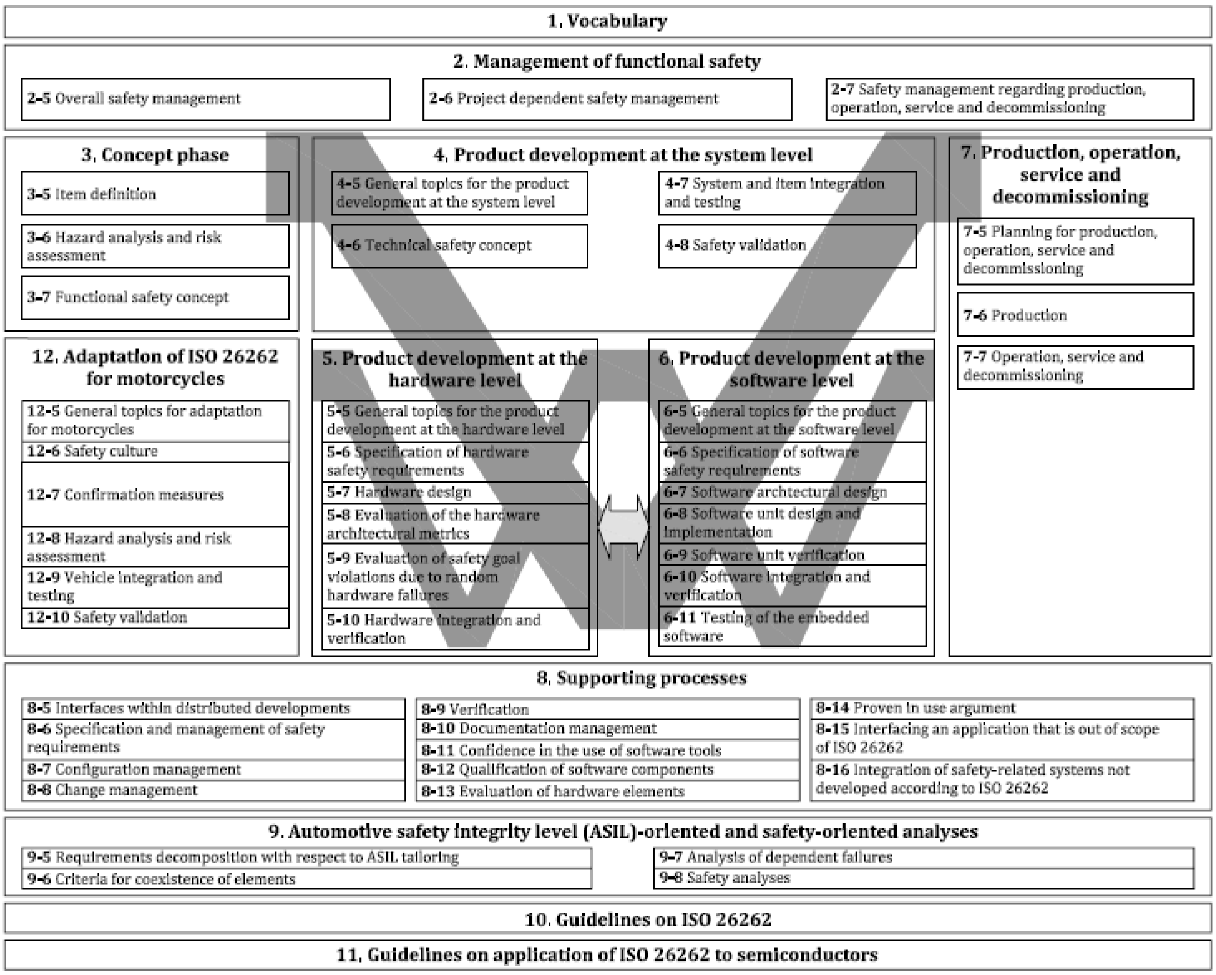


Figure 5-2: Overview of the ISO 26262 series of standards

As mentioned in the section 1.7, the scope of this thesis work is to reach the system concepts of the V-model, so the parts of interest from this standard are the ”ISO 26262-2: Management of functional safety", the ”ISO 26262-3: Concept phase" and the ”ISO 26262-9: Automotive safety integrity level (ASIL)-oriented and safety-oriented analyses".

The next chapter is the system concept, for the description first a summary of the system is disclosed with the three main components of the complete system, then a description of the embodiment with images illustrating the proposal.

6 System Concept

In this chapter, the conceptualization of the system is divided in two sections, the summary of the system where there is described the complete system, focusing in the specific three main components, and the second section is about the proposed system embodiment, like the mounting, the architecture and the description graphically of the working principle for the monitoring subsystem, the ECU & the HMI

6.1 Summary of the system

The proposed system provides to the driver detecting, diagnosing and warning/advising for abnormal conditions in the tire, through real-time monitoring and displaying tires tread temperatures and providing some hints about the issues with the tire; the system is composed by three main components: The Monitoring subsystem, the Electronic Control Unit & the Human-Machine Interface.

Monitoring subsystem
The monitoring subsystem provides parametric measurement of temperature distribution based on the infrared radiation of each tire tread within four infrared thermal array sensors (one for each tire) covering the complete tire width and mounted at a location external from the tire and an IR thermal sensor to determine the roadway temperature, both mounted in the under body of the car; the monitoring subsystem put especial attention to the temperature readings in most vulnerable zones for a breakdown in the tire, identified to be at the end of a tire constituent component such as a belt ply, because of the highest stress concentration thereon; this subsystem is in communication with the control subsystem using CAN-communication-protocol.

Electronic Control Unit
The ECU meets the functional safety standards, it is configured to receive information from

the monitoring subsystem and control the HMI, providing a relationship between symptoms detected based on the tire temperature distribution in a single tire or in a group of tires, processing the monitoring subsystem measurements, and hints about the cause of the problem deploying it in the HMI; this controller is in communication with the HMI with wired technology.

Human-Machine Interface

The HMI comprise a console with a touchscreen HMI with different windows to show different information to the user and the possibility to configure several graphical elements, it is configured to be operated by the driver; The HMI shows the temperature distribution of the tire with a graphic representation of each tire divided in three areas and can be observe by the user in a numerical-way or using a false-color color map and a color-temperature scale displayed, each tire area temperature value is the result of the average of the temperature readings obtained by the monitoring subsystem in the elements into the area; the roadway temperature value is shown in a numerical indicator. The HMI is configured to inform and alert the driver about the status of the tire monitoring and avoiding the user from the necessity of looking away from the road for a long time.

The system provides a method of tire breakdown warning, comprising the steps of: Monitoring the tire tread temperature in real-time; detecting an abnormality in the tire tread reflected in temperature increase; determine the hazardousness of the abnormality; trigger the alarm in the vehicle warning the driver about the abnormality; determine the cause of the abnormality using a guideline of the symptoms/causes/remedies [Flu03] table obtained thanks to the experts experience; Deploy the hints about the cause and remedies of the tire abnormality to the driver.

The following images help to describe the embodiment of the proposed system, featuring the mounting and the functionality of the monitoring subsystem, the system architecture, and the HMI windows for the on-board subsystem are the characteristics described.

6.2 Mounting

In the Figure 6-1 an aerial view of how the sensors would be mounted in an arbitrary vehicle is shown, in total there are 4x IR array thermal sensors planed to be mounted to measure the tread temperature of the tires right after they had contact with the roadway, the roadway thermal sensor is mounted in front of the Front-Left tire to measure the road surface temperature, this location is selected arbitrary and could be changed searching for the best mounting rigid part of the specific car.

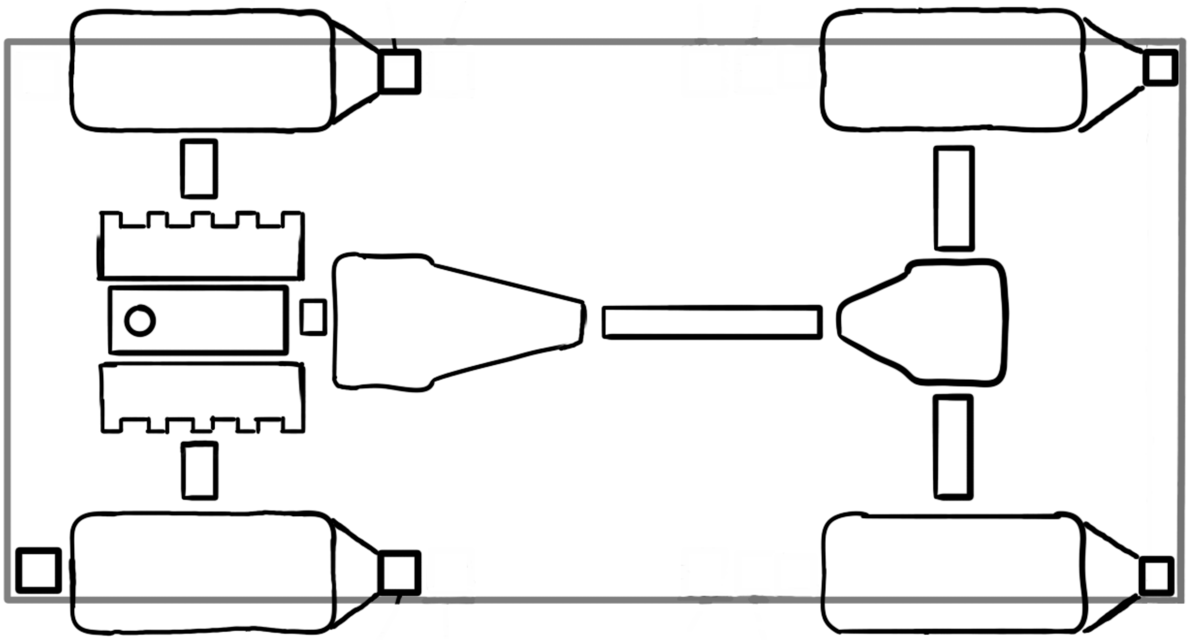


Figure 6-1: Schematic top view of a car fitted with temperature measuring devices

The Figure 6-2 is a schematic view of the embodiment of the car, here it is appreciated the mounting of the IR array thermal sensor on charge to measure the tire tread temperature while the vehicle is driving, measuring its thermal radiation, this sensor is mounted on the rocker panel of the car, (the rocker panel is located between the front and rear tires, along the floor and beneath the doors, they are made from steel and provide structural support and continuity between the front and rear, is also called sill), is appreciated as well, the assembly of the second sensor, in the engine under-tray (part usually plastic-made in the under-body of the car right under the engine of it), this sensor is IR and measure the thermal radiation in a single point of the roadway while the vehicle is driving, the assemblies are done by any suitable connection device known in the art, such as for instance Screws, bolts, and/or clamps.

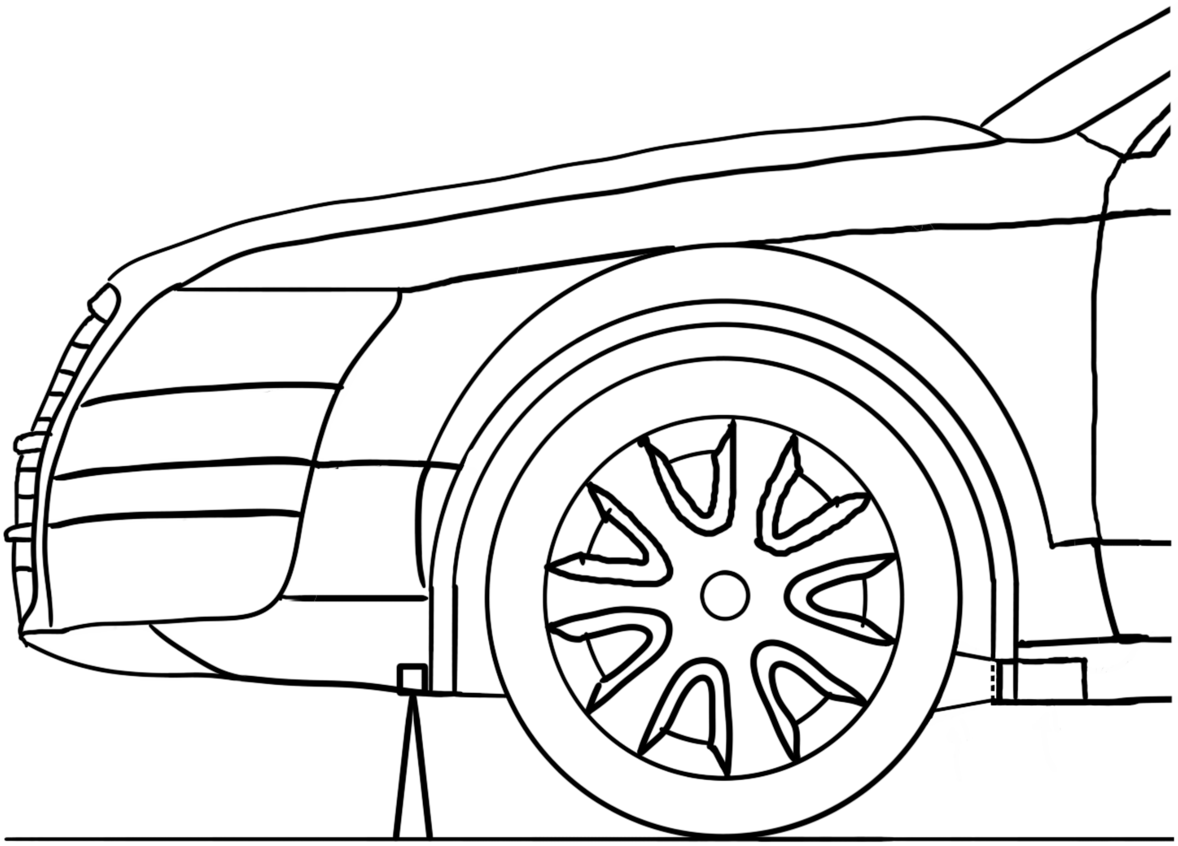


Figure 6-2: Arrangement for measuring road and tire tread temperature

6.3 System architecture schematic

Figure 6-3 is a schematic view of the present invention, the monitoring sub-system is composed by 4x IR array thermal sensors, each of them to measure the tread temperature distribution of their respective tire, and a thermal sensor measuring the roadway temperature; the control unit receives the lectures from the 4x tire sensors (Front-left, Rear-Left, Front-Right and Rear-Right) and the roadway sensor, process it and determine the respective output signal with the information to show to the user through the HMI.

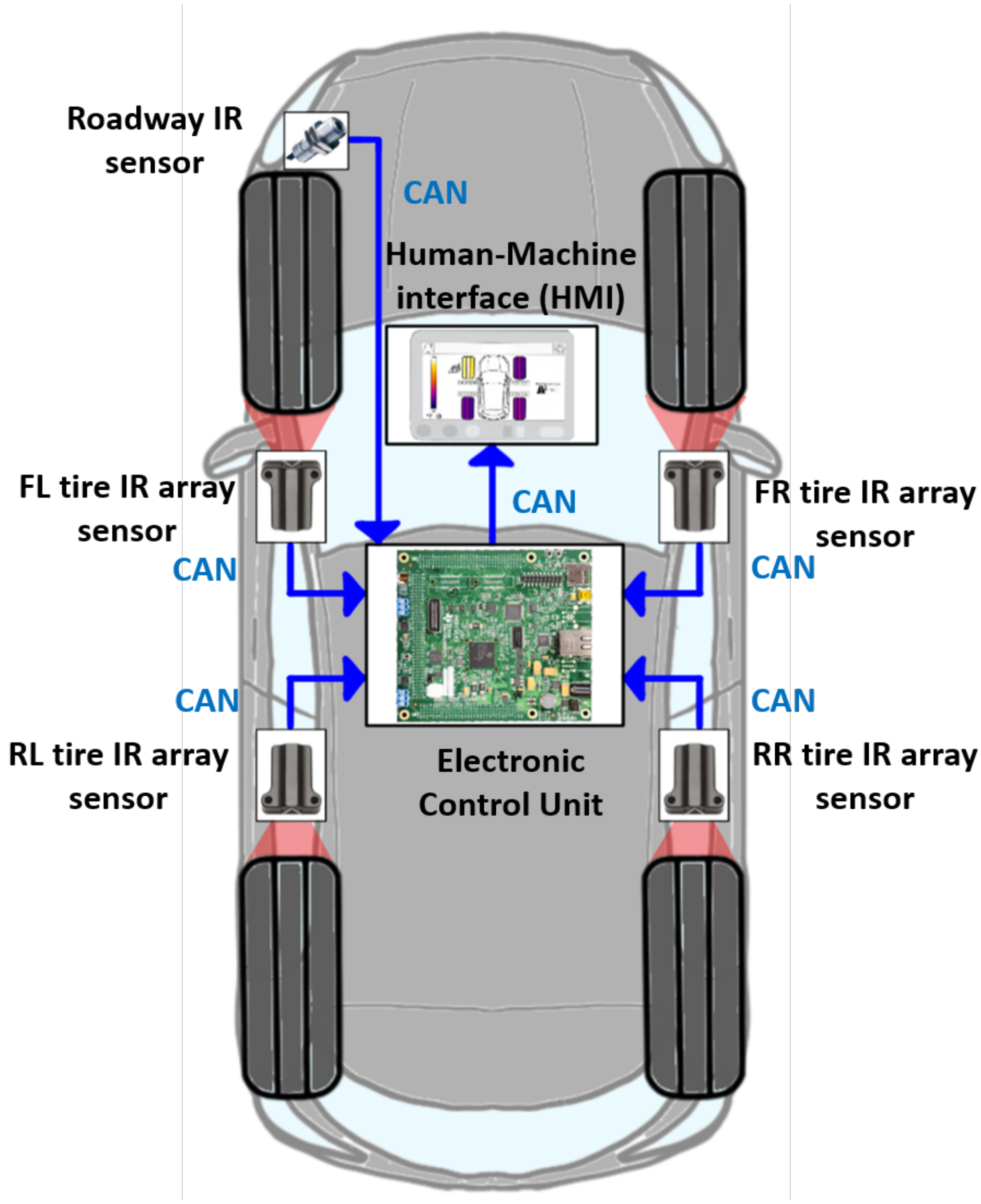


Figure 6-3: System architecture schematic

6.4 Monitoring subsystem

The Figure 6-4 is a representative figure of how the IR thermal sensor measures the temperature in a single point in the roadway contactless while the vehicle is driving.

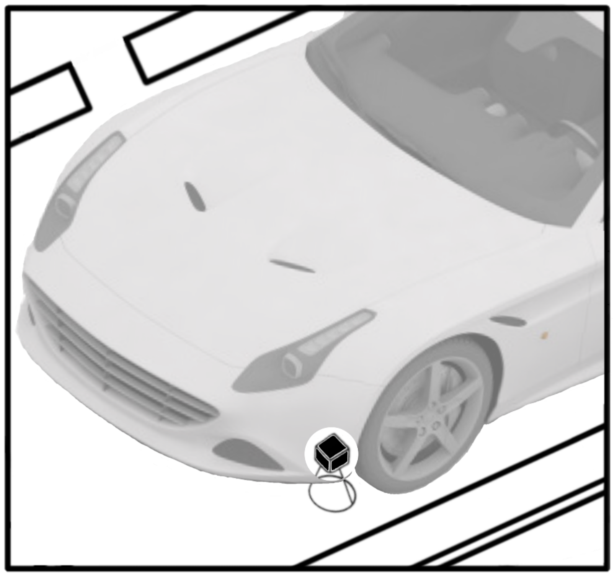


Figure 6-4: Perspective view of the roadway temperature measurement

In Figure 6-5 the IR array thermal sensor covers all the tire tread width with its complete field-of-view and the array of temperature measurements is composed of 16x single-point temperature measurement.

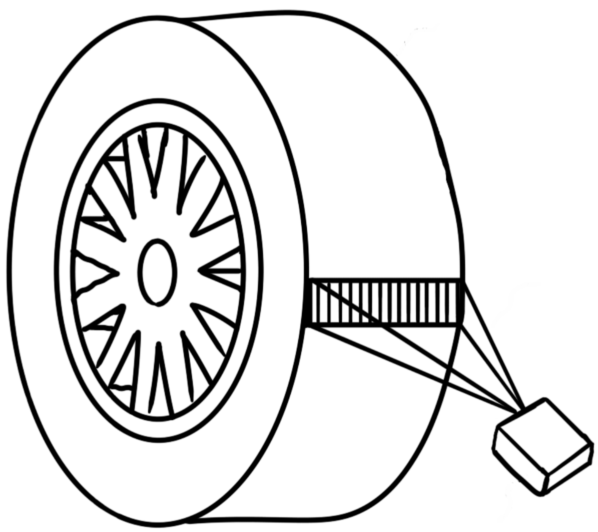


Figure 6-5: Perspective view of the tire tread temperature measurement

Figure 6-6 is a schematic view of how the tire tread temperature is discretized in the 16x single-point temperature measurements that conform the array from the field-of-view of the sensor, the tire tread block is divided in 3x areas, the inside area, the center area and the outside area; this areas being the average of several single-point temperature measurements, 5x elements for each of the outer areas and 6x elements for the center area.

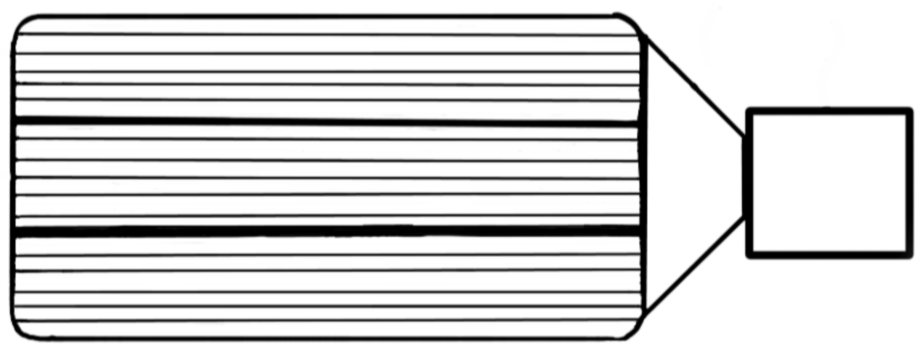


Figure 6-6: Schematic tire tread temperature measurement by elements

Figure 6-7 shows a cross-sectional view of a tire and associated thermal sensor. The tire includes a first side wall, a second sidewall, a first bead, a second bead, a radial belt section (plurality of belt plies), a carcass ply, and the tread of the tire. These are the basic elements of any type of pneumatic tire. The first bead is present at one end of the first sidewall, and the second bead is present at one end of the second sidewall. If the integrity of the tire structure is damaged, portions of the tire may generate heat through the rubbing of delaminated or separated tire components. As the components of the tire continue to separate, they may eventually detach from one another. Tread belt separation is one such condition. Tread belt separation typically occurs in portions of the tire marked as separation zones and. Separation Zone is located proximate to a first side edge of the radial belt section. Likewise, the separation zone is located proximate to a second side edge of the radial belt section. Heat may be generated in the separation zones and through the rubbing of loose wires in the radial belt section that touch one another. Over time, this heat will be conducted to the outer surface in the tire tread and form a hot spot thereon. The present system thereof senses this heat on the tire tread with an IR array thermal sensor in order to determine that an undesirable condition in the tire is taking place the way mentioned before, or if there are significant differences in temperature through the three delimited areas of the complete measured array; these senses in real-time while the vehicle is driving.

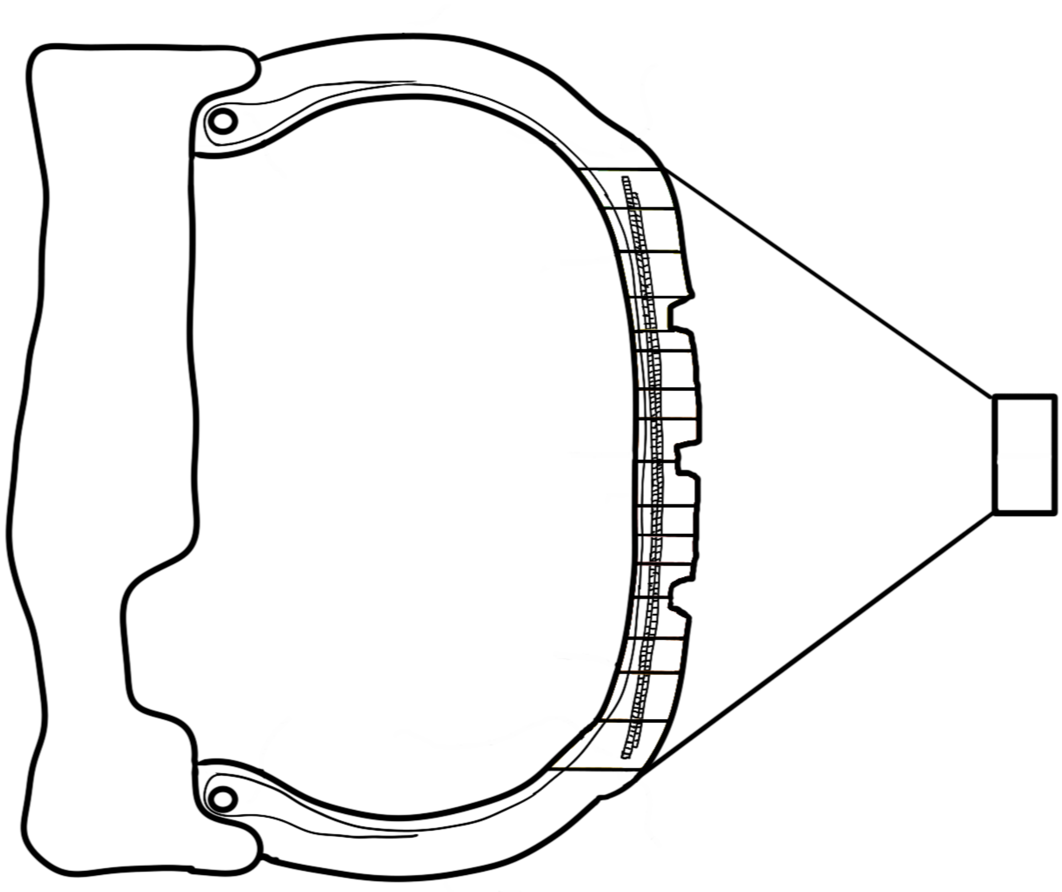


Figure 6-7: partial cross-sectional top view of any pneumatic tire

6.5 Human-Machine Interface (HMI)

Figure 6-8 shows the touchscreen HMI system to be on-board the vehicle, in the upper-part of the screen one can find two different buttons, with their respective icons for a better association with their contents, that deploys the windows for “messages" (upper-left-corner) and “Settings" (upper-right-corner), and the third window is the predefined one, the“Monitoring" window, this window will be always displayed at least you touch one of the previously mentioned buttons, in this window the driver would observe information the system offer in real-time, for the messages window, the icon will be one of two possibilities, the icon with the exclamatory mark is shown when there is a message or advice from the system and the other one if there is not a new message, for the Settings window, its icon is the commonly used gear-and-wrench icon; the rest of the HMI is the information display section, where the selected window (Monitoring, messages or settings) will be deployed and with it the corresponding controllers and/or indicators.

Figure 6-8: HMI

6.5.1 Monitoring window

Figure 6-9 shows the HMI when the monitoring window is deployed in the information display section with all the indicators the driver could observe while driving, the activation of them are conditioned for the configuration the user decide for the system or in the case of the alerts icons if there is an abnormal condition, first we have an image of an arbitrary car used just for illustrative purposes, the 4x sectioned-tire-color-temperature indicator show to the driver the temperature in each of the 3x areas the tire is divided (outside, center and inside), with an assigned color corresponding the temperature measurement from the tire 4x IR array thermal sensors, the color-temperature scale relates the color used to represent the temperature with the false color colormap used thanks to the min and max temperature values indicators, this indicator can be disabled by the driver to have a cleaner view of the display, optionally, the driver can chose to activate the temperature numerical-indicators to have a more accurate value for the temperature of each section, the driver have a roadway temperature numerical-indicator representing the temperature measurement obtained by the roadway thermal sensor, the 4x abnormal-situation indicators are activated when an abnormal condition is detected in their respective tire, it blinks to call the driver attention, in the lower-left corner of the information display section one can find two indicators, of the units used and sound-alarm on/off to clarify this two aspects to the user, depending on the driver configuration the temperature can be in °C or in °F, and the sound-alarm can be On or off.

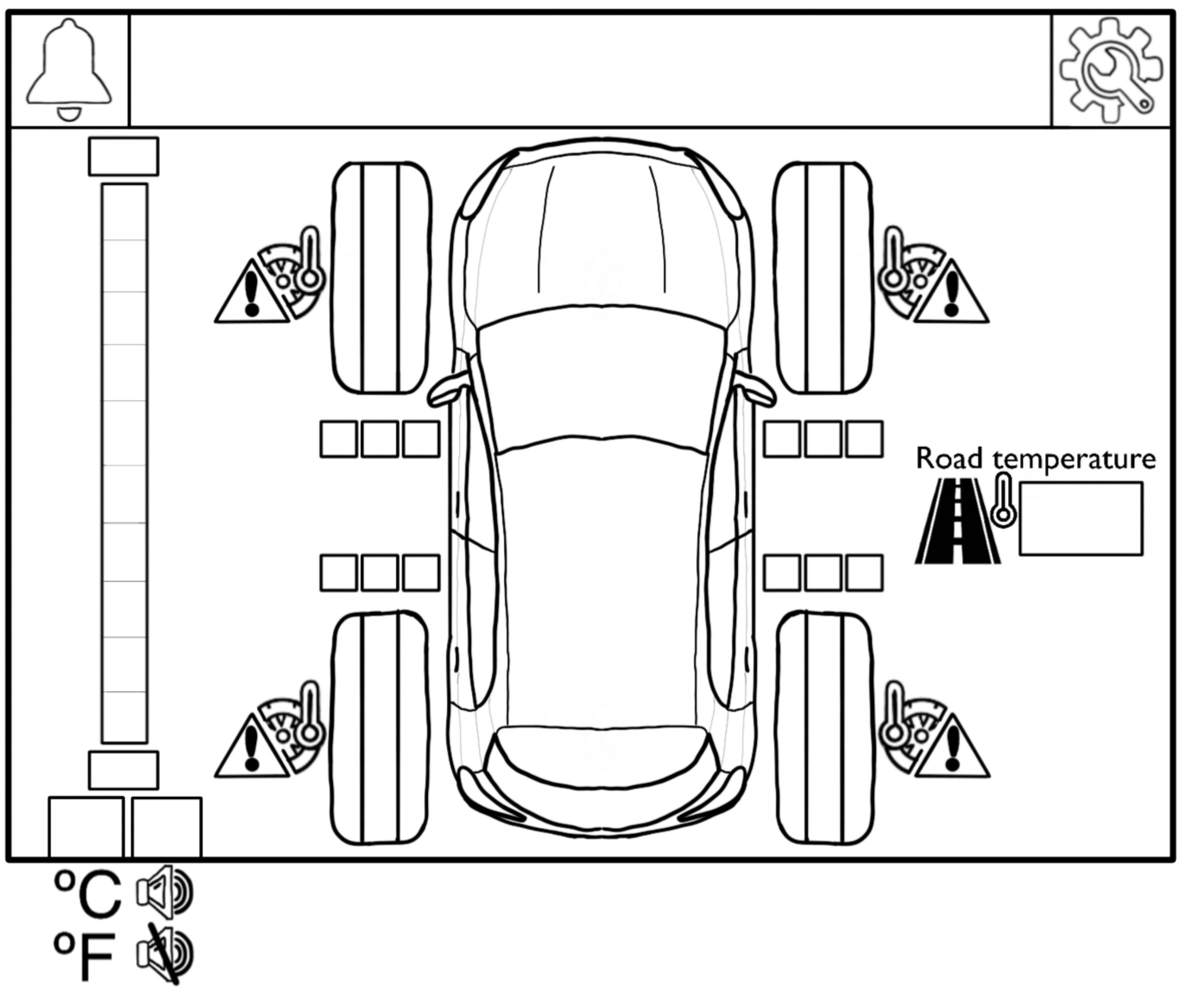


Figure 6-9: HMI - Monitoring window with the principal indicators

6.5.2 Messages window

In the Figure 6-10 the message window is deployed in the information display section, if the system detects an abnormality in any tire and the user is in another window (monitoring or settings), an exclamation mark will appear in the bell icon of the message window and just when the driver deploy this window to check for the message, the exclamation mark in the icon will disappear and the messages will be deployed in the display section of the HMI; for each abnormality detected in the tires an individual message page is deployed and the arrows on both sides of the display works to navigate through the pages of the messages, the message comprises of three main parts, the upper part point the tire where the abnormality is detected and the number of message been viewed, the message section itself describe the "symptom" of the problem and the cause and/or solution, to return to the monitoring window the driver should press the same button in the upper-left-corner that is showing the monitoring window icon.

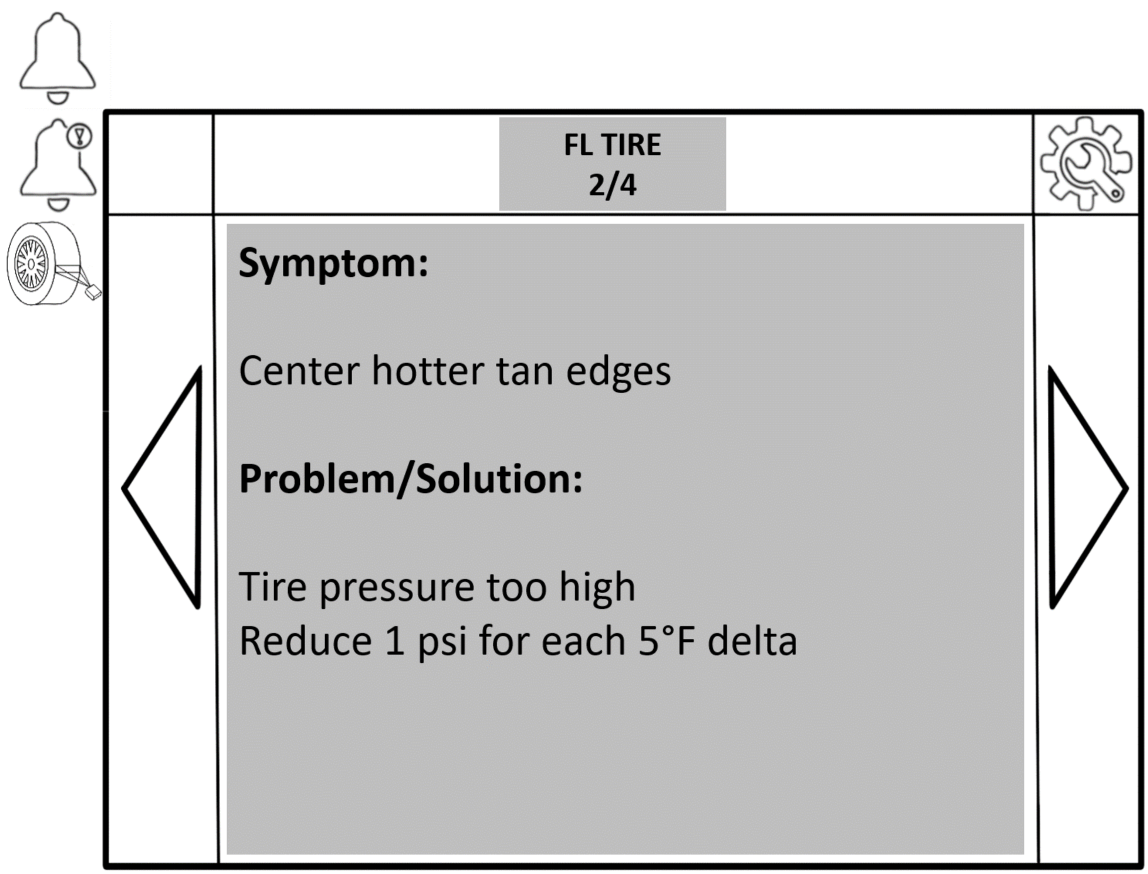


Figure 6-10: HMI - Messages window with an example of on-board message

6.5.3 Settings window

Figure 6-11 shows the HMI when the Settings window is deployed in the display section, here you can configure the temperature units in °C or °F, the sound alarm to been activated or deactivated, in the visualization topic the driver can configure the temperature-color scale to be shown or hide, the temperature numerical-indicators are configurable as well, they can be shown or hide, the temperature high-limit is set with an slider and it has a numerical indicator, the option to reset the HMI configurations to fabric defaults is presented as well with the button “Reset defaults", to return to the monitoring window the driver should press the same button in the upper-right-corner that is showing the monitoring window icon.

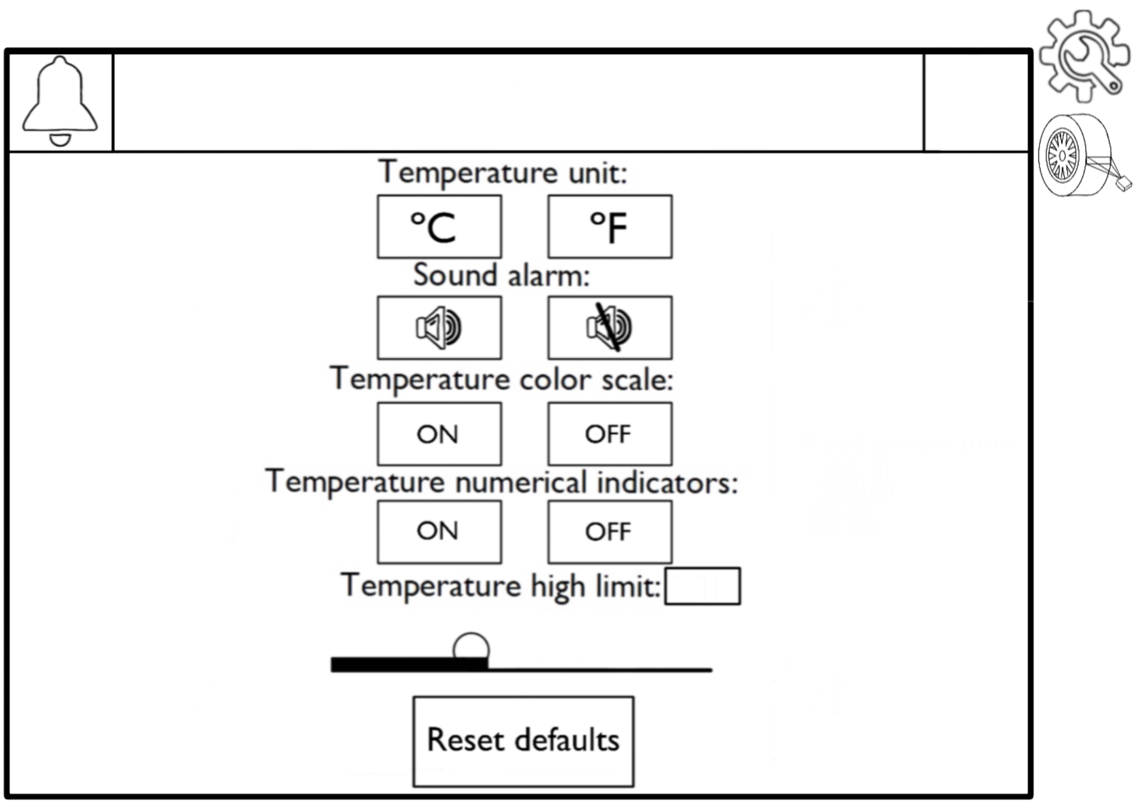


Figure 6-11: HMI - Settings window with the configurable aspects of the system

6.5.4 Colormap selection

The colormap to represent the distribution of the heat on the tires have been chosen to be the Ironbow color palette, running from black through blue, magenta, orange, yellow to bright white; this colormap (shown in Figure 6-12), have some advantages over the well-known and commonly-used rainbow palette, shown in Figure 6-13 and that was the reason to decide to use this color palette. The rainbow color palette confuses viewers because there is no natural perceptual ordering of the spectral colors, In addition to causing visual confusion, this lack of natural ordering can slow down tasks because viewers have to refer to the color key more often in order to interpret the visualization [Edd14]. If viewer have to refer more often to the color key they get more distracted and that can create a hazard situation, with the Ironbow palette this drawback is not present and is easier to understand the behavior of the colormapping without losing time seeing the color key.

Figure 6-12: Ironbow color palette

Figure 6-13: Rainbow color palette

6.5.5 Design of the Human-Machine Interface (HMI)

The HMI is composed by three main windows, the monitoring window, the messages window and the settings window, their function in the system is self-explanatory with their name.

The design and functionality have been discussed before, on the **??**, but in this section the HMI have been developed in LabVIEW program to get ready for the use for experimentation and testing in laboratory before the development for automotive embedded system.

The front panel design of the LabVIEW program is the HMI the driver will see in the infotainment console inside the car, the Figure 6-14 is the monitoring window where the driver can see graphically the distribution of the heat along the width of the tire tread.

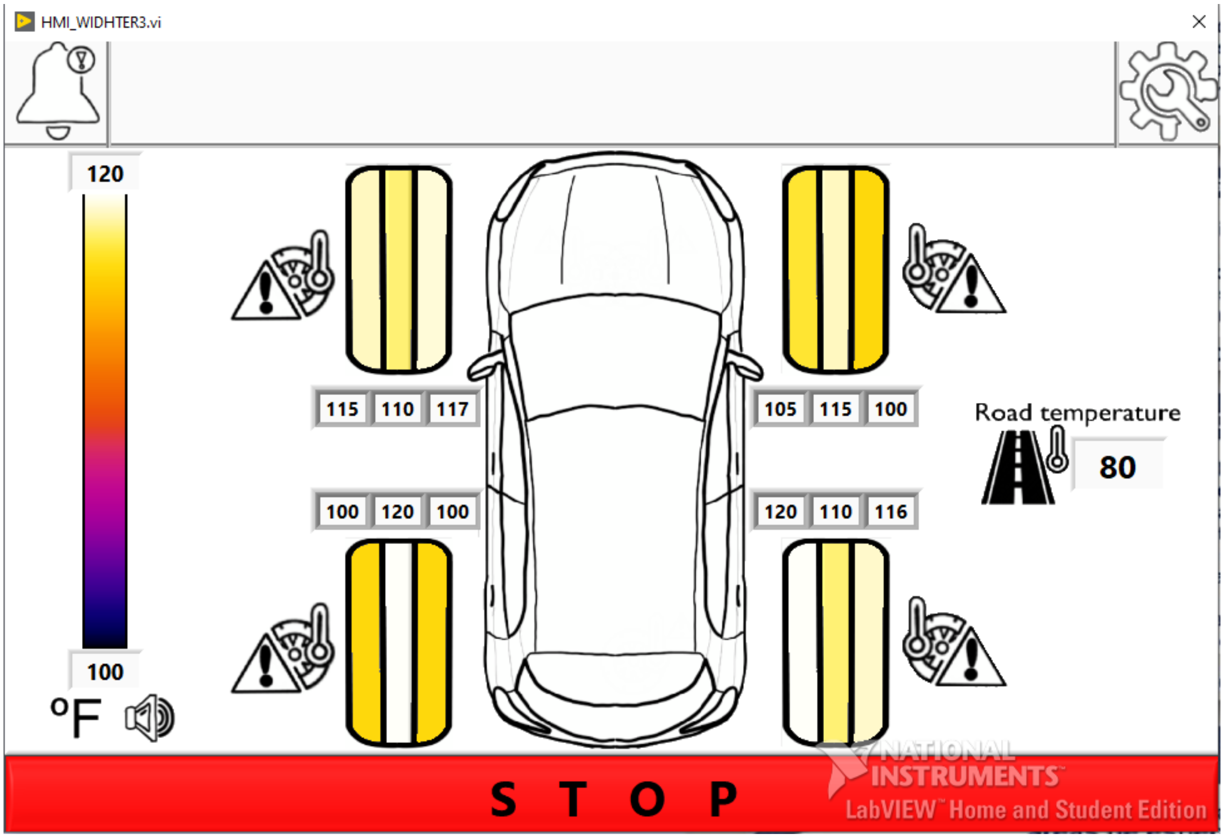
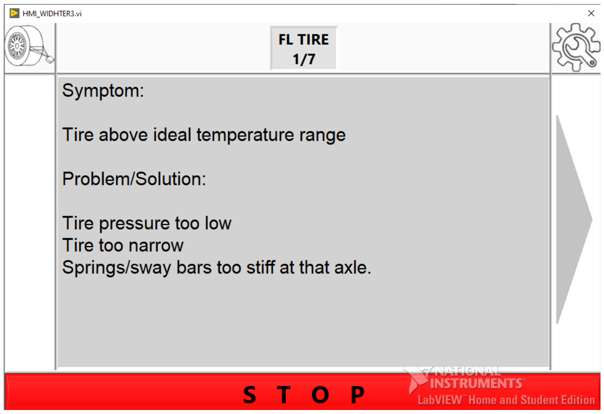
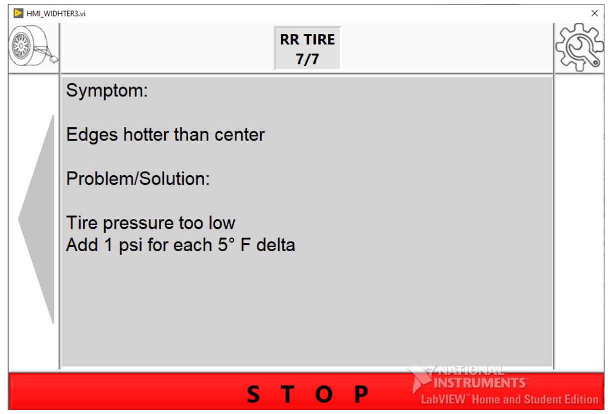


Figure 6-14: LabVIEW front panel developed program on the monitoring window

On Figure 6-15 the message window is seen, the driver can see the messages for each abnormality in the tires detected by the system, separated in pages for each symptom detected and the problem/solution statement to determine whether the driver should stop or could continue, the Figure 6-15a is the way the HMI looks on the first of several pages and the Figure 6-15b on the last of these pages.



(a) LabVIEW front panel developed program on messages window on the first page



(b) LabVIEW front panel developed program on messages window on the last page

Figure 6-15: Tire applications of IR technologies

The HMI for the driver when the menu “settings" is deployed looks like the Figure 6-16, here the driver can configure the way the monitoring window will look like and how the temperature measurement will be processed.

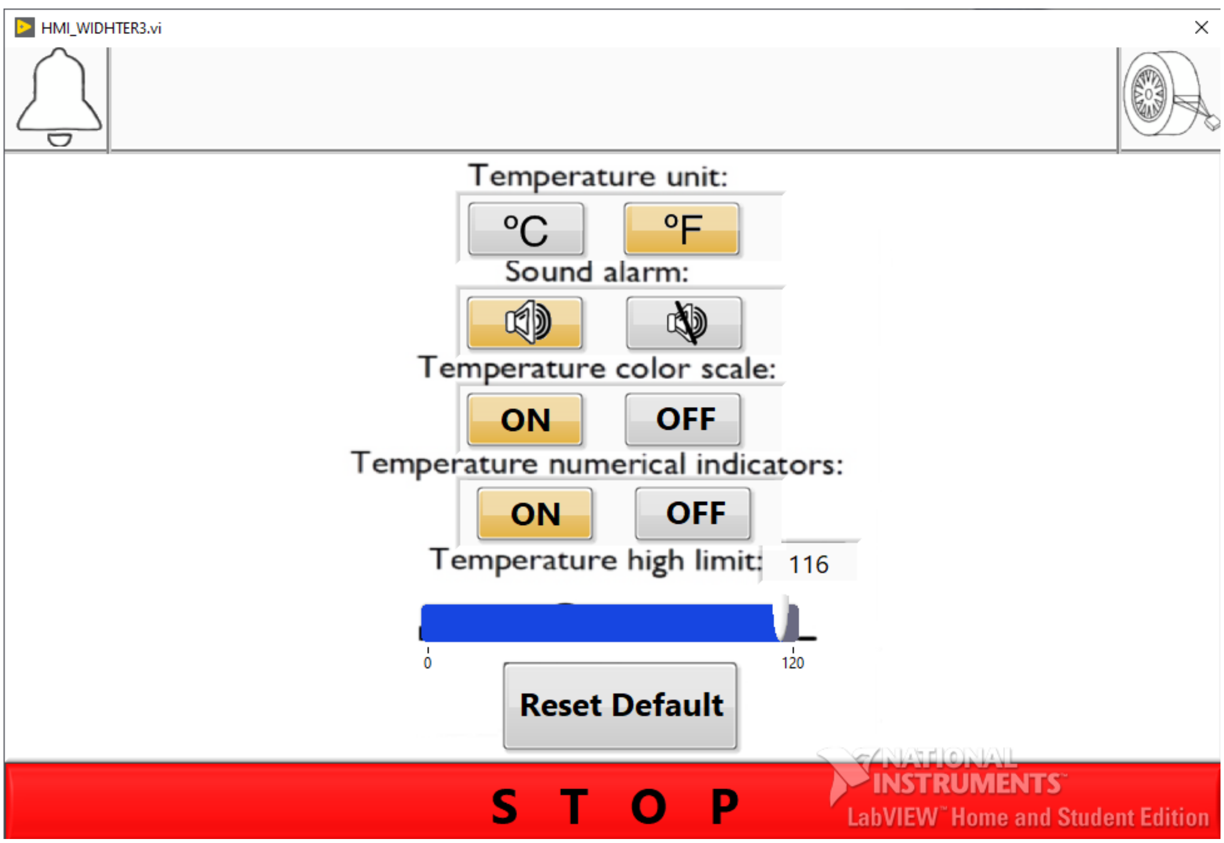


Figure 6-16: Ironbow color palette

7 Trade-Off-Analysis for critical components

In this chapter the system architecture is reviewed and a general preliminary design for each of the subsystems is described, proposing commercial products to meet the requirements for each subsystem. As mentioned previously, the system can be cataloged in three main components:

- the Monitoring subsystem,
- the Electronic Control Unit and,
- the Human-Machine Interface

As mentioned in the chapter 1, one of the principal aims of this thesis work is to develop the HMI design because this is the major contribution to the art comparing to the other subsystems. This has been done in the section 6.5 and for the trade-off analysis the technologies evolving this element is not disclosed on this section.

For the other elements, nowadays in the market one can find some tire tread temperature measuring devices for the monitoring subsystem and one can find a plurality of automotive-application control units, and in this chapter a review for the most suitable hardware for each element is gonna be realized.

The monitoring subsystem is conformed by: the Front-Left tire IR array thermal sensor, the Front-Right tire IR array thermal sensor, the Rear-Left tire IR array thermal sensor, the Rear-Right tire IR array thermal sensor and the roadway IR thermal sensor.

7.1 Monitoring subsystem

The purpose of this subsystem is to measure the temperature distributed in the width of the tire tread in real-time using contactless technology, fulfilling the functional and non-functional requirements for this subsystem, defined in the section 4.2. The subsystem consist in four IR array thermal sensors to measure the temperature of each tire and an IR thermal sensor to measure the temperature of the roadway, all of them fixed to the under-tray of the car.

7.1.1 Infrared array thermal sensor

The aim of the proposed system is to measure the temperature distribution on the complete width of the tire tread, creating the necessity to select a sensor that has an array of temperature measurements in different points along the width of the tire tread, and since the measurement should be done while the vehicle is driving, the sensor should be mounted apart from the tire and measure the temperature contactless, to meet these characteristics, and the high-level requirements defined, the reviewing of the most suitable IR array thermal sensor found on the market have been enclosed to the linear thermophile array sensors and a maximum of 32-elements, because more than these elements will be over-readings for this application.

The first general overview on the market considers some commercial general-purpose sensors, not aimed for automotive systems specific application, and they are listed below:

- Thermometrics - ZTP-188ML
- Excelitas - TPiL 8T 2246 L3.9
- Excelitas - TPiL 16T 3446 L3.9
- Excelitas - TPiL 16T 3546 L3.9
- Excelitas - TPL 32C 3343 L4.7

The Table 7-1 compares the principal parameters for the fulfillment of the system necessities. The parameters are: **Enclosure, Number of elements, Sensing temperature range, Operating temperature, Accuracy, Field Of View (FOV) (X*Y), Signal refresh time & Communication bus**

Table 7-1: Main general-purpose IR linear array thermal sensors reviewed

Parameter	ZTP-188ML	TPiL 8T 2246 L3.9	TPiL 16T 3446 L3.9	TPiL 16T 3546 L3.9	TPL 32C 3343 L4.7	TPL 32C 3774 L4.7	Unit
Enclosure	None	None	None	None	None	None	-
Number of elements	1 x 8	1 x 8	1 x 16	1 x 16	1 x 32	1 x 32	-
Sensing temp. range	-20~100	0~60	0~60(A60) 0~120 (A120)	0~60	0~60	0~60	°C
Operating temp.	-20~100	-25~100	-25~100	-25~100	-25~100	-25~100	°C
Object Temp. Accuracy	Not specified	+/- 1.5	+/- 1.5	+/- 1.5	+/- 1.5	+/- 1.5	°C
Field Of View (X x Y)	52 x 8	50 x 8	71 x 8	70 x 8	59 x 6	59 x 6	Degree
Signal refresh time	Not specified	250	400	400	380	100	ms
Output signal	UART [1]	SMBus [2]	SMBus	SMBus	SMBus	SMBus	-

[1] Universal Asynchronous Reception and Transmission (UART).
[2] System Management Bus (SMBus).

Based on the sensors parameters exposed in the Table 7-1, the more suitable option is the TPiL 16T 3446 L3.9 A120 sensor, because its sensing temperature range reach the 120°C as maximum, but it falters on the signal refresh time with 400 ms, in this area, the fastest sensor is the TPL 32C 3774 L4.7 (the improved version of the other TPL 32C) with 100 ms, but its maximum sensing temperature is just 60°C. As it was expected each of these sensors have their pros. and Cons., but the common parameters that drawback the selection of any of these sensors are the lack of enclosure and the output signal, the latter not oriented for automotive systems communication in the art, because all of the sensors are based on serial communication.

The exposed parameters values from the first overview of commercial general-purpose sensors did not fully convinced about the use for the system to develop, the mechanical and communication requirements are not considered with any of these reviewed sensors, then, a second research was realized, oriented for tire temperature monitoring systems already on the market, as the one reviewed on subsection 3.3.3. These systems are listed below:

- IZZE Racing - IRTS-V2
- RACELOGIC - RLACS272
- texense - IRN8C/IRN4C
- Avio Race - IR 200-64

The Table 7-2 compares the parameters previously reviewed for the general-purpose use sensors, now considering the listed systems, focused for automotive systems.

This table exposes the pros and cons for the reviewed sensors, in this case the sensors have ISO certified enclosures that meet the mechanical requirement previously pointed, and the IRTS-V2 by IZZE Racing and the RLACS272 by Racelogic sensors has the maximum IP rating reaching the IP66 certification; the communication protocol of all of them is the CAN bus, but the IRTS-V2 and the RLACS272 specified the bus as CAN 2.0A, certified by the ISO-11898; other aspect to highlight is the sensing temp. range where these two sensors reach a maximum value of 300°C, and the IRTS-V2 is the most versatile with 4, 8 or 16 elements configuration and 60° or 120° for the FOV.

The conclusion for the research on the market for the infrared array thermal sensors is that the IRTS-V2 by IZZE Racing suits better for the proposed system and it is the proposed sensor to be implemented in the monitoring subsystem.

Table 7-2: Main automotive system IR linear array thermal sensors reviewed

Parameter	IRTS-V2	RLACS272	IRN8C/IRN4C	IR 200-64	Unit
Enclosure	Aluminum, IP66 rated	Aluminum, IP66 rated	Aluminum	Aluminum HE 30, IP64 rated	-
Number of elements	1 x 4, 1 x 8, 1 x 16	1 x 16	1 x 8 1 x 4	4 x 16	-
Sensing temp. range	-20~300	-20~300	-20~140 -20~200	200 MAX	°C
Operating temp.	-20~85	-20~85	-20~100	-20~85	°C
Object Temp. Accuracy	+/- 1.5	+/- 1.5	+/- 1.4 +/- 2.0	+/- 1% Full Scale	°C
Field Of View (X x Y)	60 x 8 120 x 15	60 x 8 120 x 15	6.5:1	40 x 10 60 x 15 120 x 30	Degree
Signal refresh time	Not specified	250	260	400	ms
Output signal	CAN [1] 2.0A, ISO-11898	CAN 2.0A, ISO-11898	CAN Bus	CAN Bus	-

[1]Controller Area Network (CAN).

7.1.2 Infrared thermal sensor

The infrared thermal sensor is aimed to measure the temperature of the roadway while the vehicle is driving, the sensor should measure the temperature contactless and in a single point; the same requirements as the IR array thermal sensors should be fulfilled. The experience obtained from the overview of general-purpose IR array thermal sensors done in the subsection 7.1.1, and a quick research of this kind of sensors for this application expose it is pointless to do an overview of a general-purpose IR thermal sensors, because the communication protocol and the lack of proper enclosure for the application are present in these sensors, so just automotive-systems focused sensors are reviewed and these are listed below:

- IZZE Racing - IRTS-SP-V2
- texense - INFV/INFT
- texense - IRN3/IRN3-R
- Avio Race - IR 200

The Table 7-3 exposes the parameters previously identified as critical to fulfill the proposed system necessities, comparing the four sensors found on the market.

This table exposes the pros and cons for the reviewed sensors, in this case the sensors have ISO certified enclosures that meet the mechanical requirement previously pointed, and the IRTS-SP by IZZE Racing has the maximum IP rating reaching the IP66 certification; for the reviewed sensors, three out of four sensors have output signal as a linearized voltage analog signal because of the simplicity of the measurement, temperature in just one point, and the IRTS-SP sensor use the bus CAN 2.0A, certified by the ISO-11898; another aspect to highlight is that the IRN3/IRN3-R are the unique sensors of the list that are completely aimed and specially designed to measure the track temperature and the others sensors are IR thermal sensors for automotive systems but aimed for different uses as tire temperature monitoring or brake disks temperature monitoring, and the track sensors developers state that “ they have been extensively developed to accurately match track surface emissivity and has class leading accuracy".

The conclusion for the research on the market for the infrared thermal sensors is that the IRN3/IRN3-R by texense suits better for the proposed system and it is the proposed sensor to be implemented in the monitoring subsystem.

Table 7-3: Main automotive system IR thermal sensors reviewed

Parameter	IRTS-SP-V2	INFV/INFT	IRN3/IRN3-R	IR 200	Unit
Enclosure	Aluminum, IP66 rated	Aluminum	Aluminum, IP65 rated	Aluminum HE 30, IP64 rated	-
Sensing temp. range	-70~380	0~150 0~200	-40~100	150 MAX 200 MAX	°C
Operating temp.	-40~85	-20~100	-40~125	130 MAX	°C
Object Temp. Accuracy	+/- 1.0	+/- 3 +/- 4	+/- 1.5 +/- 2	+/- 0.75 +/- 1.0	°C
Field Of View	35	4:1	20	15	Degree
Signal refresh time	Not specified	50	50	260	ms
Output signal	CAN [1] 2.0A, ISO-11898	Analog signal, 50mV/°C	Analog signal, 0.9v + 21mV/°C (0-3V output) 1.5v + 35mV/°C (0-5V output)	Analog signal	-

[1]Controller Area Network (CAN).

7.2 Electronic Control Unit

The ECU is aimed to acquire the data from the monitoring subsystem, transmitted through the CAN-protocol for the IR array thermal sensors and an analog voltage signal for the IR thermal sensor, and process it to display in real-time in the on-board subsystem, the control unit then should handle CAN communication protocol, and for that it should be aimed to been used in an automotive system.

The system proposed is intended to be an automotive safety system and that converts the implementation of the functional safety standard (ISO-26262), previously reviewed on the chapter 5, in a “must to do". For reaching the requirements specified in the standard, then, the control unit should be certified under this standard, for that reason, the ECUs reviewed on the market consider only Microcontrollers (MCUs) certified on the ISO 26262 and work with CAN 2.0, communication protocol used by the IR linear thermal array sensor.

For the selection of the Microcontroller (MCU) Texas instruments have a line of products completely focused in the development of functional safety systems, the “Hercules", it is decided to focus on this line of MCUs because the workgroup where this thesis work is been developed already have some experience working with them, the documentation from the company is clear and vast, and they fully meet the characteristics that our ecu must have. In specific all their controller on this category are based on the IEC 61508, previously mentioned on the chapter 5, and over that, there are two MCUs of this line based on the ISO 26262 as well, then, the focus on the selection of the MCU will be on these two development kits listed below.

- Texas Instruments - Hercules TMDS570LS12HDK (based on the TMS570LS1227 MCU)
- Texas Instruments - Hercules TMS570LS31HDK (based on the TMS570LS3137 MCU)

The development kits of these MCUs are reviewed instead of the MCUs themselves because for the concept stage of the system development the design of the electronic to use with the MCUs is not a priority. Below the comparative table with both MCU principal characteristics is presented.

Table 7-4: Main Texas Instruments Functional safety MCUs reviewed

Parameter	**TMS570LS1227**	**TMS570LS3137**	**Unit**
CPU	Arm-Cortex-R4F	Arm-Cortex-R4F	-
Operating temp. range	-40~125	-40~125	°C
Frequency	160, 180	160, 180	MHz
Flash	1280	3072	KB
RAM	192	256	KB
Data flash	64	64	KB
PWM	Yes	No	

Observed in the table, the two differences are the Flash and the RAM and in both cases the TMS570LS3137 have more, but for the application to been develop these characteristics would not contribute much so the most suitable MCU is the TI-TMS570LS1227.

The trade-off analysis realized on the chapter clarifies the tendency on the market nowadays about components similar to the system proposed, and the importance of the automotive functional safety norm (ISO 26262) in the implementation of controllers or even sensor or actuators, the tendency to regulates the electronics of the automotive to achieve a more reliable and safer system for the automobiles is evident and just highlight the importance of have taken into account the implementation of the guidelines of the norm since the conceptualization of the proposed system.

Based on this the selection of the most suitable critical components were concluded as:

- Infrared Array Thermal sensor IRTS-V2 by IZZE Racing
- Infrared Thermal sensor IRN3/IRN3-R by texense
- Electronic Control Unit (ECU) TI-TMS570LS1227 by Texas Instruments

The next chapter contains the conclusions and further work identified for the development of the proposed system.

8 Conclusion and further work

The presented work consisted in the definition and conceptualization of a vehicular system for temperature monitoring and advice system, the creation of a preliminary design of a HMI to publish the messages from the monitoring subsystem and the trade-off of critical elements. In this regard, it is concluded that the model proposed can be developed following the functional safety norm (ISO 26262) guidelines and the feasibility and usability of a system of this kind is high.

As further work, the continuation of the next stages of the methodology established in section 1.7 is intended, following the steps of the V-model and going from the preliminary and detailed design of the system to the implementation of a functional alpha prototype that allows to test and prove concrete achievements are intended. The use of the functional safety norm (ISO 26262) as a guide for the design will be continue, the parts 4-6 of the norm are intended to been reached and take into account to finish the design and fabrication of the proposed safety system.

As well some improvements and adjustments identified during the development of the final part of the thesis work to the initially proposed system is planned to be done, the mechanical of the monitoring subsystem and the temperature acquisition and procesing of the controller.

For further work, as well, the list of identifiable symptoms of the tires abnormally behavior are planned to been improved and increased, through the methodology of a Design of Experiments (DOE) to monitor the tire tread temperature of tires under different conditions, generating real time life events. The identified standards for automotive ergonomically HMI design need to be fulfill as well.

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Acronyms

ABS Anti-lock Braking System

ASILs Automotive Safety Integrity Levels

CAN Controller Area Network

CIDESI Center for Engineering and Industrial Development

CMVSA Canadian Motor Vehicle Safety Act

CMVSR Canadian Motor Vehicle Safety Regulations

CMVSS Canadian Motor Vehicle Safety Standards

ConOps Concepts of Operations

DOE Design of Experiments

E/E/PE Electrical, Electronic and Programmable Electronic

ECE Economic Commission for Europe

ECU Electronic Control Unit

ESC Electronic Stability Control system

FFT Fast Fourier Transform

FMVSS Federal Motor Vehicle Safety Standards

FOV Field Of View

HLR High Level Requirements

HMI Human-Machine Interface

IEC International Electrotechnical Commission

IMT Instituto Mexicano del Transporte

IR infrared

ISO International Organization for Standardization

LED Light Emitting Diode

MCU Microcontroller

MCUs Microcontrollers

NCHS National Center for Health Statistics

NHTSA National Highway Traffic Safety Administration

NMVCCS National Motor Vehicle Crash Causation Survey

OEMs Original Equipment Manufacturers

SMBus System Management Bus

TASS Tires Automatic real-time Safety System

TICS Transport Information and Control Systems

TPMS Tire Pressure Monitoring System

TTPMS Tire Temperature & Pressure Monitoring System

UART Universal Asynchronous Reception and Transmission

UN United Nations

WHO World Health Organization

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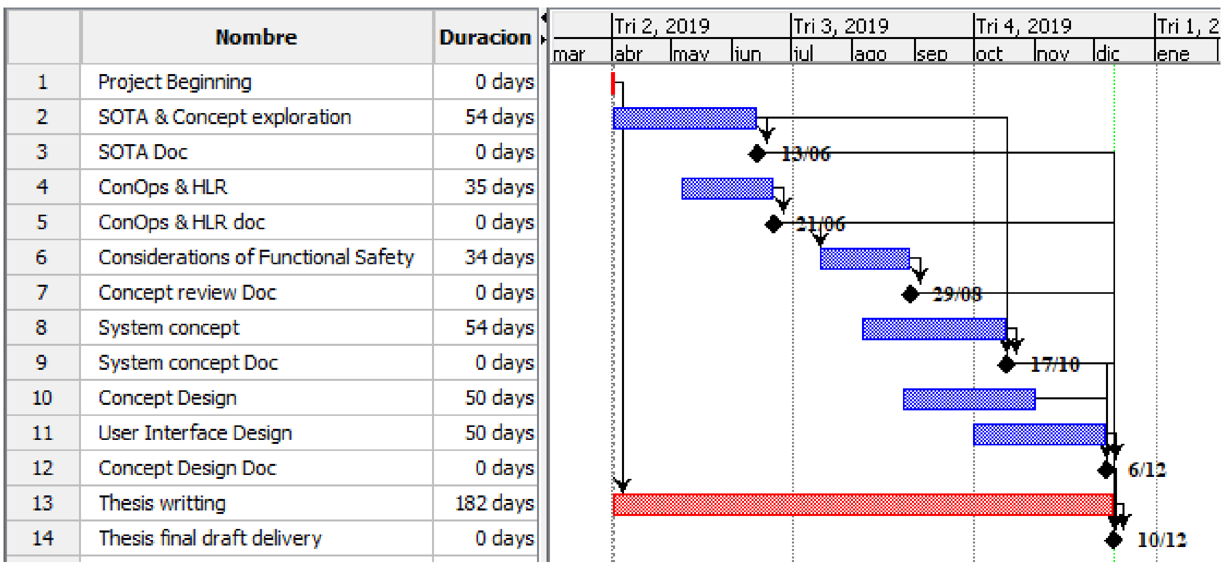
A Chronogram of activities

The Figure A-1 contain the activities realized during the period of development of the thesis, these activities are the same as the objectives defined at the beginning.



	Nombre	Duracion
1	Project Beginning	0 days
2	SOTA & Concept exploration	54 days
3	SOTA Doc	0 days
4	ConOps & HLR	35 days
5	ConOps & HLR doc	0 days
6	Considerations of Functional Safety	34 days
7	Concept review Doc	0 days
8	System concept	54 days
9	System concept Doc	0 days
10	Concept Design	50 days
11	User Interface Design	50 days
12	Concept Design Doc	0 days
13	Thesis writting	182 days
14	Thesis final draft delivery	0 days

Figure A-1: Gantt diagram for the activities done