MASTER

CarESP

an emotion vehicle with stress, personality and embodiment of emotions

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CarESP: an emotion vehicle with stress, personality and embodiment of emotions

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Graduation project

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Abstract

Affective computing studies the functionality of emotions and aims to translate those functionalities to computers. An affective computing systems has four components: recognising, expressing and generating emotions, and emotional intelligence. According to Picard [1], these components allow the computer to genuinely become intelligent and interact with humans. Autonomous driving can benefit from affective computing to design a more intelligent vehicle and have better interactions with the drivers. Furthermore, emotions incorporated to an autonomous system have advantages such as optimisation in resources, communication and decision making [2]. Picard also defined the components for an emotion model generator system [1]. An emotion model should be able to compute primary emotions, emerging when harmful events happen and trigger specific actions for protection. Also, it should be able to compute cognitive emotions, such as the emotions computed in the OCC model. Finally, an emotion model should be able to have emotional experience, in order to learn from emotions.

The work of Chouhan [3] built an emotion vehicle (CarE). This system is able to compute emotions based on events and goals. Chouhan's project implemented the cognitive emotion component. The current project extends the work of [3] by incorporating three components. First, a stress factor which allows the vehicle to compute the probability of an accident considering external and internal states of the vehicle. The stress factor has the functionality of a primary emotion. The stress factor consists of four components: vehicle's health, competency, operational states and environmental conditions. Second, the generation of personality of the vehicle based on the driver style of the user. The personality can increase the acceptance of the technology by increasing driving comfort without compromising in safety. Third, a mapping of emotions framework on the vehicle body. This component is modelled from the way humans feel emotions on their body, which can then aid in the communication and decision making. The emotion mapping component is built as a framework for Picard's emotion experience component.

This project designed a system using the SYSMOD, a Model Driven System Engineering Methodology [4]. Also, this project implemented the stress factor, personality module and body emotion mapping. It is called CarESP (Emotions car with stress and personality). Five scenarios were tested to observe and analyse the behaviour of the system, in a 3D virtual environment, using the Unity Game engine software. The results showed that the stress factor can be personalised to different types of driver styles. Also, they showed that the stress factor can produce a broader set of emotions depending on the state of the vehicle. The stress factor can be used as a decision variable to differentiate between events and actions, which are key components for the CarE model [3]. Also, the stress factor can be used to compute the probability of a goal to fail. The results also showed that the constant relative risk averse model used to generate the personality module does not work in combination with the stress factor. Thus, the personality model need to be further investigated. Finally, the construction of the body emotion's mapping framework showed promising results. The emotion mapping framework is able to send signals to specific vehicle systems as a function of the emotions. Moreover, the emotion mapping is able to combine emotions intensities in different system. For example, if the system predicts that the probability of an accident is high and the event computes an emotion of fear, a strong signal can be sent to the active safety systems, so the vehicle can protect the driver in case of an imminent accident.

Keywords: *MDSE, SYSMOD, affective computing, IBM Rhapsody, CarE, stress, driving style, emotions mapping*

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Glossary

ADAS	Advanced Driver Assistance Systems
BDD	Block Definition Diagram
CarE	Emotion Car
CarESP	Emotion car with stress and personality
CIM	Computer Independent Model
CRRA	Constant Relative Risk Averse
DoS	Desirability to not fail
DoS	Desirability of success
DS	Driving Style
ECU	Electronic Control Unit
HF	Health Factor
IoT	Internet of Things
LiDAR	Light Detection And Ranging
LoF	Likelihood of failure
LoS	Likelihood of success
MDSE	Model Driven Software Engineering
MDSI	Multidimensional Driving Style Inventory
OCC	Ortony, Clore and Collins model
PIM	Platform Independent Model
PSM	Platform Specific Model
RADAR	Radio Detection And Ranging
SF	Stress Factor
SPU	Signal Processing Unit
SYSMOD	System Modeling
TTC	Time To Collision
UDP	User Datagram Protocol
V2I	Vehicle-to-Infrastructure
V2V	Vehicle-to-Vehicle
VOS	Vehicle's Operation State

Chapter 1

Introduction and problem definition

This chapter shows the motivation of the project in the **Introduction** section. Also, the chapter shows a general overview of the project explaining the **Problem definition** and **Research Questions**. Finally, this chapter shows the structure of the document in the **Report structure** section.

1.1 Introduction

Affective computing is a branch of computer science that deals with emotions. Affective computing studies the function of emotions in humans, and how to translate these functionalities into computers [5].

According to Picard [1], the ability to recognise, understand, have and express emotions are needed to transform a computer to be genuinely intelligent and interact in a natural way with humans. An affective computing system has four components [1]. The first and second components are recognising and expressing emotions. In automotive, emotion recognition and expression components are being used in advance driver assistance systems (ADAS) to increase the safety and comfort of the driver [6]. The third component is computing emotions, an example of this component is the Ortony, Clore and Collins (OCC) model based on cognitive elicitors. The OCC model has been used for automotive applications, an example of this application is shown in Kraus et al. [7]. The last component is emotional intelligence, this component defines how a machine would understand and interact with emotions. Mattingly et at. [8] stated that emotional intelligence is the regulation and coping of emotions. The emotional intelligence concept is extended in Miners et al. [9] stating that emotional intelligence is the "ability to reason accurately about emotions, and to use emotions and emotional knowledge to enhance thought".

For the third component, emotion computation, Picard [1] stated that an emotion computation model should consist of four components. The first is *emergent emotions*, which exists in systems that do not have an implicit internal mechanism to compute or express emotions. Thus, they can be spotted by observing the behaviour of systems. An example is the sad face in a Windows OS computer after crashing, this is an apparent negative emotions presented by the system but the machine does not implicitly generate any emotion. The second component is *primary emotions*, these emotions are hardwired in humans or animals. Primary emotions can be seen in harmful events. They can even be generated without awareness of the subject. The third component is *cognitive emotions*, these types of emotions are generated using cognitive reasoning. The fourth component is *emotional experience*, this component required the labelling of the emotions by the subject and the understanding on how an emotion affects the system. The *emotional experience* component can be said that generates system's awareness [1]. The component *emotional experience* has a physiological respond, such as heart rate, breathing or even body sensations. The final component is *body-mind interactions*, where the emotions influence in decision making, learning and perception, among other functionalities.

Evidence in humans correlates emotions with the process of decision making and perception [5]. In fact, emotions are fundamental for humans so they can override our rationality in situations with high intensity emotions such as fear.

Besides affecting the process of decision making, emotions also affect learning and memory processes in human beings. Affective computing researchers believe that using cloud computing for emotion generation can provide with better decision making and improve learning and memory processes in computer systems [5].

In biological systems emotions achieve a multilevel communication. According to Fellous [2], the communication is accomplished by simplifying and having a high impact information. Then, biological systems can moderate their behaviour, being this a primary emotion's role. The moderation of behaviour implies that emotions achieved an optimisation on data transfer. This optimisation is carried out by using as less resources as possible, thus simplified the data transfer. Also, emotions facilitate the understanding and interpretation on the data, which later translates in behaviour moderation.

The implementation of affective computing in vehicles has concentrated in driver emotion's detection. The detection of driver's emotions has shown to be crucial for safety and comfort [6]. The emotion's detection systems are used in advance driver assistance systems (ADAS) to improve driving experience and driver's behaviour [6]. As it was mention previously, this functionality is only one of the four components of affective computing.

Furthermore, According to Kraus et al. [7], two challenges in the autonomous driving system development are the acceptance of the technology and the transparency of the vehicles decisions. Both challenges are claimed to be solved by implementing a emotions based system in an autonomous vehicle.

The current graduation project uses Chouhan [3] cognitive emotion model based on the Ortony, Clore and Collins (OCC) [10] model. Following Picard's model, Chouhan project implemented *emergent emotions* and *cognitive emotions* components. The current graduation project extends on Chouhan's model by implementing *primary emotions*, extending the *cognitive emotion* model and designing a framework for an *emotional experience* component. In addition, I generated vehicle's personalities by personalising the emotion's generation as a function of driver's style.

Particularly, I designed the *primary emotion* as an indicator called **stress factor**, which computes the probability of an accident. The **stress factor** concept is based on the stress a human being experiences. Each person experience different levels of stress depending on experience and personality. Thus, I modelled different levels of stress as a function of the personality and generate different **vehicle's personalities**, based on driver's operation styles. Finally, I designed a **body emotion mapping** which is based on the emotion mapping human beings. The **body emotions mapping** is designed as the framework for a multilevel communication system to all the vehicle's systems.

1.2 Problem definition

This graduation project describes the implementation of a *primary emotion* known as **stress factor**. Also, it describes the **vehicle's personality** design using the personalisation of the emotions generation. Finally, it describes the implementation of the **body emotion mapping** framework. The objective of the system is to set the basis to achieve two advantages of emotion generation: a) generate a vehicle's emotion personalised to a driver's operation and b) multilevel communication to the vehicle control system. The rapidly increasing demand on software in the automobile industry [11] could benefit from a multilevel communication approach.

Therefore, this graduation project extended the design of Chouhan's emotion model [3]. First, the design of a stress module which computes an probability of accident indicator, known as **stress factor**. Also the **stress factor** is personalised to the driver. Second, the generation of a vehicle personality module, which computes a personalised experience of a driving parameter as a function of the user's driving style. Third, a body mapping module, which is the framework for data communication between vehicle systems as a function of the emotions and its intensity. The design of the system follows the SYSMOD, a Model Driven Software Engineering's MDSE methodology.

Finally, the testing of the emotion framework is performed in scenarios that are commonly used for traffic simulation. All the testing is performed in a 3D environment built on the software Unity Game Engine.

1.3 Research Questions

The research questions then are as follow:

1. How to design a primary emotion component for a emotion vehicle model?
2. How to design a vehicle's personality based on the emotion generation for an autonomous vehicle application?
3. How to design a framework for a data communication in the vehicle based on emotion computation?

1.4 Report structure

The report has five chapters, and it is organised as follows:

Chapter 1. Introduction - introduces the project's motivation. Also, it defines the project's problem definition and research questions.

Chapter 2. Project's Background - contains all the information related to the basis of the project, such as previous research and fundamental concepts used in this graduation project.

Chapter 3. System design - contains the construction of the system using the SYSMOD approach. This sections contains the design of all the modules of the system.

Chapter4. Test Design and Results - describes the design of the test to study the system. It also contains the results obtained on the tests.

Chapter 5. Discussion, Conclusion and Future work - describes the findings of the graduation projects. It also describes future work and conclusions.

1.5 Summary

This graduation project extends a emotions cognitive model [3] by designing three new components. First a *primary emotion* as a function of the accident probability, known as **stress factor**. Second, the **vehicle's personality**, which is a function of the driver's style. And third, a framework for the vehicle's **emotion experience** as a emotion body mapping. The components aim to generate the advantages an emotion generation model gives: a) personalised driving experience and b) multilevel communication of emotions between vehicle's systems.

The report provides a detailed report on the system's features, models and implementation. Also, it contains the design process, test and test results obtained of the system. Finally, the report describes potential applications and improvements for future work.

Chapter 2

Project's Background

This chapter describes the fundamental knowledge for this project. The first section, describes the **CarE model** design by Chouhan [3], which is the emotion generation model basis for the current graduation project. The second section describes the fundamentals of **primary emotion and stress** in humans, and how these concepts can be extended to a vehicle's emotion system. The third section contains the driving style literature review which are the fundamentals of the **vehicle's personality**. Finally, the section emotion body mapping describes the functionalities of each basic emotion and a literature review on human's embodiment of basic emotions.

2.1 CarE model

The CarE model [3] is a vehicle's system which computes emotions. The emotions are computed by using a cognitive appraisal model for emotions called Em [12], which is based on the OCC model [10]. The Em model can compute 22 emotions, and its inputs are goal's ID, agent's ID, event's ID, and action's ID. These inputs are correlated to a database which contains all the information to compute the emotions.

A goal information is described in table 2.1, which contains the description of each parameter, its type and range. There are two important parameters: a) desirability and b) likelihood. The parameter desirability is split in two. First, the *DoS* (desirability of success) that define the desire of the subject for the goal to be successful. Second is the *DoS* (desirability to not fail), this parameter defines the importance of the goal to not fail. The *DoS* and *DoS* are not complementary, each can have a value within a range of 1 and 100. For example the goal *do not run a yellow light* is a goal that the subject considers important then the *DoS* can be consider to be medium-high, although the subject does not like to wait on a yellow light, thus the *DoS* can be very low. The parameter likelihood is also split in two. The *LoS* (likelihood of success) and *LoF* (livelihood of failure). The two parts of the likelihood are modelled as complementary, then they are defined by the following equation $LoS + LoF = 1$, thus, each can have value within a range of 0 to 1.

In Em model an agent is defined as the subjects that performs actions to cause events [12]. An agent information contained in the database is shown in table 2.2. There is one important parameter known as appealingness. The appealingness of an agent is defined as the level of attractiveness of that agent to the CarE.

In Em model an event is defined as the subject interpretation about an occurrence, which is independent of the subject's believes [12]. An event information contained in the data base is shown in table 2.3. There are two important parameters of an event: a) *dLoS* (change on goal's *LoS*) and b) *dLoF* (change on goal's *LoF*). When an event has occurred the correlated goal's *LoS* changed due to the occurrence of the event, the change is known as

Goal Information	Description	Type (Range)
ID	ID number of the goal	int (1 to ∞)
Name	Textual description of the goal	String
Hierarchy	Hierarchy of the goal	int (1 to ∞)
Agent ID	Correlated Agent ID	int (1 to ∞)
Desirability	Desire of the subject for the goal to be successful or to not fail	int (1 to ∞)
Likelihood	Probability of the goal to succeed or fail	float (0 to 1)

Table 2.1: Goal's information on the database.

Agent Information	Description	Type (Range)
ID	Id number of the agent	int (1 to ∞)
Name	Textual description of the Agent	String
Type	Type of agent: object or agent	int (1 || 0)
Appealingness	Appealingness of the agent	int (-100 to 100)
Goal ID	Correlated Goal ID	int (1 to ∞)

Table 2.2: Agent information on the database.

dLoS. *dLoF* has a similar function regarding the *LoF*.

Event Information	Description	Type (Range)
ID	Id number of the event	int (1 to ∞)
Name	Textual description of the event	String
dLoS	Change in goal's likelihood of success	float (-1 to 1)
dLoF	Change in goal's likelihood of failure	float (-1 to 1)
Goal ID	Correlated Goal ID	int (1 to ∞)

Table 2.3: Event information on the database.

An action is defined as the act that generates the occurrence of an event [12]. An action information contained in the database is shown in table 2.4. An important parameter of an action is the praiseworthiness. The praiseworthiness defines the appraisal of that action related to a subject's standard. The subject's standard can be of moral or performance nature. In the CarE model the standard is of moral nature.

Action Information	Description	Type (Range)
ID	Id number of the action	int (1 to ∞)
Name	Textual description of the action	String
Praiseworthiness	Praiseworthiness of the action	int (-100 to 100)
Correlated Agent	Agent ID correlated to the action	int (1 to ∞)
Responsibility	Responsibility of the correlated agent	float (0 to 1)
Correlated Event	Event ID correlated to the action	int (1 to ∞)

Table 2.4: Action information on the database.

The CarE model also computes a *Health factor* (HF). This indicator computes the overall health of the vehicle. The input for the health factor has five categories of variables. The categories are: drivers health, driver capability, vehicle health, vehicle capability and environmental state. Each category has a series of state variables which define the overall health of the vehicle. The health factor varies within a range between 1 and 5. If the HF has a value below the average ($HF_{mean} = 3$) then negative emotions are amplified. If the HF has a value above the average then positive emotions are amplified.

Depending on the the goal, agent, event and action the CarE computes the intensity of 22 emotions. After the emotion's intensity, these emotions are mapped into 7 basic emotions which are happiness, sadness, anger, disgust, fear, surprise and neutral. Then the emotions are express as emojis.

The implementation of the The CarE model was implemented in a Matlab/Simulink environment. In addition, the testing was implemented using a 3D environment created in the software *Unity game engine.* The test scenarios were two. The first scenario is when the vehicle stops before ran over a pedestrian, this first scenario results are shown in table 2.5, showing only two emotions generated. The second scenario is when the vehicle hits the pedestrian. In this scenario the CarE computes six basic emotions being the dominant emotion anger, the results are shown in table 2.6.

Emotion	Value
Happiness	96.45%
Surprise	3.55%

Table 2.5: Result of the vehicle avoids hitting pedestrian scenario.

Emotion	Value
Anger	46.83%
Disgust	15.61%
Fear	12.49%
Sadness	12.49%
Surprise	7.49%
Happiness	5.07%

Table 2.6: Result of the vehicle hits pedestrian scenario.

The CarE model successfully implemented a OCC model and Em model for an automotive application. Also, it succeeded in incorporating a health factor to the emotion computation. The CarE model also successfully implemented a method to express emotions to the driver by using emojis.

2.2 Primary emotion and stress

According to Damasio [13] a primary emotion is innate in humans beings. This type of emotions have the functionality to trigger a fast and reactive behaviour response for dangerous situations. In humans stress generate a biological response that can triggers a flight or fight response in dangerous situations [14].

According to psychologist, the stress is defined according to the response it creates [15]. The response can be of three types: a) physiological, translating in changes in the body, b) behavioural, generating changes in the behaviour of the individual to deal with the stress, and c) coping, the coping mechanism generate changes in overt behaviours [1] [15]. The stress is caused by a stressor. According to T. Malim et al. [15] an stressor is a situation generated by an individual or an object that causes a state of stress, also it can cause an internal state of conflict which generates stress.

[1] An overt behaviour is an action of an individual that can be notices by people around the individual. This action transform in an habit to cope with stress

A characteristic of stress is that it can not disappear unless the stressor is removed. Thus, human beings have a resistance to stress, this resistance is model with the General Adaptation Syndrome [15]. This model considers that each human has a maximum resistance to stress; thus the process of stress has 3 phases.

The first phase is the **Alarm phase**. The Alarm phase triggers the flight or fight response of the body. Therefore, this phase triggers the mechanisms of adaptability of the system in order to face the stressor. The second phase is the **Resistance phase**. The Resistance phase increases the resistance to stress of the body, by realising chemicals and the response of the system. An example is facing a danger such as a wild animal. The individual will trigger the alarm reaction so the body start realising adrenaline. The resistance phase plays a mayor role by continuing realising the adrenaline into the body as a survival mechanisms; the Resistance phase is the phase which groups strategies to eliminate the stressor, by generating different strategies of the body. Finally the last phase is the **Exhaustion phase**. If a stressor remains in the body for too long generates health issues. The health issues could be severe such as heart failure and could result in death.

The stress also affects the emotions of humans. According to psychologies, the stress can amplify the negative emotions [15]. Also the stress can work as a trigger for basic emotions as it was explained in the GAS model [16].

The concept of stress can also be used for the vehicle state. If it is defined as a survival mechanism then it can be considered a primary emotion. For example, a poor state of the break system should trigger a state of concern in the vehicle, which then should change the behaviour of the vehicle. Thus, the stress should be of the behavioural kind. Using this definition of stress a vehicle would suffer from stressors. These stressors are events that occur either outside or inside the vehicle. In this graduation project, I propose a model to compute stress in the vehicle. This computation is named stress factor, and it is defined as the probability of an accident, then it acts as a primary emotion for survival.

2.3 Vehicle's personality

In psychology a personality is defined by their traits [15]. A trait is a unique personal characteristic of a personality and it is related to the behaviour.

Just like the personalities, each person has a driving style defined by traits. The driving style is defined by Marina Martinez et al (2018) [17] as "the way a driver operates the vehicle controls in the context of the driving scene and external conditions". Thus, the driving style plays a key role for safety and performance of the vehicle.

In an autonomous vehicle understanding the driver style can adjust the vehicle operation to the drivers needs. This can tackle the acceptability of the technology which is one of the key problems of autonomous driving presented by Kraus et al. [7].

Each driving style has its own "traits" or characteristics related to the operation of the vehicle. Taubman-Ben-Ari et al. [18] designed a multidimensional driving style inventory (MDSI). This inventory aimed to classify a person driving style into 4 factors: a) reckless and careless, b) angry and hostile, c) anxious and d) patient and careful. The MDSI is a comprehensive self report mechanism which could classify a driver in an specific driving style, depending on behaviour during driving, self-steem, desire for control, impulsive sensation seeking and extraversion.

There are other definition for classifying driving styles, for example in Ouali et al. [19], the driving style categories are calm, normal and aggressive. Ouali et al. [19] considered the effect of the driving style depending on type of road and driving events. Another work related to driving style classification is Dörr et al. [20] where they considered a classification of three driving styles: sporty, normal and calm. Dörr et al. classified each driving style depending on parameters such as the speed, longitudinal acceleration or deceleration. The current graduation project uses the definition of driver style in Dörr et al. [20]. The reason is because the personalities in Dörr et al. can be associated with the risk aversion concept, and the vehicle operation parameters can be clearly defined for each driving style.

To understand clearly each driving style, it is also required to understand the motivation of the behaviour. Taubman-Ben-Air et al. [21] defined and associated the driving motivations to each driving style. The driving motivation can either be benefits or costs. On the one hand, the benefits of driving are impression management, pleasure, thrill, and sense of control. On the other hand, the cost of driving are distress, damage of self-esteem, annoyance and life endangerment. The results of the study showed clear correlations between the benefits and cost to the personalities.

The concepts of balancing theory can be used to model the cost and benefits. A benefit of driving can be interpret as the **Utility** of driving, and a cost of driving as the **Dis-utility**. In Schmidt-Daffy [22] a model of utility and dis-utility was built using the speed as the independent variable. The utility was model by computing the expected value of gain, which is integrated as an economic incentive and the gain probability. The probability gain is constructed by combining the probability of arriving to a finish line at a specific time and the probability of encounter an object on the road. Then Schmidt-Daffy constructed a Dis-utility function as the expected value between the probability of an accident and the amount loss (economical dis-incentive). In this graduation project I propose the constructtion of a system similar to the utility and dis-utility computation for the driving style model. The utility function is proposed to be built as the utility function in Dixit et al. [23]. The dis-utility function is proposed to be constructed as the risk level of the vehicle. In Dixit et al. [23], the utility is model as a Constant Relative Risk Averse (CRRA) function.

The risk level a vehicle faces during its operation can be objective or subjective. The subjective risk is the perceive risk a driver identifies. As explained in Eboli et al [24], the subjective risk depends on the individual driving and might underestimate the actual risk. Hence a subjective measurement of risk can generate an accident, if the driver is prone to risky behaviour.

In consequence, a objective measure of risk for the operation of the vehicle is required. Moreover, the risk of an accident is a function on the driving event. For example, if a driver is operating the vehicle in a highway alone, it is no likely that the vehicle will crash with another car, but it is likely that if the vehicle over-speeds the automobile might lose control, and have an accident.

The current project proposes an objective measurement of risk which is computed as the probability of an accident and it is a function of the driving scenario.

2.4 Emotion body mapping

The emotions has different functionalities in the human body. For example, fear has the functionality of avoid and run away from danger, so feeling afraid activates the response of either fight or run in our body [25].

In the same way, the emotions should have different functionalities in an emotional machine. [26] performed a functional analysis of emotions for robots. This paper states the fundamental functionalities of the basic emotions in human being and map them in functionalities for a robot.

Anger. This emotion's primary functionality is to organise and maintain energy or resources for activities in high levels. For example, when a goal is not achieve and a person is getting angry the body starts to reserve energy and resources to find alternative solutions.

Disgust. This emotion depicts a reaction of avoidance towards an object or a situation. This can be described as rejection.

Fear. The emotion of fear aims to trigger a fight or flight response. Therefore, this emotions acts as the motivation for escape or confront a situation.

Happiness. This emotion enhance openness to a situation. This emotions can present when a goal is achieved, or an activity is generating pleasure.

Sadness. This emotions has the capacity to slow down some activities, such as cognition. The reason to slow down some activities is to allow the system to reflect upon an action or situation and gain experience.

Surprise. This emotions is present when a stimuli is unexpected or as a result of a new discovery which is also unexpected. Hence, the cognitive process is particularly important for this emotion, to analyse and gain experience from the event.

Stress. The concept of stress, in this graduation project, is a result from dangerous situations. Hence, it triggers a protective response from the system [14].

In addition to the functionalities of the emotions, it has been documented that emotions can be felt in the human body [27]. The somatotopic sensation of emotions activates different systems according to its needs.

In Nummenmaa et al. [27, 28] a somatotopic maps was developed, by a generating a survey among 302 participants. The results showed the maps of emotions and the intensity of the emotions on the human body. The results showed that the all emotions are sensed by overlapping maps on the human body. Also, they concluded that the body sensation is an important part of the process of emotional experience. Nummenmaa et al. concluded that somatosensation and embodiment are critical in the emotional processing. Because this embodiment can automatically activate sensorimotor of the observe emotions for the brain to process emotions.

The functionalities of each basic emotion is to start processes or set actions during or after the emotion. Consequently, the emotions aid to transfer data through the entire system, by giving the appropriate priority and connecting the necessary system for a response.

For these reasons, emotion body mapping for a robot is crucial for emotion's processing. The framework for this process has to be carefully design considering the functions of each basic emotion and their embodiment in an artificial system, or in this case the vehicle. This graduation project designed the emotion body mapping for a vehicle with emotions, stress and personality a CarESP.

2.5 Summary

A system known as CarE [3] computes emotions for a vehicle, based on the OCC model and Em model. Its input are goals ID, actors ID, events ID and actions ID. These inputs are contained in a database which is then used to compute emotions and their intensity using a set of rules. Also, the CarE computes a Health factor HF, which is defined as the over-all health of the vehicle. The HF also affects the computation of emotions.

A primary emotion in innate in humans, and it normally triggers behaviour responses that are fast. Stress can also be a primary emotion when it is used for protection purposes. A characteristic of stress is that it is generated by stressor, and it can only decrease or disappear when an stressor is removed. These concepts of primary emotion and stress can be implemented in an emotion computing model for a vehicle.

A personality is characterised by its traits. In the driving domain a personality is known as the driving style. There are many definitions to classify driving styles (DS), one classification definition is the one use in Dörr et al. [20], which has three classes of DS: sport, normal and calm. This classification can be correlated to the driver's risk adverseness and its parameters are clearly defined by its average speed or gap distance. In addition, the motivation of a driver can be model using balancing theory [29], which describes the concepts of utility and dis-utility. A utility is a driver's benefit of driving, and a dis-utility is a driver's cost. A utility function in a driving domain can be model using the concept of Constant Relative Risk Aversion (CRRA) [23]. A dis-utility function can be model as the probability of an accident.

Finally, Each emotion has its own functionality and purpose. Thus, each emotion computed by a machine should have an specific purpose [25]. Also, each emotion should start a process or set actions. In addition, the emotion body mapping is an essential part to process emotional experience [28]. It has been demonstrated that humans process emotions through a somatotopic maps on their bodies. Hence, emotion body mapping in an artificial system is essential to process emotions.

Chapter 3

CarESP's System Design Description and Methodology

This chapter is dedicated in describing the **Design methodology** followed in this graduation project. In addition, this chapter depicts the **CarESP requirements**, **CarESP context**, **CarESP Use Cases** and **CarESP architecture**. Moreover, this chapter explains in detail the construction and implementation of the **Input module** , **Health module**, **Stress module** and its components, **Scenario detection module**, **Personality module** and its components, **Emotion module**, and the **Body Mapping module**.

3.1 Design Methodology

This graduation project bases its methodology of system design in Model Driven Software Engineering (MDSE) [4]. The methodology follow is *SYSMOD* [4]. Hence, the following steps are followed:

1. Requirement identification.
2. System context description.
3. Modelling system context.
4. Modelling functionalities.
5. Modelling behaviour and implementation.
6. Test.

The CIM (Computer Independent Model) model consisting on the system context description and requirement identification and the PIM (Platform Independent Model) consisting on the use cases, are designed and documented in IBM Rhapsody [30].

The prototype will be implemented in Unity Game Engine [31]. Using the previous implementation and adding extra functionalities to test the new implementation. The PSM (Platform Specific Model), consisting on the behavior of the system, is implemented in Matlab/Simulink [32]. Matlab is selected because the previous implementation is also generated in MATLAB. In addition, Matlab libraries allow an efficient computation of complex models, which are used in this project.

3.2 CarESP System Requirements

The CarESP requirements are specify in this section. The requirements were elicited based on the research questions, and derived requirements from the them. The requirements are shown next:

A name convention is used to name the requirements. All the names used for naming the requirement sand their meaning are in table 3.1. In the requirements the name is shown in *italics* at the beginning of the requirement.

Name	Description
Req	Requirement
PE	Primary Emotion
Pers	Personalised
Comm	Communication
EC	Emotion Computation
DP	Data Process
nDP	Non Data Process
St	State
DB	Database
Sc	Scenario
BenCost	Benefit and cost
EMap	Emotion mapping
fc	function of

Table 3.1: Name convention for requirements.

1. *PE_Req*: The system should compute a primary emotion, based on safety conditions.
   - 1.1 *PE_Comp_Req*: The system should compute four components for the primary emotion.
   - 1.2 *PE_Pers_Req*: The system's computation of the primary emotion should be personalised to the driver.
   - 1.3 *PE_Comm_Req*: The system's computation of the primary emotion should be communicated to the user.
   - 1.4 *PE_EC_Req*: The system's computation of the primary emotion should influence the overall emotion's computation.
2. *Comm_Req*: The system should be connected to the vehicle (ego-car), its Signal Processing Unit (SPU), other vehicles , the infrastructure, a Cloud, and a user interface and exchange data between those systems.
   - 2.1 *Comm_DP_Req*: The system should process the data from the external systems.
   - 2.2 *Comm_St_Req*: The system should transfer the processed data as states.
   - 2.3 *Comm_nDP_Req*: The system input regarding vehicle state and operation's data should be transfer to the system with no processing.
3. *DB_Req*: The system's database for scenarios should be extended.
4. *Sc_Req*: The system should detect five vehicle scenarios: vehicle driving alone, vehicle in a curve, vehicle performing a lane change, vehicle following another vehicle, and vehicle performing a overtake.
5. *BenCost_Req* - The system should compute a benefit and a cost of driving as a function of the speed of the vehicle.
   - 5.1 *BenCost_speed_Req*: The system should compute the ideal speed the user considering his benefits and costs.

6. *EMap_Req*: The system should map the emotions to the body of the vehicle.

   6.1 *EMap_fc_Req*: The system's emotion mapping should be a function of the emotion and the intensity of the emotion.

3.3 System context description and modelling

The first component of the CIM (Computer Independent Model) is the system context description, which is described in this section.

In this project I named the system CarESP. The CarESP is associated with the vehicle (ego-car) that feed the system with the internal system errors and state of the vehicle such as km travelled and speed. Other sensors of the vehicle, such as cameras, RADARs or LiDAR are also associated to an interface, which process the signal and sends information to the system such as the interpretation of the scenery, this interface is known as the Signal Processing Unit (SPU). For example if a vehicle is located ahead of the ego-car or the location of the lanes. Also it is associated with a cloud to make use of cloud computing and obtain information such as the road or weather states. It should also be associated with other vehicles (V2V) and with the infrastructure which could also be intelligent (V2I). Finally, the system is associated with the user via an interface that process the information from sensors and then send the data to the CarESP, for example the emotion of the user, the age, or even the identity of the user.

The CarESP is a system that computes emotions based on the state of the vehicle, the state of the driver, environmental conditions and the events the vehicle is experiencing. Thus, the model of the system context is shown in the figure 3.1.

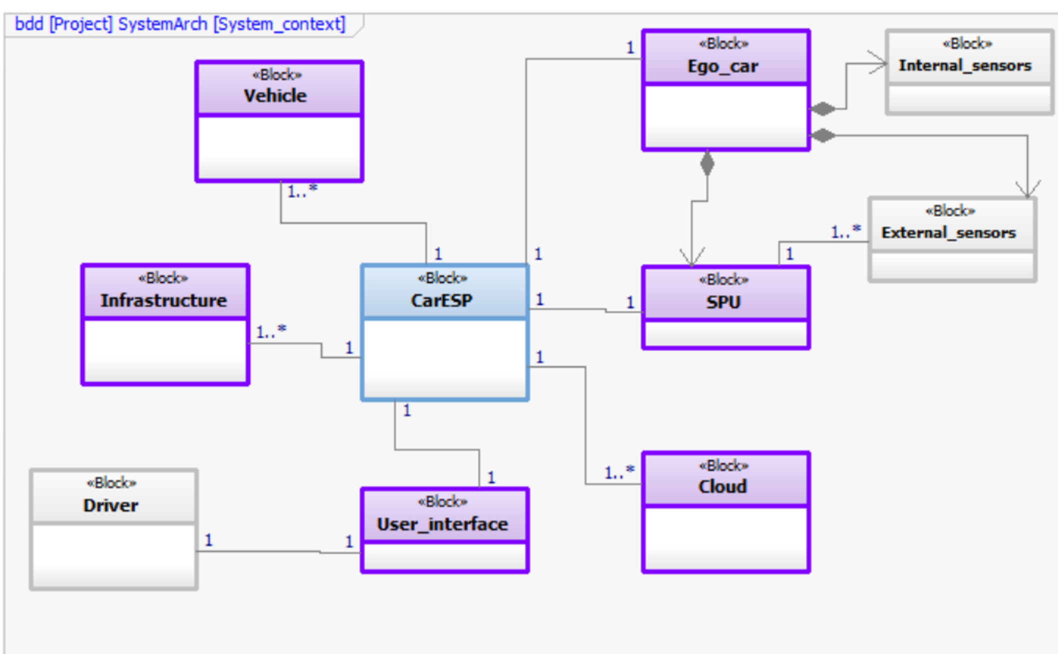


Figure 3.1: CarESP system context.

Figure 3.1 shows in colour purple the systems that are directly connected to the CarESP and in colour gray the systems or actors connected indirectly to the CarESP. It is also shown that for the case of infrastructure, other vehicles and cloud the CarESP can be connected to 1 or many entities.

3.4 CarESP Use Cases

The use cases defines the system's functionalities. In this section the new functionalities of the CarESP and the changed functionalities from [3] are presented. The new functionalities are presented in a colour green. The changed functionalities from Chouhan's project [3] are presented in colour red.

The use cases are separated in two figures. Figure 3.2 shows the Uses Cases **Process Input**, **Compute Vehicle Health**, **Compute SystemStress**, **Compute Health Stress**, **Compute VOS Stress** (VOS stands for Vehicle's Operation State), **Compute Competency Stress** and **Compute EnvironmentalStress**. In addition, figure 3.2 shows actors associated with the UC **Process Input** and the UC **Compute SystemStress**.

Further, the essential textual description of each Use Case is presented.

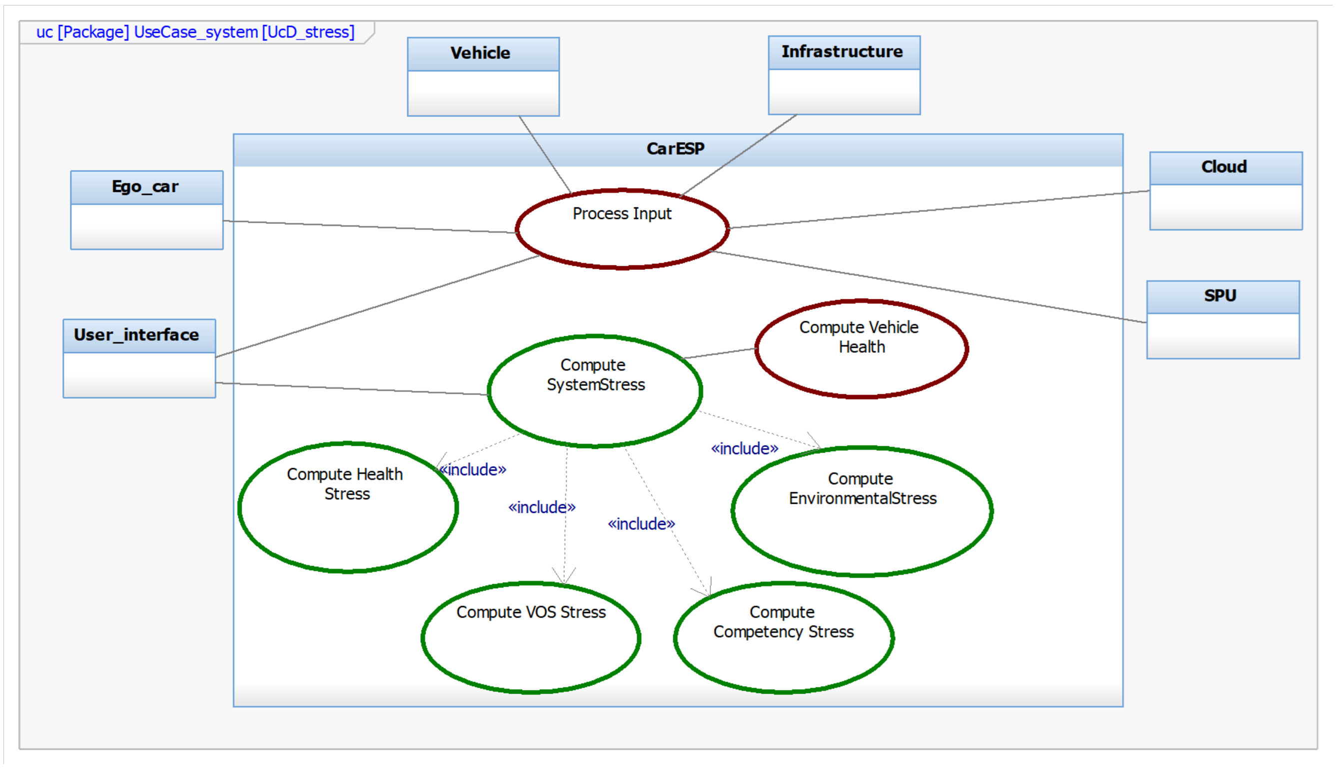


Figure 3.2: Uses cases of the stress, and health factors and the input process.

Compute SystemStress. This use case calculates the total stress of the CarESP, collecting the data from its four components and integrating them in a single indicator. This UC output is the stress factor, which can be interpreted as the probability of an accident.

Compute Health Stress. The health stress of the vehicle considers the integrity of the vehicle's components. This use case collects the data of the states of all vehicle's components, and uses a model to compute the probability of failure [29]. The probability of failure is defined as the health stress of the CarESP.

Compute VOS Stress. The vehicle's operation state is an important component for accident occurrence. This use case computes the probability of accident as a function of the operation state of the vehicle, considering the probability of control loss [33] and the probability of collision to other vehicles [34]. Thus, the probability of an accident due to the operation state of the vehicle is defined as the VOS stress.

Compute Competency Stress. The competency of an autonomous vehicle depends on the systems capacity to recognise objects [35]. This use case computes the capacity of the vehicle as a function of its capacity to recognise objects and other systems that aid in this task.

Compute EnvironmentalStress. According to Bocca et al. [36] 21% of the accidents are due to weather conditions. Also car accident rate can increase due to road conditions or surface [37] or time of the day [38]. This use case computes the probability of an accident due to the environmental conditions such as weather, road condition and time of the day.

Process Input. The system is associated to the ego-car, a user interface, other vehicles, a infrastructure, a cloud and the SPU. The use case of **Process Input** processes the information and transform it to states. The states are then used for the computation of vehicle's stress and overall health (**Compute System Stress** and **Compute Vehicle's health**). In addition, data regarding the location of the ego-car, its speed, other vehicles speed and location is not process, the data is only transmitted to the corresponding modules. A detailed explanation is found in section 3.6.

Compute Vehicle's Health. This UC computes the over-all health of the system considering as input al vehicles state and the stress factor. A detailed explanation is found in section 3.7.

Figure 3.3 shows four new UC's and two changed UC. The added UC's are the **Detect Scenario**, which is associated with the SPU (signal processing unit) of the vehicle. Another added UC's is the **Compute Personality_Utility** and the UC **Optimise speed**, the former is an extension of the UC **Compute Personality_Utility** and it is associated with the Ego-car. The UC **Embody Emotions** computes the mapping of the basic emotions , therefore it is included in the UC **Map emotions** and is associated to the Ego-car. Finally, the UC **Compute emotions_intensity** was changed.

Further, the essential textual description of the UC's in figure 3.3 are presented.

Detect Scenario. This scenario's objective is the detection of five different scenarios: a) The ego car driving alone in a straight line, b) the ego car handling a curve, c) the ego car changing lanes, d) the ego car following another vehicle and e) the ego car overtaking the leading vehicle. To detect each scenario, the UC **Detect Scenario** uses a set of rules which are explained in section 3.9.

Compute emotions_intensity. This use case computes the emotions and their intensities using a set of rules that can be found in [3]. The changes on this UC is related to the database, the details can be found in section 3.11.

Map emotion. This UC includes the UC **Embody Emotions**, the addition of this UC is the only change compared to Chouhan's work.

Compute Personality_Utility. This use case aims to compute the value of the speed to the user. The value of the speed is explained in detail in section 3.8.1. The utility is computed using a model which defines the personality of the driver's depending on the risk adverseness.

Optimised speed. This use case uses the function of utility from the UC *Compute Personality_Utility* and the stress computed in the use case *Compute SystemStress* and combines them as a function of the speed of the vehicle. The combination results in a balance function, when its value is 0 then the utility of the speed has a value which balanced out the probability of accident.

Embody Emotions. This use case maps the emotions computed in the CarESP to the body of the vehicle. The use case aims to send the intensity of the emotions to specific systems in the vehicle. A signal is sent depending on a set of rules defined as a function of the emotion computed. This is further explained in the section 3.12.

Each use case is implemented as modules of the system; the modules are shown in section 3.5. Each module is

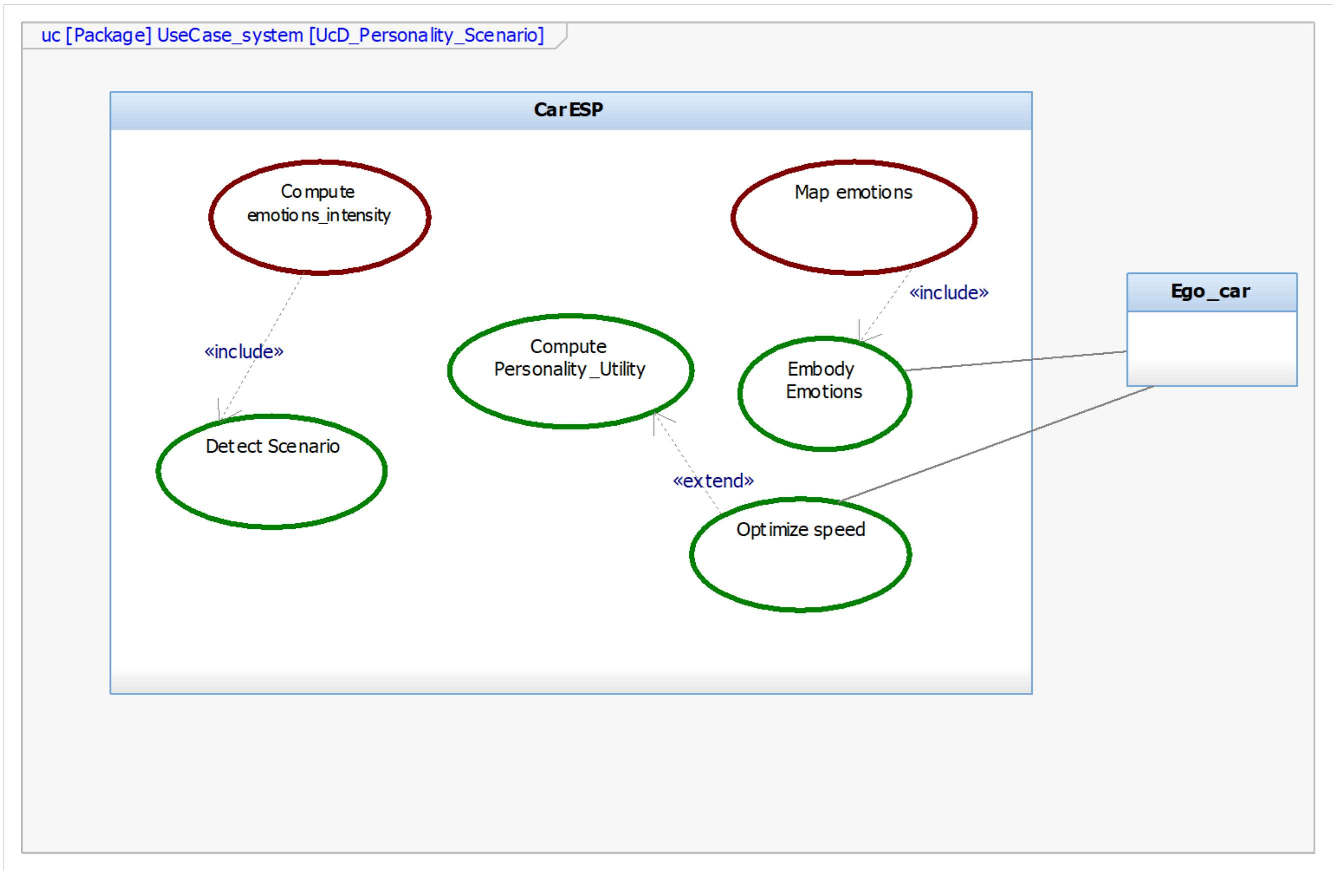


Figure 3.3: Uses cases of the scenario detection, personality utility, optimise speed and embodiment of emotions.

presented as a block. The mathematical model used in each use case is presented in the sections dedicated to each module.

3.5 CarESP System architecture

The system architecture is presented in figure 3.4. This BDD (Block Definition Diagram) shows the complete CarESP system and its data flow interactions. At the bottom of the figure a colour key is presented, the blocks in red colour are changed modules, the blocks in green colour are new modules and the blocks in purple colour are original modules.

It is important to observe that figure 3.4 only shows the data flow from the ego-car to the **Input module**, but in the system context figure 3.1 and the use case diagram figure 3.2, the **Input module** association with other external system such as a Cloud, other vehicles, the infrastructure and the user interface are shown.

The CarESP is composed of 9 modules: 1) **InputModule**, 2) **HealthModule**, 3) **StressModule**, 4)**Personality_Module** 5) **ScenarioDetectionModule** , 6) **EmotionModule**, 7) **MoodModule**, 8) **MappingModule**, and 9)**OutputModule**.

On the one hand, The **MoodModule**, **MappingModule** and **OutputModule** were not changed form the original implementation [3]. The components **IntensityModule**, **DecayModule**, **Map_emotion_module** and

FacialExpressionGenerator did not change either. These modules are shown in purple colour.

On the other hand, all the new and change modules are described in table 3.2. Moreover, the new and changed components are described in table 3.3

Module	Description
1. **InputModule**	It process its input coming from external systems such as ego-car, other vehicles, infrastructure, user interface, a cloud and SPU. The input is transform into states, they are known as behavioural variables, then transfer to the **HealthModule** and the **StressModule**. The inputs *vehicle_ data* is not processed, the **InputModule** only selects what data is transfer to the **StressModule** and the **ScenarioDetectModule**. All the behavioural variables are shown in appendix B.
2. **HealthModule**	It receives the behavioural variables states and the stress factor as inputs. Then it sends its output (health factor) to the environmental module where it is used to compute the intensity of the emotions. Further explanation is found in section 3.7.
3. **StressModule**	It computes the stress factor, which it is its output. It has four components **VOS_Stress**, **HealthStress**, **EnvironmentalStress** and **CompetencyStress**. The output is sent to the emotion module, the health module and the personality module.
4. **Personality_Module**	It is composed by two components: a) **Utility_fun** and b) **Speed_op**. This module computes the benefit of driving, using the component **Utility_fun**, Additionally, it computes an optimal speed with the component **Speed_op**. Its output is the utility of the speed and the optimal speed which is communicated to the user. A more detail explanation of the computations of this module and its components are found in section 3.8.1.
5. **ScenarioDetectionModule**	It receives *vehicle_ state* data from the input module. These state data is information such as the ego car speed, ego car location, other vehicle location and speed, lane location and changes in road degrees (for curve detection). A deeper explanation of this module is found in section 3.9.
6. **EmotionModule**	The changes from the original module were performed in its database and computation of the parameter *LoS* and *LoF*. The specific changes are explain in section 3.11.
7. **MoodModule**	Its input is the intensity of the 22 emotions from the **EmotionModule**. It analyses all the emotions and computes its mood, which is the ratio of the intensity of the positive emotions over the negative emotions.
8. **MappingModule**	It maps the 22 emotions into the 7 basic emotions. The mapping rules can be observed in [3]. It also includes the health factor into the emotions intensity, by increasing the negative emotions if the HF is below its mean value, or increasing the positive emotions otherwise.
9. **OutputModule**	It send the emotion's intensity data to the Unity Game Engine.

Table 3.2: CarESP's Modules description.

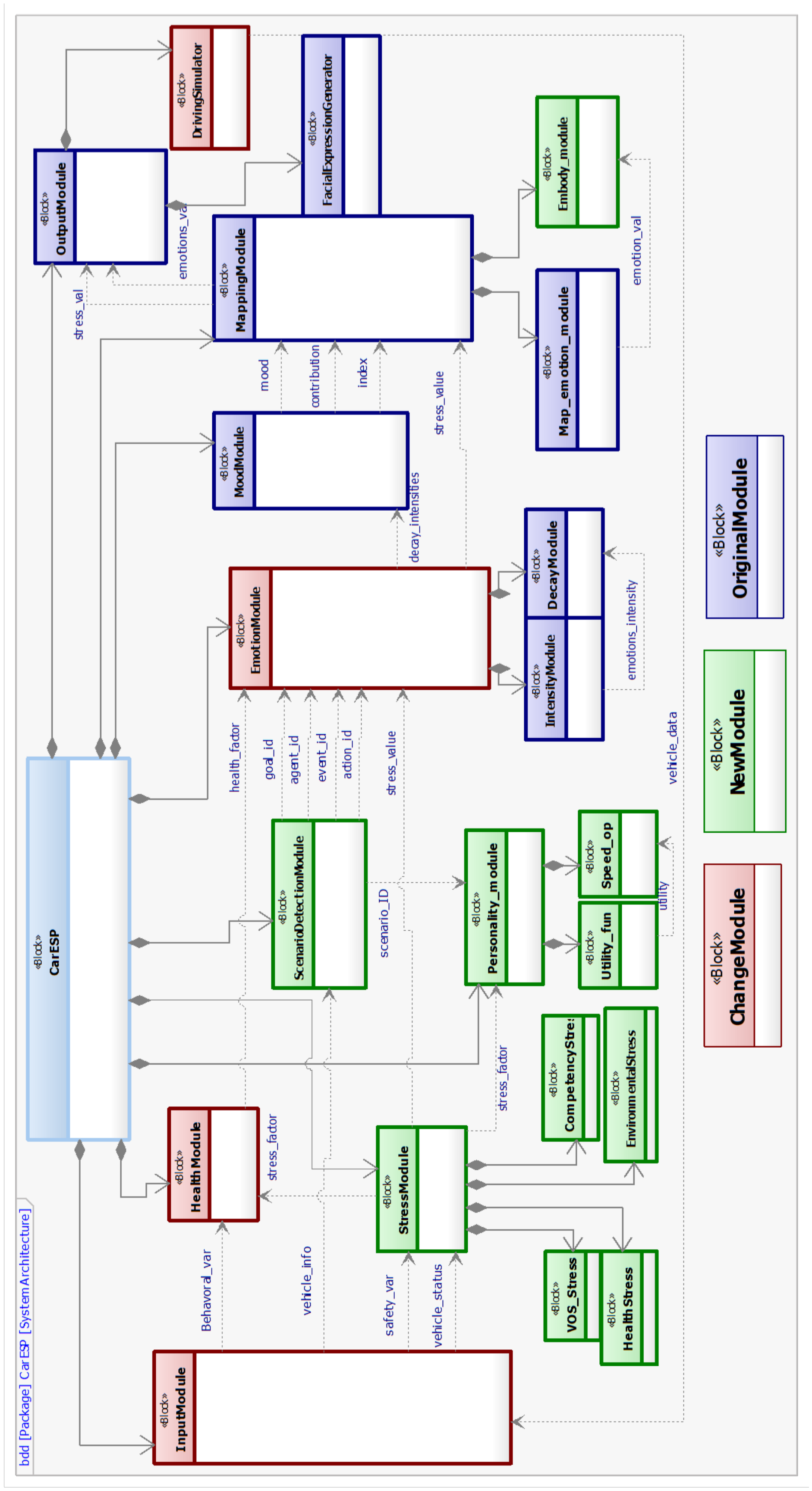


Figure 3.4: CarESP architecture.

Component	Description
VOS_Stress	It computes the stress of the vehicle a as a function of the Vehicle's operation. It uses a model that has two components, the probability of loss control and the probability of collision to other objects. Its output is then processed in the **StressModule**.
HealthStress	It computes the stress of the vehicle as a function of the internal state. It uses a predictive maintenance model to compute the states of each component and predicts a possible failure. Its output is then processed in the **StressModule**.
CompetencyStress	It computes the stress of the vehicle as a function of the vehicle's capacity to drive autonomously. It uses a model which central variable is object recognition. The model computes the probability of not recognising an object using its uncertainty and the aid other systems give to this task. Its output is then processed in the **StressModule**.
EnvironmentalStress	It computes the stress of the vehicle as a function of the environmental conditions. It uses a model with the probability of having an accident in an specific road as a central variable. Other variables such as the weather condition, time of the day, road condition and road surface might increase the probability of accident. Its output is then processed in the **StressModule**.
Utility_fun	It computes the value of the speed to the user, this value is computed using a function describing the risk adverseness of the driver.
Speed_op	It computes the optimal speed of the system. The optimal speed is computed considering the risk aversion of the driver and the stress of the system.
Embody_module	It receives data of the intensity of each basic emotion. These data is processed by defining which systems will receive a signal. Also, the intensity of the signal is computed. The transmission of the signal to specific systems is a function the emotion and the its intensity. A more detail explanation can be found in section 3.12.
DrivingSimulator	It is modified to test the new scenarios. In this graduation project, five scenarios are tested, which required changes in the simulator. The changes are explain in the section 4.

Table 3.3: CarESP components description.

The following sections explain in more detail the new modules (green blocks) and the changes in the modules (red blocks) shown in figure 3.4.

The CarESP system was implemented in Matlab/Simulink. There are two reasons for this decision. The first is that the previous implementation [3] was already implemented in Matlab/Simulink. Second, the computation needed to perform the stress factor modelling requires a powerful mathematical modelling and solving software, it also needs a real-time implementation. Both specifications are delivered by Matlab/Simulink software. The real-time running time is valuable for the testing due to the changes between scenarios. In conclusion, to test the concept functionality Matlab/Simulink implementation offered a solid foundation.

3.6 Input module

The **Input module** in [3] has five classes, the variables composing these classes are known as behavioural variables. The behavioural variable's classes are:

a *Drivers health* - contains the behavioural variables of the driver's health.

b *Driving style* - contains behavioural variables related to the driver's vehicle operation.

c *Vehicle health* - contains all the behavioural variables related to the state of all vehicle's components.

d *Vehicle competency* - contains the behavioural variables of vehicle's capability for autonomous driving.

e *Environment condition* - contains the behavioural variables related to the external environment of the driving scenario.

The vehicle health class' variables also are in line with the EU road-worthiness directive [39].All the classes and all the behavioural variables can be found in the appendix B.

The majority of the behavioural variables can have states values between 1 to 5 (being 1 the best value and 5 the worst), for some behavioural variables the worst value is 3 or 2. Additionally, the rank classifies the behavioural variables for their impact on safety, performance, driver's comfort or driver's trustworthiness. The rank used in this project is shown in Table 3.4.

Classification	**Rank**(r_{X_n})	**Weight**(W_{X_n})
Safety	1	1
Performance	2	1/2
Driver's comfort	3	1/3
Driver's trustworthiness	4	1/4

Table 3.4: Ranking the classification based on their influence on health factor's computation.

3.7 Health module

The details of the computation for the health factor uses the values of rank and weights shown table 3.4. The health module takes 54 variables as input. These inputs are divided into 4 ranks. The computation of the Health Factor (HF) follows the same methodology as [3]. The tests for the HF to observe its behavior uses five different scenarios, the tests description and results are presented in the section 4.

In addition, the health factor (HF) is modified by the stress factor (SF), motivated on the influence of stress on human health. The values of the stress factor can vary from 0 to 1. To compute the new HF affected by the stress (HF_s), equation 3.1 is used.

$$HF_s = HF - (HF - 1)SF \tag{3.1}$$

Equation 3.1 shows that the SF can only affects negatively the HF, but the SF can not reduce the value of the health factor below 1. Thus the stress factor influence decreases in accordance with the proximity of the HF with its lowest value. The value of the health factor affected by stress (HF_s) is an input to the emotion module.

3.8 Stress module

The stress module output is the stress factor, that is conceptualised as the probability of accident. The computation of the stress factor requires all the behavioural variables related to safety and the data from the ego-car such as its speed and location

To compute the stress factor four components are defined: **Vehicle operation state (VOS) stress**, **Health Stress**, **Competency stress** and **Environmental stress**. Each component is defined in the following subsections.

3.8.1 Vehicle's operation state (VOS) stress

The vehicle's operation state stress (SF_{vos}) is defined as the probability of accident as a function of the operation's state. The SF_{vos} has two components: control loss and the collision to other objects.

Specifically, the SF_{vos} is a function of the operation's parameters such as mean speed or mean acceleration of the user, which are components of a driving style. To describe the VOS stress first, the driving style and its parameters are defined in subsection Driving Style, then the components of the SF_{vos} are defined in subsection vehicles operations state stress components. .

Driver Style

A driving style can be defined by a series of parameters or "traits" related to the operation of the vehicle, such as the speed, acceleration rate and gap decision between vehicles [20, 19, 17]. Then, defining the parameters which characterised a driving style is an essential task to achieve a successful classification of a driving style. The parameters used to characterised a driver are extracted from Bonsall et al. [40], whose research aims to model the driving behavior for traffic simulation.

The parameters definitions and values used to characterised a normal driver style [40] and the parameters used to simulate each driving style are shown in table 3.5. The values for the calm and sport driving styles are computed assuming the calm driving is less aggressive than the normal, and the sport driving style is more aggressive than the normal according to the definition of these driving styles in [20]. The generation of the parameters aims to observe the behavior of the system for each extreme personality. Hence, the parameters speed, acceleration rate and deceleration rate are decreased by 50% for the calm DS compared to the normal DS, while they are increased 50% the sport DS compared to normal DS. The parameters headway and critical gap are increased by 50% for the calm DS compared to the normal DS, while they are decreased 50% the sport DS compared to normal DS

Parameter	unit	Values
Speed	m/s	Calm = 6.9 Normal = 13.9 Sport = 20.8
Headway	s	Calm = 3 Normal = 2 Sport = 1
Acceleration rate	m/s^2	Calm = 0.6 Normal = 1.2 Sport = 1.8
Deceleration rate	m/s^2	Calm = 0.5 Normal = 1 Sport = 1.5
Critical Gap	s	Calm = 5.25 Normal = 3.5 Sport = 1.75

Table 3.5: Driver style parameters for different personalities.

There are defined two types of influence to the DS: a) Environmental and b) Human [17]. Examples of environmental influence types are the driving events (lane change, curve handling, overtaking), weather, road type, among others. Examples of human influence types are behavior, risk taking, aggression potential, gender, among others. Ericsson [41] claims that the external factors can affect differently to each driver, hence significant divergence in driving style can be found in a single driver. In consequence, the parameters in table 3.5 can change according to the external conditions and the driving event. Due to the time constrain, I assumed fix parameters for all driving styles. In future research a dynamic change of the parameters according to Ericsson's research [41] can be explored.

Vehicle's operations state stress components

The Sf_{vos} has two components: loss control and object collision.

To compute the control loss component, first the state of the vehicle needs to be defined, which is defined by the parameters: vehicle's acceleration and speed. The model to compute the control loss component defines safe and unsafe areas as a function of the acceleration and speed of the vehicle based on Eboli et al. [33]. The construction of the model defined the vehicle's equations of motions. Then defines the magnitude of vehicle's force (F_s) and the magnitude of the force due to friction of the tires (F_R). Thus, the zones are defined as follows:

- if $F_s < F_R$ the vehicle is in the safe driving zone.
- if $F_s = F_R$ the vehicle is at the limit of the safe driving zone.
- if $F_s > F_R$ the vehicle is in a unsafe driving zone.

The tire friction force magnitude uses the definition in Lamm et al. [42] as a function of the speed of the vehicle. For a more detail explanation of the equations refer to the Appendix A. The indicator for control loss is then constructed by the equation 3.2.

$$R_{lc} = \frac{F_R}{F_s} \tag{3.2}$$

If $R_{lc} > 1$ then the vehicle's operation state is in a safe driving zone. If $R_{lc} = 1$ then the vehicle's operation state is in the border line between the safe and unsafe areas. Finally, if the $R_{lc} < 1$ then the vehicle's operation state is in a unsafe zone. A vehicle's operation state that is in the unsafe zone does not implied that the vehicles will have an accident. Being in a unsafe zone operation's state implies that the probability of an accident is greater.

The indicator R_{lc} is then model as an exponential pdf to transform its value to probability. The exponential pdf is chosen because of its properties. The computation of the probability of an accident as a function of the state of the vehicle is assume to be independent. This assumption is valid as long as the computation of accident probability is computed at a specific moment. The equation used for the control loss stress is equation 3.3.

$$SF_{CL} = \mu e^{-\frac{R_{lc}}{\mu}} \tag{3.3}$$

Where μ is the mean value of the risk of control loss indicator (R_{lc}). To compute the R_{lc} mean (μ), the values of the mean rate of acceleration ($\bar{a}_{rate}[m/s^2]$) and the mean speed ($\bar{V}[km/h]$) of the driver style are used. These parameters are defined for each driver, and were explained in previous subsection. The parameters values for the $\bar{a}_{rate}$ and the $\bar{V}$ are shown in table 3.5).

The second component of the vehicle's operation state VOS stress is the probability of collision. The computation of this components uses the concept of Time to Collision (TTC). The TTC is defined as "the time for two vehicles to collide if they continue at their speed on the same path"[34]. I only compute the TTC for moving objects (other vehicles). The reason to omit the TTC for non-moving objects is because in the 3D environment there are many non-moving objects, then the TTC computation causes noise. Also, it is more relevant for this project to test the TTC for moving objects that can change their speed. The equation of the TTC can be found in appendix A, it is based on the definition of Minderhoud et al. [43].

While the TTC decreases the risk of collision increases. Thus, the transformation of TTC to a probability required a pdf, the exponential pdf was selected. This pdf is used based on Elvik [44], this paper states that the risk of a collision increase exponentially respect the speed of the vehicle, and the TTC is a function of the speed. Hence, the equation describing this component of the vehicle's operation stress is equation 3.4.

$$R_{col} = G_c e^{-TTC/G_c} \tag{3.4}$$

Where G_c is the critical gap and it is measured in seconds. This parameters is defined in from the driving style subsection (table 3.5).

The computation of the total VOS stress (SF_{vos}) is computed considering that the components can occur at the same time but are independent. Therefore that are modelled as mutually inclusive probability. The equation 3.5 defines the vehicle's operation state stress SF_{vos}.

$$SF_{vos} = R_{lc} + R_{col} - R_{lc}R_{col} \tag{3.5}$$

3.8.2 Failure stress

The second component of the vehicle's stress is the internal health. The internal health of the vehicle is a function of the state of its components. The internal state of the vehicle is a function of the system failure, which can be model using predictive maintenance theory [29].

The predictive maintenance model used to compute the system failure is described in Shafiee et al. [29]. The model's parameters for each component (j) are the degradation critical level (D_j) and the intensity of the degradation (λ_j). Also the gamma pdf is used to model the probability of survival. The model is explained in detail in appendix A. An assumption of our model is that the degradation rate is linear, which is used in order to allow the computation to be in real-time. The data uses for the D_j, λ_j, and the parameters of the gamma function can be found in the appendix C.

Shafiee et al. [29] computes the survival probability of the system (F_{sys}). Then, the probability of failure is defined in equation 3.6.

$$SF_f = 1 - F_{sys} \tag{3.6}$$

3.8.3 Competency stress

According to Underwood et al 2007 [35], experience drivers are vulnerable to accidents. The main factors for their vulnerability is the inattention; which lays in their observation skills. Thus, the ability to detect objects is a major contributor to the probability of an accident. Similarly, the detection of objects from an autonomous vehicle plays a major role in the capability of the vehicle to drive autonomously. Thus, I propose a methodology to compute the competency stress (SF_c) using the object recognition variable as a central element.

The uncertainty is a measure of accuracy in a system for object recognition, and it is fundamental for safety. The uncertainty is a function of the dedicated system for object recognition (computer vision, RADAR and LiDAR). The uncertainty can be conceptualised as the probability to not recognised an object (P_{NRO}).

Other systems can aid in object recognition. For example, a communication between vehicles (V2V) or infrastructure (V2I) can aid in the detection of other vehicles in the system [45]. Also, cloud computing [46] and the capability of collective manoeuvring [45] enhance the object recognition task. Furthermore, this project developed a model to compute how these systems decrease the uncertainty of object recognition. The details of the model can be found in appendix A.

Each enhancement is defined as the percentage of improvement of component j (PI_j). If the system j is enable then $0 < PI_j < 1$, if the system j is disable then $PI_j = 0$. The value of each PI_j was defined by conducting a literature review, the results of this research are shown in appendix C The equation to compute the competency stress factor is equation 3.7

$$SF_c = P_{NRO} \prod_{1}^{N} (1 - PI_j) \tag{3.7}$$

Equation 3.7 shows the relationship between the competency stress and its probability of not recognising objects. In the case that non of the systems that enhances the object recognition task are enable, then the system relies on fully dedicated systems for object detection such as computer vision, RADAR of LiDAR. In consequence, the competency stress is equal to the probability of not recognising objects. On the other hand, if any of the systems to enhance the object recognition is enable, the competency stress decreases depending on the value of the PI_j of the component j . For this project, the enhancement systems for object recognition are four. For $j = 1$ the component is V2V, for $j = 2$ the component is V2I, for $j = 3$ the component is cloud connectivity, and for $j = 4$ the component is collective manoeuvring.

3.8.4 Environmental stress

The driving safety is also affected by external factors. Astrom et al. [47] states that the surface friction plays a significant role in driving safety. Additionally, the weather condition are relevant in safety while driving [36].

In Ifthikar et al. [48] a design system is proposed to map road accident's hot spots. This system can be used in autonomous vehicles to obtain the information of the probability of accident in specific locations. Then, this project proposed that the environmental stress is computed using as a central variable the **Probability of accident in an specific road** (P_{RAcc}). Although, other factors can affect the probability of an accident. These factors are surface condition, surface type, weather or time of the day. Therefore, I propose a probabilistic model to compute the environmental stress as the probability of an accident as a function of the external conditions.

The model to compute the environmental stress is defined as a mutually inclusive probability. It follows the following algorithm. The probability of accident of component i is P_i, then:

1. i=0.
2. if $i = 0$ then $P_{temp} = P_{RAcc}$.
3. i=i+1.
4. $P_{temp} = P_{temp} + P_i - P_{temp}P_i$
5. if $i = 4$ then $SF_{env} = P_{temp}$ else go back to 3.

Probability of accident in an specific road (P_{RAcc}) is model as a normal pdf. Its mean and standard deviation were extracted from [49] data. Component $i = 1$ is surface condition, $i = 2$ is surface type, $i = 3$ is weather condition, $i = 4$ is time of the day. The data used for the computation for each component and these state can be found in table C.3.

3.8.5 Total stress factor

After computing the stress factor for each class the integration between them is also a probability. The stress factor is modelled as a mutually inclusive probability.

The equation that computes the Stress factor is presented in equation 3.10. The steps are described in equations 3.8 and 3.9.

$$SF_{f-C} = SF_f + SF_c - (SF_f)(SF_c) \tag{3.8}$$

$$SF_{f-C-env} = SF_{f-C} + SF_{env} - (SF_{f-C})(SF_{env}) \tag{3.9}$$

$$SF_{tot} = SF_{f-C-env} + SF_{vos} - (SF_{f-C-env})(SF_{vos}) \tag{3.10}$$

Where SF_f is the failure stress, SF_c is the competency stress, SF_{env} is the environmental stress, SF_{vos} is the vehicle;s operation state stress and SF_{tot} is the total stress or stress factor. The definition in equation 3.10 can only have values between 0 and 1.

3.9 Scenario detection module

To test the CarESP system, it is required to identified different scenarios. Thus, the **Scenario detection module** performs this task. Only five scenarios are selected to perform the systems tests, they were selected because there was a short time to test. The first four scenarios are selected to be representative among traffic simulation scenarios [40]. The fifth scenario is selected to test a common complex scenario in naturalistic driving, which is built upon other scenarios [50].

Those scenarios are a) **driving in a straight line**, b) **lane change**, c) **curve handling**, d) **vehicle following**, e) **overtaking**. Each scenario has start and end triggers.

The **straight line** scenario includes the vehicle driving alone on a lane. The initial trigger is the start of the vehicle ($speed = 0$), or the finalisation of another scenario as long as the vehicle is not in a curve. The end trigger happens when another scenario has started.

The scenario's **lane change** starting trigger happens when the vehicle has touched the lane marker (white line) with one of its front tires. The end trigger happens when the vehicle has touched the lane markers with the rear opposite tire [51].

The scenario's **curve handling** starting trigger occurs when the forward path start having an angle with respect to the direction of the vehicle. The angle of the curve could be positive (making a left turn) or negative (making a right turn). This scenario's end trigger happens when the street degrees are in line (0 degrees) with the vehicle.

The **vehicle following** scenario has three starting triggers. First, the second car (leading vehicle) must be in the same lane as the vehicle. Second, the other vehicle must be in the same direction. And third, the vehicle (ego car) must be located behind the leading vehicle. The end trigger can be either when the leading vehicle is no longer in the same lane or any of the vehicles have changed to another road.

The **overtaking** scenario has many variants. For the purpose of this paper only one variant was tested. This variant, has the same 3 starting triggers as the scenario **vehicle following** with an additional trigger. The additional trigger is the lane change of the ego car with the intention of leaving the leading vehicle behind [50]. This variant assumes that in the scenario there is only the leading car and the ego car.

3.10 Personality Module

This project aims to model the driver style using the concept of balancing theory. Then first, it is required to build the utility function. Conceptually the utility can be built as a benefit of driving such as the thrill. This utility can be a function of one parameter shown in table 3.5. To test the concept, this project only considered one parameter: the speed. The construction of the utility function is based on Dixit et al. [23]. Dixit et al modelled the utility as a Constant Relative Risk Averse (CRRA) function. Equation 3.11 shows the utility function.

$$U(C) = \frac{C^{(1-r)}}{1-r} \tag{3.11}$$

Where $U(C)$ is the utility, C is the cost, and r is the risk parameter. Ir $r = 0$ then the subject is risk neutral, if $r > 0$ the subject is risk averse, and if $r < 0$ the subject is risk lover.

The construction of the curve needs to obtain data of the subject (driver) regarding their risk aversion. Dixit et al. methodology used an indirect measure. An indirect measure of risk does not necessarily represent the subject behavior while driving [52]. Also a self-report methodology for risk while driving not necessarily is correlated to the actually speeding behavior [52]. In consequence, the characterisation of the utility function requires data from actual speeding behavior couple with a measurement of a benefit or cost. An example, is the measurement suggested by Healey et al. [53]. Healey et al. measure the stress of the driver is certain driving conditions. The stress can be used as the parameter to characterised the utility.

The utility function could not be fitted due to lack of data correlating any parameter from the table 3.5 to a driving style. Instead to demonstrate and test the behavior of this module, this project selected the speed to be model with parameters of risk aversion which are representative of the three risk personalities: risk neutral, risk aversion and risk lover.

According to Dörr et al. [20], the driving styles (DS) sport, normal and calm are characterised by the speeding behavior they presented. The sport DS in average drives with greater speed than the normal DS, while the former drives with a greater speed than the calm DS [20]. Following this idea, each DS can be matched to a risk personality. The sport DS is matched with the risk lover personality, the normal DS is matched with the risk neutral personality and the calm DS is matched with the risk averse personality. In addition, it can be implied that if three drivers each with different DS are driving at the same speed, the sport DS will feel less stress than the normal DS, and the former less stress than the calm DS.

To model the dis-utility, this project propose to use the stress factor component vehicle's operation state stress (SF_{vos}).Since the values of the dis-utility have values within a range of 0 and 1, the utility function needs to be normalised so it can take values within a range of 0 and 1. Equation 3.12 shows the normalised utility function.

$$U = \frac{U(C)}{U(C^*)} \tag{3.12}$$

Where $U(C)$ is the utility of the desired variable and a moment. $U(C^*)$ is the utility of the maximum speed that the vehicle can achieve, for example the speed the governor systems allows. Then the utility function is normalised with within the range of 0 and 1. In this way this function can be compared with the dis-utility function.

Finally, once the utility and dis-utility are calculated, the balancing utility can be defined as the subtraction of the utility and the dis-utility. Equation 3.13 shows the balancing utility definition.

$$BU = U - SF_{vos} \tag{3.13}$$

In balance theory, the balance utility can compute an optimal speed. This project proposed that the optimal speed occurs when the balance utility value is 0. This value is selected because in the value when the balance utility is 0, the stress of an accident and the benefit of the speed values are equal. The maximum of the balance utility is not chosen because in the case of a risk lover, the maximum will always be computed as the maximum possible speed. This is a weakness on this methodology. Future research can be performed in order to find a more robust optimisation algorithm.

3.11 Emotion Module

Emotion Module is composed of two sub-modules - **Intensity Module** and **Decay Module**. **Intensity Module** generates intensity values of emotions based on its input parameters. These inputs are Goal ID, Action ID, Event ID, and Agent ID. The computation of the emotions are based in a database related to those ID's and computes the intensity values of 22 emotions. The **Decay Module** takes the output of the **Intensity Module** and decreases the intensity values of the emotions with time.

I changed and extended the database used to compute the emotions. The purpose of the changes and extension is to test the five scenarios presented previously and test the SF as an identification variable between events and actions.

Each scenario is connected with a goal and an agent in the data based. This relationship is shown in table 3.6. The relationship between scenarios, events and actions can be seen in table 3.7.

Scenario	**Goal**	**Agent**
Driving in straight line	Stay under speed limit	Me
Lane change	Perform proper lane change	Me
Curve handling	Perform proper curve handling	Me
Following a vehicle	Maintain proper distance with agents	Vehicle in front
Over -take	Perform proper lane change Maintain proper distance with agents Avoid collision with vehicles	Vehicle in front

Table 3.6: Relationship between scenarios, goals and agents.

I propose to use the SF as an event identification variable, thus it can identify which event and action are triggered within the scenarios. Furthermore, I implemented the SF to be equal to the likelihood of failure (LoS). Particularly for the scenarios: **lane change**, **curve handle** and **following a vehicle**.

For the scenario **driving in a straight line** the decision variable is whether the ego-car has surpass the maximum legal speed limit, in which case the event over-speeding is triggered.

The SF threshold to decide between events or action is $SF = 0.5$. This threshold is selected because if $SF < 0.5$ and $SF_{tot} = LoF$ then $LoS > LoF$ then there is more probability that the goal succeed. Therefore the selected event should the positive outcome. However, if $SF > 0.5$ and and $SF_{tot} = LoF$, then $LoS < LoF$ then there is more probability that the goal is not achieved, hence the selected event should be the event with a negative outcome. For example, in the scenario **lane change** if the SF_{tot} value is above 0.5 then the event improper lane should be triggered. If the SF_{tot} is equal or less that 0.5 then event proper lane should be triggered.

Scenario	Event	Action
Driving in straight line	1. Staying under speed limit 2. Overspeeding detected	1. I stayed under the speed limit 2. I over-speed
Lane change	1. Proper lane change performed 2. Improper lane change performed	1. I performed proper lane change 2. I performed improper lane change
Curve handling	1. Proper curve handles performed 2. Improper curve handle performed	1. I performed proper curve handle 2. I performed improper curve handle
Following a vehicle	1. Proper distance maintained with agents 2. Improper distance maintained with agents	1. I maintained proper distance with agents 2. I maintained improper distance with agents
Over -take	1. Proper lane change performed 2. Improper lane change performed 3. Proper distance maintained with agents 4. Improper distance maintained with agents 5. No collision detected 6. Collision detected	1. I performed proper lane change 2. I performed improper lane change 3. I maintained proper distance with agents 4. I maintained improper distance with agents 5. I detected no collision 6. I detected a collision

Table 3.7: Relationship between scenario event and action.

The scenario **Overtake** considers 6 events (table 3.7). Each event depends on the sub-scenario detected (table 3.6). Thus the event and action selected follows the same rules as for each sub-scenario. In the case the ego-car has collided or has overtaken the leading vehicle the decision variable is the detection of collision, thus the possible events and action are no collision detected or collision detected.

3.12 Body Mapping Module

The body mapping module's is the framework design to communicate emotions and their intensities to specific systems located on the body of the vehicle. The presence of an specific emotion in a specific situation yields the need to have a response form the system.

The functionality of each emotion was described in section 2.4, thus an emotion's functionality is related to an action of some systems. Also, the functionality requires that the intensity of the signal is coherent with the intensity of the emotions being generated by the emotions module.

The framework is defined by the analysis made for each emotion's functionality. As it was stated in Nummenmaa et al. [28], the experience of emotions and communication happen when the emotion sends a signal to the body, which is sensed in specific parts of the body with different intensities. Hence, a correlation between the functionality of the emotion and a vehicle body part was designed. The functionality of emotion sends a signal to a system in the vehicle's body to generate a message of an action. The relationship between emotions, functionality and which systems components are receiving the signal are shown in table 3.8. The communication of emotions and systems occurs between the CarESP and the ECU [1] of each system. Thus, the systems shown in table 3.8 relates to the ECU of that system.

Emotion	Functionality	Systems
Anger	Store resources for alternative solutions	Transmission, motor, decision process unit
Disgust	Rejection	Transmission, decision process unit
Fear	Protect, escape or avoid situation	Transmission, body, doors, dashboard,
Happiness	Openness, glad to succeed	Cabin, decision process unit and communication
Sadness	Slowdown processes and reflection	Cabin, vision systems, communication, decision process unit
Surprise	Unexpected stimuli, learn from stimuli and stop process	Transmission
Stress	Protect user	Dashboard,doors, body

Table 3.8: Emotions functionalities and correlated systems.

The emotion **anger** aims to store resources to find alternative solutions. The resources of the vehicle can be two, energetic resources and computational resources. In consequence, the CarESP should send the signal to the motor, the transmission and the decision process unit [2]. The decision process unit must have a signal to find an alternative solution because the current strategy is not working and the goal is not achieved. Also the reallocation of computational resources could be needed. To perform the new strategy the motor and transmission must be aware of the changes, for example a quick diagnostics of the state of those components could aid in the decision of a new strategy. The set of possible strategies are out of the scope of the current project.

The emotion **disgust** aims to reject the current event or action. Then a signal should be sent to the decision process unit and the transmission. In general, a rejection of an event produces an action of moving away from the event, thus a signal to the transmission could stop the vehicle or change of the direction.

The objective of the emotion **fear** is to protect, escape or avoid an specific situation (fight or flight response). The **fear** emotion has a more intense rejection purpose than the disgust emotion. Also, **fear** could produce a need of protection. When the emotion is generated due to the need to escape then the signal should be sent to the transmission. On the other hand, if the required action is protect, then the signal should be sent to the body, doors and dashboard. In table 3.8 is possible to see that the **stress** emotion also contains the systems dashboard, doors and body. As it was mention previously, stress is model as an emergent emotion of protection, then the stress will increase the signal to the systems that would protect the user against danger. The protection should activate all the active safety systems. In consequence, the activation of a protect response or escape response is function of the stress factora and **fear** emotion.

The emotion **happiness** has the functionality of openness or generate a reward to the system about an outcome. Then, it can trigger an action of sharing (openness) and storing (reward) the strategy the vehicle followed to achieved an specific goal. In the case of a machine learning implementation, a reinforce learning model could benefit on storing and analysing the data from a succeeded goal, hence the system decision process unit should receive a signal. Furthermore, using a collective manoeuvring, sharing the positive outcome could benefit a cloud machine learning algorithm, thus the communication system should received the signal too. Therefore, the systems that should received a signal are the cabin, decision process unit and communication. The cabin receives the signal to communicate the result to the user, this can give more transparency to the specific strategy followed.

The emotion **sadness** aims to slowdown some systems and to process and reflect upon an action. The emotion **sadness** could act as a trigger to record an specific action, process it and send it to a cloud. The actions could be

[1] ECU:Electronic Control Unit

[2] The decision process unit is defined as the computing resource dedicated to make decision of an autonomous vehicle

then process in a machine learning algorithm for the benefit of collective manoeuvring with higher safety standards. Then, the systems to receive the signal should be the communication, the decision process unit and the vision system. I represented the vision system as the windshield and the illumination system. Also, the emotion should be communicated to the user then the cabin should also receive a signal.

Finally, the emotion **surprise** is computed when an unexpected stimuli occurs. In the driving domain an unexpected event means an unexpected obstacle appearing, which yield the need for emergency stop. In consequence, the resources should go to the transmission so it has the necessary resources to stop the vehicle in a safe manner.

The framework is implemented using the rules stated in table 3.8. When an emotion intensity is computed the signal is model as a colour changed in the vehicle body, motivated by the work in [28]. Also, depending on the intensity of the emotion the colour is selected. The signal straight is send using the colour standard shown in figure 3.5.

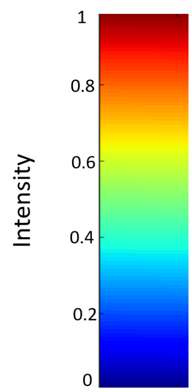


Figure 3.5: Colour standard representing the intensity of the emotion on the body of the vehicle.

3.13 Summary

This chapter presented the methodology followed to design the system CarESP, and a detailed explanation of the design of the system. Section 3.1 describes SYSMOD steps, a MDSE methodology. Section3.2 shows the elicited requirements extracted from the research questions. Section 3.3 describes the CarESP system context. Section 3.4 describes the Use Cases of the CarESP, showing the new functionalities such as **Compute SystemStress** and its components, **Detect Scenario**, **Compute Personality_Utility** and its components, and **Embody Emotions**.

Section 3.5 shows the CarESP architecture, showing all the modules: new, changed and original. Then the chapter describes each new and changed modules. Section 3.6 describes the changes in the **Input Module** and its functionality. Section 3.7 describes the functionality of the **Health module**. Section 3.8 shows the model of the stress factor and the procedure to compute the stress factor, all the components of the **Stress Module** are described in this section. Section 3.9 describes the rules followed by the **Scenario detection module** to identify a scenario. Section 3.10 describes the **Personality Module** functionalities and its components. Section 3.11 describes the functionalities of the **Emotion Module** and its database. Finally, section 3.12 describes the **Body Mapping Module**, which is a framework design for the data transmission of emotions and their intensities to the vehicle's systems.

Chapter 4

Test design and results

This chapter describes the unit tests and system test design. The chapter also presents the results of each tests. The discussion of each test is presented in chapter 5. First, the chapter presents the testing design and results of the health module, the stress module, the personality module and the emotion's body mapping. Then, the test design and results of the the system is described.

4.1 Unit results

This section presents the design of each unit test and the result of the tests. First the test for the health factor. Second, the test for the stress factor. Third, the test for the personality module. Finally, the test for the body mapping module.

4.1.1 Health Module test

The results of the health factor are shown in table 4.1. The first test, in table 4.1, consisted in setting the best state value of all behavioral variables, the result yielded a health factor of 5. The second test consisted in setting the worst state value to all the behavioral variables, which result yielded a health factor of 1. The results of these two test is the expected results, because the best and worse values of the behavioural variables yield the expected results.

Test 3 shows the impact of the behavioral variables labelled as safety, by setting the worst state value to the safety variables and the best state value to all the others, the health factor is just above the average health value ($H\bar{F} = 3$). The results of the health factor showed that the behavioral variables labelled as safety contributes greatly to the over-all health factor computation, this results is desired, because shows that the safety state is a major contributor to the health of the vehicle.

Test 4 consisted in setting the worst state values to the behavioral variables labelled as trustworthiness. The result showed the impact of the variables "trustworthiness" was less than from the "safety" variables, obtaining a health factor of 4.5. These result showed that the behavioral variable labelled as trustworthiness has a minor impact to the over-all health, although still affects the health and then the emotion computation. The results of the HF on test4 is desired.

Finally, test 5 considered setting the state value to the worst state for the safety and trustworthiness labelled variables. The result was a value of the health factor of 2.58, showing the dynamic calculation of the health factor. Also, the results $HF = 2.58$ shows that if 2 the greater contributor and the lowest contributor to the HF have their worse value they will drop the HF to a value below the average, which will amplified negative emotions in the **Emotion Module**.

#	Description	Result
1	Set the best state value to all the behavioral variables	5
2	Set the worst state value to all the behavioral variables	1
3	Set the best state value for all behavioral variables with the exception of the variables libelled as safety. The safety labelled variables are set to have the worst state value	3.06
4	Set the best state value for all the behavioral variables. Except for the variables labelled as trustworthiness, which are set to have the worst state value	4.5
5	Set the best state value for all the behavioral variables except for the variables libelled safety and trustworthiness. These variables are set to have the worst state value	2.58

Table 4.1: Results of health factor tests.

4.1.2 Stress Module test

All the test for the stress factor were computed using the 3D environment, setting one vehicle (ego-car) in the environment. The duration of the driving depends on the test. The unit test for the stress factor were performed per component.

First, the component **Health Stress** was tested. This stress is a function of the vehicle's distance travelled. The initial distance was set at 14,000 km, then the distance was increased with time. At the same time, the **Vehicle's Operation State (VOS) Stress** was computed.

Second, the component **Competency Stress** was tested. The test consist in beginning with the probability of not recognising objects (P_{NRO}) equal to 0, and all the enhancing systems such as V2V, V2I, digital data communication and cooperative manoeuvring disabled. Then in the second 15 P_{NRO} is set to 0.5. In the second 30 the first variable the V2V was enable. In the second 40 the V2I was enable. In the second 50 the digital data connectivity was enable. In the second 60 the cooperative manoeuvring was enable. Finally in the second 70 the P_{NRO} was equal to 0 again.

Finally, the test for the component **Environmental Stress**. For this test, the probability of accident in an specific road (P_{RAcc}) was set to be 11% , the weather state was set to clear sky, and the road surface was set to asphalt. In the second 40 the weather state was change to Sunny. In the second 55 the weather state was set to rain. In second 70 the weather state was set to snow. In second 90 the weather state was set to storm. Then in second 110 the road surface state was set to concrete. In second 140 was set to ice. In second 160 the road surface was set to wet. In second 180 the road surface state was set to no road. Finally in second 240 the initial values of the variables were set.

Figure 4.1 left shows the results of the health stress test. The **Health Stress** increasing trend can be seen (blue line). This figure also shows the variance of the **VOS Stress** (purple line). In addition, the figure shows that the component with the highest probability plays a high role in the computation of the total stress (green line). The total stress is always above any stress component. In second 70 is clear that the components **Health Stress** and **VOS Stresss** are together forming the total stress, being the **Health Stress** the main cause of stress.

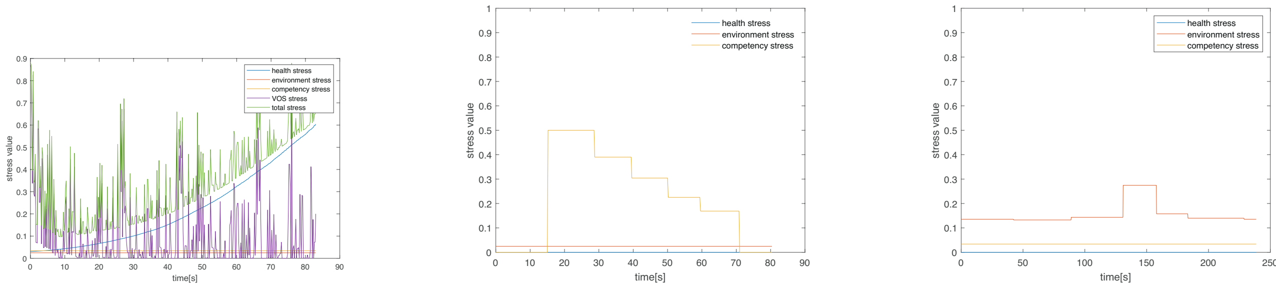


Figure 4.1: Left: results for health and vehicle's operation stresses, centre: results for capability stress, right: results for environmental stress.

Figure 4.1 centre shows the result of the competency stress test. This figure only contains the components: **Competency Stress**, **Environmental Stress** and **Health Stress**. It was decided to just show this three components to observe clearer the **Competency Stress** behavior. The increase of the **Competency Stress** was high in second 15. In the subsequent seconds, it is clear when each system was enable, decreasing the **Competency Stress** in each step. Each decrease depends on the improvement value (PI_j) to the object recognition task of each system.

Figure 4.1 right shows the results of the **Environmental Stress** test. The increase of accident probability of each weather state can be seen in table C.3. In second 140, the road surface state ice was selected, increasing the **Environmental Stress** to a value above 0.3.

4.1.3 Personality Module test

The tests for the personality module were perform using the 3D environment in Unity Game Engine. The scenario **lane change** was selected to perform the test of the personality, because it has a an stable speed during the simulation.

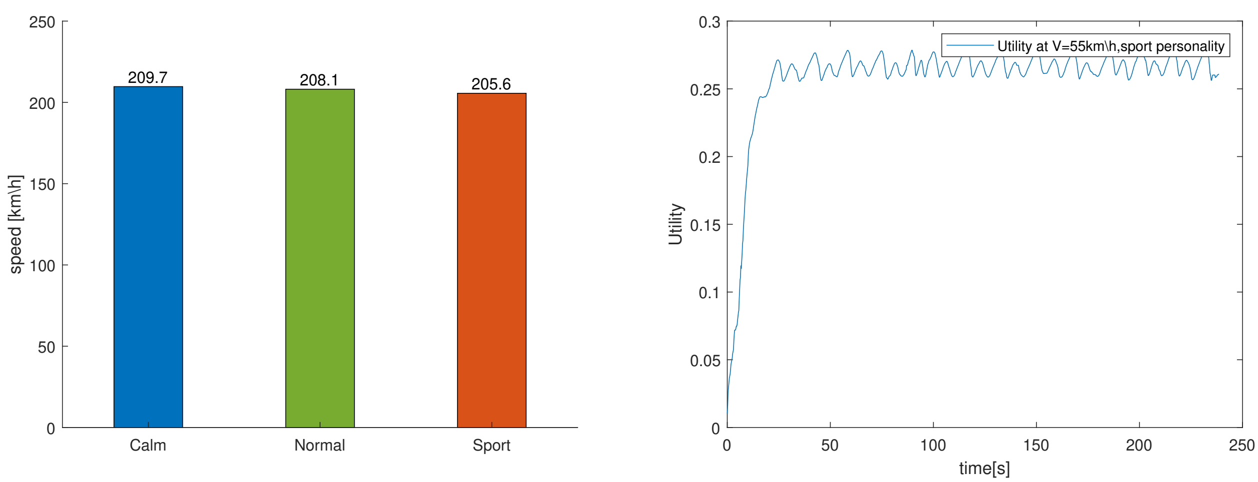


Figure 4.2: Left: balancing utility optimisation for event lane change in different DS. Right: utility computation for sport personality at 55 $[km/h]$ average speed.

Figure 4.2 shows the results of the personality module tests. Figure 4.2 left shows the results of the optimisation of the speed for each personality in the **lane change** scenario. It shows that the optimised speed for the calm personality is higher that the normal, and the former higher than the sport personality. Also it shows that the optimised speed is higher that 200 [km/h]. The results in figure 4.2 are higher than expected and follows a inverse trend than expected.

Figure 4.2 right shows the computation of the utility of an scenario **lane change** for a sport personality with an average speed of 55 [km/h]. Figure 4.2 shows the computation in each instant of the utility as a function of the speed that varies during the simulation, showing a real-time utility computation according to the utility model.

4.1.4 Emotions body mapping

The emotion's body mapping test was performed using the 3D environment. The test was conducted using the scenario **Following Car**. This scenario was selected because it shows a variety of emotions that allows the visualisation of the embodiment.

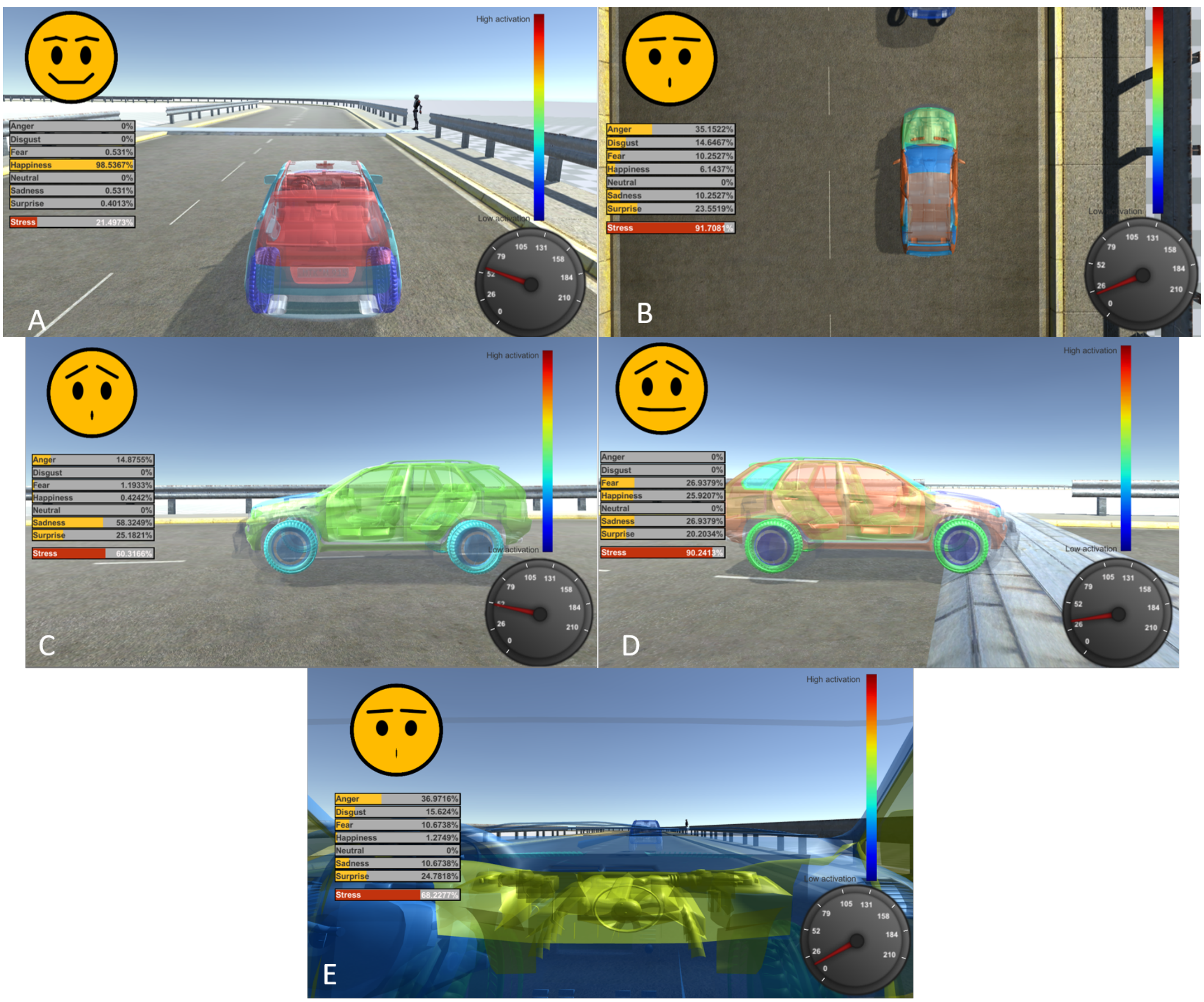


Figure 4.3: Emotions body mapping results. A: rear camera; B: sky camera; C: left camera; D: right camera,E: cabin camera.

Figure 4.3 shows some results of the emotion body mapping in different camera views. Each view also contains a different set of emotions. Figure 4.3-A shows the emotion of happiness and the systems which receive the high intensity signal (red colour), which is the cabin. In 4.3-B the system shows high stress and anger, then the signal was distributed between the motor (colour green) and the doors and tires (colour orange), showing greater intensity on the doors and tires. Figure 4.3-C shows sadness and high stress distributing the signal between the body of the vehicle, the tires and the cabin, which represent the active safety systems. Figure 4.3-D shows that the dominant emotions are stress and fear, this combination shows the high intensity signal to the active safety system such as the body of the vehicle, also it shows a medium signal to the tires. Finally, figure 4.3-E shows the cabin view with a emotion of high stress and anger. The high stress sent an intense signal to the dashboard presented in yellow colour.

4.2 System test

The tests of the system were performed in a 3D environment design in the Unity Game Engine. The connection between the Unity game engine and Matlab/Simulink was done by a UDP communication protocol. The UDP protocol was selected due to its fast data transfer. A few snapshots of the test scenarios are shown in the figure 4.4.

The testing consisted in five different scenarios presented in figure 4.4. These scenarios were design to test the behavior of the system. The first three scenarios involved only one test vehicle (ego-car) which contained the emotion system (CarESP). The 4^{rd} and 5^{th} scenarios had a second vehicle, which is called leading vehicle. For the first four scenarios the vehicles were driven for a total of 2.5 $[km]$, a path was designed for the ego-car to follow during the tests.

For all the scenarios, the torque of the ego-car was 530$[Nm]$. For the 4^{rd} and 5^{th} scenarios, the leading vehicle maximum torque was 480 $[Nm]$. Also, the ego-car could approach the leading vehicle to a maximum of 4.5 [m], and its maximum gap distance is 8 [m]. The gap interval allows the test of TTC stress computation variation.

An statistical analysis was performed for all the collected data. For each goal and event the values of emotions and stress is collected with fix time rate of 0.2 [s]. The mean and variance of the emotions and stress value are reported.

For all the tests, the behavioral variables of the health stress, competency stress and environmental stress were set to have their best state values. This set up allows the simulation to consider only the vehicle's operation state as the main stress factor contribution. This is justified because the other stress' components are used in planning stages.

Each table contains the mean value and in brackets the variance, which presented in percentage notation (%) to facilitate the reader. The results display in all the figure is presented within a range of 0 to 1, which is the value range computed from the system for emotions and stress.

4.2.1 Systems test results

The results for the goals *Speed-limit* and *Curve handle* are shown in figure 4.5. Figure 4.5-left shows the results of the goal *Speed-limit* while figure 4.5-right shows the results of the goal *Curve handle*. The numeric value of the goals *Speed-limit* and *Curve handle* results are presented in table 4.2.

Figure 4.5-left shows the emotions and stress values from 0 to 1 and their variance in brackets. The figure shows that in the event under-speeding the dominant emotion was happiness, followed by fear, sadness and then surprise. While the event over-speeding the dominant emotion was still happiness with a decrease of 8%, emotions like sadness and surprise showed an increased, while fear decreased and the emotion anger appeared. Also the difference appeared

Figure 4.4: Testing scenarios. A. Driving in straight line, B. Curve Handling, C. Lane change, D. Following vehicle, E. Overtaking.

in the stress mean value increasing by 1% in over speeding limit. These results showed to be stable because the variance is low. The results are coherent with the stress model because the negative and positive emotions are influenced by the stress.

Figure 4.5-right shows the results of the curve handle goal. In the *event - proper curve handle* the dominant emotion was happiness. While in the *event improper curve handle* sadness and surprise were the dominant emotions. The stress was also a clearly different in each event. The stress in the *event - proper curve handle* was 4 times smaller than the stress in the *event - improper curve handle*. These results also showed high stability like the results on the goal speed limit, due to their low variance. These results are coherent with the stress model, which increase the values of the negative emotions when the stress is high.

The results of the goals *Lane change: event - proper lane change* and *Car following: event - proper distance with agents* are shown in figure 4.6. This figure shows the results obtained setting the likelihood of failure (LoF) fix and

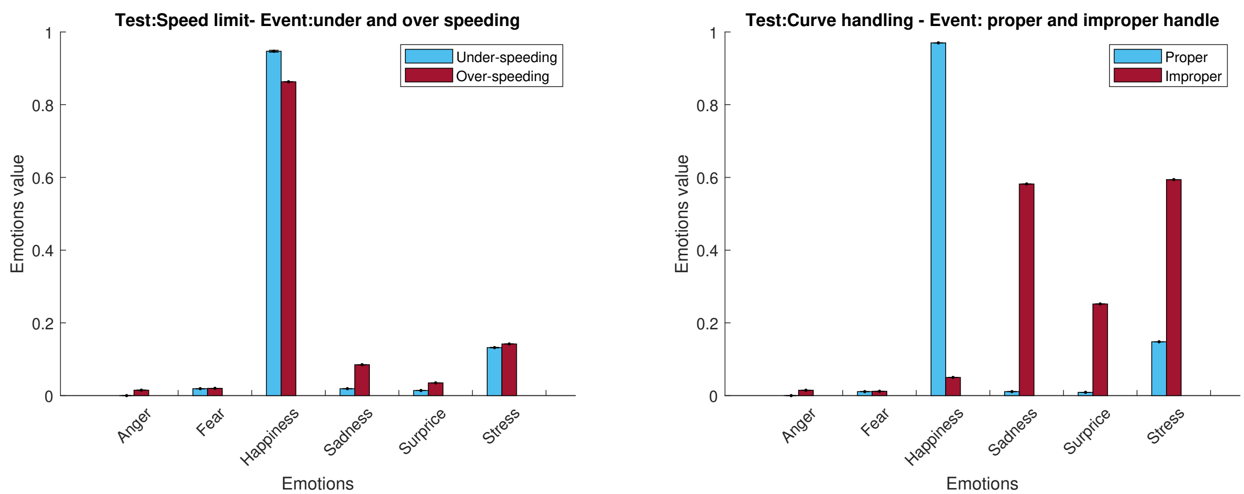


Figure 4.5: Results. Left: goal speed limit. Left: goal curve handle.

Emotion	Goal:Speed-limit		Goal:Curve handle	
	Under speed limit	Over speeding limit	Proper	Improper
Anger	0 (0.1)	1.5 (0.01)	0 (0)	14.8 (0)
Disgust	0 (0)	0 (0)	0 (0)	0 (0)
Fear	1.9 (0.15)	0.2 (0)	1.1 (0.06)	1.2 (0)
Happiness	94.8 (5.13)	86.3 (1.13)	97 (0.5)	0.5 (0)
Neutral	0 (0)	0 (0)	0 (0)	0 (0)
Sadness	1.9 (1.56)	8.5 (0.44)	1.1 (0.06)	58.2 (0)
Surprise	1.4 (0.34)	3.5 (0.07)	0.9 (0.04)	25.2 (0)
Stress factor	13.2 (2.28)	14.2 (1.55)	14.8 (1.42)	59.4 (0.49)

Table 4.2: Results of the scenarios speed limit and curve handle.

setting LoF equal to the stress factor, then dynamic LoF. The numeric value of the goals *Lane change: event - proper lane change* and *Car following: event - proper distance with agents* results are presented in table 4.2.

Figure 4.6-right shows the results for the goal *Lane change: event - proper lane change*. Figure 4.6 shows that the dynamic LoF changes slightly the results. It shows that the dominant emotion was happiness for both tests but a lower value for the the fix LoF test than the dynamic LoF text. Also, the dynamic LoF showed lower variance than the results for the fix LoF. The difference in stress factor was small, having a difference of 1.4% between tests. The small differences in results between the fix LoF and the dynamic LoF is due to the low stress in the **Lane change** scenario. Then the results are coherent with the stress model.

The results of the scenario *Car following: event - proper distance with agents* are shown in figure 4.6-right. These results showed four dominant emotions for both tests: fix and dynamic LoF. The happiness value on the fix LoF is smaller than in the dynamic LoF. However, the values of the fear, sadness and surprise emotions are higher in the fix LoF than in the dynamic LoF. Also, the stress factor was higher in the fix LoF test, than in the dynamic LoF by 6.9%. The higher mean value of stress in the fix LoF test generated the higher values of negative emotion. These results were expected because the dynamic LoF in a positive event can increase the values of the positive emotions.

Figure 4.7 show the scenarios *Car Following: event - improper distance with agents* and *Overtake: event- no collision detected* tests, to analyse the behaviour of the personalities. The numeric value results of the goals *Car Following: event - improper distance with agents* and *Overtake: event- no collision detected* are shown in table 4.4. Figure 4.7-right shows the results of the scenario *Car following- event: improper distance* and figure 4.7 left shows the

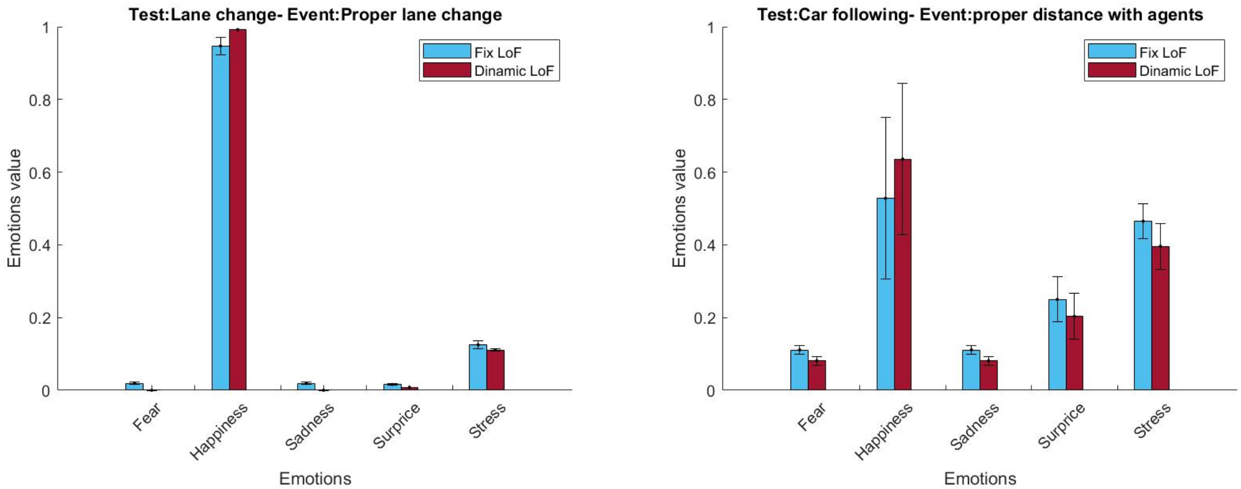


Figure 4.6: Results. Left: Proper lane change event emotions and stress. Right: Car following, improper distance.

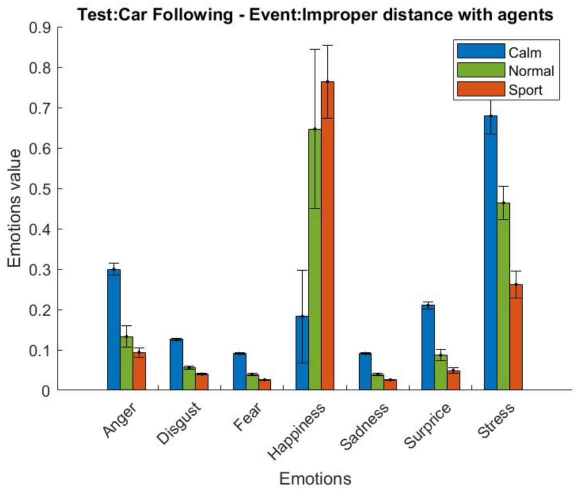
Emotion	Lane change - proper lane change		Car Following: proper distance	
	Fix LoF	Dynamic LoF	Fix LoF	Dynamic LoF
Anger	0 (0)	0 (0)	0 (0)	0 (0)
Disgust	0 (0)	0 (0)	0 (0)	0 (0)
Fear	1.9 (0.3)	0 (0)	11.1 (1.2)	8.1 (1.2)
Happiness	94.7 (2.4)	99.2 (0)	52.8 (22.3)	63.6 (20.8)
Neutral	0 (0)	0 (0)	0 (0)	0 (0)
Sadness	1.9 (0.3)	0 (0)	11.1 (1.2)	8.1 (1.2)
Surprise	1.6 (0.2)	0.8 (0)	25 (6.3)	20.3 (6.3)
Stress	12.5 (1.1)	11.1 (0.3)	46.5 (4.8)	39.6 (6.3)

Table 4.3: Results of the events proper lane change and proper distance with agents.

results of the scenario *Overtake - event: no crash detected*. The test for the scenario car following had an mean speed of 53[km/h]. The test for the scenario overtake had a average speed of 52.3 [km/h]

The results of the scenario *Car following - event: improper distance* (figure 4.7-left) shows that each personality computes different emotions intensity. The personality calm showed the highest mean value of the emotions anger, disgust, fear, sadness and surprise 0.21(21%, and the lowest happiness mean value. The normal personality showed mean values of all emotions located between the mean values of the calm and the sport personalities. The personality sport showed the lowest mean value of the emotions anger, disgust, fear, sadness and surprise, and the highest happiness mean value. The stress factor showed a similar trend as the negative emotions, the highest stress was experienced in the calm personality, the normal personality was the second highest and the lowest stress mean value was experience by the sport's personality. The results are coherent with the aggressiveness of the personalities, I was expecting that the negative emotions were more intense in a calm personality than in a normal personality and the former more intense than in a sport personality when an improper distance is taken by the ego-car.

A similar trend can be seen in the results for the *Overtake scenario:event - no crash detected* (figure 4.7-right). The positive emotion, happiness, was experienced less in the calm personality, the second lowest was experienced by the normal personality and the sport personality experienced the highest happiness value. The stress and the negative emotions such as fear, sadness and surprise were experienced with more intensity in the calm personality. The second highest personality which experienced negative emotions and stress was the normal personality. Finally, the sport personality experienced the lowest negative emotions and stress. The mean stress value experience on the calm personality is nearly 4 times higher than in the sport personality. These results are coherent with the risk



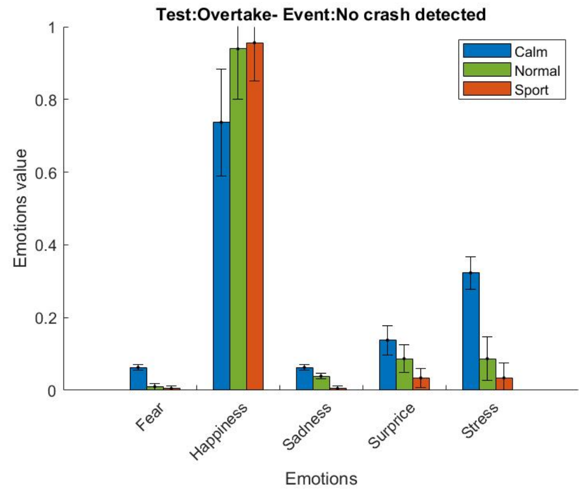


Figure 4.7: Results. Left: Car Following, improper distance. Right: Overtake, non collision detected.

aversion of each personality, which stress is expected to be higher in a calm personality driving in a similar speed and gap than a sport personality.

Emotions	Car following : event - improper distance			Overtake: event - no collision		
	Calm	Normal	Sport	Calm	Normal	Sport
Anger	30 (1.5)	13.3 (2.7)	9.4 (1.2)	0(0)	0 (0)	0 (0)
Disgust	12.6 (0.3)	5.6 (0.5)	4 (0.2)	0 (0)	0 (0)	0 (0)
Fear	9.1 (0.1)	3.9 (0.2)	2.6 (0.1)	6.3 (0.8)	1 (0.8)	0.5 (0.7)
Happiness	18.3 (11.5)	64.7 (19.6)	76.4 (9)	73.7 (14.7)	93.9 (13.7)	95.6 (10.5)
Sadness	9.1 (0.1)	3.9 (0.2)	2.6 (0.1)	6.3 (0.8)	1 (0.8)	0.5 (0.7)
Surprise	21 (0.8)	8.7 (1.3)	4.9 (0.6)	13.8 (4)	4.1 (3.8)	3.4 (2.6)
Stress	67.9 (4.5)	46.4 (4.1)	26.2 (3.3)	32.3 (4.5)	15.6 (6.1)	8.8 (4.2)

Table 4.4: Results of scenario Car Following: event - improper distance and scenario Overtake: event - no collision.

4.3 Summary

This chapter showed the design of the unit tests and the systems test. The unit test of the health factor, stress factor and emotion body mapping showed coherent results according to the design and purpose of the system unit. Nonetheless, the test for the personality module showed non promising results, yielding the need to do further research to model the utility of the speed parameter.

In addition, this chapter showed the results of the systems tests. The goals tested were *Speed limit*, *Curve handle*, **Lane change**, **Car following** and **No collision during Overtake**. The results were promising, showing the behavior of the stress factor in the emotions computation. The results also showed the differences between the use of a fix LoF and a dynamic LoF; showing that a dynamic LoF aids in the computation of emotion's intensity. Finally, the systems tests showed a clear trend for personalities, showing that the intensity of negative emotions for less aggressive personalities, such as the calm, are higher than for a more aggressive personality, like the sport.

Chapter 5

Discussion, conclusions and future work

This chapter shows the discussion and conclusions of the results shown in chapter 4. Section 5.1.1 shows the discussion and conclusion of the unit tests. Section 5.1.2 shows the discussion and conclusion of the system tests and explains how the research questions are tackle by the system CarESP design and behaviour. Finally, section 5.2 suggests future research work.

5.1 Discussion and conclusions

5.1.1 Unit results discussion

- The test of the **Health Module** showed that the health factor computation is coherent with its design. They showed that safety behavioral variables have great impact to the over-all health of the system, which then translate in emotions computation.
- The results of the **Stress module** showed to be coherent with its design, and how its components behave. The results showed how the **health, competency and environmental stress** interact with the overall stress computation.
- The **Health stress** results showed that the health stress increases with the degradation component with the shortest life-span, which in this case are the braking equipment (table C.1). This can be used to warn the user for a possible failure or for the system to consider a different strategy to follow due to possible failure of one component.
- The **Competency stress** results showed how the systems V2V or V2I aid the object recognition by reducing the stress. Thus, if the system faces with a high uncertainty in object recognition it can use other systems in order to compensate the uncertainty. Although, a more robust model should be generated that can consider a dynamic computation of the uncertainty and how each system could aid the object recognition. Moreover other competencies should be incorporated such as control or decision making.
- The **Environmental stress** results showed that the system can predict a probability of accident due to external condition, this information can be used in planning the path of the vehicle, maybe avoid dangerous streets.
- The **VOS stress** showed results in real-time, increasing and decreasing the stress depending on the state of the vehicles operations. For example if the vehicles was accelerating and it reached a force magnitude superior to

the friction force, at that moment the vehicle's operation stress was high. This behavior can also be observed when the ego-car was too close to the leading vehicle, increasing the stress, but when the ego-car increase the gap, the stress decreased. The results of the **VOS stress** are helpful to evaluate a operation state which is dangerous for the driver, as a function of the user behaviour. The user behaviour is parameterized in the **VOS stress** by fitting the stress parameters of the average acceleration, speed and gap into the components of the **VOS stress**.

- The design of the **stress factor** allows to combine an optimisation algorithm to minimise the stress of the vehicle by removing the stressor, or implementing strategies to deal with the stress.
- The results of the **Personality module** showed the **Utility** computed in real-time and as a function of the speed. The results of the utility are coherent with the real-time fluctuation of the speed.
- The **optimised speed** of the vehicle changed during the simulation as a function of the personality. Although, the speed optimisation component did not show promising results. The trend showed in figure 4.2-left clearly shows an opposite expected trend, the calm personality should compute a lower speed than the normal and the former a lower speed than the sport personality. It also shows much higher values than expected. The values of the speed are above 200 [km/h] which are not safe speeds in many scenarios.
- In conclusion, the used of the Constant Relative Risk averse CRRA as a utility function in combination with the proposed stress factor does not work, because the resulting balance utility maximum could go to infinity if the function would not have been bounded by the maximum speed the vehicle can offer. Then, a utility function needed to be constructed which has a maximum value within the bounded speed, similar to Dixit et al. approach [23]. This function can be constructed by measuring the stress of the driver in different speeds [53].
- The results of the **Body Mapping module** showed that each emotion sent a signal intensity to the designated system. Also, they showed the combination of fear and stress signals. In figure 4.3-D clearly shows a fear intensity of 26% and a high stress factor (98%), this scenario showed the prioritisation on the active safety components. Figure 4.3-D that the colour is close to red for the body of the vehicle because it is predicting a high probability of an accident; but at the same time is sending a signal to the tires to perform an action. In consequence, the results showed a promising framework.

5.1.2 System results discussion

- The results on the *Speed limit* goal showed similar results for the events under and over speeding. In this goal, the **stress factor** is not used as a selection variable for the scenarios. They showed influence of the stress factor in the emotions computation, the changes in happiness, sad and surprise emotions were small because the **stress factor** differences were small. To personalised this computation the DoS and DoS should be correlated to the driver's personality, this parameterisation will yield stronger differences between the events emotions computation.
- The *Curve handling* goal results showed the used of the stress factor as a selection variable between events and as the value of LoF. It is safe to conclude that the emotions of sadness and surprise intensity were increased due to the stress computation. The generation of an improper curve handle is a function of the vehicle's state (acceleration and speed) during the curve. The emotion sadness presence infers that the curve should be taken in a safer way, thus, reflect upon the vehicle's safety state of the curve. Then, the **stress factor** showed its importance and use as a selection variable by aiding the intensity of the sadness and surprise emotions.
- The tests of the goal *Lane change* and *car following* showed the results of using the **stress factor** as the LoF. They showed promising results to use the **stress factor** as the LoF.
- In the *Lane change* goal scenario the differences between fix and dynamic LoF are small. The dynamic LoF showed more stability and an increase in the happiness generation when proper lane change was performed.

- In the goal *Car following* the use of the stress factor as LoF was clearly shown. It shows that emotions generation are more intense when the LoF is dynamic. In consequence, the intensity of the signal will be more accurate as a function of the danger of the situation.
- The fix LoF did not allow to consider the danger of the situation or the measurement to fail the goal. Hence, these scenarios showed the value of the stress factor as the definition of LoF.
- The results of the personalities in the *Car following* and *No collision Overtake* goals showed the functionality of the vehicle's operation state stress as a personalization variable. Figure 4.7 shows that for each personality the emotions can be unique, due to the **stress factor** computation.
- For the goal *Car following*, the simulations between personalities were designed for the ego car to be in a similar gap. Then, the calm personality should experience negative emotions and stress with more intensity, than the normal personality and the former experienced higher intensity of negative emotions and stress than the sport personality, based on the parameters of each personality. The results are coherent, and showed a clear trend of stress and negative emotions intensities between personalities.
- In the goal *No collision during overtake*, the positive emotions should be more intense for the calm personality, but he trend shows otherwise. The trend showed in the *No collision during overtake* goal was due to the decay of emotions. During all the simulation, the calm personality was more stress, showed in the stress values, because of the gap between vehicles, then the negative emotions were computed. Even after the vehicle has detected no crash, the negative emotions appeared in the computation. This explanation is also valid for the trend in the normal personality respect to the sport personality. It is safe to conclude, that the **stress factor** is also a good tool to personalise the emotions computation.

Then the research questions can be answer as follow.

1. **How to design a primary emotion component for an emotion vehicle model?** The stress factor can be used as a primary emotion component. It is design as a survival mechanism. Also as a decision variable and equal to the LoF in the emotion model.
2. **How to design a vehicle's personality based on the emotion generation for an autonomous vehicle application?** The **stress factor** component, **vehicle's operation state (VOS) stress**, is the tool to personalise the emotions computation. The attempt to compute the utility for speed was not successful, but a different utility function can be designed. The stress factor is still valid to personalised the emotions computation.
3. **How to design a framework for a data communication in the vehicle based on emotion computation?** The emotion's body mapping showed promising results. This framework can be used. It is based on the functionalities of the basic emotions. A more robust framework can be designed by analysing each of the 22 emotions than can be computed in OCC model.

5.2 Future work

- Nowadays, this system can be implemented in an ADAS system. The emotion generation model can aid the driver to increase the level of safety in his or her driving behaviour, with the personality parameters, the system considers the comfort of the driver. Thus, in future work how to implement this system in an ADAS can be explored.
- This system can communicate with the external systems such as intelligent infrastructure and IoT systems. The communication can increase the safety features and comfort. Then, in future research, how to connect the systems and what data should be exchange should be explored.

- This graduation project designed the concept of the **stress factor**. This concept showed to be useful, but still need a more robust implementation. Particularly for the components **competency and environmental stress**. The competency component needs to be design to reflect all the capabilities to autonomously drive the system and detects gaps in automation. The component of environmental stress should consider all the external parameters that affects a driving situation.
- The implementing a **predictive path collision** [54] can enhance the collision prediction. A **predictive path collision** is a model that can successfully computes a path of at least 50 [cm] ahead, which then accelerate the computation of collision objects. A **predictive path collision** can also allow the implementation of probability of collision with non-moving objects, with no noise.
- This project showed conceptually that **personalisation of the emotions** can be performed. Thus, further research on parameters that describes the driving style in a real driving situation the user should be modelled. Furthermore, a larger implementation should be done, using a multi parameter utility function or multiple utility functions to represent a more complete definition of driving benefit for a user.
- Also, a **machine learning** algorithm to learn from the user should be defined. The current system assumed the parameters to test the system, but it did not feed any training data. In consequence, the data should be generated or find in previous research and a machine learning algorithm implemented to generate a system that represent an actual driving style.
- The project designed the **communication framework of emotions** with systems on the vehicle. A future work can dedicate to generate a model to establish strategies for each emotion. The strategies translate in generating a decision making algorithm based on emotions, so each system has dedicated activities depending on emotions and their intensity. A model with strategies could be the first attempt to construct a emotional intelligence vehicle, completing the affective computing model in automotive domain.
- This system parameter of Likelihood of failure (LoF) is a parameter than can be used to analyse the **functional safety** of the scenarios, **lane change** and **curve handle**. The stress factor is being used as the LoF, and it is a measurement of the probability of an accident, then, the Stress factor can be used as a functional safety parameter. Hence, functional safety analysis using the SF should be consider for future work. furthermore, extending the SF concept or similar indicators can improve an analysis of functional safety in the automobile domain.

5.3 Summary

This chapter discuss and concluded all the test. The unit test for the **Health module**, **Stress module** and **Body mapping module** discuses the promising results. However, the results for the **Personality module** showed a discrepancy between the utility model and the dis-utility model, showing that different model for the utility function should implemented, a data-driven model could be tested.

The system tests results also shown promising results. This chapter discusses the positive use of the **stress factor** as a event identification variable, also as the value of LoF (likelihood of failure). The test results also demonstrate the possibility to compute personalised emotions using the **stress factor** as a personalization tool, with the component **VOS stress**.

Finally, future work is also suggested in this last chapter. The future work concentrates in improving the current CarESP system and in the implementation of the emotional intelligence component in an automotive domain.

Bibliography

[1] R.W. Picard. *Affective Computing.* The MIT press, United States, 1997.

[2] Jean-Marc Fellous. From human emotions to robot emotions. *American Association for Artificial Intelligence*, 2004.

[3] S. G. R. Chouhan. An emotion model of a vehicle. Master's thesis, Eindhoven University of Technology, Eindhoven, Netherlands, August, 2019.

[4] T. Weilkiens. *Systems Engineering with SysML/UML: Modeling, Analysis, Design.* The MK/OMG Press. Elsevier Science, 2011.

[5] Eerik Vesterinen. Affective Computing. *Research Seminar on Interactive Digital Media*, page 11, 2001.

[6] Florian Eyben, Martin Wöllmer, Tony Poitschke, Björn Schuller, Christoph Blaschke, Berthold Färber, and Nhu Nguyen-Thien. Emotion on the Road-Necessity, Acceptance, and Feasibility of Affective Computing in the Car. *Advances in Human-Computer Interaction*, 2010:17, 2010.

[7] Sven Kraus, Matthias Althoff, Bernd Heißing, and Martin Buss. Cognition and emotion in autonomous cars. In *IEEE Intelligent Vehicles Symposium, Proceedings*, pages 635–640, 2009.

[8] Victoria Mattingly and Kurt Kraiger. Can emotional intelligence be trained? A meta-analytical investigation. *Human Resource Management Review*, 29(2):140–155, 6 2019.

[9] Christopher T. H. Miners, Stéphane Côté, and Filip Lievens. Assessing the Validity of Emotional Intelligence Measures. *Emotion Review*, 10(1):87–95, 1 2018.

[10] Gerald Clore Andrew Ortony and Allan Collins. The cognitive structure of emotions. *Cambridge university press,*, 1990.

[11] Dajsuren Yanja and Mark van den Brand. Automotive Systems and Software Engineering. *Springer*, 2019.

[12] WS Neal Reilly. *Believable social and emotional agents.* PhD thesis, Carnegie Mellon University, USA, 1996.

[13] Damasio A. Descartes' error, emotion reason and the human brain. Grosset/Putnam, 1994.

[14] SC Segerstrom and GE Miller. Psychological Stress and the Human Immune System; a Meta-analytic Study of 30 Years of Inquiry. *Psychological Bulletin*, (130):601–630, 2004.

[15] Tony Malim and Ann Birch. *Introduction to Psychology.* British Library. McMillan, Press LTD, 1998.

[16] Aaron J. Cunanan, Brad H. DeWeese, John P. Wagle, Kevin M. Carroll, Robert Sausaman, W. Guy Hornsby, G. Gregory Haff, N. Travis Triplett, Kyle C. Pierce, and Michael H. Stone. The General Adaptation Syndrome: A Foundation for the Concept of Periodization, 4 2018.

[17] Clara Marina Martinez, Mira Heucke, Fei Yue Wang, Bo Gao, and Dongpu Cao. Driving Style Recognition for Intelligent Vehicle Control and Advanced Driver Assistance: A Survey, 3 2018.

[18] Orit Taubman-Ben-Ari, Mario Mikulincer, and Omri Gillath. The multidimensional driving style inventory - Scale construct and validation. *Accident Analysis and Prevention*, 36(3):323–332, 5 2004.

[19] Tarek Ouali, Nirav Shah, Bill Kim, David Fuente, and Bo Gao. Driving Style Identification Algorithm with Real-World Data Based on Statistical Approach. In *SAE Technical Papers*, volume 2016-April. SAE International, 4 2016.

[20] Dominik Dörr, David Grabengiesser, and Frank Gauterin. Online driving style recognition using fuzzy logic. In *2014 17th IEEE International Conference on Intelligent Transportation Systems, ITSC 2014*, pages 1021–1026. Institute of Electrical and Electronics Engineers Inc., 11 2014.

[21] Orit Taubman-Ben-Ari and Dalia Yehiel. Driving styles and their associations with personality and motivation. *Accident Analysis and Prevention*, 45:416–422, 3 2012.

[22] Martin Schmidt-Daffy. Prospect balancing theory: Bounded rationality of drivers' speed choice. *Accident Analysis and Prevention*, 63:49–64, 2 2014.

[23] Vinayak Dixit, Glenn W. Harrison, and E. Elisabet Rutström. Estimating the subjective risks of driving simulator accidents. *Accident Analysis and Prevention*, 62:63–78, 1 2014.

[24] Laura Eboli, Gabriella Mazzulla, and Giuseppe Pungillo. How to define the accident risk level of car drivers by combining objective and subjective measures of driving style. *Transportation Research Part F: Traffic Psychology and Behaviour*, 49:29–38, 8 2017.

[25] Cynthia Breazeal and Brian Scassellati. Infant-like Social Interactions between a Robot and a Human Caregiver. *Adaptive Behavior*, 8(1):49–74, 1 2000.

[26] Cynthia Breazeal and Rodney Brooks. Robot emotion: A functional perspective. *J.M. Fellous and M.A. Arbib, Oxford University Press*, 2005.

[27] Lauri Nummenmaa, Riitta Hari, Jari K. Hietanen, and Enrico Glerean. Maps of subjective feelings. *Proceedings of the National Academy of Sciences of the United States of America*, 115(37):9198–9203, 9 2018.

[28] Lauri Nummenmaa, Enrico Glerean, Riitta Hari, and Jari K. Hietanen. Bodily maps of emotions. *Proceedings of the National Academy of Sciences of the United States of America*, 111(2):646–651, 1 2014.

[29] Mahmood Shafiee and Maxim Finkelstein. An optimal age-based group maintenance policy for multi-unit degrading systems. *Reliability Engineering and System Safety*, 134:230–238, 2015.

[30] IBM Corporation. *Rational Rhapsody User Guide*, 2009.

[31] Unity Technologies. Unity user manual (2019.3). `https://docs.unity3d.com/Manual/index.html`. Accessed 04 February 2020.

[32] Inc The MathWorks. Matlab: Object oriented programming. `https://nl.mathworks.com/help/pdf_doc/matlab/matlab_oop.pdf`. Accessed 04 February 2020.

[33] Laura Eboli, Gabriella Mazzulla, and Giuseppe Pungillo. Combining speed and acceleration to define car users' safe or unsafe driving behaviour. *Transportation Research Part C: Emerging Technologies*, 68:113–125, 7 2016.

[34] John C Hayward. NEAR-MISS DETERMINATION THROUGH USE OF A SCALE OF DANGER. *Highway Research Record*, (384), 1972.

[35] G. Underwood. Visual attention and the transition from novice to advanced driver. *Ergonomics*, 50(8):1235–1249, 2007.

[36] Federal Highway Administration. U.S. Departament of Transportation. How Do Weather Events Impact Roads? - FHWA Road Weather Management, 2 2020.

[37] Md Tawfiq Sarwar. *THE EFFECT OF PAVEMENT DETERIORATION ON RURAL AND URBAN ROADWAY ACCIDENT INJURY-SEVERITIES*. PhD thesis, State University of New York, 2016.

[38] Sean T. Doherty, Jean C. Andrey, and Carolyn MacGregor. The situational risks of young drivers: The influence of passengers, time of day and day of week on accident rates. *Accident Analysis and Prevention*, 30(1):45–52, 1 1998.

[39] Directive 2014/45/eu of the european parliament and the council of 3 april 2014 on periodic roadworthiness tests for motor vehicles and their trailers and repealing directive 2009/40/ec, 2014.

[40] Peter Bonsall, Ronghui Liu, and William Young. Modelling safety-related driving behaviour - Impact of parameter values. *Transportation Research Part A: Policy and Practice*, 39(5):425–444, 6 2005.

[41] Eva Ericsson. Variability in urban driving patterns. *Transportation Research Part D: Transport and Environment*, 5(5):337–354, 9 2000.

[42] Ruediger. Lamm, Basil. Psarianos, and Theodor. Mailaender. Highway design and traffic safety engineering handbook. pages 137–171, 1999.

[43] Michiel M. Minderhoud and Piet H.L. Bovy. Extended time-to-collision measures for road traffic safety assessment. *Accident Analysis and Prevention*, 33(1):89–97, 1 2001.

[44] Rune Elvik. A re-parameterisation of the Power Model of the relationship between the speed of traffic and the number of accidents and accident victims. *Accident Analysis and Prevention*, 50:854–860, 1 2013.

[45] Laurens Hobert, Andreas Festag, Ignacio Llatser, Luciano Altomare, Filippo Visintainer, and Andras Kovacs. Enhancements of V2X communication in support of cooperative autonomous driving. *Infocommunications Journal*, 8(3):27–33, 2016.

[46] Dániel Tokody, Attila Albini, László Ady, Zoltán Raynai, and Ferenc Pongrácz. Safety and Security through the Design of Autonomous Intelligent Vehicle Systems and Intelligent Infrastructure in the Smart City. *Interdisciplinary Description of Complex Systems*, 16(3):384–396, 2018.

[47] Henrik Astrom and Carl-Gustaf Wallman. Friction Measurement Methods And The Correlation Between Road Friction And Traffic Safety. A Literature Review. *Vti*, page 47, 2001.

[48] Arshardh Ifthikar and Saman Hettiarachchi. Analysis of historical accident data to determine accident prone locations and cause of accidents. In *Proceedings - International Conference on Intelligent Systems, Modelling and Simulation, ISMS*, volume 2018-May, pages 11–15. IEEE Computer Society, 7 2018.

[49] ERSO. Annual Accident Report 2018. Technical report, 2018.

[50] Rong Chen, Kristofer D. Kusano, and Hampton C. Gabler. Driver Behavior During Overtaking Maneuvers from the 100-Car Naturalistic Driving Study. *Traffic Injury Prevention*, 16(sup2):S176–S181, 10 2015.

[51] Mark R Savino. *STANDARDIZED NAMES AND DEFINITIONS FOR DRIVING PERFORMANCE MEASURES A thesis submitted by.* PhD thesis, Tufts University, Massachusetts, 5 2009.

[52] Stephen P. Greaves and Adrian B. Ellison. Personality, risk aversion and speeding: An empirical investigation. *Accident Analysis and Prevention*, 43(5):1828–1836, 9 2011.

[53] Jennifer A. Healey and Rosalind W. Picard. Detecting stress during real-world driving tasks using physiological sensors. *IEEE Transactions on Intelligent Transportation Systems*, 6(2):156–166, 6 2005.

[54] Aris Polychronopoulos, Manolis Tsogas, Angelos J. Amditis, and Luisa Andreone. Sensor fusion for predicting vehicles' path for collision avoidance systems. *IEEE Transactions on Intelligent Transportation Systems*, 8(3):549–562, 9 2007.

[55] Tarek Sayed, Gerald Brown, and Francis Navin. Simulation of traffic conflicts at unsignalized intersections with TSC-Sim. *Accident Analysis and Prevention*, 26(5):593–607, 10 1994.

[56] Dawn L. Massie, Kenneth L. Campbell, and Allan F. Williams. Traffic Accident involvement rates by driver age and gender. *Accident Analysis and Prevention*, 27(1):73–87, 1995.

[57] Shirley Regev, Jonathan J. Rolison, and Salissou Moutari. Crash risk by driver age, gender, and time of day using a new exposure methodology. *Journal of Safety Research*, 66:131–140, 2018.

[58] H Moskowitz, M Burns, D Fiorentino, A Smiley, and P Zador. Driver characteristics and impairment at various BACs. *National Highway Traffic Safety Administration (NHTSA)*, (April 2016):809–875, 2000.

[59] American Addiction Center. Effects of blood alcohol levels on the body, 2020.

[60] American Addiction Center. Bac legal limits in different sates, countries and cities, 2020.

[61] S. F. Liang, C. T. Lin, R. C. Wu, Y. C. Chen, T. Y. Huang, and T. P. Jung. Monitoring driver's alertness based on the driving performance estimation and the EEG power spectrum analysis. *Annual International Conference of the IEEE Engineering in Medicine and Biology - Proceedings*, 7 VOLS:5738–5741, 2005.

[62] Joanne M. Wood and Rod J. Troutbeck. Effect of age and visual impairment on driving and vision performance. *Transportation Research Record*, 36(1438):84–90, 1994.

[63] Vincent Cantin, Martin Lavallière, Martin Simoneau, and Normand Teasdale. Mental workload when driving in a simulator: Effects of age and driving complexity. *Accident Analysis and Prevention*, 41(4):763–771, 2009.

[64] Lisa A. D'Ambrosio, Laura K.M. Donorfio, Joseph F. Coughlin, Maureen Mohyde, and Joachim Meyer. Gender differences in self-regulation patterns and attitudes toward driving among older adults. *Journal of Women and Aging*, 20(3-4):265–282, 2008.

[65] Sharon Newnam, Ioni Lewis, and Amanda Warmerdam. Modifying behaviour to reduce over-speeding in work-related drivers: An objective approach. *Accident Analysis and Prevention*, 64:23–29, 2014.

[66] Thomas L Mcdole and James O'Day. Effect of commercial vehicle systematic preventive maintenance on specific causes of accidents. Technical report, Highway safety Research Institute, University of Michigan, Ann Arbor, Michigan, 1975.

[67] Reza Tolouei and Helena Titheridge. Vehicle mass as a determinant of fuel consumption and secondary safety performance. *Transportation Research Part D: Transport and Environment*, 14(6):385–399, 2009.

[68] European Union. Directive 2014/45/EU of the European Parliament and of the Council of 3 April 2014 on periodic roadworthiness tests for motor vehicles and their trailers. 2014(March), 2014.

[69] Subir Biswas, Raymond Tatchikou, and Francois Dion. Vehicle-to-vehicle wireless communication protocols for enhancing highway traffic safety. *IEEE Communications Magazine*, 44(1):74–82, 2006.

[70] Chairit Wuthishuwong and Ansgar Traechtler. Vehicle to infrastructure based safe trajectory planning for autonomous intersection management. *2013 13th International Conference on ITS Telecommunications, ITST 2013*, pages 175–180, 2013.

[71] Massimo Cellario. Human-Centered Intelligent Vehicles: Toward Multimodal Interface Integration. *IEEE Intelligent Systems*, 16(4):78–81, 2001.

[72] Michael Fagan, Mohammad Maifi Hasan Khan, and Ross Buck. A study of users' experiences and beliefs about software update messages. *Computers in Human Behavior*, 51(PA):504–519, 2015.

[73] Ali Behnood and Fred Mannering. The temporal stability of factors affecting driver-injury severities in single-vehicle crashes: Some empirical evidence. *Transportation Research Part F: Traffic Psychology and Behaviour*, 1(4):7–32, 2015.

[74] Md Tawfiq Sarwar and Panagiotis Ch Anastasopoulos. The effect of long term non-invasive pavement deterioration on accident injury-severity rates: A seemingly unrelated and multivariate equations approach. *Analytic Methods in Accident Research*, 13:1–15, 2017.

[75] Frank Saccomanno Chris Lee, Bruce Hellinga. Real-Time Crash Prediction Model for Application to Crash Prevention in Freeway Traffic. *Journal of the Transportation Research Board*, 180(1):67–77, 2003.

[76] Diana Hintea, James Brusey, Elena Gaura, John Kemp, and Neil Beloe. Comfort in cars: Estimating Equivalent Temperature for comfort driven Heating, Ventilation and Air Conditioning (HVAC) control. *ICINCO 2013 - Proceedings of the 10th International Conference on Informatics in Control, Automation and Robotics*, 1:507–513, 2013.

[77] Radu Musat and Elena Helerea. Parameters and Models of the Vehicle Thermal Comfort. *Acta Universitatis Sapientiae Electrical and Mechanical Engineering*, 1(January 2009):215–226, 2009.

[78] DICK DE WAARD, MAAIKE JESSURUN, FRANK J. J. M. STEYVERS, PETER T.F. REGGATT, and KAREL A. BROOKHUIS. Effect of road layout and road environment on driving performance, drivers' physiology and road appreciation. *Ergonomics*, 38(7):1395–1407, 1995. PMID: 7635129.

[79] Markku Kilpeläinen and Heikki Summala. Effects of weather and weather forecasts on driver behaviour. *Transportation Research Part F: Traffic Psychology and Behaviour*, 10(4):288–299, 2007.

[80] T. Åkerstedt, G. Kecklund, and L. G. Hörte. Night driving, season, and the risk of highway accidents. *Sleep*, 24(4):401–406, 2001.

[81] J. Todorović, Č Duboka, and Ž Arsenić. Operational life expectancy of rubbing elements in automotive brakes. *Tribology International*, 28(7):423–432, 11 1995.

[82] Troy R. Hawkins, Bhawna Singh, Guillaume Majeau-Bettez, and Anders Hammer Strømman. Comparative Environmental Life Cycle Assessment of Conventional and Electric Vehicles. *Journal of Industrial Ecology*, 17(1):53–64, 2 2013.

[83] E. A. Azrulhisham, Y. M. Asri, A. W. Dzuraidah, N. M. Nik Abdullah, A. Shahrum, and C. H. Che Hassan. Evaluation of fatigue life reliability of steering knuckle using pearson parametric distribution model. *International Journal of Quality, Statistics, and Reliability*, 2010, 2010.

[84] Yong-Sang Kim and Jung-Gu Kim. Evaluation of Corrosion Fatigue and Life Prediction of Lower Arm for Automotive Suspension Component. *Met. Mater. Int*, 23(1):98–105, 2017.

[85] Zhan Guang Zheng, Gan Wei Cai, and Shu Qin Pan. Fatigue life prediction of automotive steel wheel using damage mechanics. In *2010 International Conference on Computer Design and Applications, ICCDA 2010*, volume 3, 2010.

[86] Shmuel L Weissman, Jerome L Sackman, David Gillen, and Carl Monismith. Extending the Lifespan of Tires : Final Report. (July):146, 2003.

[87] Yicong Wang, Gustavo De Veciana, Takayuki Shimizu, and Hongsheng Lu. Performance and scaling of collaborative sensing and networking for automated driving applications. In *2018 IEEE International Conference on Communications Workshops, ICC Workshops 2018 - Proceedings*, pages 1–6. Institute of Electrical and Electronics Engineers Inc., 7 2018.

[88] Yisheng Lv, Yanjie Duan, Wenwen Kang, Zhengxi Li, and Fei Yue Wang. Traffic Flow Prediction with Big Data: A Deep Learning Approach. *IEEE Transactions on Intelligent Transportation Systems*, 16(2):865–873, 4 2015.

[89] Guchan Ozbilgin, Umit Ozguner, Onur Altintas, Haris Kremo, and John Maroli. Evaluating the requirements of communicating vehicles in collaborative automated driving. In *IEEE Intelligent Vehicles Symposium, Proceedings*, volume 2016-August, pages 1066–1071. Institute of Electrical and Electronics Engineers Inc., 8 2016.

[90] Julia B. Edwards. The Relationship between Road Accident Severity and Recorded Weather. *Journal of Safety Research*, 29(4):249–262, 12 1998.

Appendix A

Stress factor mathematical model

This appendix explains in more detail the mathematical modelling of each component of the stress factor.

A.1 Vehicle's Operation State (VOS) stress

The vehicle operation stress has 2 components, their equations are explained in the following sub-sections.

Risk of losing control

First, we explain the methodology to compute the risk of losing control. This risk is extracted from the work of Eboli et al (2016) [33]. Eboli et al (2016) [33] designed a methodology to identify the risk level the based on the acceleration and speed of the vehicle. This methodology define a safe and unsafe driving condition areas.

The methodology is as follow. First the vehicle's equations of motion are defined, first the force magnitude of the vehicle (F_s) defined by Newton's law :

$$F_s = m_v|\bar{a}| \tag{A.1}$$

where m_v is the mass of he vehicle, and $\bar{a}$ is the acceleration of the vehicle, which can be define as:

$$|\bar{a}| = \sqrt{a_{lat}^2 + a_{long}^2} \tag{A.2}$$

Where a_{lat} is the vehicle's lateral acceleration the vehicle has, and a_{long} is the vehicle's longitudinal acceleration.

The friction force magnitude from the tires on the road (F_R) is defined as:

$$F_R = m_v g \mu \tag{A.3}$$

Where g is the gravitational acceleration (9.81 m/s^2) and μ is the friction coefficient between the road and the tires.

After defining the force equations, Eboli at al (2016) [33] define the zones according to the force equilibrium. It is important to mention that the equations A.1, A.2 and A.3 do not consider the impact of the elevation, thus these equations only consider forces in the plane of the vehicle direction.

The zones defines in [33] are:

a) if $F_s < F_R$ the vehicle is in the safe driving zone.

b) if $F_s = F_R$ the vehicle is at the limit of the safe driving zone.

c) if $F_s > F_R$ the vehicle is in a unsafe driving zone.

Lam et al (1999) [42] developed a correlation between the tires friction coefficient and the speed of the vehicle, as cited in [33]. The correlation is described in equation A.4.

$$\mu_{longmax} = 0.214\left(\frac{V}{100}\right)^2 - 0.640\left(\frac{V}{100}\right) + 0.615 \tag{A.4}$$

Where V is the vehicle speed in kilometers per hour.

Also Lam et al (1999) [42] defined the relationship between the longitudinal friction coefficient and lateral friction coefficient.

$$\mu_{lat} = 0.925\mu_{long} \tag{A.5}$$

Considering the definition of safe and not safe zones it is possible to generate an indicator computing how close is the vehicle to reach the limit of safe zone. The indicator is defined as the vehicle Risk of losing control (R_{lc}).

$$R_{lc} = \frac{F_s}{F_R} \tag{A.6}$$

It is important to defined which the lateral (μ_{lat}) or longitudinal (μ_{long}) friction coefficient is used to compute the friction force (F_R). The definition of which friction coefficient depends on the scenario the vehicle is facing.

The lateral friction coefficient (μ_{lat}) is used in the scenarios curve handling and lane change. While, the longitudinal friction coefficient (μ_{long}) is used for the scenarios driving in straight line and car following.

In the scenario of curve handling the friction coefficient used for the friction force is the lateral coefficient .

For the scenarios Lane change and Overtaking, the lateral friction coefficient (μ_{lat}) is used only while the vehicle is performing the lane change maneuver. When the maneuver is completed and the vehicle is located in a lane, the longitudinal coefficient is used (μ_{long}).

Object collision risk

The second measurement for risk is the risk of collision to a moving object such as another vehicle in the road. To compute the risk the definition of Time to Collision (TTC) is used. This indicator was first used in Hayward (1973)

[34] defined as "the time for two vehicles to collide if they continue a their persistent speed on the same path". This indicator is widely used for traffic simulations [55].

The definition of the TTC is defined in equation A.7 is extarcted from Minderhoud et al. (2001) [43].

$$TTC = \frac{X_{lead}(t) - X_{ego}(t) - l_{lead}}{V_{ego}(t) - V_{lead}(t)} \qquad \forall V_{ego}(t) > V_{lead}(t) \tag{A.7}$$

Where $X_{lead}(t)$ denotes the location of the leading vehicle in the moment t.The variable $X_{ego}(t)$ denotes the location of the *ego-car* in the moment t. The variable l_{ego} denotes *ego-car* length. The variables V_{ego} and V_{lead} as the speed of the *ego-car* and leading vehicle respectably.

Equation A.7 clearly states that it can be used as long as the speed of the *ego-car* is greater than the speed of the leading car. This is because in case the speed of the leading car is greater, then the leading car would move away, in consequence the TTC would be infinite. Similarly, in the case that both vehicles has the same speed then the equation would have a 0 in the denominator which is mathematically undefined, thus the TTC will also be infinite.

This definition of risk can be used for the scenarios where the *ego-car* is driving among other cars, such as the vehicle following and the Over-taking.

In the scenario of vehicle following and over-taking the X_{lead} and V_{lead} variables belong to the leading car (vehicle located in front of the *ego-car*).

The TTC is defined as the time for an imminent collision, following that direction and speed. The risk is a variable with values between 0 and 1, thus to transform the variable TTC into the risk of a collision a exponential probability density function can be used.

According to the definition of TTC, as the TTC is reduced the risk of a collision increases. Furthermore, the TTC is a function of the vehicle speed, according to Elvik (2013) [44] the increase in speed can increase exponentially the risk of an accident. Thus, the probability of collision is modelled as a negative exponential function. Thus the risk of collision is defined in equation A.8.

$$R_{col} = e^{-TTC/G_c} \tag{A.8}$$

where G_c is the parameter which defines the average TTC that the *ego-car* will experience, this is known as critical gap measure in seconds. This parameters merge the driving style discussed in section 3.8.1 with the TTC indicator of an accident. Additionally, equation A.8 is always between 0 and 1 and increase its value when then time to collision decreases.

A.2 Failure stress model

The methodology to predict a failure is inspired in Shafiee et al 2015 [29]. Hence, the following assumptions are considered in the current project regarding the failure modelling.

1. The components follows a gradual degradation phenomena. This degradation follows a Non-homogeneous Poisson process[1].

[1] The NH-Poisson process is a probabilistic model, which predict the probability discrete random events, where the average inter-arrival time is known. In the case of NH-Poisson process the average inter-arrival time can vary in time.

2. Each component can reach a critical point, thus the component fails. Thus, this failure prediction is a degradation model.
3. If a component fails, hence it has reached the critical point, the systems fails.
4. There is only one external NH Poisson process with a known rate to affect all the components.
5. The rate of the NH-Poisson process is linear.
6. The probability density and cumulative function to reach the critical point of degradation in each component follows a gamma probability function.
7. The degradation process depends on the use of the system represented in kilometers in this project.

The model followed by Shafiee et al [29] is an stochastic model. This project proposed to follow a similar approach. The variables of the approach are as follows:

N	number of component in the system
j	index for components
d_{sys}	current distance travel by the vehicle during its life time [km]
D_j	critical level of degradation for component j [km]
m_{sys}	intensity function of degradation of the system
λ_j	intensity degradation rate of component j [1/km]
U_j	distance to reach critical size D_j [km]
g_j	probability density function for U_j
G_j	probability cumulative distribution for U_j
F_{sys}	survival function of the system
SF_f	failure stress
μ_j	mean distance for component j to fail [km]
σ_j	standard deviation distance for component j to fail [km]
α_j	shape parameter of component j for gamma probability distribution
β_j	scale parameter of component j for gamma probability distribution

The table in annex C.1 contains the information to construct the probability density and cumulative functions (α_j,β_j), the intensity function of degradation of each component(m_j) and the critical level of degradation (D_j) for each component consider for the computation of the failure stress.

The methodology starts by calculating the distance to reach the critical point for each component. The equation A.9 computes this value for each component.

$$U_j = D_j - d_{sys} \forall j \tag{A.9}$$

It is important to mention, that the value of U_j can only be positive. In the scenario that the distance travel by the system (d_{sys}) is superior to the critical point the system (D_j) should have failed and stopped its operation.

Let us the define the distance to reach the critical point of the system (U_{sys}). According to the assumption 3 the system would fail if one component fails, then U_{sys} is computed folling equation A.10.

$$U_{sys} = \min(U_j, j = 1, 2, ..., N) \tag{A.10}$$

Equation A.10 allows us to find the component with the shorter distance to reach the critical point, let us call this component j_{min}.

Additionally, the system intensity function of degradation needs to be computed. Following assumptions 1 and 4. The selection of the intensity degradation rate of the system (λ_{sys}) is define in equation A.11.

$$\lambda_{sys} = \max(\lambda_j, j = 1, 2, ..., N) \tag{A.11}$$

Following assumption 5 the intensity function of degradation is linear. Therefore m_{sys} is defined in equation A.12. To evaluate the function $x = d_{sys}$.

$$m_{sys} = \lambda_{sys} x \tag{A.12}$$

Since the U_{sys} has been defined, the parameters of the probability density function of U_{sys} can be defined as the parameters of the component j_{min}. In consequence the gamma probability distribution of the system is defined in equation A.13, evaluated as $x = d_{sys}$.

$$g_{sys} = \frac{1}{\beta_{j_{min}}^{\alpha_{j_{min}}} \Gamma(\alpha_{j_{min}})} x^{\alpha_{j_{min}}-1} e^{-\frac{x}{\beta_{j_{min}}}} \tag{A.13}$$

Then the gamma cumulative distribution is defined as the integral of the equation A.13 from 0 to d_{sys}.

$$G_{sys} = \int_0^{d_{sys}} g_{sys} dx \tag{A.14}$$

According to Shafiee et al 2015 [29] the survival function of the system (F_{sys}) is the probability of the system to not fail. F_{sys} is defined as a probability cumulative distribution of a exponential distribution with a parameter equal to the convolution function of the degradation intensity function (m_{sys}) from equation A.12 and the gamma cumulative distribution (G_{sys}) from equation A.14. The equation defining the survival function is shown in equation A.15.

$$F_{sys} = e^{-\int_0^{d_{sys}} m_{sys}(x) G_{sys}(d_{sys}-x) dx} \tag{A.15}$$

Finally with equation A.15 is possible to define the probability of failure as the complementary probability of F_{sys}. The equation of the Failure stress is defined in equation A.16.

$$SF_f = 1 - F_{sys} \tag{A.16}$$

A.3 Competency stress model

The methodology followed to compute the competency stress considers the following assumptions:

1. The central variable is the **Object recognition**, then this variable range is between 0 and 1.
2. The value of the Object recognition is consider to be known.

3. All the other variables state affects the competency stress by increasing it or not affecting it.

In line with the assumption 3, the table C.2 the percentage improvement of the system complete depending on the state of the subsystem. For example, if the state of the subsystem Vehicle to vehicle ($V2V$) communication is enable, thus state of the subsystem is 1; then the uncertainty of the system will decrease by the percentage of improvement stated in table C.2.

The methodology to compute the Competency stress (SF_c) is explained next. First let us define the variables.

N	number of sub-systems in the system
j	index for subsystem
$P_{missobj}$	Uncertainty of object recognition
PI_j	Percentage of improvement to system from subsystem j in

As stated in assumption 2, the probability of not recognising objects of P_{NRO} is known. Then equation A.17 defines how each PI_j affects the uncertainty of the system.

$$SF_c = P_{NRO} = P_{missobj} \prod_{1}^{N} (1 - PI_j) \tag{A.17}$$

Consequently, the uncertainty of the object recognition decreases. In the scenario that the sub-system do not affect the uncertainty of the object detection then $PI_j = 0$.

Appendix B

Input variables rationale

This appendix shows the behavioral variables used to model the CarESP system.

Table B.1 shows the behavioral variables for the driver's health class.

#	Variable	Prioritazion Feature		Grade	Score	Weights	Reference
		Partial automation	Fully autonomous				
1	Driver age	Safety	Comfort	>55 35 to 55 25 to 35 18 to 25 16 to 18	3 4 5 2 1	1/5 4/15 1/3 2/15 1/15	[56], [57]
2	Driver blood alchohol level	Safety	Comfort	<0.02% 0.02%-0.03% 0.03%-0.04% 0.04%-0.05% >0.05%	5 4 3 2 1	1/3 4/15 1/5 2/15 1/15	[58], [59], [60]
3	Driver alertness level	Safety	NA	Fully alert Alert Neutral Drowsy Sleepy	5 4 3 2 1	1/3 4/15 1/5 2/15 1/15	[61]
4	Driver vision	Safety	NA	6/6 naked eyes Glasses Sunglases Losing one eye Cataracts	5 4 3 2 1	1/3 4/15 1/5 2/15 1/15	[62]
5	Driver workload	Safety	Comfort	Very low Low Medium High Very High	5 4 3 2 1	1/3 4/15 1/5 2/15 1/15	[63]

Table B.1: Input variable for Driver's Health class.

Table B.2 shows the behavioral variables for the driving style class.

#	Variable	Prioritazion Feature		Grade	Score	Weights	Reference
		Partial automation	Fully autonomous				
1	Driver attitude towards driving	Safety	Trustworthiness	Love Like Neutral Dislike Hate	5 4 3 2 1	1/3 4/15 1/5 2/15 1/15	[64]
2	Frequency of over-speeding (measured by times in a week)	Safety	NA	<1 1 to 2 2 to 3 3 to 4 >4	5 4 3 2 1	1/3 4/15 1/5 2/15 1/15	[65]
3	Correctness of vehicle maintenance	Performance	Performance	Always correct Usually correct Accordingly correct Seldom correct Never correct	5 4 3 2 1	1/3 4/15 1/5 2/15 1/15	[66]
4	Periodic maintenance	Performance	Performance	Always on time Usually on time Accordingly on time Seldom on time Never on time	5 4 3 2 1	1/3 4/15 1/5 2/15 1/15	[66]
5	Driving Gap	Safety	Safety	> mean gap mean gap < mean gap	5 3 1	1/3 1/5 1/15	[40]

Table B.2: Input variables for driver style.

Table B.3 shows the behavioral variables for the vehicle's health class.

#	Variable	Prioritazion Feature		Grade	Score	Weights	Reference
		Partial automation	Fully autonomous				
1	Vehicle mass	Safety	Safety	85kg +100kg +200kg +300kg +400kg	5 4 3 2 1	1/3 4/15 1/5 2/15 1/15	[67]
2	Braking equipment	Safety	Safety	Excelent Fair Poor	5 3 1	1/3 1/5 1/15	[68]
3	Service braking performance and efficiency	Performance	Performance	Excelent Fair Poor	5 3 1	1/3 1/5 1/15	[68]
4	Secondary (emergency) braking performance and efficiency	Safety	Safety	Excelent Fair Poor	5 3 1	1/3 1/5 1/15	[68]
5	Parking braking performance and efficiency	Performance	Performance	Excelent Fair Poor	5 3 1	1/3 1/5 1/15	[68]
6	Axles	Safety	Safety	Excelent Fair Poor	5 3 1	1/3 1/5 1/15	[68]

#	Variable	Prioritazion Feature		Grade	Score	Weights	Reference
		Partial automation	Fully autonomous				
7	Direction indicator and hazard warning lamps	Safety	Safety	Excelent Fair Poor	5 3 1	1/3 1/5 1/15	[68]
8	Doors	Comfort	Comfort	Excelent Fair Poor	5 3 1	1/3 1/5 1/15	[68]
9	Electromagnetic interference suppression	Trustworthdiness	Trustworthdiness	Excelent Fair Poor	5 3 1	1/3 1/5 1/15	[68]
10	Front and rear fog lamps	Safety	Safety	Excelent Fair Poor	5 3 1	1/3 1/5 1/15	[68]
11	Headlamps	Safety	Safety	Excelent Fair Poor	5 3 1	1/3 1/5 1/15	[68]
12	Noise	Comfort	Comfort	Loud Fair Low	5 3 1	1/3 1/5 1/15	[68]
13	Parking braking performance and efficiency	Performance	Performance	Excelent Fair Poor	5 3 1	1/3 1/5 1/15	[68]
14	Positive ignition engine emissions	Performance	Performance	Excelent Fair Poor	5 3 1	1/3 1/5 1/15	[68]
15	Compression ignition engine emissions	Performance	Performance	Excelent Fair Poor	5 3 1	1/3 1/5 1/15	[68]
16	Reversing lamps	Safety	Safety	Excelent Fair Poor	5 3 1	1/3 1/5 1/15	[68]
17	Safety-belts/buckles and restraint systems	Safety	Safety	Excelent Fair Poor	5 3 1	1/3 1/5 1/15	[68]
18	Airbag	Safety	Safety	Excelent Fair Poor	5 3 1	1/3 1/5 1/15	[68]
19	Seats	Comfort	Comfort	Excelent Fair Poor	5 3 1	1/3 1/5 1/15	[68]
20	Steering	Safety	Safety	Excelent Fair Poor	5 3 1	1/3 1/5 1/15	[68]
21	Wheel alignment	Performance	Performance	Excelent Fair Poor	5 3 1	1/3 1/5 1/15	[68]
22	Electronic Power Steering (EPS)	Safety	Safety	Excelent Fair Poor	5 3 1	1/3 1/5 1/15	[68]
23	Steering wheel, column and handle bar	Safety	Safety	Excelent Fair Poor	5 3 1	1/3 1/5 1/15	[68]

#	Variable	Prioritazion Feature Partial automation	Prioritazion Feature Fully autonomous	Grade	Score	Weights	Reference
24	Stop Lamps	Safety	Safety	Excelent Fair Poor	5 3 1	1/3 1/5 1/15	[68]
25	Suspension system	Safety	Safety	Excelent Fair Poor	5 3 1	1/3 1/5 1/15	[68]
26	Tell-tales	Safety	Safety	Excelent Fair Poor	5 3 1	1/3 1/5 1/15	[68]
27	Road wheel hub	Safety	Safety	Excelent Fair Poor	5 3 1	1/3 1/5 1/15	[68]
28	Wheels	Safety	Safety	Excelent Fair Poor	5 3 1	1/3 1/5 1/15	[68]
29	Tyres	Safety	Safety	Excelent Fair Poor	5 3 1	1/3 1/5 1/15	[68]
30	Cab and bodywork	Safety	Safety	Excelent Fair Poor	5 3 1	1/3 1/5 1/15	[68]
31	Transmission	Performance	Performance	Excelent Fair Poor	5 3 1	1/3 1/5 1/15	[68]
32	Engine performance	Performance	Performance	Excelent Fair Poor	5 3 1	1/3 1/5 1/15	[68]
33	Chassis or frame and attachments	Safety	Safety	Excelent Fair Poor	5 3 1	1/3 1/5 1/15	[68]

Table B.3: Input variables for Vehicle's Health.

Table B.4 shows the behavioral variables for the vehicle's competency class.

#	Variable	Prioritazion Feature Partial automation	Prioritazion Feature Fully autonomous	Grade	Score	Weights	Reference
1	Recognition of surrounding objects	Safety	Safety	100% 75% 50% 25% $< 25\%$	5 4 3 2 1	1/3 4/15 1/5 2/15 1/15	[56]
2	Able to communicate with other vehicles	Safety	Safety	Yes No	5 1	1/3 1/15	[69]
3	Able to communicate with infrastructure	Safety	Safety	Yes No	5 1	1/3 1/15	[70]
4	Friendly human vehicle interaction system	Trustworthiness	Trustworthiness	Yes Some degree No	5 3 1	1/3 1/5 1/15	[71]
				1 2	5 4	1/3 4/15	

#	Variable	Prioritazion Feature Partial automation	Prioritazion Feature Fully autonomous	Grade	Score	Weights	Reference
5	Vehicle software update frequency	Trustworthiness	Trustworthiness	3 4 >5	3 2 1	1/5 2/15 1/15	[72]
6	Electronic Asistant Systems (ESC)	Safety	Safety	yes no	5 1	1/3 1/15	[68]
7	Digital data connectivity	Safety	Safety	Yes No	5 1	1/3 1/15	[46]
8	Digital user interface	Trustworthiness	Trustworthiness	Good Fair Bad	5 3 1	1/3 1/5 1/15	[46]
9	Capability of cooperative manuvering	Safety	Safety	Good Fair Bad	5 3 1	1/3 1/5 1/15	[45]
10	Capability of cooperative sensing	Safety	Safety	Good Fair Bad	5 3 1	1/3 1/5 1/15	[45]

Table B.4: Input variables for Vehicle's Competency.

Table B.5 shows the behavioral variables for the environment state class.

#	Variable	Prioritazion Feature Partial automation	Prioritazion Feature Fully autonomous	Grade	Score	Weights	Reference
1	Road surface	Safety	Safety	Asphalt Concrete Ice Potholes No road	5 4 3 2 1	1/3 4/15 1/5 2/15 1/15	[73]
2	Road conditions	Safety	Safety	Excellent Fair poor	5 3 1	1/3 1/5 1/15	[74]
3	Probability of accidents on that road	Safety	Safety	<0.1 0.1 to 0.25 .25 to .4 0.4 to 0.55 >0.55	5 4 3 2 1	1/3 4/15 1/5 2/15 1/15	[75]
4	Probability of obstruction due to nearby construction	Performance	Performance	<0.1 0.1 to 0.25 .25 to .4 0.4 to 0.55 >0.55	5 4 3 2 1	1/3 4/15 1/5 2/15 1/15	[73]
5	Cabin temperature	Comfort	Comfort	>35°C 25 to 35°C 10 to 25°C 5 to 10°C -5 to 5°C	5 4 3 2 1	1/15 4/15 1/3 1/5 2/15	[76]
6	Cabin humidity	Comfort	Comfort	>50% 45% to 50% 40% to 45% 30% to 35% <30%	5 4 3 2 1	1/15 4/15 1/3 1/5 2/15	[77]

#	Variable	Prioritazion Feature		Grade	Score	Weights	Reference
		Partial automation	Fully autonomous				
7	Driving environment condition	Comfort	Comfort	highway city Mountain Rural Crowded	5 4 3 2 1	1/3 4/15 1/5 2/15 1/15	[78]
8	Weather	Safety	Safety	Clear sky Sunny Rain Snow Storm	5 4 3 2 1	1/3 4/15 1/5 2/15 1/15	[79]
9	Time of the day	Safety	Safety	Morning Noon Afternoon Evening Night	5 4 3 2 1	1/3 4/15 1/5 2/15 1/15	[80]

Table B.5: Input variables for Environment State.

Appendix C

Data for the Stress models

Table C.1 shows the parameters used for the computation of the health stress. The sources contains the mean values (μ) and standard deviation (σ) of the components. Then the computation of the gamma pdf parameters is performed using equations C.1 and C.1.

$$\alpha = \frac{\mu^2}{\sigma^2} \tag{C.1}$$

$$\beta = \frac{\mu^2}{\sigma} \tag{C.2}$$

Then the computation of the degradation critical level (D) is performed using equation C.3. The computation of the intensity of degradation (λ) is performed using equation C.4.

$$D = \mu + \sigma \tag{C.3}$$

$$\lambda = \frac{1}{\mu} \tag{C.4}$$

Variable	μ[km]	σ[km]	α	β	D[km]	λ	Source
Braking equipment	13,802.5	4,995.6	7.63	1,808.08	18,798.10	72.45×10^{-6}	[81]
Secondary braking system	13,802.5	4,995.6	7.63	1,808.08	18,798.10	72.45×10^{-6}	[81]
Parking braking	13,802.5	4,995.6	7.63	1,808.08	18,798.10	72.45×10^{-6}	[81]
Axles	150,000.0	36,000.0	17.04	9,061.42	191,762.79	6.48×10^{-6}	[81]
Direction indicator and hazard warning lamps	150,000.0	36,000.0	17.04	9,061.42	191,762.79	6.48×10^{-6}	[82]
Front and rear fog lamps	150,000.0	36,000.0	17.04	9,061.42	191,762.79	6.48×10^{-6}	[82]
Headlamps	150,000.0	36,000.0	17.04	9,061.42	191,762.79	6.48×10^{-6}	[82]
Reversing lamps	150,000.0	36,000.0	17.04	9,061.42	191,762.79	6.48×10^{-6}	[82]
Safety-belts/buckles and restraint systems	150,000.0	36,000.0	17.04	9,061.42	191,762.79	6.48×10^{-6}	[82]
Airbag	150,000.0	36,000.0	17.04	9,061.42	191,762.79	6.48×10^{-6}	[82]
Steering	17,280.0	1,440.0	144.00	120.00	18,720.00	57.87×10^{-6}	[83]
Electronic Power Steering (EPS)	150,000.0	36,000.0	17.04	9,061.42	191,762.79	6.48×10^{-6}	[82]

Variable	μ[km]	σ[km]	α	β	D[km]	λ	Source
Steering wheel, column and handle bar	17,280.0	1,440.0	144.00	120.00	18,720.00	57.87×10^{-6}	[83]
Stop Lamps	150,000.0	36,000.0	17.04	9,061.42	191,762.79	6.48×10^{-6}	[82]
Suspension system	90,909.1	21,818.2	40.50	1,444.44	67,692.39	17.09×10^{-6}	[84]
Tell-tales	150,000.0	36,000.0	17.04	9,061.42	191,762.79	6.48×10^{-6}	[82]
Road wheel hub	61,236.0	12,565.0	12.50	8,000.00	128,284.27	10×10^{-6}	[85]
Wheels	61,235.0	12,565.0	12.50	8,000.00	128,284.27	10×10^{-6}	[85]
Tyres	45,500.0	9,192.4	24.50	1,857.14	54,692.39	21.98×10^{-6}	[86]
Cab and bodywork	150,000.0	36,000.0	17.04	9,061.42	191,762.79	6.48×10^{-6}	[82]
Chassis or frame and attachments	150,000.0	36,000.0	17.04	9,061.42	191,762.79	6.48×10^{-6}	[82]

Table C.1: Parameters to compute the health stress factor.

Table C.2 shows the parameters used for the computation of the competency stress. These parameters where extracted and analysed from the sources referred in this table.

Variable	State	Value	Source
Able to communicate with other vehicles	enable	0.2	[87]
	disable	0	
Able to communicate with infrastructure	enable	0.2	[87]
	disable	0	
Digital data connectivity	enable	0.04	[88]
	disable	0	
Capability of cooperative Autonomy	enable	0.096	[89]
	disable	0	

Table C.2: Parameters to compute the competency stress factor.

Table C.3 shows the parameters used for the computation of the environmental stress. These parameters where extracted and analysed from the sources referred in this table.

Variable	State	Value	Source
Road surface	Asphalt	0.12	[47]
	Concrete	0.12	
	Ice	0.49	
	Wet	0.16	
	No road	0.11	
Road conditions	Excellent	0	[74]
	Fair	0.0149	
	poor	0.0181	
Weather	Clear sky	0.235	[90]
	Sunny	0.235	
	Rain	0.227	
	Snow	0.227	
	Storm	0.256	
Time of the day	Morning	0.000006	[80]
	Noon	0.000006	
	Afternoon	0.000009	
	Evening	0.000012	

Variable	State	Value	Source
	Night	0.00026	

Table C.3: Parameters to compute the environmental stress factor.