Study and validation of data recorded in the vehicles' EDR in order to perform a road accident's dynamic reconstruction

Master degree in Automotive Engineering

Francisco Gonçalo Mendes Laranjeira

Leiria, September of 2022

Study and validation of data recorded in the vehicles' EDR in order to perform a road accident's dynamic reconstruction

Master degree in Automotive Engineering

Francisco Gonçalo Mendes Laranjeira

Project Report under the supervision of Professor Sérgio Pereira dos Santos, and Professor Carlos Daniel Henriques Ferreira

Leiria, September of 2022

PAGE INTENTTIONALLY LEFT BLANK

Originality and Copyright

This project report is original, made only for this purpose, and all authors whose studies and publications were used to complete it are duly acknowledged.

PAGE INTENTTIONALLY LEFT BLANK

Dedication

The present project work is mainly dedicated to my parents and brothers, who permitted and always encouraged me on the academic path I fortunately followed.

I also dedicate this project to the closest friends, special people, and school and course colleagues who supported and accompanied me along the past study years.

Additionally, this work is dedicated to the professors who vastly contributed to my academic formation and personal evolution.

PAGE INTENTTIONALLY LEFT BLANK

Acknowledgments

I would like to acknowledge and express my gratitude to my project work supervisors, Professor Sérgio Pereira dos Santos, and Professor Carlos Daniel Henriques Ferreira, who presented their availability to follow, support, and guide me through this project work's development. I would like to give them my thanks for all the enriching knowledge provided and for the dispensed tools and working space to progress with the project work.

Additionally, I wish to express my gratitude to my family, all the closest friends, and special people who kept giving me encouraging words to develop and complete this project work.

PAGE INTENTTIONALLY LEFT BLANK

Abstract

Road accident reconstruction is an issue which involves multiple and differentiated subjects. A collision contours' determination requires the investigation and the analysis of all the evidence provided from highly distinct sources and remaining from uncertain and, sometimes, chaotic scenarios. People are vastly involved in traffic accident situations, either being drivers, victims, injured or witnesses. Therefore, accident investigation is a sensitive matter which requires objectiveness, accuracy, efficiency, and effectiveness, to draw faithful and factual conclusions about the collisions' contours. The accidents reconstruction science's main objective is to determine and describe the involved vehicles dynamics, which is accomplished by collecting and interconnect all the available evidence extracted from the impacts' scenarios, from the vehicles, and from the involved people.

In the past, many authors developed mathematical models which describe, approximately, the vehicles' dynamics involved in a road traffic collision. Over the years, with the technology evolution and the advances on the area, multiple solutions have been created and enhanced to provide to accident reconstructionists better and more reliable evidence, allowing them to perform crash reconstructions with higher accuracy. These solutions include numerical methods, simulation and evaluation software, and tools for evidence collection. However, the introduction of the Event Data Recorder (EDR) on the vehicles consists of a great progression concerning the availability of valid and meaningful clues which can be used as inputs for the scientific crash reconstruction, since the EDR stores data that was unavailable and was difficult to deduce from the accident's remaining evidence, previously.

On the scope of this project, a vehicle data logging device was developed and tested regarding the validation of the EDR's recorded data. The device's purpose is to acquire the most relevant variables for crash reconstruction, which are also stored by the EDR, and provide a source of information for comparison and validation. This device was integrated with the respective sensors, programmed with a developed software, and tested on a vehicle. The tests for dynamic data acquisition consisted of travelling a defined path around the school campus, since there was not the opportunity to perform a real crash test with an EDR equipped vehicle.

Keywords: accident reconstruction, EDR, instrumentation, data collection, variables, validation

PAGE INTENTTIONALLY LEFT BLANK

Contents

PAGE INTENTTIONALLY LEFT BLANK

List of Figures

List of Tables

PAGE INTENTTIONALLY LEFT BLANK

List of Abbreviations and Acronyms

2D	Two-Dimensional
3D	Three-Dimensional
ABS	Anti-lock Braking System
ACCS	Adaptative Cruise Control System
ACM	Airbag Control Module
ACSF	Automatically Commanded Steering Function
ADC	Analogue to Digital Converter
AEBS	Automated Emergency Braking System
AECS	Accident Emergency Call System
CAN	Controller Area Network
CCS	Cruise Control System
CDR	Crash Data Retrieval
CG	Centre of Gravity
CSF	Corrective Steering Function
DAC	Digital to Analogue Converter
EDM	Electronic Distance Measurement
EDR	Event Data Recorder
EES	Energy Equivalent Speed
ESC/ESP	Electronic Stability Control / Electronic Stability Program
ESF	Emergency Steering Function
ESTG	School of Technology and Management
FSR	Force Sensing Resistors
GMR	Giant Magnetoresistance
GNSS	Global Navigation Satellite System
GPIO	General Purpose Input/Output
GPS	Global Positioning System
I2C	Inter-Integrated Circuit
ID	Identifier
IMU	Inertial Measurement Unit
IPL	Polytechnic Institute of Leiria
ISR	Interrupt Service Routine
LDWS	Lane Departure Warning System
LED	Light Emitting Diode

LKAS	Lane Keeping Assist System
LSB	Least-Significant Bit
OBD	On-Board Diagnostic
PCB	Printed Circuit Board
PDOF	Principal Direction of Force
PHV	Plug-in Hybrid Vehicle
PID	Parameter ID
PWM	Pulse Width Modulation
RAM	Random-Access Memory
RPM	Revolutions Per Minute
RTC	Real Time Clock
RTK	Real Time Kinematics
SD	Secure Digital
SPI	Serial Peripheral Interface
TCS	Traction Control System
TLS	Terrestrial Laser Scanners
TPMS	Tyre Pressure Monitoring System
UAV	Unmanned Aerial Vehicle
USB	Universal Serial Bus
VDL	Vehicle Data Logger
VRU	Vulnerable Road Users

1. Introduction

The accident reconstruction science involves multiple domains, each detail has a considerable meaning and influence on the process of recreating and understanding which were the collision's circumstances, how did it occurred and what was involved on its causes.

An accident reconstructionist must take note of each detail on what concerns the accident scene, such as road type and configuration, traffic signalization, visibility issues, skid and slide marks, damage on the environment's infrastructures, vehicles' debris positioning and so on. For this reason, the collision scenario's data collection methods should be as effective and efficient as possible, in order to promote accurate reconstructions without missing details.

Besides, it must be done an extensive analysis to the intervenient vehicles' damages, evidence, and specifications, on what concerns its mechanical conditions, crash promoted deformations and clues on the details which define key aspects as the exact points of contact between vehicles and involving infrastructure, for an exact and precise damage compatibility analysis. On this domain, the vehicles deformation profiles' analysis methods have great relevance on what concerns the trustworthy determination of vehicles' deformation energy and Energy Equivalent Speed (EES).

The commonly utilised methods for collision reconstruction only rely on the evidence which remain subsequently to the impact's occurrence. These clues consist mainly of the vehicles' damage profile and of the evidence left on the accident scenario, such as vehicles' final positions, skid marks, and infrastructural damage. Therefore, investigators must work backwards to raise and test hypotheses about the collision's contours, looking forward to develop a valid accident reconstruction.

The availability of data from before and during the collision phases might vastly contribute to increase the road accident reconstruction's reliability and accuracy, besides promoting the process' efficiency. With the introduction of event data recorders, the accident expert has valuable information available to complement and corroborate his analysis. This information mainly refers to the vehicle's dynamic data elements occurred before and after a collision, as accelerations, cumulative changes in velocity, angular displacements and angular rates, data about the driver's intentions and behaviour, and others which are described on this report. In the past, these details were completely unknown, what could limit the reconstructions' accuracy.

The information provided by the Event Data Recorder (EDR) may have its own limitations and uncertainties. Subsequently to the development of a computational accident simulation, collision investigators are capable to extract the vehicles' dynamic variables as outputs from the software and compare them with the data obtained by recovering the EDR reports.

However, to perform better validation for the EDR information, it is idealised the development of an autonomous data acquisition device which is responsible for recording the same dynamic variables as the EDR, since dynamic data is the most relevant for road accident reconstruction.

Finally, the fact is that there are always people involved on a crash situation. Independently of being a driver, a passenger, a pedestrian, a cyclist or a witness, there is always relevant information which heavily contributes to an accident reconstruction. It must be made a deep study about people's injuries and physiognomic characteristics, in case of collisions with vulnerable road users, and about witnesses' statements to unveil the truth about facts.

All the information from the multiple domains must be gathered, combined, and used as valuable inputs for road accidents' investigations, as synthesised by the diagram represented on Figure 1.1, to draw conclusions regarding the collisions' circumstances with a considerable level of accuracy, precision, and reliability.

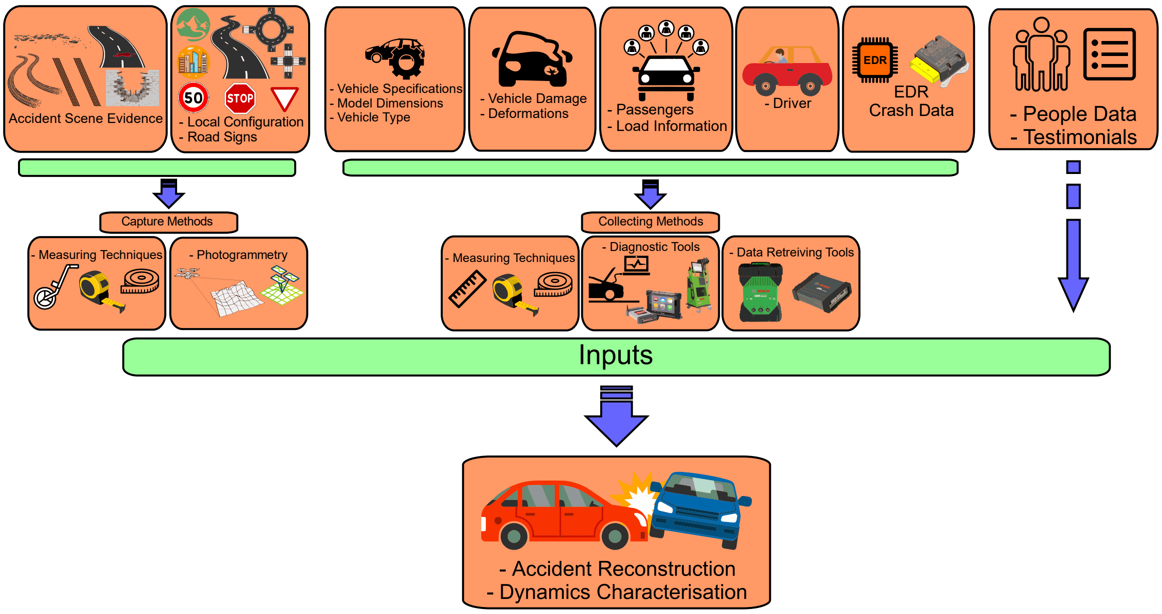


Figure 1.1 - Data inputs' schematic for road accident reconstruction

The main objectives of the present project work consist of presenting and characterizing the data and information provided by the EDR devices implemented and regulated for the road vehicles nowadays, as well as its functioning principle. Furthermore, it is intended to develop, implement, and test a parallel prototype device with capabilities to acquire dynamic variables which must be comparable to the data that can be retrieved from the EDR's reports, looking forward to perform a validation analysis.

This report begins by introducing the road accident reconstruction issue through a brief framework. Then, follows by presenting the classical methods and base principles used for the mathematical determination of motion parameters which approximately describe the vehicles' dynamics performed on the accident. As collision scenarios consist of a high relevant evidence source, the methods for accident scene data collection are described subsequently. Through the years, sophisticated technologies have been implemented since every remaining detail on scene must be interpreted as a possible clue for the impacts' reconstruction. Afterwards, as vehicles' damage results from the collision and vehicles' impact speeds, the analysis of their final deformation profiles, after the accident, might provide valuable evidence to evaluate the vehicles' pre-impact and post-impact velocities. For this reason, the damage analysis techniques are also described.

The following chapter is dedicated to the internal information and evidence which the vehicles' might be able to provide for the accidents' contours determination, so being the information captured by the Event Data Recorder (EDR) device. The EDR is responsible for the registration of a wide variety of parameters and data elements, which involves vehicle's dynamic data (accelerations, velocities, yaw, …), driver's intents (steering, braking, throttle, …), safety systems' functioning status (ABS, ESC, TCS, …), and other control parameters (restraint systems' usage and deployment, timing variables, …). Each recorded variable is enumerated, described, and characterized on what concerns the accuracy, data sample rate, and range required by the regulations. Besides, it is defined and explained the vehicles' instrumentation that is essential regarding the data elements' collection, as well as exposed the way these elements appear on the reports which are typically retrieved from the EDR device.

Subsequently, a computational road accident reconstruction case study, performed on the PC-Crash® software, is presented on this project work report. The intervenient vehicles are characterized, and the accident's scenario is described, as well as the utilized methodology to capture its environmental appearance and evidence data. Additionally, the resultant collision dynamics' simulation is presented according to the remaining and available evidence and clues. To close this chapter, the vehicles' dynamic variables outputted from the computational simulation dynamics are extracted and presented as reference to validate the utility of previously having evidence of the vehicle's dynamics through the EDR recordings.

Finally, the present project work report describes the development and testing of an autonomous data acquisition system with the main objective of performing a validation analysis for the EDR device, on a real case study. This consists of a device which registers determined dynamic EDR data elements with the same or improved accuracy, data sample rate and range.

2. Framework

2.1. Definitions

The meaning of accident refers to an unexpected and not desired event, which may lead to negative consequences. For this reason, accident investigation is required to find the causes and implement measures to avoid the involved effects. Vehicle accident reconstruction consists of the forensic science which preconizes the determination of how an accident occurred, the reasons why it happened and the factors that contributed to the accident's occurrence (Thivierge, 2018). The reconstruction is accomplished by retrieving and analysing the evidence which remain from the accident, recreating and studying the collision's timeline, which involves the events that happened during the accident, that preceded the accident and that followed the accident. (Williams, 2016)

In fact, accident reconstruction experts need to work in a reverse manner, as they recover and study all clues left on the crash scenario and move backwards on the timeline to draw conclusions about the impact's causations and dynamics. (Daniel, 2022)

Vehicle accidents' study might involve mainly impacts between two or more vehicles, between vehicles and stationary environment objects (for example, walls or trees), or between vehicles and pedestrians or cyclists. Intervenient people's lives and valuable goods are usually at stake, that is why accident reconstruction focuses on evaluating the collision itself and on determining the possible causes for the accident's occurrence.

Detailed study of collisions can be achieved by combining two base physical principles which guide this analysis, the law of conservation of momentum and law of conservation of energy.

On accident reconstruction, there are multiple sources of information which must be integrated together after a, sometimes, difficult and traumatic collecting process. These facts represent some reasons why accident reconstruction can become a complex subject. (*Accident Reconstruction*, 2019)

2.2. Accident reconstruction relevance

Frequently, automobile accidents can result on victims of several injuries and even fatalities. Sometimes, even crime committed scenarios may occur. These are the main reasons why it is very important to fully investigate the accidents' contours, so being accident reconstruction a crucial element for these types of investigation cases. Besides, large-scale collisions involving multiple intervenient require special attention, as there can be various causes, uncertain responsibilities, and high value patrimonial and non-patrimonial damage. (*Accident Reconstruction*, 2019)

For this reason, collisions' remaining clues analysis and accident reconstructions are often presented as evidence in criminal and civil court cases, in order to draw conclusions and find the causative factors. (Thivierge, 2018)

In cases involving single or multiple vehicles and wrongful death or individual injury, accident reconstruction consists of a high valuable service, on what concerns the litigation resolution. Collisions' accurate recreation can present the actual impact contours, help to determine the truth of the facts, and validate witnesses' testimonies.

Ideally, accident reconstruction experts may be able to determine the various elements which characterize the collision's contours, for example the impact's location, the vehicles' positioning before the impact, the vehicles' velocities at the impact, the force and energy involved on the collision, and many other multiple factors.

Fault and causes determination, allowed by the help of accident reconstruction, can identify negligent, careless, or aggressive behaviours on the accident's intervenient individuals, faulty pavement and road conditions, vehicle's equipment malfunctions, or a variety of other factors which may have contributed to the collision's occurrence. Without the help of this forensic science, courts would have to rely and depend on disperse evidence and inaccurate and colliding witnesses' testimonies. (Gipe, 2015)

Specialists on accident reconstruction can give valuable advice on how the collision could be avoided, as their investigation conclusions and observations may lead to the recognition of designing issues on certain vehicles' systems, and projecting mistakes on road and highway infrastructures. (*Importance Accid. Reconstr.*, 2015)

This way, accident reconstruction may reveal a set of factors that might have guided to a collision occurrence, such as, (Daniel, 2022):

- Driver responsibility: Speeding, disrespecting stop signs and red lights, incorrect turning and lane changes, negligent, careless, and aggressive driving;
- Vehicle malfunction: Loss control due to a vehicle's part or system failure, or a vehicle defect;
- Environment factors: Dangerous and faulty road conditions, visibility issues.

2.3. Accident expert's tasks

In order to understand which were the key elements that contributed to an accident's origin and severity, specialists on reconstruction resort to a variety of sophisticated methodologies. The main aspects of accidents reconstruction may include:

- Deep inspection of the vehicles involved in the accident;
- Vehicle and crash scene images' analysis;
- Traffic collision report's review (testimonials transcripts, witnesses' statements, crash test reports, published studies, and other documents);
- Victims' medical records' evaluation (to determine if the available evidence match consistently the intervenient individuals suffered injures).

If already available, experts might also evaluate the information retrieved from the vehicle's Event Data Recorder (EDR) to acquire valuable clues on what concerns vehicle's collision dynamics. (Daniel, 2022)

Besides, experts must collect and evaluate all the physical evidence available at the crash scenario such as the vehicles' final positions, the vehicles' wreckage, deformation and damage, the configuration, length and pattern of the skid and road marks, the positioning of all the scattered debris and trace elements left from the impact, and the presence of alcohol and drug related objects. (*Importance Accid. Reconstr.*, 2015)

Experts or authorities that reach firstly the accident scene may also take photographs which catalogue the scenario's environmental conditions, for example the landscaping and local framing, the weather conditions, the traffic signalization, and the road configuration. They should also conduct interviews to the present witnesses and involved survivors. Additionally, if possible, the drivers', passengers' and pedestrians' physical state and behaviour should be examined to determine if there were any alcohol, drugs, sleep deprivation, or criminal intent issues that might have led to the accident's occurrence. (Thivierge, 2018)

Sometimes, accident specialists might not have the opportunity to visit and investigate the collision scenario, because police and other authority forces have the responsibility to collect evidence and clear accident site as fast as possible, to release the road blockage and allow the traffic to flow. Investigators have to develop an accident reconstruction from all the collected evidence after requiring access to all the available information, which may include the police accident report, photographs, and all the previously mentioned data items.

Initially, accident investigators define the general collision scenario and, subsequently, add the factual evidence details available. Vehicles' damages and their final positions are the start point for the accident dynamics reconstruction, as these are often well established. Experts must work backwards to unveil each vehicles' movements involved on the impact.

Usually, an accident reconstructionist can resort to the conservation of energy and momentum equations attempting to draw conclusions about the vehicles' initial velocities, which is a big step on what concerns finding the collision's contours. Vehicles' deformation examination, often done subsequently, can also provide valuable information regarding vehicles' velocities. (*Accident Reconstruction*, 2019)

The multiple areas involved on vehicular accidents, such as crash simulation, 3D modelling and animation, and forensic mapping are subjects of high value of interest which require extensive and constant training by the accident reconstruction experts. (Gipe, 2015)

From an extensive and deep analysis of each clue and evidence, accident reconstruction experts may develop, objectively, accurate 3D models and simulations, and impartial written reports which demonstrate the accidents' contours and allow courts to make more precise judgements. (Daniel, 2022)

3. Accident reconstruction methodologies study

3.1. Kinematic methods' definition

The aim to obtain more accurate solutions to reproduce, recreate and investigate the collision brought various methodologies and tools applied vehicle's identification and collision impact's evaluation. Mathematical modelling of complex mechanical systems involving vehicles and other objects in a road accident is executed by modern computer technology and software, providing the tool needed to solve specific accident simulation problems. To calculate both vehicles' energy of deformation, usually, forensic reconstructionists resort to the Standard Test Method for Impact Testing, however, the vehicles' kinetic energy evaluation in post-collision, taking into account the vehicles' rotation and linear displacement, is one of its limitations. Ideally, the friction coefficient's variations, suspension's elasticity and damping should be considered on the dynamic traffic simulation to improve the analysis. The commonly used method is based on two main principles: the Principle of Conservation of Mechanical Energy and the Principle of Conservation of Momentum (Brunt & Brunt, 2013) at the impact phase.

The method based on the Law of Momentum Conservation used on vehicle impact can be expressed as:

$$\vec{Q} = m_1\overrightarrow{V_1} + m_2\overrightarrow{V_2} = m_1\overrightarrow{u_1} + m_2\overrightarrow{u_2}$$

where:

m_1 and m_2 – vehicles' masses,

$\overrightarrow{V_1}$ and $\overrightarrow{V_2}$ – the two vehicles' centres of mass pre-impact velocities,

$\overrightarrow{u_1}$ and $\overrightarrow{u_2}$ – the two vehicles' centres of mass post-impact velocities.

This vectorial equation is projected on two mutually perpendicular axes, resulting on a system of two equations with two unknowns, which describe the collision's plane orthogonal components. (Karapetkov et al., 2019; J. Neades & Smith, 2011; Wach et al., 2016)

Each method's results have their own inaccuracies and uncertainties, as some predefined considerations are used as approximation strategies. On this method, for example, the tire-road friction coefficients are estimated, and the involved vehicles are considered to be material points, according to the Centre-of-Mass Motion Theorem. Besides, the effect of post-impact vehicle rotation and the resulting angular velocity are not considered. Indeed, after a collision, the vehicles' movement consists of a linear displacement combined with simultaneous rotation. (Karapetkov et al., 2019)

On what concerns vehicle collisions, delta-v (∆v) is a parameter which can be used to evaluate the vehicle occupants' injuries and the crash severity. This parameter consists of the change in velocity vector during the impact (the difference between the velocity at impact and the residual velocity after energy absorption and interaction with the target vehicle) including the velocity's magnitude and direction changes. Delta-v depends on the vehicles' masses, on the vehicles' relative impact speed, and on restitution coefficient. (Dima & Covaciu, 2019)

According to the Monte Carlo method, on a planar collision, vehicles' pre-impact and post-impact velocity vectors can be represented on a crash plane defined by a coordinate system, as shown in Figure 3.1. (Rose et al., 2001)

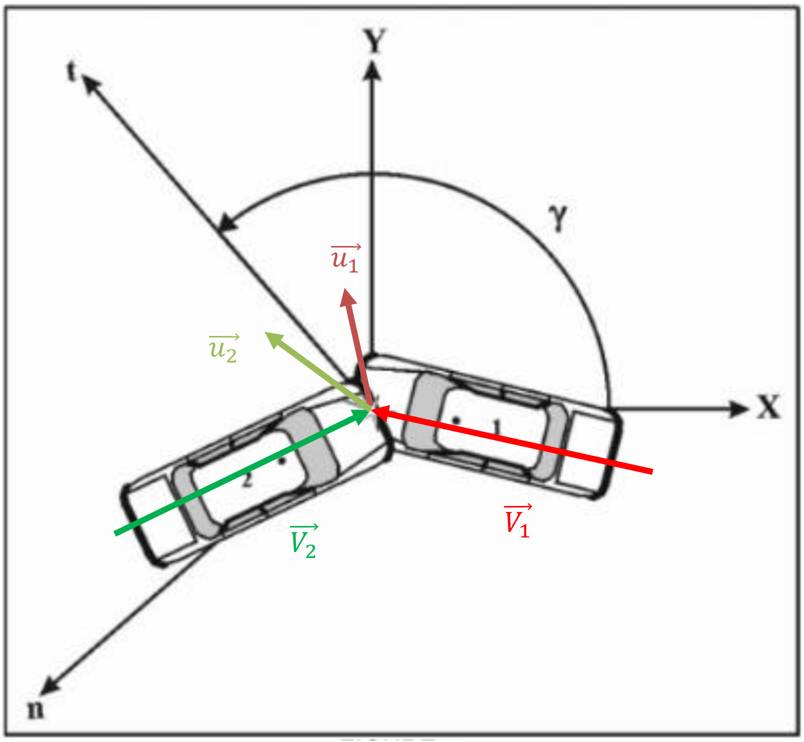


Figure 3.1 - Monte Carlo's impact plane with pre and post impact velocities (not on scale), adapted from (Rose et al., 2001)

According to the Slibar model, the collision involved vehicles' movement is decomposed on a translation, followed by a rotation. Besides, the energy exchange should be considered (deformation energy), as there is crush on the vehicles' metal components during the impact. (Dima & Covaciu, 2019)

In practice, the vehicles' movement is planar and there is a complex rotation dynamic of a multi-mass system of bodies, apart from the linear displacement. For this reason, a method which also considers the vehicles' post-impact rotation motion and deformation energy should be a more precise approach to vehicle dynamics evaluation.

Integrating previous equation to the Principle of Conservation of Mechanical Energy, it results in (Dima & Covaciu, 2019; Karapetkov et al., 2019; J. G. J. Neades, 2011):

$$\frac{m_1V_1^2}{2}+\frac{m_2V_2^2}{2}=\frac{m_1u_1^2}{2}+\frac{m_2u_2^2}{2}+\frac{I_1\omega_1^2}{2}+\frac{I_2\omega_2^2}{2}+E_1+E_2$$

with:

m_1 and m_2 – the vehicles' masses,

I_1 and I_2 – the two vehicles' mass inertia around the vertical axis O_z,

V_1 and V_2 – the vehicles' centre of mass pre-impact velocities,

u_1 and u_2 – the vehicles' centre of mass post-impact velocities,

ω_1 and ω_2 – the vehicles' bodies post-impact angular velocities around the vertical axis O_z,

E_1 and E_2 – the vehicles' bodies deformation energy.

This method's results inaccuracy is due to errors on determining the vehicles' motion correctly before and after the impact. Usually, the velocity vector's direction is oriented from the vehicle's centre of mass at the impact moment to the vehicle's centre of mass at the final rest position. Indeed, involved vehicles might perform a complex spatial movement which includes translation and rotation, and even a tire-road friction dynamic that varies along the vehicle's motion.

This method can be effective on the study of collisions involving vehicles from the same mass range. When there is a heavy goods vehicle involved on an accident with a passenger vehicle, there may be some uncertainties due to the significant mass difference. (Karapetkov et al., 2019)

3.1.1. Separation velocity

In order to determine the vehicles' pre-impact velocities, the immediate post-impact vehicles' velocities must be known firstly. Post-impact motion and skid marks sometimes allow experts to determine the post-impact velocities and include them on the previously mentioned equations.

Usually, on the post-impact movement the vehicles' wheels keep in contact with the soil. According to the principles or Burg and Marquard, post-impact motion parameters can be determined as the following equations state, considering that vehicles move to the rest positions with constant frictional resistances. This way, the vehicles' separation linear and angular velocities can be given by (Davis, 2009; Wach et al., 2016):

$$v_i' = \sqrt{2 \cdot a_i^* \cdot d_i + v_i''^2}$$

$$\omega_i' = \sin(\Delta\varphi_i) \cdot \sqrt{\frac{m_i \cdot g \cdot w_r \cdot l_i}{I_i} \cdot |\Delta\varphi_i|}$$

where:

$$a_i^* = \mu_i \cdot g \cdot [f_i + (1 - f_i) \cdot \sin\varphi_i^*]$$

with: $$\sin\varphi_i^* = \begin{cases} \sin(|\Delta\varphi_i|/2) & for \quad \Delta\varphi_i < 60° \\ 0.5 & for \quad \Delta\varphi_i \geq 60° \end{cases}$$

where:

i – the vehicle's index,

$\Delta\varphi_i$ – the total rotation angle in post-impact motion, [rad],

μ_i – the road-tyre friction coefficient,

g – the gravity acceleration, 9.81 m/s^2,

I_i – the vehicle's inertia moment in relation to the vertical axis, going through the centre of gravity CG, [kg.m^2],

m_i – the vehicle's mass, [kg],

l_i – the vehicle's wheelbase, [m],

d_i – the distance between the vehicle's CG at the pre-impact and at the final position, [m],

v_i'' – the vehicle's velocity at the end of the considered movement, [m/s],

f_i – the post-impact motion drag coefficient (from 0 for all wheels freely rotating to 1 for all wheels locked),

w_r – the rotational drag coefficient (0.15 front or rear impact, for 0.35 for side impact).

3.1.2. Energy exchange

On a collision event, the involved vehicles are moving and bring kinetic energy which is characterized by the vehicle's mass and its velocity, ate the pre-impact stage. When the collision occurs, part of each vehicles' kinetic energy is transferred to mechanical energy and heat, during the vehicles' components deformation. On a post-impact stage, vehicle's keep the remaining kinetic energy which produce their final motion to the rest position.

The total energy exchange, during collision, including both translation and rotation, can be given by (Dima & Covaciu, 2019):

$$\Delta E = (E_1 + E_2) - (E_1' + E_2')$$

with:

$$E_i = \frac{1}{2} m_i V_i^2 + \frac{1}{2} I_i \omega_i^2 \; with \; V_i^2 = V_{ix}^2 + V_{iy}^2$$

$$E_i' = \frac{1}{2} m_i u_i^2 + \frac{1}{2} I_i \omega_i'^2 \; with \; u_i^2 = u_{ix}^2 + u_{iy}^2$$

i – the vehicle's index

resulting on:

$$\Delta E = \frac{1}{2}\left[m_1(V_{1x}^2 - u_{1x}^2) + m_1\left(V_{1y}^2 - u_{1y}^2\right) + m_2(V_{2x}^2 - u_{2x}^2) + m_1\left(V_{2y}^2 - u_{2y}^2\right) + I_1(\omega_1^2 - \omega_1'^2) + I_2(\omega_2^2 - \omega_2'^2)\right]$$

where ω's are now:

ω_1 and ω_2 – the vehicles' pre-impact angular velocities, around the vertical axis O_z,

ω_1' and ω_2' – the vehicles' post-impact angular velocities, around the vertical axis O_z

3.1.3. EES

The energy exchange involved on a collision consists mainly of deformation energy. This way, the deformation energy can be given by the difference between the kinetic energy before the impact moment, and the kinetic energy after the impact instant. This energy exchange on deformation can be as well expressed as kinetic energy, where its velocity corresponds to a speed which is equivalent to the performed deformation on the vehicles. This equivalent velocity is denominated by Energy Equivalent Speed (EES). (Dima & Covaciu, 2019; Vangi, 2009)

$$\Delta E = \frac{1}{2} m_1 EES_1^2 + \frac{1}{2} m_2 EES_2^2$$

As a velocity that it is, the EES is expressed in m/s.

According to the Monte Carlo method, EES velocity vectors are placed on the coordinate system as shown on Figure 3.2. Deformation energy equivalent momentum is represented with the collision's deformation plane direction.

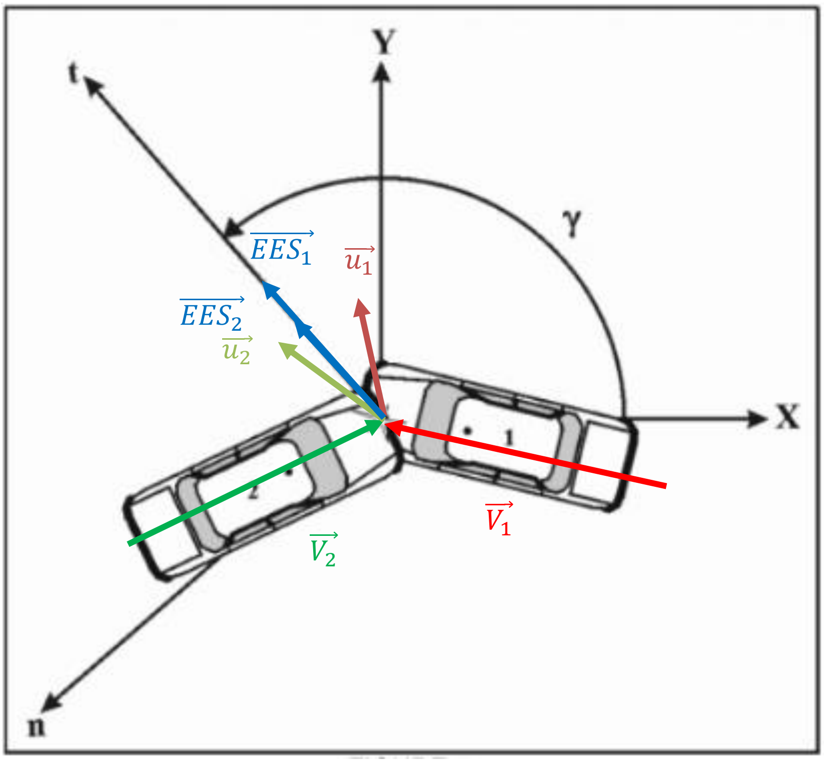


Figure 3.2 - Monte Carlo's impact plane with pre, post, and EES impact velocities (not on scale), adapted from (Rose et al., 2001)

The EES was introduced by Burg and Zeidler, it can be considered a measure for the deformation occurred on the impact, or the equivalent kinetic energy.

In case of a barrier impact with complete overlap (100%), the delta-v parameter and the EES present similar magnitudes, as it consists of a collision without glace-off. However, on an impact with partial overlap only, rebound may occur and the EES might present a higher value compared to the delta-v magnitude.

For a single vehicle which collides with a fixed, non-deformable barrier, without spin-off movement, the deformation energy is (Dima & Covaciu, 2019):

$$\Delta E = \frac{1}{2} m_1 v_1^2 = \frac{1}{2} m_1 EES_1^2$$

Delta-v magnitude is usually different from the EES, as delta-v represents the vehicle's centre of gravity velocity change during the collision. Delta-v can be determined by integrating the vehicle's registered acceleration on its longitudinal direction if the vehicle does not execute a rotation movement. Otherwise, all the vehicle's acceleration components must be considered.

The "speed ratio" is an existing control parameter for the collision dynamics, which compares the Energy Equivalent Speed (EES) to delta-v and is given by (Dima & Covaciu, 2019):

$$SR = \frac{\Delta v_i}{EES_i}$$

where:

Δv – delta-v magnitude (the speed change, during the impact),

i – the vehicle's index.

The speed ratio (SR) value may belong to different ranges which characterize the collision's type, according to the following list (Dima & Covaciu, 2019):

- 0.9 < SR < 1.2 – collision with no rebound,
- 0.75 < SR < 0.9 – collision with slight rebound,
- SR < 0.75 – collision with significant rebound.

From these base principles, authors developed mathematical models which allow to determine the vehicle's velocity change from a collision, considering the principal direction of force (PDOF) on the impact, and its influence on the vehicle's dynamics, and even the restitution effect.(J. G. J. Neades, 2011; J. Neades & Smith, 2011; Rose et al., 2001)

3.1.4. Dynamic Analysis of Post Impact Motion of Vehicles

The previously described methods may be too general and consider various approximations which can guide to certain results' inaccuracies, as they do not completely cover the vehicles' post-impact dynamic analysis. This is due to the fact that the suspensions' elasticity and damping are not considered, and the complex dynamic related to tire-road surfaces friction is also not taken into account, for example. Besides, the centre of mass motion theorem's consideration might also induce some uncertainties on the results.

In order to obtain more precise results, the multiple forces involved on the vehicles' dynamics should be considered, such as the earth's gravitational force, the suspension's elasticity and damping forces, the friction forces, and the aerodynamic resistance. (Karapetkov et al., 2019)

On this approach, the vehicle's whole post-impact kinetic energy is determined by a system of twelve differential equations which are based on the Newton's Second Law, and consider the vehicle as a multi-mass system, as shown on Figure 3.3.

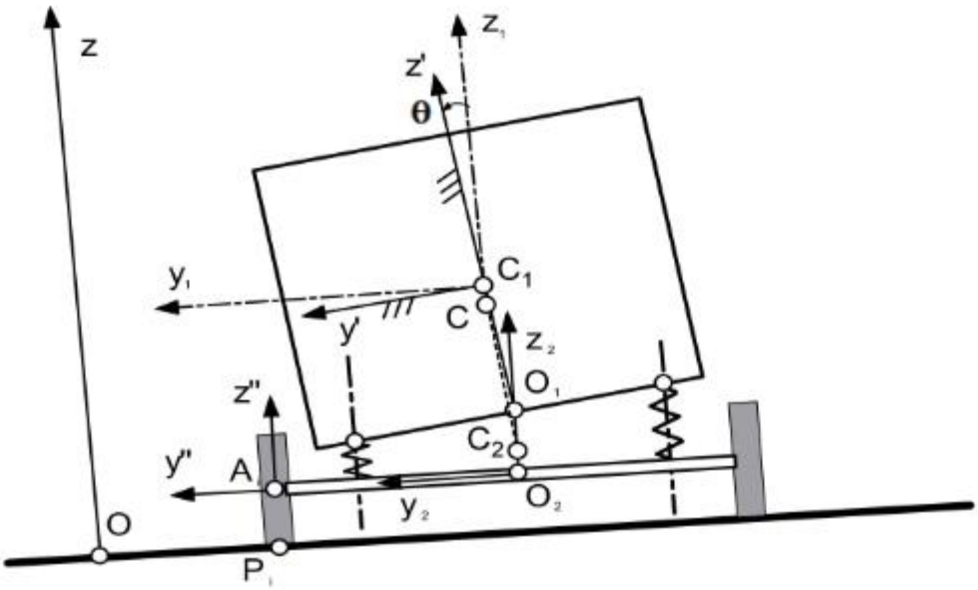


Figure 3.3 - Vehicle's multi-mass system representation (rear view), adapted from (Karapetkov et al., 2019)

This analysis aims to determine the vehicle's centre of mass post-impact velocity, u, and its angular velocity after the impact, ω_z.

This way, considering the vehicle as a multi-mass spatial mechanical system, the motion differential equations for the vehicle's post-impact dynamics, corresponding to the three orthogonal axis, are represented as follows (Karapetkov et al., 2019):

$$m\ddot{x}_C = \sum_{i=1}^{4} [F_{ix}] + mg\sin\alpha - W_x\sqrt{\dot{x}_C^2 + \dot{y}_C^2}\dot{x}_C$$

$$m\ddot{y}_C = \sum_{i=1}^{4} [F_{iy}] + mg\sin\beta - W_y\sqrt{\dot{x}_C^2 + \dot{y}_C^2}\dot{y}_C$$

$$m\ddot{z}_C = \sum_{i=1}^{4} N_i - \frac{mg}{\sqrt{1 + tg^2\alpha + tg^2\beta}}$$

where:

α – the road's longitudinal slope,

β – the road's transverse slope.

3.2. Accident scene information collection methods' definition

Multiple different public and private entities perform road traffic accident scenarios' reconstitution, so being a contemporary and high relevance issue. Accident scene data collection requires balancing the efforts to accomplish two fundamental and, however, colliding objectives which involve thoroughly collecting and register as much information as possible, so that there are no missing evidence and relevant details, and, on the other hand, work fast and clean the road to re-establish the traffic flow and minimise the constraints as briefly as possible. For this reason, accident scene reconstitution and data collection must be effective, efficient, objective, and as much rigorous as possible.

The reconstructed impact scenario and the accident sketch with measurements consist of the base information, evidence, and clues' source, which allow accident experts to draw hypotheses and conclusions about the collision's contours, since the crash simulations are developed on and from the recreated scenario which must be scaled to the real road dimensions. Besides, when there are multiple events on a coincident zone, it is also possible to identify road infrastructures' projecting faults, lack of signalisation, or potential risk behaviours with the help of an accident scene which is correctly and accurately reconstructed. The identification of these flaws might allow the implementation of measures to minimise road sinistrality, resorting to physical interventions or road users' sensibilization. (Pádua et al., 2020)

Typically, authorities are the first entities which arrive the road accident's scene. Firstly, they must ensure that proper medical assistance is provided to any possible victim. Secondly, authorities should maintain the collision site as similar as it resulted from the impact, preserving all the evidence, debris, and traces on their final rest position, while managing the best alternatives for traffic re-routing. Then, evidence must be identified and collected as thoroughly as possible, developing accident sketches which include the various elements, such as vehicles' final positions, skid marks, the present traffic signs, and so on. Additionally, precise measurements must be taken to allow crash scenario fully definition, the environmental conditions should be noted (for example, visibility and sun positioning), and photographic registers should be acquired for future visual records. Ideally, as there are multiple elements to analyse and retrieve, the data collection procedures should be simple, quick and precise. (Pádua et al., 2020)

3.2.1. Tape, Wheel, Photography, Sketches

Nowadays, authorities still resort to classical methods for data collection. Despite minimal differences, the accident scenario sketch is mainly based on manual measurements done by the principle of triangulation or parallel lines to reference the positions on a coordinate system, for example. The instruments used by the authorities to catalogue this information consist of the measuring tape and measuring wheel, Figure 3.4, the notepad and pencil to draft the sketch, chalk to mark the pavement, and a camera to acquire photographic registers. This way, the accident scene reconstitution accuracy and precision rely essentially on the authority officers' professionalism and experience.

This classical method for data collection represents some unfavourable aspects, such as, the significant amount of time required for this sluggish task, the high probability of missing relevant details, the need to block or restrict the road traffic flow, and the authority officers' exposure to situations which might involve some risk. (Pádua et al., 2020)

Figure 3.4 - Measure tools for the classic method: measuring tape (left) (KOMELON | Tapes, 2022), and measuring wheel (right) (KOMELON | Measuring Wheels, 2022)

3.2.2. Total Station

Total station devices also consist of valuable tools to precisely reconstruct an accident scene, since their theodolite has an angular measurement capability which allow to determine horizontal and vertical angles, and inclined distances to specific points, resorting to electronic distance measurement (EDM). With the measured linear and angular distances to the points of interest, and using triangulation and trigonometry, total stations can reference each point on its own coordinate system, which is relative to the main device's position, on what concerns planar and elevation coordinates. However, to perform these measurements there must not be obstacles between the target points and the total station device. Total stations may also determine absolute locations, nevertheless, it must survey at least two or more points with known coordinates and with line of sight. (Chekole, 2014)

As total station measurements are made with the laser electronic distance measurement (EDM) technology, any object which intercepts momentarily the total station line of sight may produce errors on the surveying results. These inaccuracies may occur if surveying is being conducted on a collision scenario with flowing road traffic, for example.

Some total stations include a feature sensor to recognise specific targets and perform distance and angular measurements, and coordinate determination automatically, the designated automatic target recognition (ATR) sensor. These specific targets consist of auxiliar tools with a prism that can be detected by the device's optical sight and allow to acquire results with higher accuracy. (Chekole, 2014)

This way, total stations have two operation modes, so being the targeted EDM mode and the reflector-less mode. On the targeted EDM mode the previously mentioned prisms are required, and operators must place them on the points of interest to acquire high accuracy measurements. For the reflector-less mode the prisms are not needed and the total station functions as a laser pointer on the surfaces. This mode performs less accurate measures. (Dustin & Liscio, 2016)

Figure 3.5 represents the appearance of a total station device, on the left, and a typical target prism used as reflector on the targeted EDM mode for more accurate measurements.

Figure 3.5 - Total station device (left) (Leica FlexLine TS10, 2022), and reflector prism (right) (Reflectors | Leica Geosystems, 2022)

Accident scene data collection may involve signalizing the relevant clues with evidence markers (vehicles’ final positions, road lines and boundaries, traffic signalization, debris, traces, skid marks, and so on), then collecting some tape measurements to establish the digital image’s scale, defining ground control points, and total station image capturing with a minimum defined overlap.

Total station surveying for accident scenes reconstitution still might be a lengthy process and an expensive method for road collision on-site data collection. Even combining the classic methods with the total station surveying, the information capturing process may take significant time, approximately two hours on some cases. (Osman & Tahar, 2016)

3.2.3. GNSS Receivers

The GNSS (Global Navigation Satellite System) receivers working principle consists of determining global coordinates continuously, or for specific points, through the signal’s analysis incoming from the satellites. GPS (Global Positioning System) surveying is a differential method, as positions, distances and velocities are determined through the monitoring and integration of the receivers’ global position acquired with a certain frequency. The use of multiple GNSS receivers, acquiring signals from the same group of satellites, allow the mitigation of external factors’ influence which promote results’ inaccuracy.

A GNSS receiver is illustrated on Figure 3.6, on the left, as well as a GNSS smart antenna, on the right side.

Figure 3.6 - GNSS receiver (left) (Leica Viva GS25, 2022), and GNSS smart antenna (right) (Leica GS18 T GNSS RTK, 2022)

The GPS precision and accuracy are influenced by a variety of external factors which cannot be controlled, such as the atmospheric conditions, involving the weather and the ionospheric disturbance, the number of tracked satellites by the receivers and signal blockage on urban areas with major buildings and covered areas, for example.

In order to refine the data collection accuracy, GPS readings can be complimented with the RTK (Real Time Kinematics) technology which implement differential corrections to the data collection process from stationary base receivers installed on determined locations. Typically, the correction signals are real-time transmitted from the base station to the mobile receiver through radio communication. Since signal corrections are made simultaneously as measurements are performed, the results do not need further data processing, being available immediately. For this reason, GPS combined with RTK mode is a faster method for surveying and geodetic measurements, compared to the previously mentioned technologies. (Chekole, 2014)

3.2.4. Laser Scanning

For applications which require surfaces scanning or sampling, the laser scanning technology consists of an effective method, since it digitally collects information regarding physical objects' shape and appearance. Laser scanning is comparable to a photography capture with depth information, as it creates a spatial distributed point cloud used to form a mesh which allow the digital reconstruction of 3D models and precise 2D drawings, resorting to dedicated software. In a relatively short period of time, laser scanners can retrieve a high quantity of points with considerable accuracy. However, multiple scan positions and iterations are required to completely cover a structure's shape, since laser scanners are line-of-sight tools as well as total stations. (Chekole, 2014; D'Anniballe et al., 2020)

Figure 3.7 presents an example of a 3D laser scanner device.

Figure 3.7 - 3D laser scanner (Leica RTC360, 2022)

On what concerns accident reconstruction, terrestrial laser scanning allowed the collision scenario documentation on a 3D format which might be more explicit and accurate. Besides, it promotes data collection in a more flexible and efficient way, since the tool can be operated by a single technician under the various luminosity conditions, and in a safer manner, as capturing can be performed from off the road avoiding road traffic interruptions in some cases. Three-dimensional accident scene models may provide additional information so the experts can draw hypotheses about the collision's contours, for example, on what concerns road configuration, and drivers' visibility. The integral data collection promoted by laser scanning might allow the complete capture of relevant evidence remaining on the collision scenario, minimizing the possibility of missing important details. This fact consists of a major advantage, as accident investigators keep the opportunity to objectively review all the collision's evidence. (Dustin & Liscio, 2016; Pagounis et al., 2006)

Terrestrial laser scanners (TLS) are valuable tools with great potentialities regarding data collection for road accident reconstruction. This technology's main advantages include:

- Safety. TLS are remote sensing instruments. this way, the operator has not the need to place target prisms on the interest points for data collection.
- Brief data acquisition. TLS data collection method might be significantly quick (1-400 kHz, depending on instrument), which contributes to the minimisation of lane closure time, if needed.

During data acquisition, the environmental conditions, the objects' surface characteristics and hardware issues are the main causes for laser scanning results' inaccuracies or uncertainties. Temperature, interfering radiation, and atmospheric conditions consist of the environmental influence factors. On what concerns the objects' characteristics, the surfaces' reflectivity might induce some errors on the data collection, since the technology is based on laser beams. With respect to the hardware issues, scanners' mechanical and optical instabilities may generate discrepancies and influence the results' accuracy. (Dustin & Liscio, 2016; Pagounis et al., 2006)

Ideally, for complete and detailed accident scenario reconstitution, multiple and independent laser scans should be done from different directions. To integrate all the scans on a common coordinate system there must be proper spherical or retro-reflective targets which are always captured on the multiple scans performed. However, despite the increased accuracy, the special targets' usage, placement, and scanning might also increase the time required for data acquisition. The alternative is to select other stationary objects which already belong to the collision scenario and are favourably positioned. (Dustin & Liscio, 2016; Pagounis et al., 2006)

3.2.5. Photogrammetry

The photogrammetry is the technique which involves overlapping same object or location multiple portraits that were taken from different perspectives. This methodology allows measurements and metric information retrieving from 2D photographs, and subsequently to produce 3D models, through close range or terrestrial photogrammetry, and 3D maps, through aerial photogrammetry. (D'Anniballe et al., 2020) Nowadays, photogrammetry technology is being gradually adopted for the road accident reconstruction, as it presents high capabilities to recreate faithfully detailed collision scenarios and allow the effective development of representative and accurate 3D models. Photogrammetry advantages, such as efficiency, effectiveness, and ease of use to develop precise models are being recognized and accepted by various law enforcement entities.

For road accident reconstitution the used methodology is the aerial photogrammetry assisted by light and small multi-rotor unmanned aerial vehicles (UAVs), which can be operated manually with a remote controller, by the accident investigators, or travel autonomously above the collision scenario to collect multiple portraits.

To capture photographs and perform their global georeferencing, photogrammetric UAVs for data acquisition, regarding the collision scenarios' reconstruction, are frequently equipped with a camera and a GNSS receiver. Besides, these UAVs' GPS capabilities allow the autonomous surveying of accident scenes by previously defining the paths to be followed by the device. (Pádua et al., 2020)

An unmanned aerial vehicle for photogrammetry equipped with its camera sensor, and the respective controller are illustrated on Figure 3.8.

Figure 3.8 - Drone for photogrammetry (left), and drone controller (right), adapted from (DJI Phantom 4 Pro V2.0, 2022)

The use of UAV assisted photogrammetry technology allow the overcoming of multiple adversities verified on the usage of other accident scene data collection methodologies, which could induce potential errors and lead to inaccurate results. Nevertheless, the UAV photogrammetry results may also be influenced by certain conditions which involve unfavourable luminosity conditions, as verified on the night period and during environmental phenomena, and the presence of stationary objects which cover or block completely or partially the UAV´s camera sight or surveying path above the collision scenario.

After the photographs’ capturing routine, the collected data must be treated to obtain an orthophoto mosaic, resorting to a photogrammetric software. The resultant virtual model digitally documents the road accident scene with significant accuracy. Using specific software, compatible with Computer Aided Design (CAD) models or Geographic Information Systems (GIS) data, it is possible to take real scale precise measurements and complement the accident’s evidence with information after importing the reconstructed and georeferenced collision scenario’s 3D model or point cloud. (Pádua et al., 2020)

To sum up this report’s section, Table 3.1 presents a brief comparison between the described methodologies to address road accident scenarios reconstitution, on what concerns their advantages, disadvantages, and main outputs.

Table 3.1 - Comparison table for collision's scenario data collection methods, adapted from (Pádua et al., 2020)

Technology	Advantages	Disadvantages	Outputs
Measuring Tape or Wheel	+ Ease of use + Low cost	× Time consuming × Prone to errors × No visual data × Data not georeferenced	- Manual measurements
Sketches and Photographs	+ Ease of use + Low cost	× Time consuming × Inaccurate × Data not georeferenced	- Measurements - Images - Forensic sketches
Total Station	+ Rigorous	× Time consuming × Skilled operator × Not suitable for mobility × Considers line of sight × Expensive	- Precise measurements (angles and distances)
GNSS Receivers	+ Rigorous	× Time consuming × Prone to signal obstruction × Expensive	- Precise georeferenced points
Laser Scanning	+ Rigorous + 3D Visualisation	× Time consuming × Loss of information due to its position × Confined action range × Expensive	- Point clouds - Images
Photogrammetry with UAS	+ Ease of use + Large coverage + Multiple outputs + 3D visualisation + Cost effective	× Data acquisition constrains × Liable to collisions × Requires training × Rigidly regulated	- Point clouds - 3D meshes - Orthophoto mosaics - Digital surface models

3.3. Vehicle damage collection and analysing methods

In case of accident occurrence, the vehicles' structure and body perform an important role on the vehicle occupants' protection and injury severity minimisation. The vehicle's structure suffers deformation to absorb the impact energy and lower the amplitude of the accelerations registered and transmitted to the occupants during a collision event, while the colliding vehicles are in contact between each other or with an obstacle. The vehicle's most rigid components, as the engine and structural chassis, produce decelerations with higher amplitude values, while its fewer rigid parts, such as the bumpers and body metal sheet, cause lower amplitude deceleration pulses. This way, manufacturers design their vehicles' body and structure regarding a main objective of lowering the acceleration amplitude and occupants' injuries, in case of accident, through the identification of solutions to manage the energy absorption. (Dima & Covaciu, 2019)

As manufacturers produce new vehicle models, they are submitted to various crash tests to assure the vehicle's integrity and occupants' protection requirements. These tests also allow the determination of the vehicles' stiffness parameters which can be used to relate the deformation displacement to the deformation energy, in case of a collision event. For this reason, determining the vehicles' suffered deformations after an impact is a high relevant issue regarding the road accidents reconstruction, as it allows the calculation of the involved vehicles' EES parameters. (Dima & Covaciu, 2019)

3.3.1. Classic method

To evaluate a vehicle's damage and the respective deformation energy, the distributed impact load's amplitude ([N/m]) is considered to be directly proportional to the vehicle's plastic deformation, through a linear function given by the vehicle's stiffness coefficients constants. This linear function can be expressed as (Karapetkov et al., 2019):

$$\frac{dF}{dl} = q = A + Bc$$

where:

F – the impact force;

c – the plastic deformation's depth, measured perpendicularly to the respective contact plane under impact;

l – the deformation axis, perpendicular to the measured contact deformation and lying in the plane, where plastic deformation results. The l coordinate's maximum value is the total width of deformation zone L;

A – the coefficient which characterizes the structure's elasticity [N/m];

B – the coefficient which characterizes the function's linear increase (function slope) [N/m^2].

Figure 3.9 represents the change in the distributed load amplitude, resulting from the impact forces, as a plastic deformation linear function.

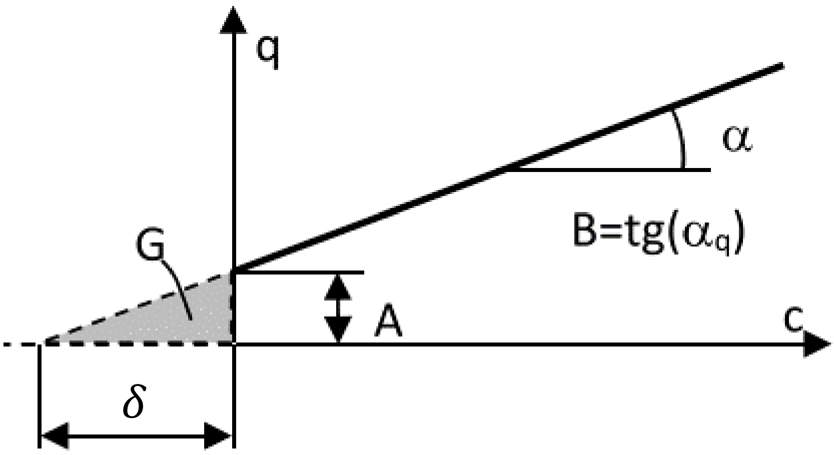


Figure 3.9 - Graph of the impact's distributed load as function of plastic deformation, adapted from (Karapetkov et al., 2019)

Before plastic deformation occurrence, the vehicles' components deform elastically absorbing a small quantity of energy on deformation which is restored when the impact forces stop acting on the vehicle. The vehicle's elastic deformation energy is represented by the area that is denoted by G, on the graph represented on Figure 3.9. This way, the rectangular triangle base's length represents the vehicle's maximum elastic deformation, which can be given by $\delta = A/B$. The amplitude of the distributed load responsible for elastic deformation can also be assumed to be linear to the elastic strain (Evtyukov et al., 2020; Karapetkov et al., 2019):

$$q_e = \frac{dF}{dl} = Bc$$

where:

c – the total elastic strain, whose maximum value is $\delta = A/B$.

The following integral allows the calculation of the elastic and plastic deformation's relative energy per unit width:

$$dE = \left[\int_0^{\delta} q_e dc + \int_0^{c} q dc\right] dl$$

$$dE = \left[\int_0^{\delta} Bc dc + \int_0^{c} (A + Bc) dc\right] dl$$

$$dE = \left[G + Ac + B\frac{c^2}{2}\right] dl$$

where G is given by:

$$G = \frac{B}{2}\delta^2 = \frac{A^2}{2B}$$

The area denoted by G, Figure 3.9, represents the vehicle's elastic deformation, this way, if it is integrated in the plastic deformation, it consists of an integration constant.

The energy exchange absorbed by the vehicle's deformation can be determined for the whole deformation width, L, by the integral expression (Karapetkov et al., 2019; Numata et al., 2018):

$$E = \int_0^L dE = \int_0^L \left[\frac{A^2}{2B} + Ac + B\frac{c^2}{2}\right] dl$$

$$E = \int_0^L \left[Ac + B\frac{c^2}{2}\right] dl + \frac{A^2}{2B}L$$

To simplify the calculus and facilitate the expression's use, the integral can be solved for discrete points along the deformation width. Considering six uniformly distributed points on the vehicle's deformation profile, and the correction factor due to the principal direction of the impact force (PDOF), it is possible to determine the deformation energy by the formula (Karapetkov et al., 2019; Numata et al., 2018):

$$\begin{aligned} E = \frac{L}{5}\Bigg[&\frac{A}{2}(c_1 + 2c_2 + 2c_3 + 2c_4 + 2c_5 + c_6) \\ &+ \frac{B}{6}\left(c_1^2 + 2c_2^2 + 2c_3^2 + 2c_4^2 + 2c_5^2 + c_6^2 + c_1c_2 + c_2c_3 + c_3c_4 + c_4c_5 + c_5c_6\right) \\ &+ 5\frac{A^2}{2B}\Bigg] \times (1 + tg^2\theta_{PDOF}) \end{aligned}$$

with:

θ_{PDOF} – the angle between impact's normal and the principal direction of force;

L – the deformation depth's width [cm];

c_i ($i =$ 1, 2, …, 6) – the deformation depth's magnitude [cm];

A and B – the vehicle's stiffness coefficients set respectively in $[N/cm]$ and $[N/cm^2]$.

Commonly, vehicles' deformation is approximated by the acquisition of two, four or six damage depth measurements and the authors defined specific solutions for the integral to calculate the crush energy. However, these approximations may lead to results' inaccuracy since the deformation profile can be very complex. Ideally, accident investigators should select and adapt the number of damage depth samples to obtain accurate results with reasonable calculation efforts. For this reason, the crush force and energy can also be determined for an arbitrary number of evenly distributed damage depth measurements along the vehicles' deformation profile. This way, assuming constant stiffness coefficients, A and B, for all the vehicle's crush zones, the total force (F) and work promoting deformation energy (E) for arbitrary (n) damage depth measurements (C_1, …, C_n) can be calculated by the following expressions (Evtyukov et al., 2020; J. G. J. Neades, 2011):

$$F = \sum_{i=1}^{n-1} F_i = L\left(A + \frac{B}{2(n-1)} \cdot \eta\right)$$

$$E = \frac{L}{(n-1)}\left(\frac{A \cdot \eta}{2} + \frac{B \cdot \kappa}{6} + \frac{(n-1)A^2}{2B}\right)$$

where:

$$\eta = \sum_{i=1}^{n-1} [C_i + C_{i+1}]$$

$$\kappa = \sum_{i=1}^{n-1} \left[C_i^2 + C_i C_{i+1} + C_{i+1}^2\right]$$

As already referred previously, typically, the main impact force at the instant of maximum amplitude does not act perpendicularly to the surface from which the damage measurements are being performed. For this reason, the calculated deformation energy must be corrected by a factor which comprises the principal direction of force at the impact. This correction is given by (J. G. J. Neades, 2011; Numata et al., 2018):

$$E_{corrected} = E(1 + tg^2\theta_{PDOF})$$

The classic method relies on expedited manual measurements of the damage's depth, which require the idealisation of the vehicle's non deformed shape and the use of measure tapes, rulers, ropes, and plummets to collect the damage profile at the vehicle's bumper height. The quantity of kinetic energy, which is transferred to deformation energy during impact, is determined by inserting the taken measurements on the previously defined equations. This method's accuracy depends vastly on the operator's skills, as the human intervention is highly required. Besides, the vehicle's original shape must be deduced from the manufacturers' specifications or through the comparison with other vehicles without deformation from the same model, make and year.

The vehicle's damage depth measurements must be performed as shown on Figure 3.10, with the help of reference lines which are parallel to the vehicle's rear axle, which is assumed to be undeformed on frontal impact collisions. The number of measures acquired by the investigator is arbitrary, nevertheless, he must take into consideration the pretended results' accuracy, according to the damage profile's configuration and width. Besides, the first and last measurements should be performed on alignment with the vehicle's lateral limits or with the deformation's lateral limits, depending on the situation. (Evtyukov et al., 2020; Morales et al., 2017)

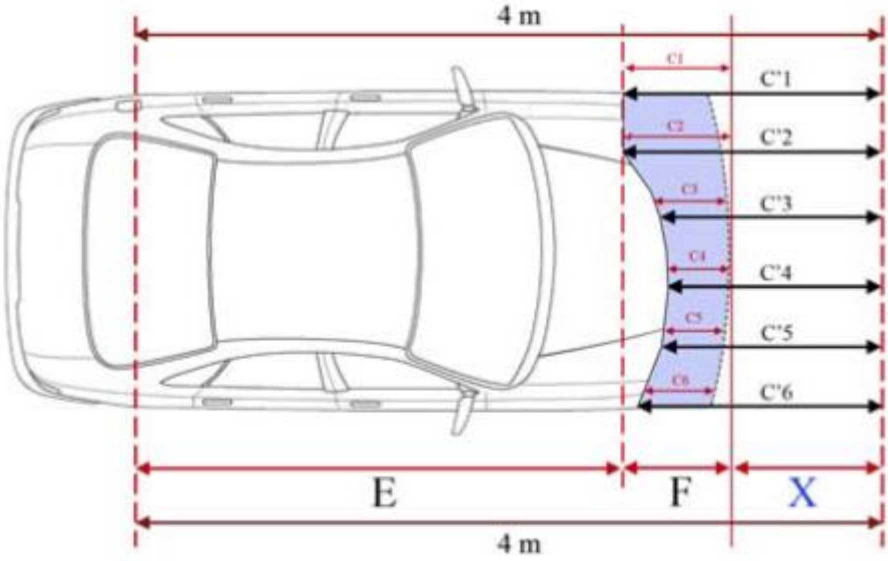


Figure 3.10 - Vehicle's deformation depth measurement procedure, adapted from (Morales et al., 2017)

3.3.2. Photogrammetry and laser scanning

The classic method's potential geometric errors and inaccuracy, resulting from the limited number of measurements, the idealisation of the vehicle's geometry, and human errors during the data acquisition, may influence the results obtained from the vehicle's deformation analysis and lead to wrongful hypotheses about the accident's contours and the vehicles' pre-impact velocities. For this reason, the recently available technologies might allow the vehicles' damage profile collection more precisely and accurately, to avoid some possible uncertainties and mitigate the classic method's limitations.

As well as for road accident scenario reconstruction, vehicles' deformations can also be collected by laser scanning or photogrammetry strategies, in order to effectively and reliably acquire the damage profile as similar to the reality as possible. The use of metric cameras or laser technology allows to digitalise and develop faithful vehicles' 3D models, which contribute to further investigate the impact's contours, and to determine more accurate estimations for the respective deformation energy and EES (Energy Equivalent Speed), subsequently, since the human intervention is minimised. (Morales et al., 2017; Pagounis et al., 2006)

Photogrammetry can be performed by the investigators using conventional cameras or even smartphones, to acquire the portraits that represent and describe the vehicles' deformation profile. Multiple photographs, focusing the vehicle's damaged area, must be taken according to a cross disposition. The central portrait captures the area of interest perpendicularly, while the remaining photographs should be captured from the above, below, left, and right positions relatively to the centre image, and with a determined perspective angle to focus the centre of the damaged area. Figure 3.11 represents the adequate positioning for the portraits' capturing. The reconstruction of the vehicle's deformed zone and undamaged surrounding components is allowed by the photographs' perspective orientation and the minimum overlap of 80% between adjacent images, promoted during the capture process. (Morales et al., 2017)

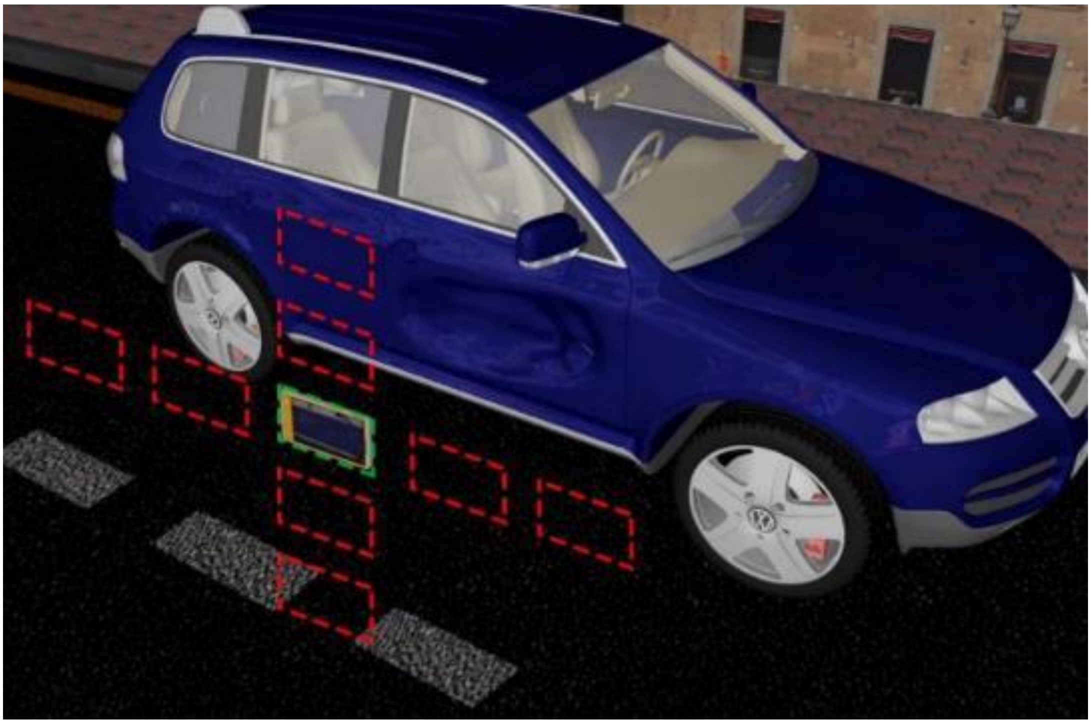


Figure 3.11 - Portraits' capture method for vehicle's deformation photogrammetric data acquisition, adapted from (Morales et al., 2017)

With the aid of computational resources and dedicated photogrammetric software, it is possible to develop 3D models which represent and describe the vehicle's deformation profile by uploading the captured images, characterizing the camera's specifications, and scaling the model with pattern measurements taken physically. With the digitally reconstructed 3D model, it is possible to compute the vehicle's deformation and conduct the energetic analysis to obtain the EES and generate accurate and objective reports. (Morales et al., 2017; Pagounis et al., 2006)

By uploading the damaged vehicle's 3D model to a dedicated analysis software, it is possible to virtually take multiple deformation depth measurements to specific reference points, or automatically determine its damage profile along the width by uploading a 3D model of a vehicle from the same model, make and year without deformation as reference, additionally. This way, the software determines and evaluates the vehicle's deformation by comparison, through the quantification of the discrepancies verified between the damaged and the undamaged models' shapes. Evaluation software can output colour maps on the 3D models with colour scale to ease the vehicle deformations' magnitude analysis, as presented on Figure 3.12. (Morales et al., 2017)

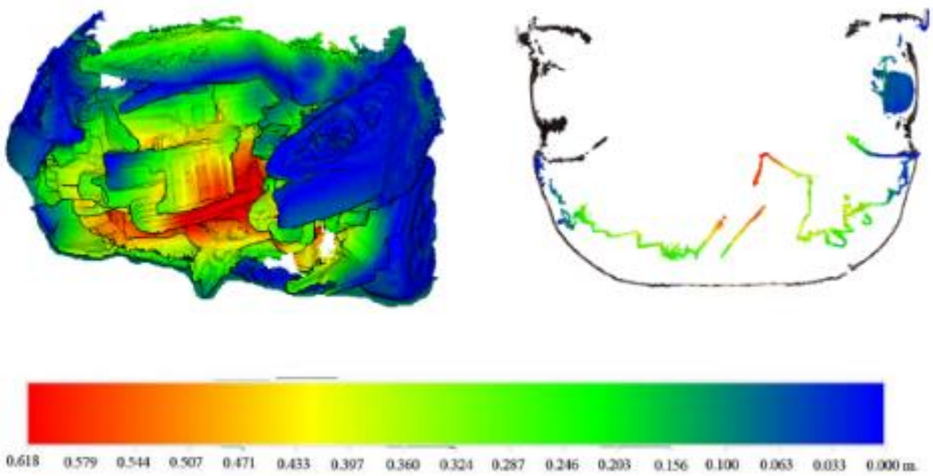


Figure 3.12 - Damaged 3D model's isometric view (left), horizontal planar cross section at the vehicle's bumper height, with the undamaged reference shape in black, for energetic analysis (right), and deformation depth colour scale (below), adapted from (Morales et al., 2017)

Having the vehicle's deformation well defined, the energetic analysis to determine the deformation energy and the EES can be performed similarly to the traditional method, using an arbitrary number of discrete damage depth measurements, or by integration of the deformation magnitude along the vehicle's width, resorting to the computational capabilities. (Morales et al., 2017)

Besides photogrammetry, 3D laser scanning is also a well disseminated technology on what concerns the digitalisation of objects' physical shape. 3D laser scanners reconstruct objects' surfaces by creating a point cloud data set, which can be subsequently used to develop meshes for the objects' 3D models, through dedicated software. (D'Anniballe et al., 2020)

Nowadays, 3D laser scanning is also becoming a valid solution to implement on the collection of the deformation profile from vehicles involved on road traffic accidents. As well as for photogrammetry, laser scanning allows the creation of 3D models which describe the vehicles' damage and permit multiple precise deformation measurements performed on the horizontal cross section at the vehicle bumper's height, as represented by the Figure 3.12 (right). A high number of discrete data collection points is used to determine the deformation energy involved in the collisions with higher accuracy.

In case of impacts with rigid and stationary objects, the EES (Energy Equivalent Speed) resulting from the vehicle's deformations analysis can be compared to the delta-v parameter determined by the vehicle's Event Data Recorder (EDR), if already available, since their determination is based on different principles. For collisions involving two vehicles, the comparison analysis should be performed differently, because the proportion of deformation energy distributed by the vehicles might be unknown. (Numata et al., 2018)

4. The EDR and the vehicles' electronic systems

4.1. EDR definition

The Event Data Recorder (EDR) consists of a storage device, usually installed close to the vehicle's centre of mass, and associated to the Airbag Control Module (ACM). The main functionality of this device is to record, with robustness and reliability, some certain technical data elements related to the vehicle's dynamics, functioning conditions, driver's intentions and behaviours, restraint systems' usage or deployment status, and other systems' operability and activation moments just before and during a collision. (NHTSA, 2022; UNECE, 2021a)

The EDR is a device developed to record event related information which refer to road traffic accidents, in this case. Audio recordings, video recordings, and hours of service data logging, as verified on heavy goods vehicles, are not comprised by this device. (NHTSA, 2022)

The stored variables are listed and described later, on this report's section 4.3. Each data element is monitored continuously during the vehicle's circulation and is acquired by the vehicle's network of sensors, control modules and actuators. However, these values are only recorded on permanent memory if one of the crash's thresholds is met, which is characteristic of an imminent accident condition, otherwise the information is just permanently refreshing on a volatile memory buffer so that it can be ready to be immediately stored when a collision happens.

According to the regulations, the EDR's recording criteria refer to changes on vehicle's velocity and restraint systems' activation. This way, the recording thresholds are reached when the vehicle suffers at least a change in longitudinal or lateral velocity of 8km/h within a time interval of 150ms, what corresponds to a 14,81m/s^2 or 1,51G average acceleration. Besides, the recording criteria is also met if there is the activation of any non-reversible occupant restraint system or vulnerable road user (VRU) protection system. (UNECE, 2021a)

Depending on the manufacturer, the Event Data Recorder (EDR) may have different storage capacities, however, if data memory for distinct events is full, the older data might be replaced by the information associated to an event which occurs subsequently. Nevertheless, some events have higher priority, or bigger relevance, and must not be overwritten by those which are not as critical as these higher priority events. The events for which the EDR's memory shall be locked consists of events at which there is the deployment of non-reversible occupant restraint systems or the activation of vulnerable road user (VRU) secondary safety system. Besides, if a vehicle is not equipped with a frontal impact non-reversible occupant restraint system, the event data must also be locked in memory if a frontal collision with a 25km/h change on vehicle's velocity along the longitudinal axis within an 150ms interval occurs, what corresponds to a minimum average acceleration threshold of 46,3m/s^2 or 4,72G. These most critical events shall only be overwritten by other events which reach at least the same criteria described. (UNECE, 2021a)

As nowadays regulations refer, the EDR must record at least five seconds of pre-crash data and at least a short period of 250ms of data which refers to the crash pulse, after the moment of collision, as illustrated on the timeframe represented on Figure 4.1. These data periods are the least required to get some clues about the vehicle's behaviour before the crash and about the vehicle´s dynamics promoted by the collision, as effect of the contact.

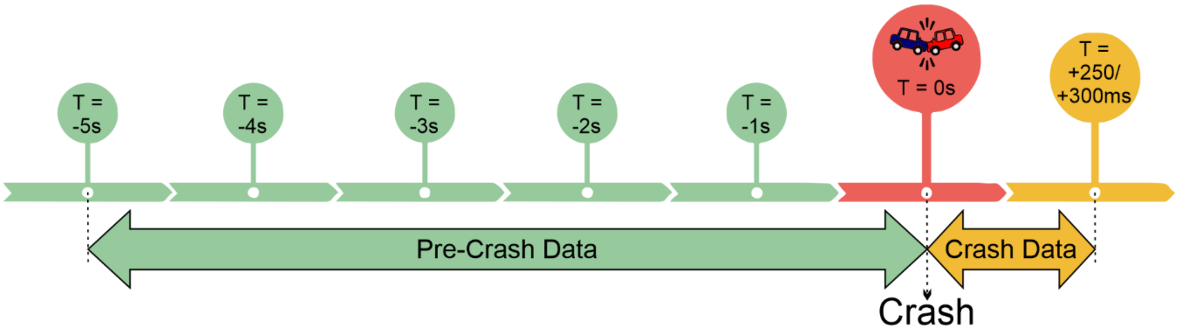


Figure 4.1 - EDR data recording timeframe

The Event Data Recorder (EDR) is connected and powered by the vehicle's electric circuit. In case of power loss or electrical circuit rupture, due to a collision, the device must be equipped with integrated capacitors which guarantee its own functioning and data registration on semi-permanent memory. Besides, the EDR must have a considerable physical and working integrity, so that any possible impact consequences cannot damage the device and affect its functioning. According to regulations, the Event Data Recorder unit must support and maintain the data retrievability after impacts with a severity level defined by the United Nations regulations numbers 94 (UNECE, 2021c), 95 (UNECE, 2021d) or 137 (UNECE, 2021b), which rule the crash tests' conditions. (UNECE, 2021a)

4.2. Vehicles' instrumentation and EDR recordings

The Event Data Recorder (EDR) is a device that stores and manages data, variables and information provided by other systems, sensors and actuators which are equipped on the respective vehicle. To acquire each variable as they are shown and registered on the Crash Data Retrieval (CDR) report, the EDR communicates with the various sensors, either directly or through the vehicle's data networks and other electronic control modules.

On this section are explored the sensors and instrumentation devices needed for each variable captured by the EDR, analysed its outputs and shown some examples of the data reported on the retrieving process. However, note that some data examples from the available reports might not meet the minimum parameters defined by the regulation, since these example reports were already extracted some years ago.

The required devices and instrumentation, so that the EDR may monitor each of the variables listed on the United Nations' regulation, are presented on the following sections. (UNECE, 2009)

4.2.1. Longitudinal and lateral Delta-V; Lateral, longitudinal, and normal acceleration (post-crash); Longitudinal and lateral acceleration (pre-crash):

To record acceleration variables, a triaxial accelerometer or a group of combined accelerometers which are capable of measuring acceleration values on the three orthogonal directions, corresponding to the vehicle's X, Y and Z axis. These accelerometers consist of small devices referred to as Micro-Electro-Mechanical Systems (MEMS) accelerometers built according to one of the three most common principles which are piezoelectric, piezo resistance and capacitive technologies. When the sensor vibrates or moves, there are changes in voltage, resistance or capacitance promoted by the electromechanical components which move slightly inside the accelerometer's body, depending on its technology. Figure 4.2 illustrates the functioning principle of a capacitive accelerometer, on the left, and the appearance of an accelerometer integrated circuit, on the right.

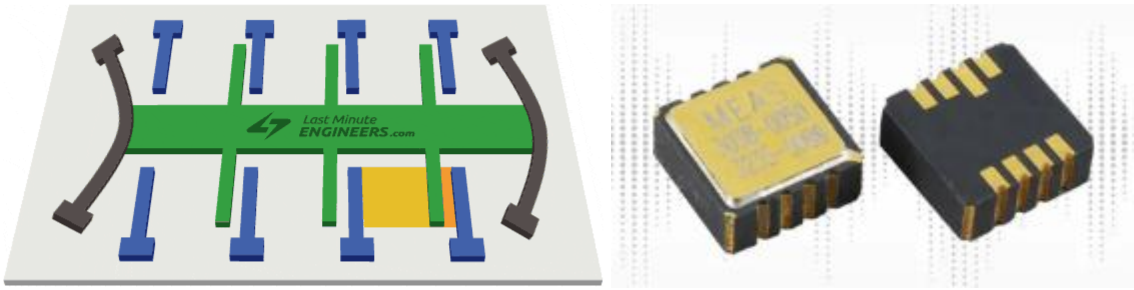


Figure 4.2 - Capacitive accelerometer's functioning principle (left) (Last Minute Engineers, 2022), and accelerometer integrated circuit's appearance (right) (TE Connectivity, 2022)

These variations promote voltage outputs for each direction which can be processed and correlated to the respective acceleration values, by a microcontroller inside a processing unit. These types of accelerometers are usually integrated inside the vehicle's electronic stability control (ESC) unit, Inertial Measurement Unit (IMU), or similar, placed on a position near the vehicle's centre of gravity or geometric centre. The acceleration values are continuously monitored at system's frequency, and the processed values are sent to the Airbag Control Module (ACM) and to the Event Data Recorder (EDR) through the vehicle's data network. On the ACM, the received acceleration values and those acquired directly by the ACM own sensors are used to decide whether if there should be a restraint system deployment or not, and on the EDR, these values are buffered and stored, if there is an algorithm enable, after their integration over time, to obtain the speed variation occurred as consequence of the collision, as Delta V refers to. (Gabler et al., 2004; Jost, 2019; TE Connectivity, 2022)

The Event Data Recorder (EDR) stores the vehicle's longitudinal and lateral Delta-V data during the collision (post-crash), and the vehicle's longitudinal, lateral, and normal acceleration values before and during the accident (pre-crash and post-crash). The Delta-V variables present the vehicle's cumulative velocity change which results from the crash, while acceleration variables present directly the values measured by the vehicle's accelerometers. This way, Delta-V variables are internally derived from the acceleration data, in the EDR. These variables represent the respective vectorial components of vehicle's acceleration on a time basis. This dynamic information is useful to determine the vehicle's behaviour before, during, and after the collision on an accident event.

On the Crash Data Retrieval (CDR) report, the mentioned data elements must be presented according to the minimum specifications defined in the regulations. (UNECE, 2021a) Table 4.1 resumes the minimum requirements and parameters for Delta-V and acceleration variables' recording on the EDR.

Table 4.1 - Requirements for Delta-V and acceleration variables recording (UNECE, 2021a)

Variable	Requirement	Interval	Frequency	Sensitivity
Longitudinal Delta-V	Mandatory	[0; 250] ms	100 Hz	1 km/h
Lateral Delta-V	Mandatory	[0; 250] ms	100 Hz	1 km/h
Longitudinal Acceleration (post-crash)	If recorded on non-volatile memory	[0; 250] ms	500 Hz	1 G
Lateral Acceleration (post-crash)	If recorded on non-volatile memory	[0; 250] ms	500 Hz	1 G
Longitudinal Acceleration (pre-crash)	Mandatory	[-5.0; 0] s	2 Hz	0.1 G
Lateral Acceleration (pre-crash)	Mandatory	[-5.0; 0] s	2 Hz	0.1 G
Normal Acceleration	If recorded on non-volatile memory	[-1.0; 5.0] s	10 Hz	0.5 G

Figure 4.3 represents the graph format for longitudinal Delta V data from a 2012 BMW CDR example report, and the Figure 4.4 indicates the same data on the respective table format.

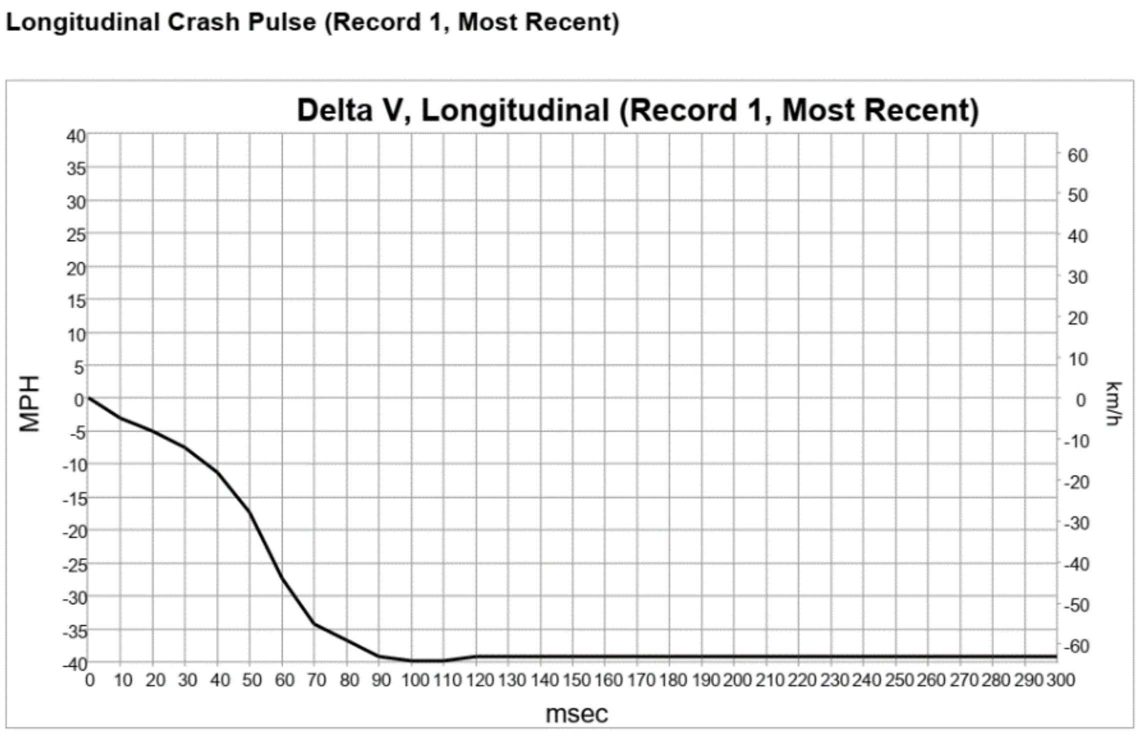


Figure 4.3 - Longitudinal delta-v data on graph format

Longitudinal Crash Pulse (Record 1, Most Recent)

Time (msec)	Delta-V, Longitudinal (MPH [km/h])
0	0.0 [0.0]
10	-3.1 [-5.0]
20	-5.0 [-8.0]
30	-7.5 [-12.0]
40	-11.2 [-18.0]
50	-17.4 [-28.0]
60	-27.3 [-44.0]
70	-34.2 [-55.0]
80	-36.7 [-59.0]
90	-39.1 [-63.0]
100	-39.8 [-64.0]
110	-39.8 [-64.0]
120	-39.1 [-63.0]
130	-39.1 [-63.0]
140	-39.1 [-63.0]
150	-39.1 [-63.0]
160	-39.1 [-63.0]
170	-39.1 [-63.0]
180	-39.1 [-63.0]
190	-39.1 [-63.0]
200	-39.1 [-63.0]
210	-39.1 [-63.0]
220	-39.1 [-63.0]
230	-39.1 [-63.0]
240	-39.1 [-63.0]
250	-39.1 [-63.0]
260	-39.1 [-63.0]
270	-39.1 [-63.0]
280	-39.1 [-63.0]
290	-39.1 [-63.0]
300	-39.1 [-63.0]

Figure 4.4 - Longitudinal delta-v data on table format

On the vehicle, the hardware required for Delta V, lateral, longitudinal, and normal accelerations, post-crash, and pre-crash variables detection consist of the mentioned accelerometers integrated on the Electronic Stability Control (ESC) module, or on an Inertial Measurement Unit (IMU), which communicates with the Airbag Control Module (ACM) and the Event Data Recorder (EDR), usually coupled on the same encapsulation, through the vehicle's data network. Figure 4.5 represents the respective connection schematic.

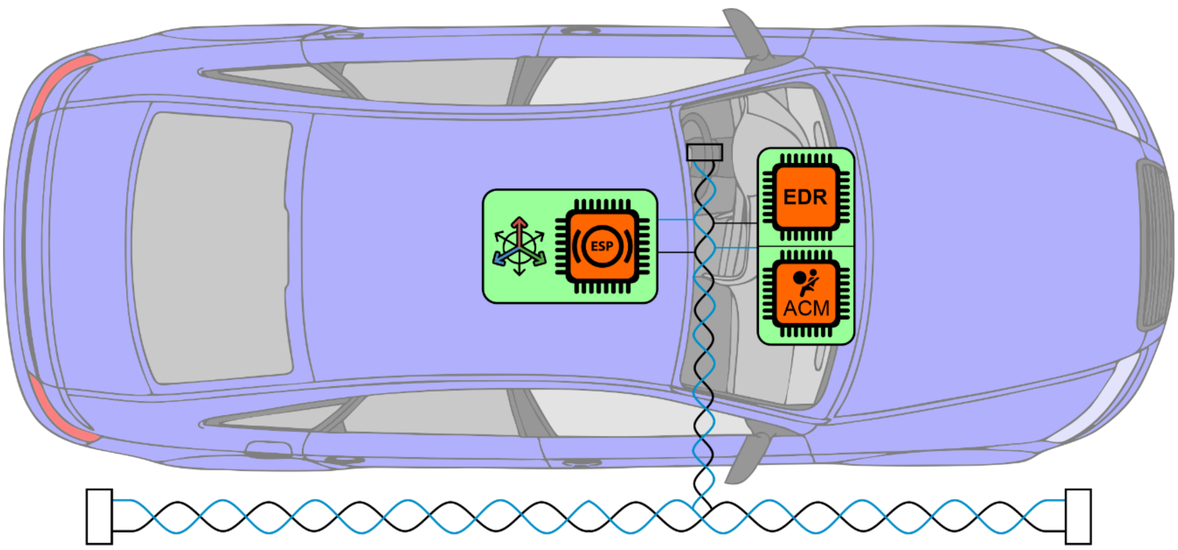


Figure 4.5 - Vehicle's instrumentation schematic for EDR's acceleration variables acquisition

4.2.2. Maximum Delta-V, Longitudinal and lateral:

The devices used to measure the Maximum Delta V are the same as the ones which measure Delta-V itself. To acquire maximum values, the Event Data Recorder (EDR) processes the buffered data to store the highest speed variation recorded within the defined period.

On the Crash Data Retrieval (CDR) report, longitudinal and lateral maximum Delta V data appears on data lines, presenting the highest Delta V values recorded during the crash pulse. According to the regulations, the Maximum Delta V values must refer to the highest value of speed variation occurred on a time interval of 300ms from the beginning of the event, or until the event's end plus 30ms whichever is shorter, during the crash pulse. The EDR must record these variables as single samples. (UNECE, 2021a) Figure 4.6 represents the data lines which refer to the longitudinal and lateral maximum Delta V data values from a 2012 BMW CDR example report (above), and from a 2011 Nissan CDR example report (below).

System Status at Event (Record 1, Most Recent)

Maximum Delta-V, Longitudinal (MPH [km/h])	-39.8 [-64.0]
Maximum Delta-V, Lateral (MPH [km/h])	-0.6 [-1.0]

System Status at Event (Event Record 1)

Maximum Delta-V, Longitudinal (MPH [km/h])	-4 [-6]
Maximum Delta-V, Lateral (MPH [km/h])	16 [26]

Figure 4.6 - Longitudinal and lateral maximum delta-v data lines

On the vehicle, the hardware required for Delta V detection consist of the mentioned accelerometers integrated on the stability control module which communicates with the Airbag Control Module and the Event Data Recorder, usually coupled on the same encapsulation, through the vehicle's data network. Figure 4.5 represents the respective connection schematic.

4.2.3. Restraint systems' deployment times and other time variables:

In order to measure time variables, the Event Data Recorder (EDR) must be equipped with timers which can count the elapsed time between two defined boundaries or set a timing for the collision's events, data and records. Timers are included on embedded systems and are managed by its software. Timers require a clock source which defines their working frequency. They work as a counter of tick periods which are generated by the pulses from a digital square wave provided from the timer's clock source, which generally consists of an oscillator device. (Colley, 2020)

On the EDR, time variables are usually relative to the event's time zero, which refers to the moment at which the EDR's recording algorithm was enabled on the crash. The device stores multiple time data elements manly for evaluation and control. Among these variables are the times at which the maximum peaks for Delta-V occurred, and the times that some passive safety systems took to deploy after crash detection, for example. On the Crash Data Retrieval (CDR) report, the time variables appear as single samples on a table format and are recorded on the post-crash timeframe of data. (UNECE, 2021a) As example, Figure 4.7 represents the data lines which refer to the time of maximum longitudinal, lateral, and resultant Delta V data from a 2012 BMW CDR example report (above), and from a 2012 Mazda CDR example report (below).

System Status at Event (Record 1, Most Recent)

Time, Maximum Delta-V, Longitudinal (msec)	104
Time, Maximum Delta-V, Lateral (msec)	90
Time, Maximum Delta-V, Resultant (msec)	104

System Status at Event (Event Record 1)

Time, Maximum Delta-V, Longitudinal (msec)	232.5
Time, Maximum Delta-V, Lateral (msec)	87.5
Time, Maximum Delta-V, Resultant (msec)	232.5

Figure 4.7 - Longitudinal, lateral, and resultant maximum delta-v time data lines

4.2.4. Speed, vehicle indicated:

The indicated vehicle speed recorded by the Event Data Recorder (EDR) consists of the same values which are shown on the vehicle's speedometer and, thus, obtained in the same way. These values are based on the wheels' rotational speed which are acquired by a wheel speed sensor for each vehicle's wheel.

On the Crash Data Retrieval (CDR) report, indicated vehicle speed data comes on table format, presenting a value for each timestep moments before the crash pulse. According to the regulations, indicated vehicle speed values must be at least reported by the EDR on a time interval of 5 seconds before the beginning of the event until the event's time zero, with a frequency of 2 samples per second (pre-crash data). (UNECE, 2021a) Figure 4.8 presents the indicated vehicle speed data table from a 2012 BMW CDR example report.

Pre-Crash Data -5 to 0 sec (Record 1, Most Recent)

Time (sec)	Speed, Vehicle Indicated (MPH [km/h])
-5.0	35 [56]
-4.5	35 [56]
-4.0	35 [56]
-3.5	35 [56]
-3.0	35 [56]
-2.5	35 [56]
-2.0	65 [105]
-1.5	81 [130]
-1.0	96 [155]
-0.5	112 [180]
0.0	35 [56]

Figure 4.8 - Vehicle's indicated speed data tables

On the vehicle, the hardware required for indicated vehicle speed detection consist of the mentioned wheel speed sensors connected to the ABS module which communicates with the Airbag Control Module (ACM) and the Event Data Recorder (EDR), usually coupled on the same encapsulation, with the Traction Control System (TCS), the Electronic Stability Control (ESC) and the speedometer through the vehicle's data network. Figure 4.9 represents the respective connection schematic.

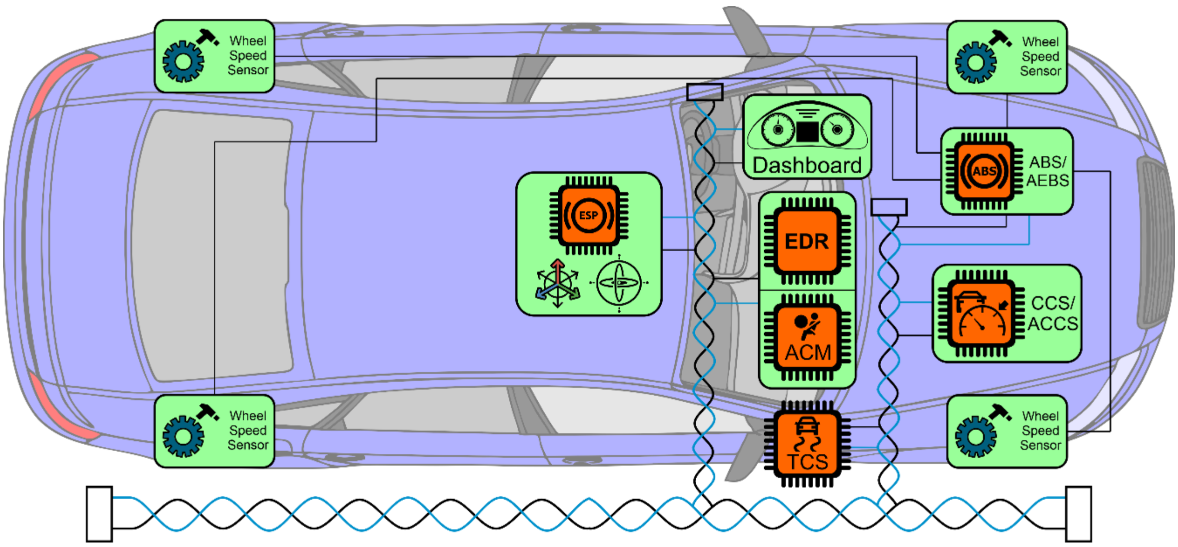


Figure 4.9 - Vehicle's instrumentation schematic for EDR's vehicle indicated speed variable acquisition

4.2.5. Engine throttle, % full (or accelerator pedal, % full):

The Event Data Recorder (EDR) stores the engine throttle percentage variable to evaluate the driver's load request to the engine before the moment of crash. This variable is also used by the Engine Control Unit (ECU) to manage the fuel delivery to the engine, the throttle valve actuator, ignition, and injection timing, in case of internal combustion, or torque delivery, in case of electric motors. (*Throttle Position Sensor*, 2022)

The engine throttle variable is acquired by an electromechanical sensor which is coupled to the vehicle's accelerator pedal or to the intake manifold's throttle valve, that is commanded by the accelerator pedal. The throttle position and the accelerator pedal sensors usually work by the potentiometer, Hall effect or inductive functioning principles. This device consists of an angular position sensor which promotes a voltage output signal proportional to the accelerator pedal depress or throttle valve's position and movement. (Bosch, 2022a)

The Engine Control Unit (ECU) acquires and processes the accelerator pedal voltage output to determine the drivers request for engine load on a percentual basis, where 0% corresponds to pedal released and 100% to pedal fully pressed. After this processing, the ECU sends these values to the vehicle's data network, so that it can be used by other electronic modules and units.

On the Crash Data Retrieval (CDR) report, engine throttle percentage data comes on table format, presenting a value for each timestep moments before the crash pulse. According to the regulations, engine throttle percentage values must be at least reported by the EDR on a time interval of 5 seconds before the beginning of the event until the event's time zero, with a frequency of 2 samples per second (pre-crash data). (UNECE, 2021a) Figure 4.10 presents the engine throttle percentage data table from a 2012 BMW CDR example report.

Pre-Crash Data -5 to 0 sec (Record 1, Most Recent)

Time (sec)	Accelerator Pedal, % Full (%)
-5.0	82
-4.5	92
-4.0	2
-3.5	12
-3.0	22
-2.5	32
-2.0	42
-1.5	52
-1.0	62
-0.5	72
0.0	82

Figure 4.10 - Engine throttle percentage data tables

On the vehicle, the hardware required for engine throttle percentage detection consist of the mentioned accelerator pedal or throttle position sensors connected to the ECU which communicates with the Airbag Control Module (ACM) and the Event Data Recorder (EDR), coupled on the same encapsulation, through the vehicle's data network. Figure 4.11 represents the respective connection schematic.

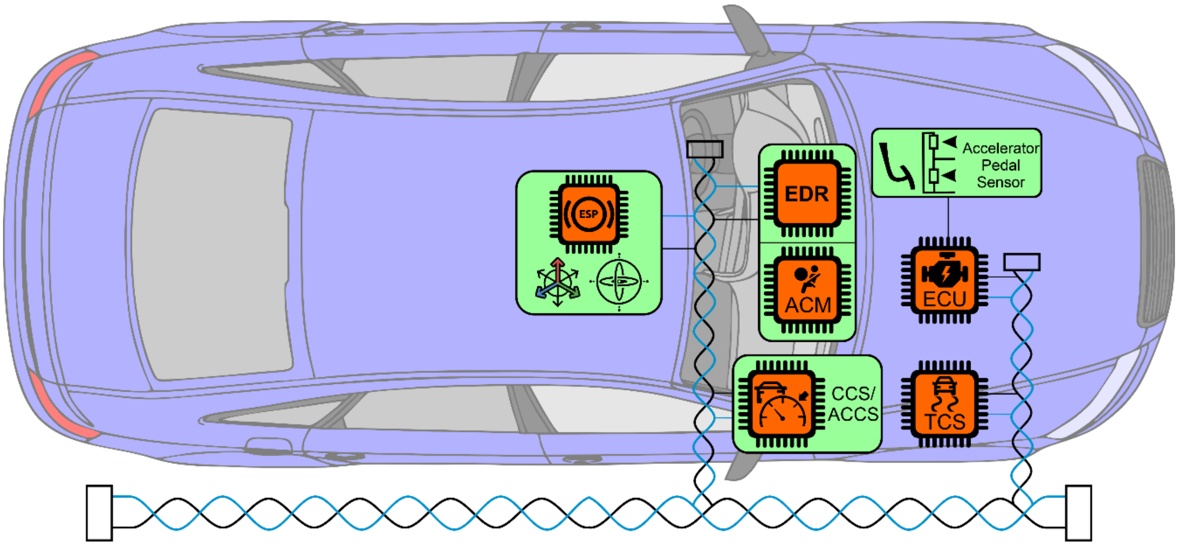


Figure 4.11 - Vehicle's instrumentation schematic associated to the engine throttle percentage variable

4.2.6. Service brake, on/off:

The Event Data Recorder (EDR) stores the service brake pedal's state variable to evaluate the driver's intention to brake before the moment of crash. This variable is acquired by the brake light switch which is used for the brake lights system at the rear of the vehicle, for the Anti-lock Brake System (ABS), for the Electronic Stability Control (ESC), for the Cruise Control System (CCS), for the push-button start system and the gear selector shift on some vehicles. (*Brake Light Switches*, 2021)

The brake light switch consists of a press switch installed on the brake pedal's mechanism. (Samarins, 2021) Usually, this switch is pressed when the brake pedal is released, opening the electronic circuit for the brake lights. When the driver presses the brake pedal, the switch is released, and the circuit is completed activating the rear brake lights and signalling other systems that the brake pedal was pressed.

On the Crash Data Retrieval (CDR) report, service brake state data comes on table format, presenting a condition for each timestep moments before the crash pulse. According to the regulations, service brake state must be at least reported by the EDR on a time interval of 5 seconds before the beginning of the event until the event's time zero, with a frequency of 2 samples per second (pre-crash data). (UNECE, 2021a) Figure 4.12 presents the service brake state data table from a 2012 Nissan CDR example report.

Pre-Crash Data -5 to 0 sec [2 samples/sec] (Event Record 1)
(the most recent sampled values are recorded prior to the event)

Time Stamp (sec)	Service Brake (On, Off)
-5.0	Off (Brake Not Activated)
-4.5	Off (Brake Not Activated)
-4.0	On (Brake Activated)
-3.5	On (Brake Activated)
-3.0	On (Brake Activated)
-2.5	On (Brake Activated)
-2.0	On (Brake Activated)
-1.5	On (Brake Activated)
-1.0	On (Brake Activated)
-0.5	Off (Brake Not Activated)
0.0	Off (Brake Not Activated)

Figure 4.12 - Service brake activation status data tables

On the vehicle, the hardware required for service brake state detection consist of the mentioned brake light switch connected to the ECU which communicates with the Airbag Control Module (ACM) and the Event Data Recorder (EDR), coupled on the same encapsulation, through the vehicle's data network. Figure 4.13 represents the respective connection schematic.

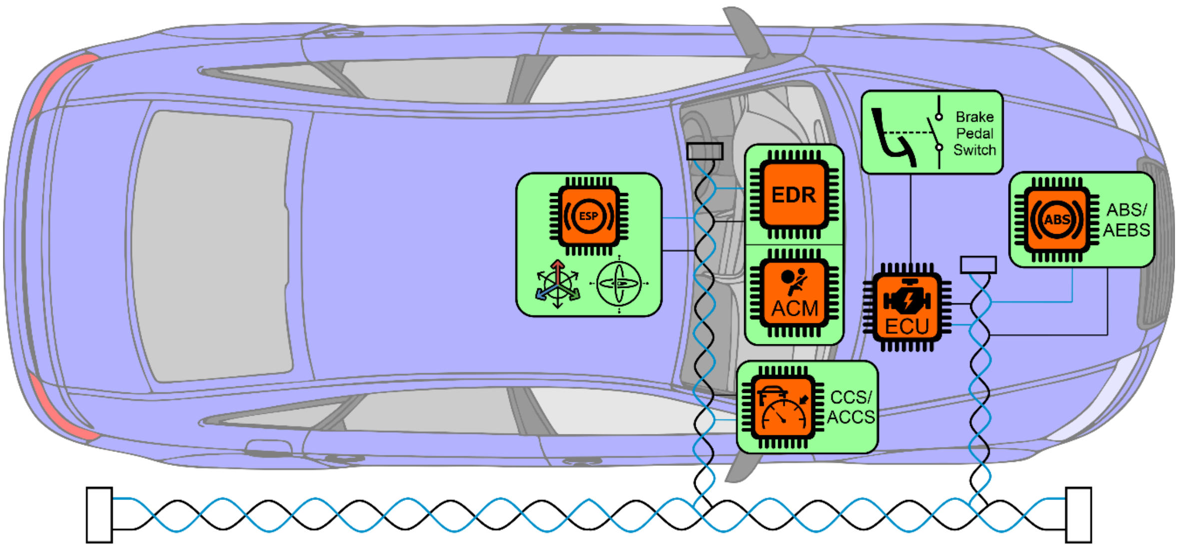


Figure 4.13 - Vehicle's instrumentation schematic associated to the service brake activation status variable

4.2.7. Ignition Cycle count, at crash and download; Number of events, on Multi-event; Complete file recorded:

The Event Data Recorder (EDR) records the ignition cycle count variable in the moment of crash and at the data retrieval instant to evaluate if there was any attempt to start the vehicle's engine and move it to a different position after the collision. The ignition cycle count variable is directly captured by the EDR. The EDR's microcontroller is programmed to increase by one a variable, which stores the ignition cycle count, each time there is a power on cycle to the vehicle's ignition. This power on cycle refers to the transition from no electrical power to the supply power of 12 Volt voltage applied to the EDR and Airbag Control Module, as the driver switches on the ignition key or presses the vehicle's ignition start button. (UNECE, 2021a)

According to the regulations, ignition cycle count at the crash moment must report the number verified on storage one second before the event's time zero. At the time of data retrieval, the CDR tool must recover the ignition cycle count on storage at that time for the ignition cycle at download variable. Both variables are stored as single samples for each crash event. (UNECE, 2021a) Figure 4.14 represents the ignition cycle count at crash and at download data lines from a 2012 BMW CDR example report (above), and from a 2012 Nissan CDR example report (below).

Pre-Crash Data -1 Sec (Record 1, Most Recent)

Ignition Cycle, Crash (cycle)	7,822

System Status at Retrieval

Ignition Cycle, Download (cycle)	8,145

System Status at Event (Event Record 1)

Ignition Cycle, Crash	104
Ignition Cycle, Download	105

Figure 4.14 - Ignition cycle count at crash and download data lines

Besides the ignition cycle count variables, the Event Data Recorder (EDR) also stores the number of events which happen sequentially on a collision with multiple events. This data element is also determined by the EDR itself, using a software defined counting variable. A multi-event crash occurs when the EDR's criteria, for the recording algorithm's activation, is met within a five second time interval after the first event's time zero. This way, the events' count starts on one, at the first crash, and increases as other events begin on the next five second period. (UNECE, 2021a) As example, Figure 4.15 represents the events' number data line for multi-event from a 2012 BMW CDR example report (above), and from a 2012 Volvo CDR example report (below).

System Status at Event (Record 1, Most Recent)

Multi-Event, Number of Events	1

System Status at Event (Event Record 1)

Multi-Event, Number of Events (1,2)	Event Number 1

Figure 4.15 - Event's number data lines

Sometimes, due to some failure on the vehicle's data network or on the supply power to the Airbag Control Module (ACM) promoted by the collision, the data recording might be corrupted or incomplete. The EDR has a variable which is designated to evaluate the recorded file completion.

On the Crash Data Retrieval (CDR) report, complete file recorded data comes on data line format, presenting its status as "yes" or "no". According to the regulations, complete file recorded variable is mandatory, and must be assigned after the remaining information being stored. This data is useful for the report's interpretation by the CDR expert. (UNECE, 2021a) Figure 4.16 represents the complete file recorded data line from a 2012 BMW CDR example report (above), and from a 2012 Nissan CDR example report (below).

System Status at Event (Record 1, Most Recent)

Complete File Recorded (Yes, No)	Yes

System Status at Event (Event Record 1)

Complete File Recorded (Yes/No)	Yes (Complete)

Figure 4.16 - Complete file recorded data lines

On the vehicle, the hardware required for ignition cycle count variables, events' count data, and complete file recorded detection consist of the Event Data Recorder (EDR) itself, which is integrated on the vehicle's Airbag Control Module (ACM). No peripheral instrumentation is required.

4.2.8. Safety belt status, driver, front passenger, and other occupants:

The Event Data Recorder (EDR) stores the safety belts' status variable to evaluate if safety belts were coupled moments before the collision event. This variable is frequently used by the Airbag Control Module (ACM) as input to decide which are the best restraint systems' deployment routines. (Paruszkiewicz, 2018)

The safety belt status is captured by the safety belt switches which consist of Reed sensors that work by the magnetism principles. The Reed sensor is a contactless switch which is operated magnetically when there is a magnetic field nearby, as they are typically built with two contacts made from a ferromagnetic material sealed inside a glass or plastic encapsulation with an inert gas atmosphere, to promote reliability. (Woodford, 2021) The Reed sensors are integrated on the vehicle's seat belt buckles, while the magnetic field source consists of the seat belts' thorns, which work as magnets. (Paruszkiewicz, 2018)

On the Crash Data Retrieval (CDR) report, safety belt status data comes on data line format, presenting each safety belt status as single samples reporting the "fastened" or "not fastened" conditions, or other equivalent designations defined by the manufacturer. According to the regulations, safety belts statuses must be reported by the EDR referring to the statuses verified one second before the event's time zero (pre-crash data). (UNECE, 2021a) Figure 4.17 presents the safety belt status data lines from a 2012 BMW CDR example report (above), from a 2012 Nissan CDR example report (middle), and from a 2011 Toyota CDR example report (below).

Pre-Crash Data -1 Sec (Record 1, Most Recent)

Safety Belt Status, Driver	Belted
Safety Belt Status, Front Passenger	Belted

System Status at Event (Event Record 1)

Safety Belt Status, Driver	On (Fastened)
Safety Belt Status, Right Front Passenger	Off (Unfastened)

Pre-Crash Data, 1 Sample (Most Recent Event, TRG 3)

Buckle Switch, Driver	Buckled
Buckle Switch, Passenger	Buckled

Figure 4.17 - Safety belt status data lines

On the vehicle, the hardware required for safety belt status detection consist of one of the mentioned Reed switch sensors for each seatbelt present on the vehicle, connected to the Airbag Control Module (ACM) and the Event Data Recorder (EDR), coupled on the same encapsulation. Figure 4.18 represents the respective connection schematic.

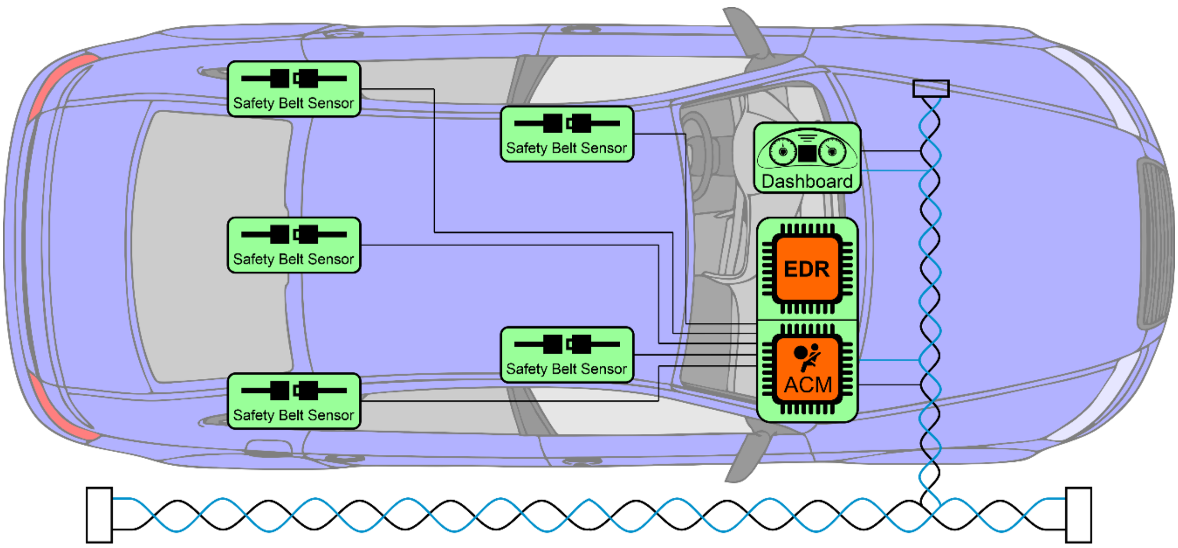


Figure 4.18 - Vehicle's instrumentation schematic for EDR's safety belts' status variables acquisition

4.2.9. Systems' warning indicators status (Airbag, Tyre Pressure, Vulnerable Road User):

The Event Data Recorder (EDR) stores the status of some vehicle systems' malfunction indicator lights (MIL) which appear on the vehicle's dashboard (Law Insider, 2022). This registration is useful to determine whether if there was any malfunction or warning to the driver or not, moments before the crash event. The Event Data Recorder (EDR) monitors the vehicle's data network and collects the different modules' messages promoting the warning lights activation, to evaluate which were their status moments before the collision event.

On the Crash Data Retrieval (CDR) report, warning indicators statuses data comes on data line format, as a single sample collected moments before the crash pulse, reporting the lights' on or off states. According to the regulations, the EDR must report at least the warning indicator lights statuses for the airbag, tyre pressure monitoring and vulnerable road users' protection systems at the time of one second before the event's time zero (pre-crash data). (UNECE, 2021a) Figure 4.19 presents the examples for the airbag warning light status data line from a 2012 BMW CDR example report (above), and from a 2012 Nissan CDR example report (below).

Pre-Crash Data -1 Sec (Record 1, Most Recent)

Air Bag Warning Lamp (On,Off)	On

System Status at Event (Event Record 1)

Frontal Air Bag Warning Lamp (On, Off)	Off

Figure 4.19 - Airbag warning light status data lines

On the vehicle, the warning lamps' statuses are detected directly by the Event Data Recorder (EDR) through the vehicle's data network, as each system's electronic control module sends the lamps' activation instructions through this network too. These messages are also acquired by the dashboard, which activates the respective malfunction indicator lights, so the driver can be aware of any anomaly. Figure 4.20 represents the respective connection schematic.

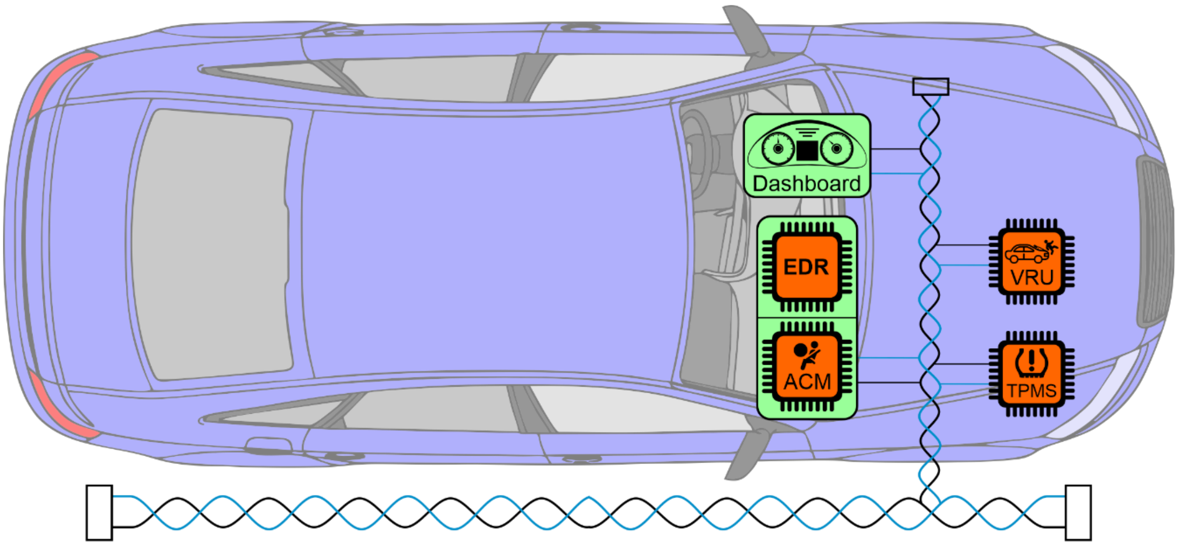


Figure 4.20 - Vehicle's instrumentation schematic associated to systems warning indicators status variables

4.2.10. Engine RPM:

The engine's revolutions per minute (RPM) recorded by the Event Data Recorder (EDR) consist of the same values which are presented to the driver on the vehicle's tachometer and, thus, obtained the same way. These values are based on the engine's flywheel rotational speed, which is acquired by a speed sensor from the same type as the vehicle's wheel speed sensors. The Event Data Recorder (EDR) acquires the engine's RPM values from the vehicle's data network.

On the Crash Data Retrieval (CDR) report, engine RPM data comes on table format. According to the regulations, engine's RPM values are mandatory and must be at least reported by the EDR on a time interval of 5 seconds before the beginning of the event until the event's time zero, with a frequency of 2 samples per second (pre-crash data). Besides, for vehicles powered by other powertrain systems, such as hybrid technology and electric motion, this variable should refer to the revolutions per minute associated to the motive force device's output shaft. (UNECE, 2021a) Figure 4.21 presents the engine's RPM data table from a 2012 Nissan CDR example report.

Pre-Crash Data -5 to 0 sec [2 samples/sec] (Event Record 1)
(the most recent sampled values are recorded prior to the event)

Time Stamp (sec)	Engine RPM
-5.0	2650
-4.5	1750
-4.0	1200
-3.5	1150
-3.0	950
-2.5	950
-2.0	900
-1.5	850
-1.0	850
-0.5	1100
0.0	1150

Figure 4.21 - Engine's RPM data tables

On the vehicle, the hardware required for engine's RPM detection consist of the mentioned crankshaft speed sensor connected to the ECU module which communicates with the Airbag Control Module (ACM) and the Event Data Recorder (EDR), usually coupled on the same encapsulation, and the tachometer through the vehicle's data network. Figure 4.22 represents the respective connection schematic.

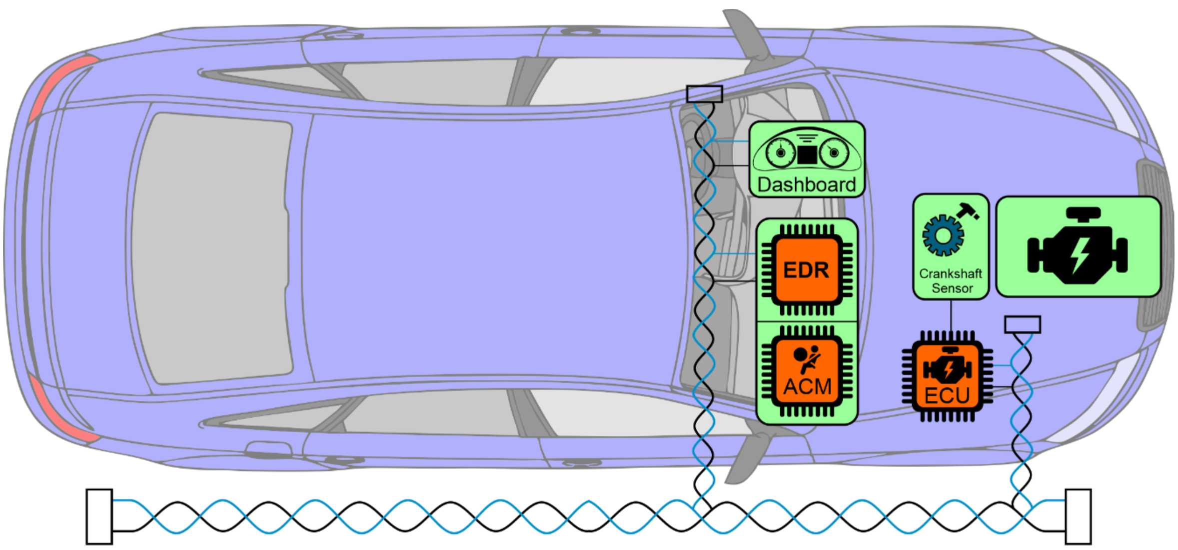


Figure 4.22 - Vehicle's instrumentation schematic associated to the engine's RPM variable

4.2.11. Vehicle roll angle, roll rate, and yaw rate:

In order to measure the rotational dynamic variables during collision, vehicles must be equipped with a triaxial gyroscope or a group of combined gyroscopes which are capable of measuring values for angular displacement and angular rate along the three orthogonal directions, corresponding to the vehicle's X, Y and Z axis. As well as the accelerometers, gyroscopes also consist of small devices referred to as Micro-Electro-Mechanical Systems (MEMS). With the help of Earth's gravity force, gyroscope sensors can determine its own orientation, measure rotation and angular velocities on a certain axis. The sensing arms motion can be converted to electronic signals, due to capacitance variations. (ELPROCUS, 2022; Fei & Yang, 2011; WatElectronics, 2020; Watson, 2016) Figure 4.23 illustrates a prof mass's inner structure of a vibration gyroscope, on the left, and its functioning principle, on the right.

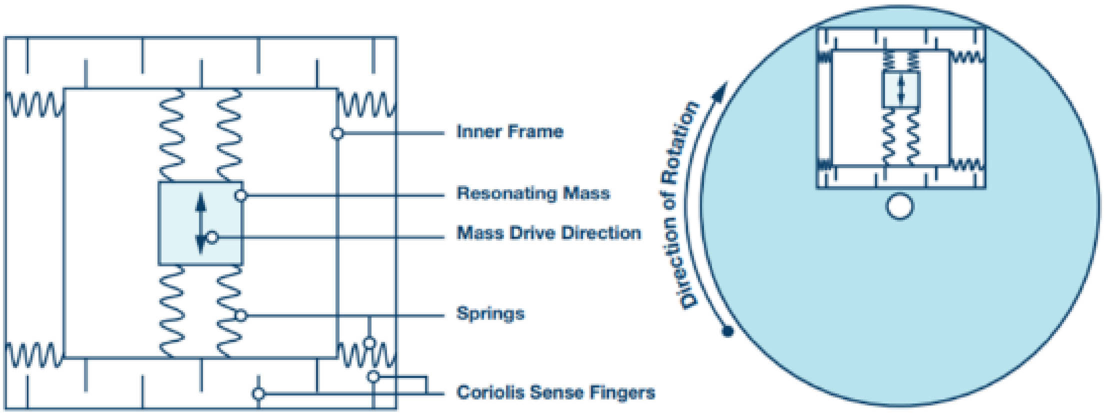


Figure 4.23 - Gyroscope proof mass inner structure (left), and its functioning principle (right), adapted from (Watson, 2016)

On the Crash Data Retrieval (CDR) report, vehicle's roll angle, roll rate, and yaw rate data appear on graph and table formats, and must be presented according to the minimum specifications defined in the regulations. (UNECE, 2021a) Table 4.2 resumes the minimum requirements and parameters for the mentioned variables' recording on the EDR.

Table 4.2 - Requirements for roll and yaw variables recording (UNECE, 2021a)

Variable	Requirement	Interval	Frequency	Sensitivity
Roll Angle	If recorded on non-volatile memory	[-1.0; 5.0] s	10 Hz	10 degrees
Roll Rate	Mandatory	[-1.0; 5.0] s	10 Hz	1 degree/s
Yaw Rate	Mandatory	[-5.0; 0] s	2 Hz	0.1 degrees/s

As example, Figure 4.24 represents the graph format for vehicle's roll angle data from a 2012 Volvo CDR example report.

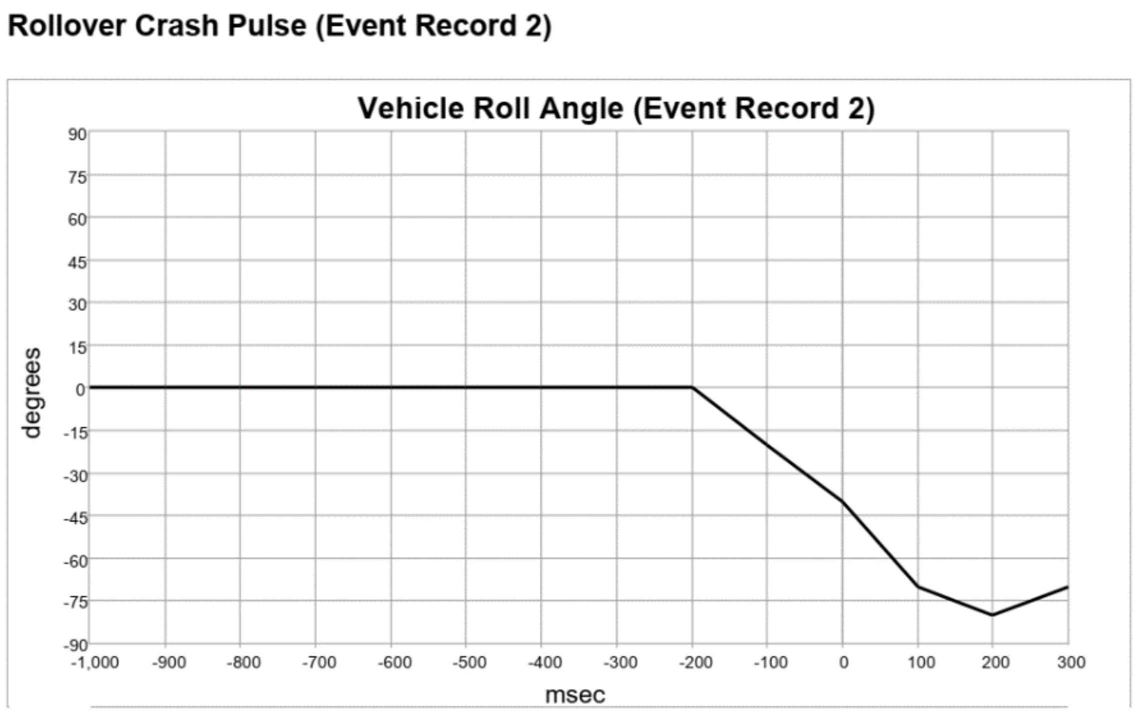


Figure 4.24 - Roll angle data on graph format

On the vehicle, the hardware required for vehicle's roll angle, roll rate, and yaw rate detection consist of the mentioned gyroscopes integrated on the Electronic Stability Control (ESC) module, or on an Inertial Measurement Unit (IMU), which communicates with the Airbag Control Module (ACM) and the Event Data Recorder (EDR), usually coupled on the same encapsulation, through the vehicle's data network. Figure 4.25 represents the respective connection schematic.

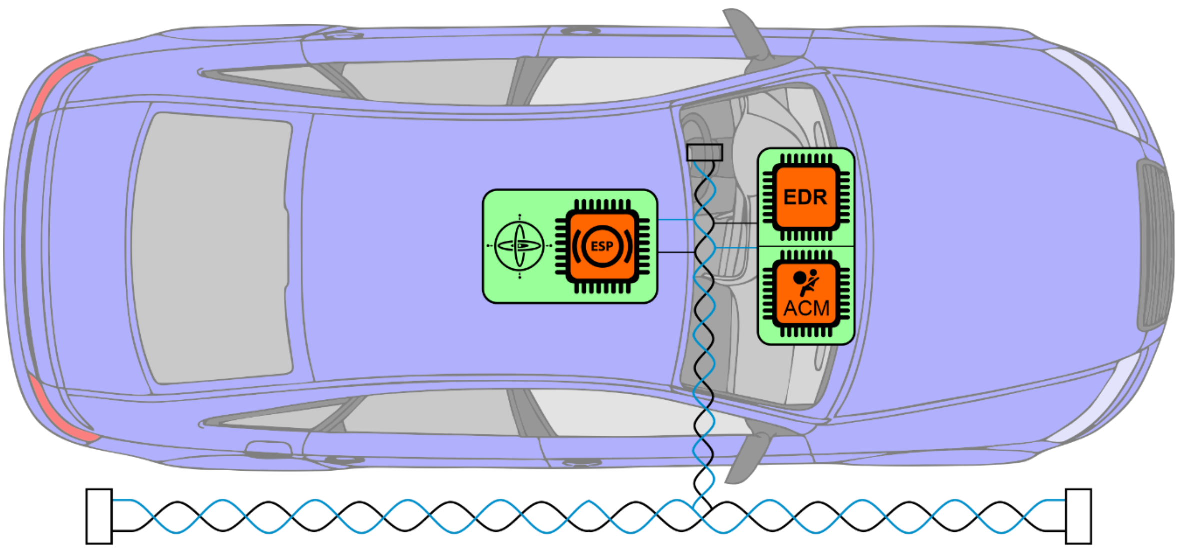


Figure 4.25 - Vehicle's instrumentation schematic for EDR's roll angle and angular rate variables acquisition

4.2.12. Active safety systems' functioning status:

Vehicles' active safety systems have a considerable influence on its dynamics and behaviour. This way, the intervention of these systems, such as Anti-lock Brake System (ABS), stability control, Traction Control System (TCS), and so on, at the collision moment must be taken into consideration on the vehicle's dynamics interpretation, during the accident event. The Event Data Recorder (EDR) monitors the vehicle's data network and collects the different modules' messages on what concerns their availability and operation states, to evaluate which were the active safety systems' status moments before the collision event.

On the Crash Data Retrieval (CDR) report, the active safety and driving assistance systems' statuses data come on data table format, and must be presented according to the minimum specifications defined in the regulations. (UNECE, 2021a) Table 4.3 resumes the minimum requirements and parameters for the mentioned variables' recording on the EDR.

Table 4.3 - Requirements for active safety and driving assistance systems' status variables recording (UNECE, 2021a)

Variable	Requirement	Interval	Frequency	States
ABS, ESC, TCS, AEBS, CCS, ACCS, LDWS, CSF, ESF, ACSF status	Mandatory	[-5.0; 0] s	2 Hz	On, Off, Activated, Deactivated, Faulted, Intervening, Warning
AECS status	Mandatory	Event	NA	Faulted, On but not triggered, On and triggered

Figure 4.26 presents the examples for the ABS activity and stability control status data table from a 2012 BMW CDR example report.

Pre-Crash Data -5 to 0 sec (Record 1, Most Recent)

Time (sec)	ABS Activity (Engaged, Non-engaged)	Stability Control (On Engaged, Non-engaged)
-5.0	Unknown	Unknown
-4.5	Unknown	Unknown
-4.0	ABS Activity	Non-engaged
-3.5	ABS Activity	Non-engaged
-3.0	ABS Activity	Non-engaged
-2.5	ABS Activity	Non-engaged
-2.0	No ABS Activity	Non-engaged
-1.5	No ABS Activity	Non-engaged
-1.0	No ABS Activity	Non-engaged
-0.5	No ABS Activity	Non-engaged
0.0	Unknown	Unknown

Figure 4.26 - ABS and stability control systems status data table

On the vehicle, the active safety and driving assistance systems' states are detected directly by the Event Data Recorder (EDR) through the vehicle's data network, as each system's electronic control module sends its availability and operability conditions through this network too. These messages are also acquired by the dashboard, which activates or blinks alternately the respective malfunction indicator lights, so the driver can be aware of any anomaly, warning, or activation. Figure 4.27 represents the respective connection schematic.

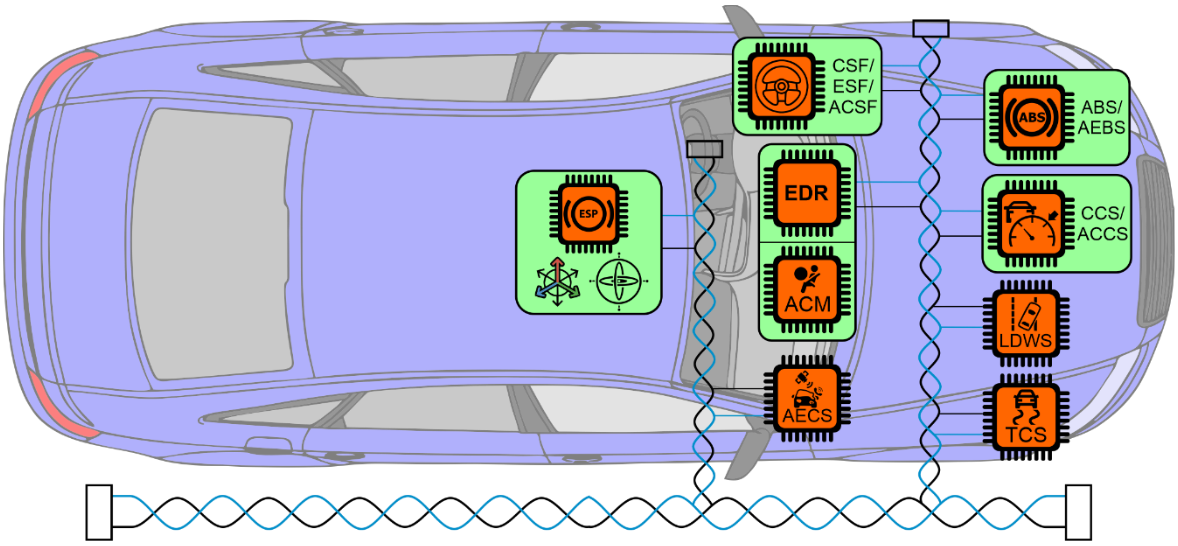


Figure 4.27 - Vehicle's instrumentation schematic associated to the active safety systems status variables acquisition

4.2.13. Steering input:

The Event Data Recorder (EDR) stores the steering input angle variable to evaluate the driver's intention to avoid any obstacle or collision moments before the crash event. These values are also useful for the management of power steering, Electronic Stability Control (ESC), and other active safety and driving assistance systems. (Delphi Technologies, 2022) The steering angle input variable is acquired by an electromechanical sensor which is coupled to the vehicle's steering column. These devices provide information on what concerns steering angle, steering rate, and steering torque. (Delphi Technologies, 2022; Gajjar, 2017) The steering column sensor processes its measurements internally and sends the information to the other vehicle's modules through its CAN (Controller Area Network) data network or through a serial communication interface. (Bosch, 2022b, 2022c)

On the Crash Data Retrieval (CDR) report, steering angle input data comes on table format. According to the regulations, steering input values must be at least reported by the EDR on a time interval of 5 seconds before the beginning of the event until the event's time zero, with a frequency of 2 samples per second (pre-crash data). (UNECE, 2021a)

Figure 4.28 presents the steering angle input data table from a 2012 Nissan CDR example report.

Pre-Crash Data -5 to 0 sec [2 samples/sec] (Event Record 1)
(the most recent sampled values are recorded prior to the event)

Time Stamp (sec)	Steering Input (deg)
-5.0	-32
-4.5	-2
-4.0	28
-3.5	14
-3.0	4
-2.5	4
-2.0	-48
-1.5	-98
-1.0	-160
-0.5	-194
0.0	-218

Figure 4.28 - Steering angle input data table

On the vehicle, the hardware required for steering angle detection consist of the mentioned steering column sensor which sends the data directly through the vehicle's CAN data network. The Airbag Control Module (ACM) and the Event Data Recorder (EDR), coupled on the same encapsulation, retrieve steering angle information from this vehicle data network. Figure 4.29 represents the respective connection schematic.

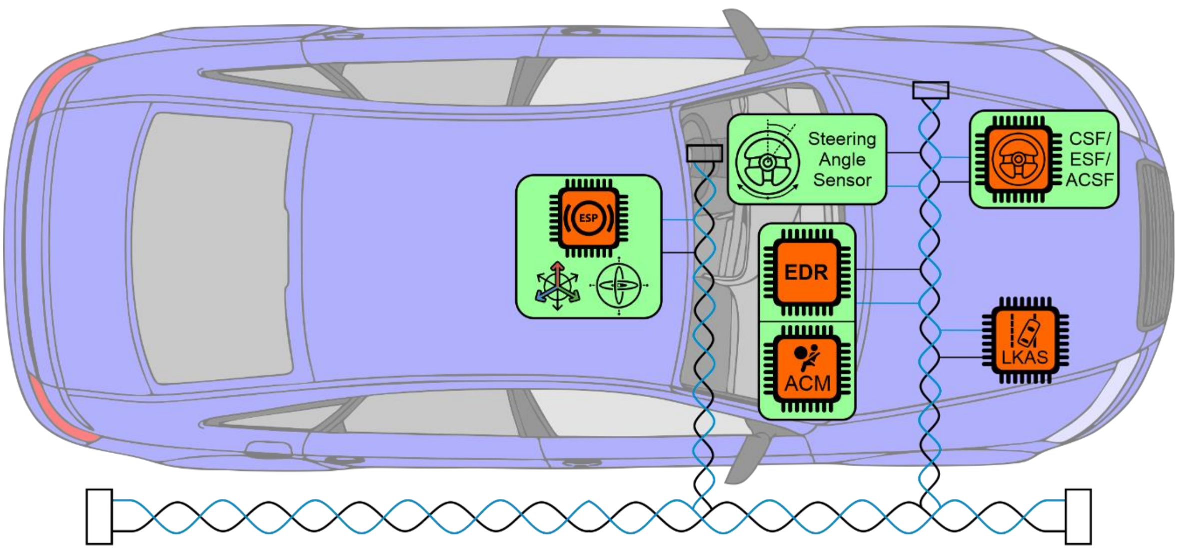


Figure 4.29 - Vehicle's instrumentation schematic associated to the steering angle input variable

4.2.14. Passenger front air bag suppression status:

The Event Data Recorder (EDR) stores the passenger's front airbag suppression status variable so that the expert can evaluate if the passenger's front airbag should have been deployed or if it was the driver's intention to deactivate this airbag, in case of collision, when a child or a child seat is placed or detected in the front occupant position. (Campbell et al., 2005) The passenger's airbag suppression switch is connected to the Airbag Control Module (ACM) so it can manage the airbag's deployment.

On the Crash Data Retrieval (CDR) report, passenger's front air bag suppression status data comes on data line format, as a single sample collected moments before the crash pulse, reporting the airbag's suppression on or off states one second before the event's time zero (pre-crash data). (UNECE, 2021a) Figure 4.30 presents the passenger's front airbag suppression status data line from a 2012 Nissan CDR example report (above), and from a 2012 Volvo CDR example report (below).

System Status at Event (Event Record 1)

Frontal Air Bag Suppression Switch Status	On (AS airbag inhibit)

Pre-Crash Data -1 Sec (Event Record 1)

Frontal Airbag Suppression Switch Status, Front Passenger	On

Figure 4.30 - Passenger's front airbag suppression status data lines

On the vehicle, the hardware required for passenger's front airbag suppression status detection consist of the mentioned switch and the front passenger's seat occupant detection sensor connected to the ACM which communicates with the Event Data Recorder (EDR), coupled on the same encapsulation. Figure 4.31 represents the respective connection schematic.

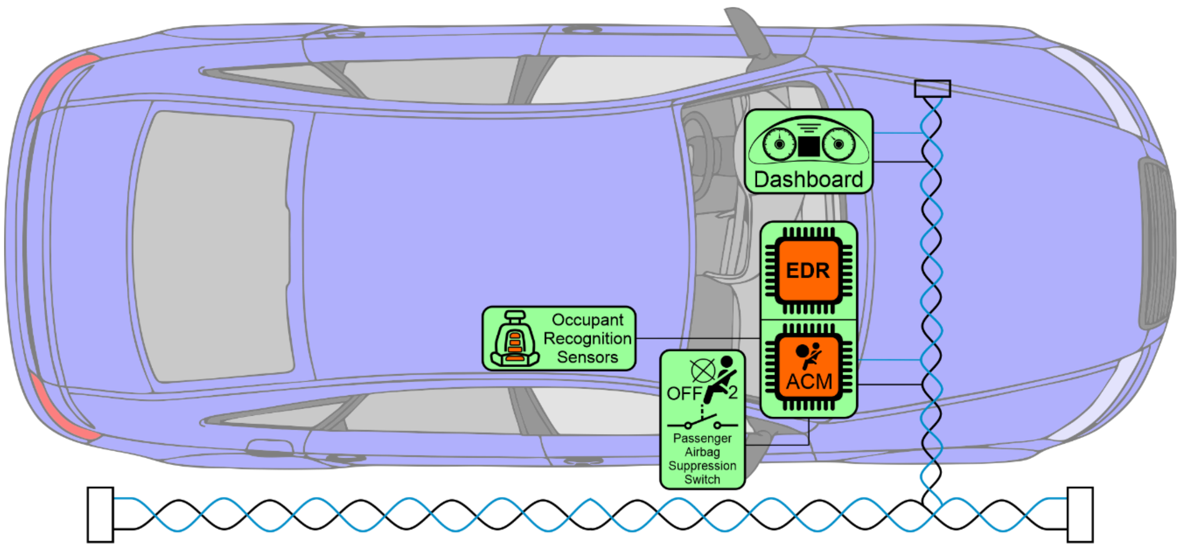


Figure 4.31 - Vehicle's instrumentation schematic associated to the passenger's front airbag suppression status variable

4.2.15. Seat track position switch, foremost, status:

The Event Data Recorder (EDR) stores the driver's and front passenger's seat position, so that the expert can evaluate if the driver's and front passenger's airbags deployment routines were correctly implemented by the Airbag Control Module (ACM), according to the circumstances, in comparison with the registered deployment times. The seat track position sensors are connected to the ACM so it can manage the airbag's deployment strategies.

On the Crash Data Retrieval (CDR) report, driver's and passenger's seat track position switch status data comes on data line format, as a single sample collected moments before the crash pulse, reporting the seats' foremost position states one second before the event's time zero (pre-crash data). (UNECE, 2021a) Figure 4.32 presents the seat track position switch, foremost, status data lines from a 2012 BMW CDR example report (above), and from a 2012 Mazda CDR example report (below).

Pre-Crash Data -1 Sec (Record 1, Most Recent)

Seat Track Position Switch Status, Driver	Not Foremost
Seat Track Position Switch Status, Foremost, Front Passenger	Not Foremost

System Status at Event (Event Record 1)

Seat Track Position Switch, Foremost, Status, Driver	Rearward

Figure 4.32 - Seat track position switch status data lines

On the vehicle, the hardware required for driver's and passenger's seat track position switch, foremost, status detection consist of the mentioned Hall effect switches connected to the ACM which communicates with the Event Data Recorder (EDR), coupled on the same encapsulation. Figure 4.33 represents the respective connection schematic.

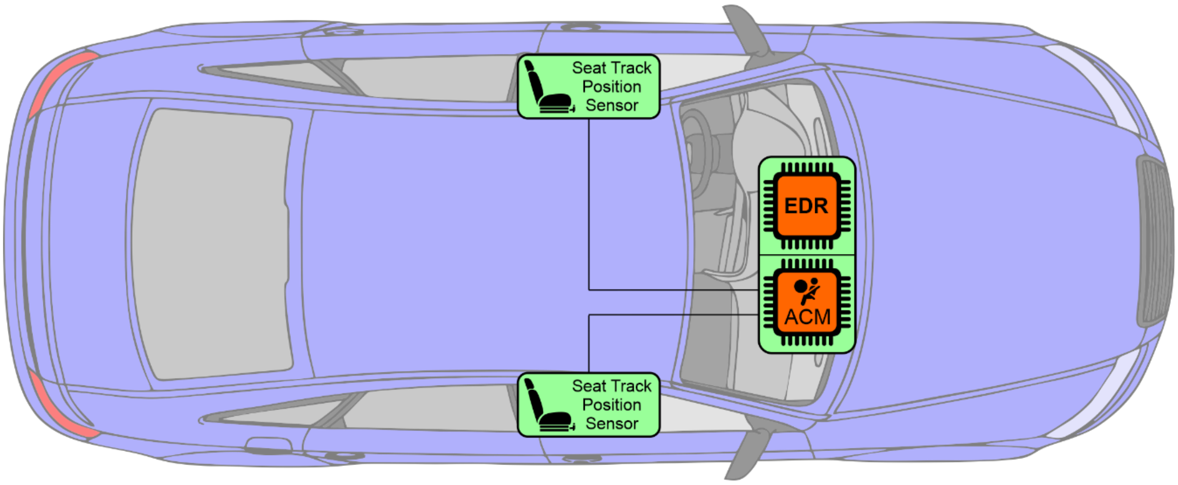


Figure 4.33 - Vehicle's instrumentation schematic for EDR's seat track position switch status variables acquisition

4.2.16. Occupant size classification:

Similarly to the seat track position variables, the Event Data Recorder (EDR) might store the driver's and front passenger's size classification in order to evaluate the airbag's deployment algorithms adequation. The airbag's deployment force and routines must be adapted to the occupant's size and position, otherwise their deployment, in case of collision, might cause more harmful injuries.

To evaluate the occupants' size the vehicle must be equipped with an occupant recognition system. This system can include the vehicles' passengers on designated categories depending on the predefined classification parameters. The occupant recognition system includes occupant classification sensors and electrical field detection sensors displaced along the seat plain, the backrest and sometimes even on the dashboard's airbag cover. (Becker et al., 2001; Stanley Subaru, 2012)

On the Crash Data Retrieval (CDR) report, driver's and passenger's size classification data comes on data line format, as a single sample collected moments before the crash pulse, reporting the categories on which the occupants' sizes integrate one second before the event's time zero (pre-crash data). (UNECE, 2021a) Figure 4.34 presents the occupant size classification data lines from a 2011 Toyota CDR example report (above), and from a 2012 Mazda CDR example report (below).

Pre-Crash Data, 1 Sample (Most Recent Event, TRG 3)

Occupancy Status, Passenger	AM50

System Status at Event (Event Record 1)

Occupant Size Classification, Front Passenger	Not Adult

Figure 4.34 – Occupant's size classification data lines

On the vehicle, the hardware required for driver's and front passenger's occupant size classification detection consist of matrixes of pressure sensitive FSR (Force Sensing Resistors) cells and a group of capacitive electric field sensors connected to the Airbag Control Module (ACM) which communicates with the Event Data Recorder (EDR), coupled on the same encapsulation. Figure 4.35 represents the respective connection schematic.

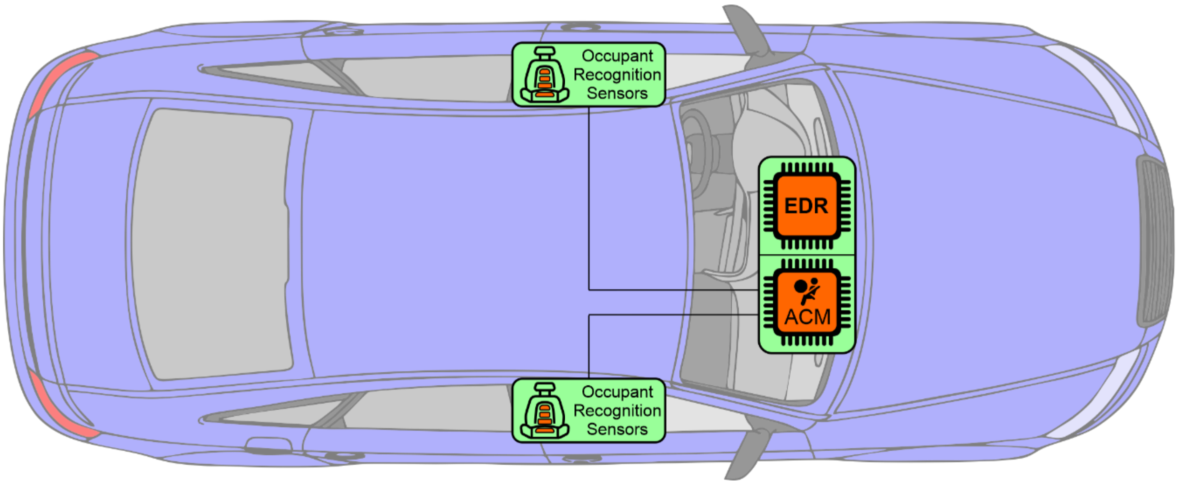


Figure 4.35 - Vehicle's instrumentation schematic for EDR's occupant's size classification variables acquisition

On the appendix A it is possible to see an overview representation of the vehicle's complete instrumentation set to record each one of the EDR's variables.

4.3. Recorded variables definition and characteristics

There is a predefined group of variables and parameters, on what concerns vehicles' accident dynamics and functioning status, which must or should be stored by the Event Data Recorder (EDR), depending on the regulations. These variables will apply to vehicles that are equipped with an EDR and belong to the M1 and N1 categories, by 2022 (UNECE, 2021a). Among which, are included passenger cars with less than eight seats, including the driver, and light duty vehicles, for goods' transportation, that cannot exceed the maximum mass of 3,5 tonnes. (UNECE, 2017)

The majority of the following data elements entered into force by July 2022 for new vehicle models and for new registrations by July 2024. However, the later defined data elements will have an additional two-year period before entering into force, so being the limits of July 2024 for new vehicle models and July 2026 for vehicles' new registrations. The implementation of EDR regulations on heavy goods' transportation vehicles and buses will be regulated later by 2029. (euDARTS, 2022)

Only if the vehicle is equipped, from manufacturer, with the systems or the sensors capable of monitor and provide each variables' values with the required characteristics (accuracy, range, resolution, and sample rate) and if they are operational at the time of storing the data, the designated variables must be recorded. Otherwise, the EDR might just store the systems' status or the hypothetical sensors' state of failure or inoperability. (UNECE, 2021a)

According to the United Nations Regulation, the Event Data Recorder (EDR) must and should register the following variables and data elements, which allow experts to analyse accident's circumstances, make considerations and reach some factual conclusions.

4.3.1. Delta-V, longitudinal and lateral:

Delta-V variables evaluate, on a time basis, the cumulative velocity variation suffered by the vehicle at the crash moment, along the vehicle's longitudinal axis (x-axis) and horizontal transversal axis (y-axis). Useful to understand the vehicle's dynamics during the collision pulse and evaluate the crash's severity. Delta-V values are derived from the acceleration measurements promoted by the vehicle's inertial measurement unit (IMU). (Gabler et al., 2004; UNECE, 2021a)

4.3.2. Longitudinal, Lateral and Normal Accelerations (pre-crash and post-crash):

Acceleration variables describe, on a time basis, the acceleration suffered by the vehicle before and at the moment of crash, along the vehicle's longitudinal axis (x-axis) for longitudinal acceleration, along the vehicle's horizontal transversal axis (y-axis) for lateral acceleration and along its vertical transversal axis (z-axis) for normal acceleration. Resorting to mechanical and mathematical models, it is possible to reconstruct the vehicle's linear movements on a predefined referential. This way, acceleration variables acquisition, by the Event Data Recorder (EDR), is useful to understand the vehicle's dynamics before the collision and during the crash pulse, as effect of the accident's contact. (Jost, 2019; UNECE, 2021a)

4.3.3. Vehicle's roll angle, roll rate and yaw rate:

The roll angle and yaw and roll rates evaluate, on a time basis, the vehicle's rotation angle variation and displacement over time along its longitudinal axis (x-axis) for roll rate and roll angle, and along its vertical transversal axis (z-axis) for yaw rate, before and during the crash event. Roll angle is measured between the ground plane and the vehicle's horizontal transversal axis (y-axis), while the yaw angle is measured between a longitudinal vertical plane and the vehicle's longitudinal horizontal axis (x-axis). Resorting to mechanical and mathematical models, it is possible to reconstruct the vehicle's angular movements over itself. This way, angular rate variables acquisition, by the Event Data Recorder (EDR), is useful to understand the vehicle's dynamics before the collision, on what concerns understeering and oversteering situations. Besides, it is also useful to evaluate the vehicle's rotational movements promoted by the contact, during the crash pulse, and the rollover situation after the collision. (ELPROCUS, 2022; UNECE, 2021a)

4.3.4. Speed, vehicle indicated:

The indicated speed describes, on a time basis, the vehicle's longitudinal speed, along its x-axis, before the moment of crash, acquired by the wheel speed sensors and shown on the dashboard. This speed is determined by the vehicle's Anti-lock Braking System (ABS) module as a mean of the speed values sensed on each wheel. The vehicle's indicated speed acquisition by the Event Data Recorder (EDR) might be useful to determine its circulation velocity, moments before the collision event. (Continental, 2022; UNECE, 2021a)

4.3.5. Engine's throttle percentage | Service brake activation | Engine rpm | Steering input:

The Event Data Recorder (EDR) stores some data elements which describe, on a time basis, the driver's intentions and commands to the vehicle, and the vehicle's functioning before the beginning of the crash event. Among these data elements, there are the engine's throttle percentage, the service brakes' actuation, the steering wheel's angular displacement and the engine's revolutions per minute variables.

The engine throttle percentage variable evaluates, on a time basis, the driver´s intention of acceleration before the moment of crash, this variable is also used to manage the fuel delivery to the engine, the throttle valve actuator, ignition, and injection timing, in case of internal combustion, or power delivery, in case of electric motors. This data element is acquired and processed to determine the driver's request for engine load on a percentual basis, where 0% corresponds to pedal released and 100% to pedal fully pressed. (*Throttle Position Sensor*, 2022)

The service brake pedal's activation variable describes, on a time basis, the status of driver´s braking intention before the moment of crash, acquired by the brake switch sensor on the brake pedal system. This information is used on the vehicle's various active safety systems. Usually, the ON state refers to the brake pedal pressed, while the OFF state indicates that the brake pedal is released. This variable acquisition might be useful to determine the vehicle's deceleration moments before the collision event. (Samarins, 2021)

The steering angle variable evaluates, on a time basis, the driver´s intention of steering or avoiding an obstacle before the moment of crash, acquiring the steering wheel's angular displacement by the steering column sensor, relatively to its straight-ahead position. Knowing the steering column's angle, it is possible to determine the front wheels' directional orientation, which can be useful to understand the vehicle's dynamics before the collision. This information is also used on the vehicle's various active safety and driving assistance systems. (Delphi Technologies, 2022)

Engine RPM generally describes, on a time basis, the engine's crankshaft revolutions per minute (RPM). Depending on the type of powertrain system the vehicle is equipped with (internal combustion engine, hybrid technology or electric propulsion), this variable might represent the transmission gearbox's input shaft revolutions per minute, or even the output shaft revolutions per minute of other device supplying motive power. (UNECE, 2021a)

4.3.6. Safety belts status | Passenger air bag suppression status | Seat track positions | Occupants sizes classification:

The Event Data Recorder (EDR) records certain occupancy data elements which allow the Airbag Control Module (ACM) to determine the best passive safety systems activation and restraint systems deployment routines. Among these variables are the safety belts' fastening status, the passenger's airbag suppression, the occupancy detection and the front seats' position adjustment.

The safety belts' status variables demonstrate if the various occupants' safety belts were coupled moments before the collision event. Usually, this information is used to determine which restraint systems, such as air bags and pretensioners, should deploy and used on the safety belt usage warning system, usually displayed on the dashboard.

The airbag suppression variable indicates the passenger's air bag suppression status moments before the collision event, so that the expert can evaluate if the passenger's front airbag should have been deployed or if it was the driver's intention to deactivate this airbag, in case of collision. Usually, the ON state refers to the passenger's front airbag suppressed, while the OFF state indicates that this airbag was not supressed.

The seat track position variable demonstrates if the driver's seat was adjusted to a forward position, moments before the collision event. With this data, the expert can evaluate if the driver's and front passenger's airbags deployment routines were correctly implemented by the Airbag Control Module (ACM). Depending on the seats' positions, the distance between the occupant and airbags may vary, and their deployment sequence must be adapted to the circumstances, looking forward to better impact absorption and least occupant injuries. Usually, if the seats are adjusted forwards, these variables might record the "Yes", "Foremost", "Forward", or similar states, while in other seat adjustment positions the variables may register the "No", "Not Foremost", "Rearward", or an equivalent status. (Graham, 2022)

The occupant size classification variables describes if the driver's and front passenger's size either belongs to a small stature individual standard or not, based on the fifth percentile female for the driver and based on the 6yr old HIII US ATD or Q6 ATD model for the front passenger. This data element is recorded moments before the collision event. The Event Data Recorder (EDR) might store the driver's and front passenger's size classification to evaluate the airbag's deployment algorithms adequation. The airbag's deployment force and routines must be adapted to the occupant's size and position, otherwise their deployment, in case of collision, might cause more harmful injuries. (UNECE, 2021a)

4.3.7. Warning lamps status | Active safety and driving assistance systems activity and status:

The Event Data Recorder (EDR) takes register of airbag's system, some vehicle's active safety and automated driving assist systems functioning and availability. Vehicles' active safety systems have influence on its behaviour. This way, the intervention of these systems, such as Anti-lock Brake System (ABS), Traction Control System (TCS), and so on, at the collision moment must be taken into account on the vehicle's dynamics interpretation, during the accident event. Regularly, the active safety systems must be ready to act in case of vehicle instability or loss of control by the driver. However, due to certain conditions, malfunctions or lack of maintenance, these safety systems might be deactivated or miss its activation thresholds, in some rare cases. This way, in case of accident, these systems' operation status and availability should be well known, in order to recognise if there was any factor which could influence the vehicle's behaviour and increase the crash severity or lead to the collision.

Warning indication lights EDR variables demonstrate if there was any malfunction with the respective systems, short instants before the crash event. Otherwise, systems' status variables describe, on a time basis during the pre-crash period, if the respective system was either on, off, activated, deactivated, faulted, intervening, warning, or other similar states which the manufacturer might find relevant, moments before the accident. (UNECE, 2021a)

4.3.8. Time variables and Control variables:

Finally, the Event Data Recorder (EDR) stores some control data elements which give the experts relevant clues for the accident's interpretation. These variables mainly consist of the maximum values for Delta-V, the time at which they occurred, the count for the vehicle's number of ignition cycles, the number of registered events associated to the same accident and the respective elapsed time between them, the flag for recorded file completion and the multiple deployment times for each occupants' restraint systems and vulnerable road users' protection system.

The maximum Delta-V variables demonstrate the maximum values for the cumulative velocity change experienced by the vehicle at the moment of crash, along the vehicle's longitudinal and lateral axis (x-axis and y-axis), while the respective time variables indicate the time at which these maximum values occurred. This information might be useful to evaluate the crash's severity and the respective moments of higher severity.

The ignition cycle data elements indicate the count of ignition power cycles to the ignition switch at the crash event moment and at the time of recorded file's retrieving, since the first use of the EDR. The comparison of these values can be useful to evaluate the driver's intention to start and drive the vehicle to other position after the accident.

The number of event variable presents the events' count and the respective designator number for each event recorded by the EDR and stored on its non-volatile memory. Multiple events can be associated to the same accident if all of them start within a 5 second interval since the first event's time zero. Together with the time elapsed between events data element, this information is essential for the experts' work of framing EDR data from different events which occurred on the same accident.

The complete file data element describes if the report file was completely recorded to the non-volatile memory with success, which is required so the experts can understand if there was any error or corrupted information during the data storing process at the time of crash.

The time to deploy variables demonstrate how much time the various airbags, pretensioners and vulnerable road user's protection systems took to be activated by their respective deployment command, since the accident's time zero. This information is useful to verify if the deployment strategies were correct and adequate to the crash situation. These time variables present values relative to the respective event's time zero, which represent its beginning. (UNECE, 2021a)

4.3.9. Recorded variables resume

Among all the variables and parameters stored by the EDR, there are some variables which refer to the vehicle's dynamics and might allow the experts to reconstruct its behaviour on a time frame which integrates the collision event. The mandatory variables, stored by the EDR, which might contribute to the vehicle's dynamic behaviour reconstruction are the longitudinal and lateral Delta-V, the longitudinal, lateral, and normal accelerations, roll angle, yaw rate, and roll rate, vehicle's indicated speed, the steering angle input, and brake pedal's activation. Figure 4.36 illustrates the variables diagram and the vehicle's dynamic reconstruction perspective.

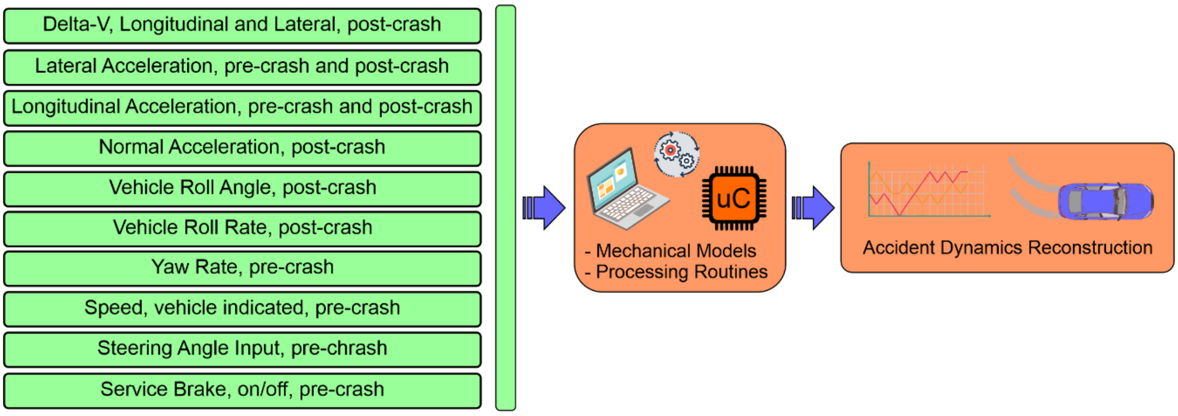


Figure 4.36 – EDR's most relevant dynamic variables for road accident reconstruction

Figure 4.37 represents the on-vehicle architecture on what concerns the mentioned dynamic data acquisition.

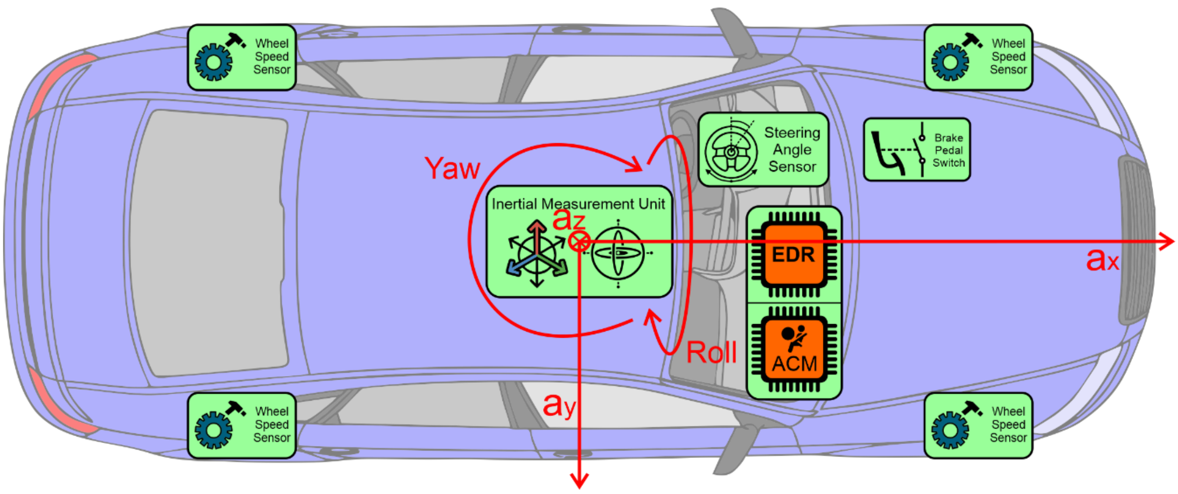


Figure 4.37 - Vehicle's architecture for the EDR's dynamic variables acquisition

5. Accident Reconstruction – Case Study

In this chapter is described a case study of a crash reconstruction. Are presented some methodologies commonly used on collisions' investigations. This crash reconstruction was performed using the PC-Crash® software, which implements and executes multiple computational calculations to simulate the vehicles' collision dynamics, as reliably as possible, through the characterisation of vehicles hypothetical pre-impact motion. The software stores information from the vehicle manufacturers' data bases and utilises these specifications to develop simulations with dynamically and visually representative 3D models.

5.1. Intervenient vehicles

The vehicles involved on the accident were a passengers' light vehicle, Chevrolet Aveo, and a motorcycle, BMW R1200GS Adventure, as the following Table 5.1 and Table 5.2 describe, respectively.

Table 5.1 - Passengers' vehicle technical data, adapted from (Car.info, 2022)

Vehicle's Technical Data		
Make	Chevrolet	
Model	Aveo	
Year	2008	
Displacement [cm^3]	1206	
Curb Weight [kg]	1065	
Wheelbase [mm]	2480	**Figure 5.1 - Model vehicle, adapted from (Auto ABC, 2022)**

Table 5.2 – Motorcycle's technical data, adapted from (MotorCycleSpecs, 2022)

Motorcycle's Technical Data		
Make	BMW	 Figure 5.2 - Model motorcycle, adapted from (MotorCycleSpecs, 2022)
Model	R1200GS Adventure	
Year	2012	
Displacement [cm^3]	1170	
Curb Weight [kg]	256	
Wheelbase [mm]	1507	

The final damage is presented in Figure 5.3 and Figure 5.4 for the passenger vehicle and for the motorcycle, respectively. This allows to perform the deformations' compatibility analysis and evaluate the vehicles' positions at the impact moment.

Figure 5.3 - Passengers' vehicle resultant deformation

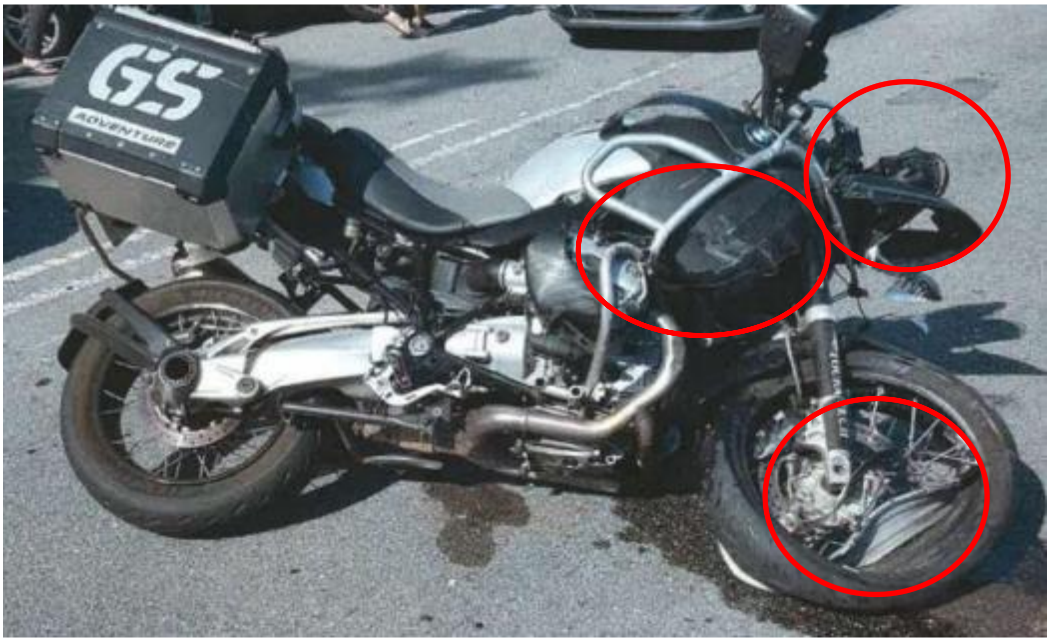


Figure 5.4 - Motorcycle's resultant deformation

According to the vehicles' damage profiles, it is possible to understand that the motorcycle collided with the vehicle as represented on Figure 5.5, which was extracted from the PC-Crash® software.

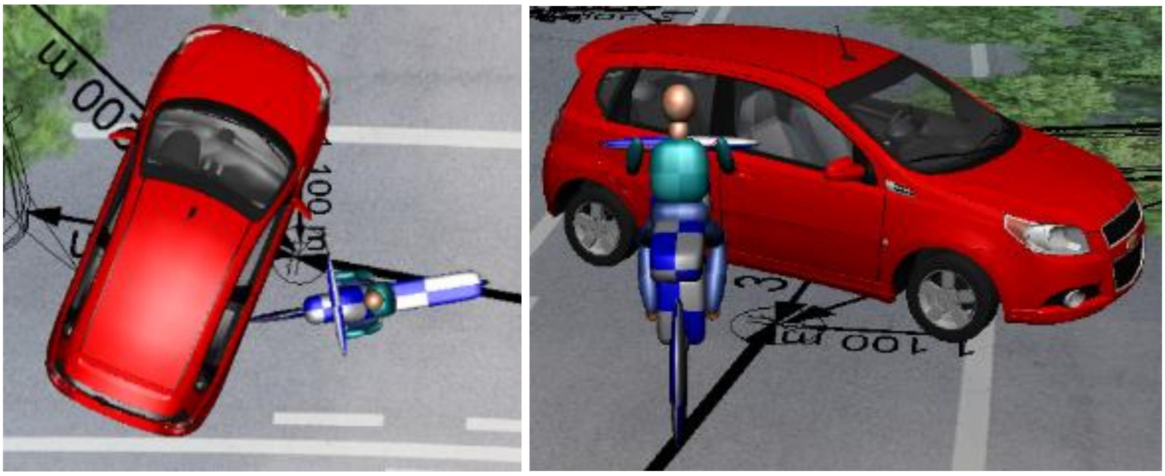


Figure 5.5 - Vehicles' impact position

5.2. Accident scenario

The collision occurred on a national road located on the north region of Portugal. The accident's scenario was visited to capture its topology using the photogrammetry digitalisation method assisted by an unmanned aerial vehicle (UAV) and its camera sensor. After the photographs' acquisition, a photogrammetry software compiled the retrieved data to develop a representative precise and accurate model for the accident's scenario. Figure 5.6 represents an example of the orthophotos' treatment process.

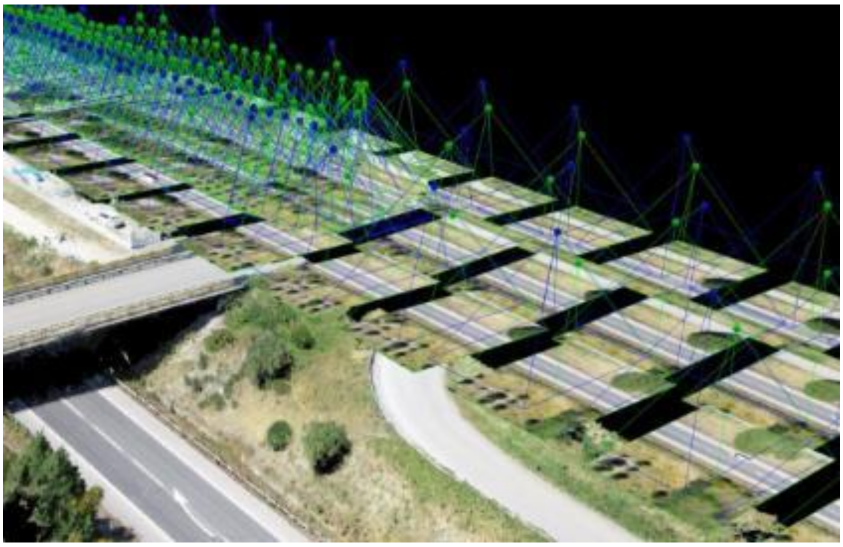


Figure 5.6 - Example of orthophotos' treatment process

As result from the photogrammetry process, a 2D detailed and accurate scenario model was developed for the accident simulation. A 3D representation was not obtained due to difficulties on the point cloud's generation, possibly because of big dimension vegetation present on the collision local.

As the accident was reconstructed considerably later than the collision's occurrence, the evidence and remaining clues were collected by the responsible authorities, previously to the accident's scenario photogrammetric surveying. For this reason, the accident's participation information was considered, and the resultant collision's sketch used as the base for the computational simulation is shown on Figure 5.7.

Figure 5.7 - Accident's sketch

5.3. Accident dynamics

Multiple collision simulations were performed by varying the vehicles' velocities and initial positions, in order to unveil the vehicles' behaviour during impact and to determine the vehicles' dynamics needed so that they reach their defined final positions, according to the authorities' reports.

As a motorcycle is involved in the accident, the simulation was performed only for the crash pulse and post-impact phases, since the motorcycle and driver must be represented by a multibody system, unlike the passengers' vehicle which consists of a single body. Besides, as there were not skid marks registered, there is no solid evidence to develop the pre-impact analysis.

The final simulation allowed the determination of the most likely position for the accident's occurrence, and the vehicles' traveling velocities at the impact's instant. Figure 5.8 to Figure 5.13 represent the multiple frames which describe the developed computational simulation.

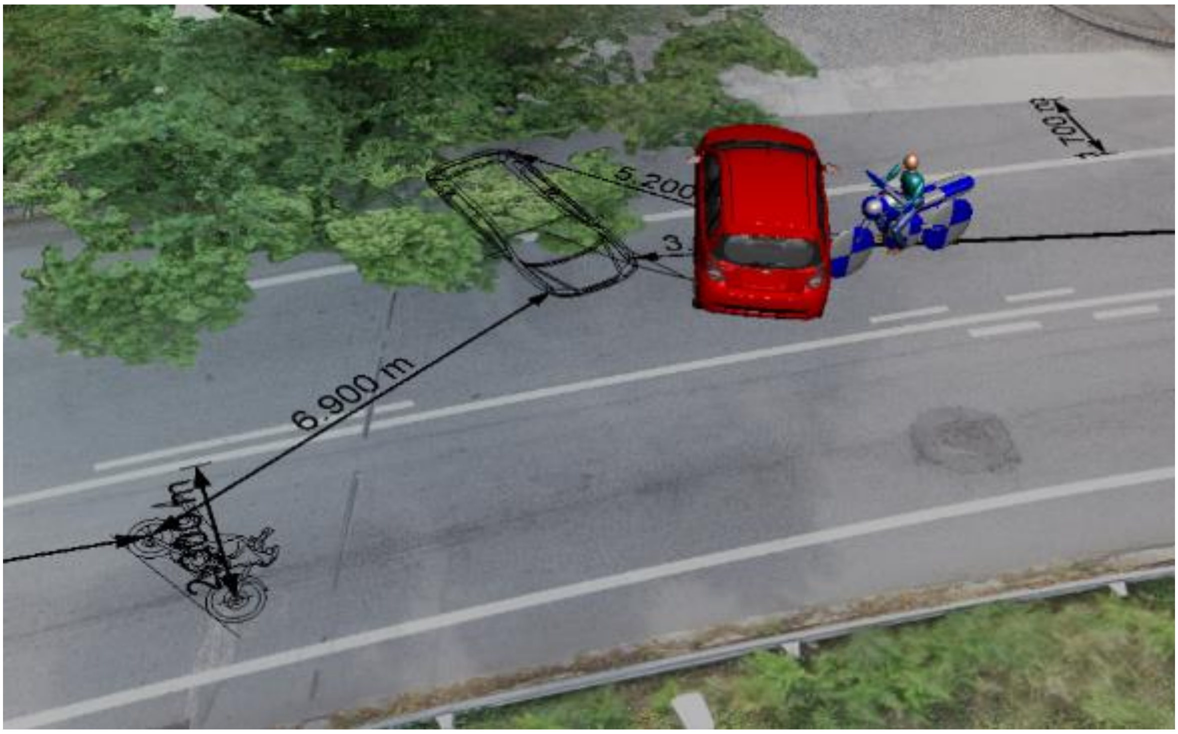


Figure 5.8 - Collision's simulation at t=0s

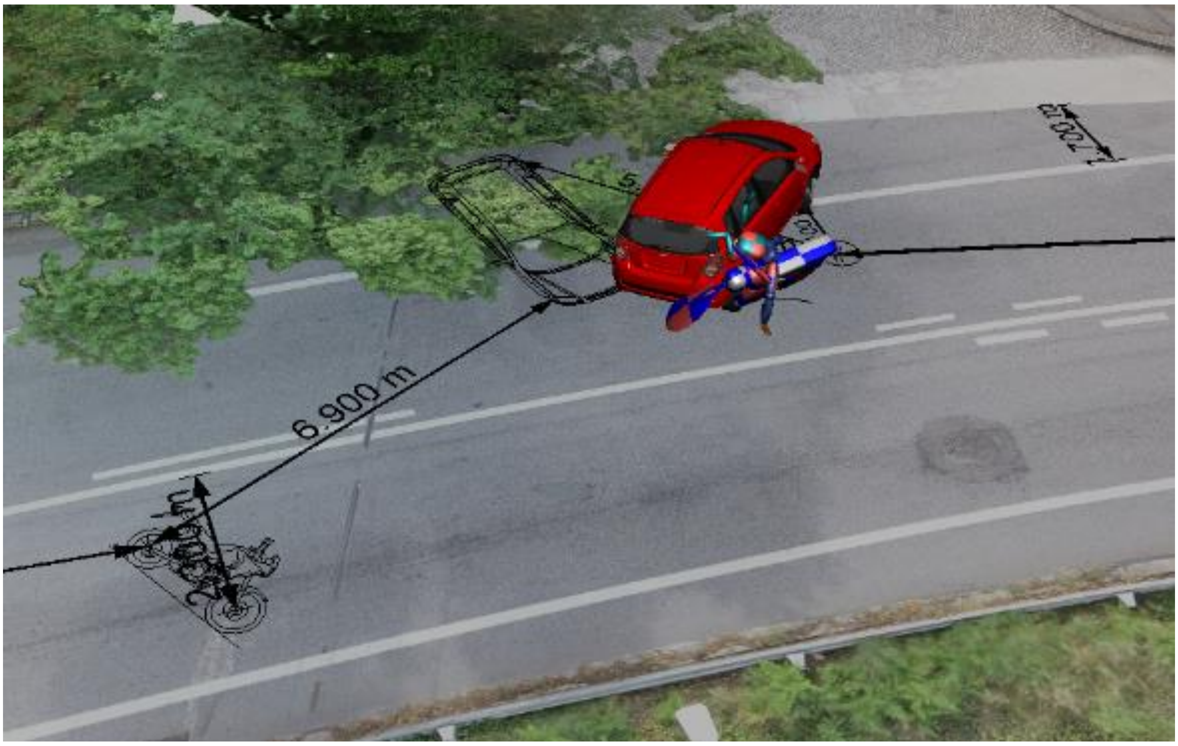


Figure 5.9 - Collision's simulation at t=0.2s

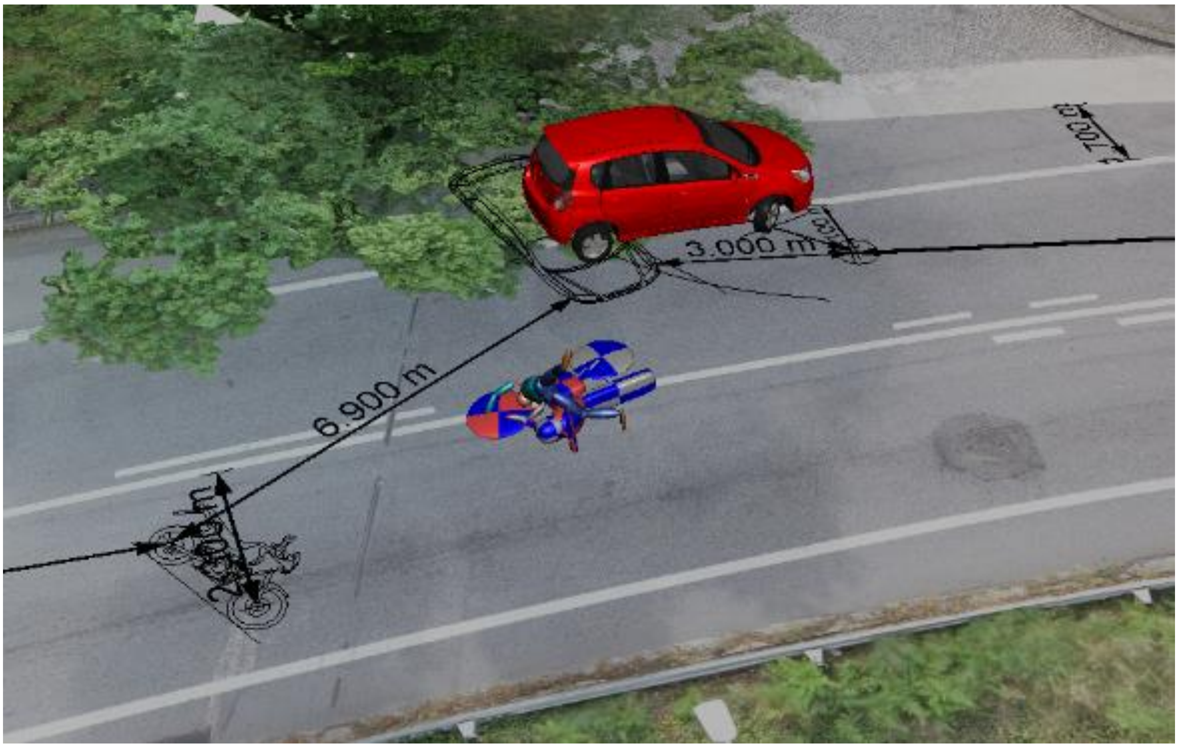


Figure 5.10 - Collision's simulation at t=0.6s

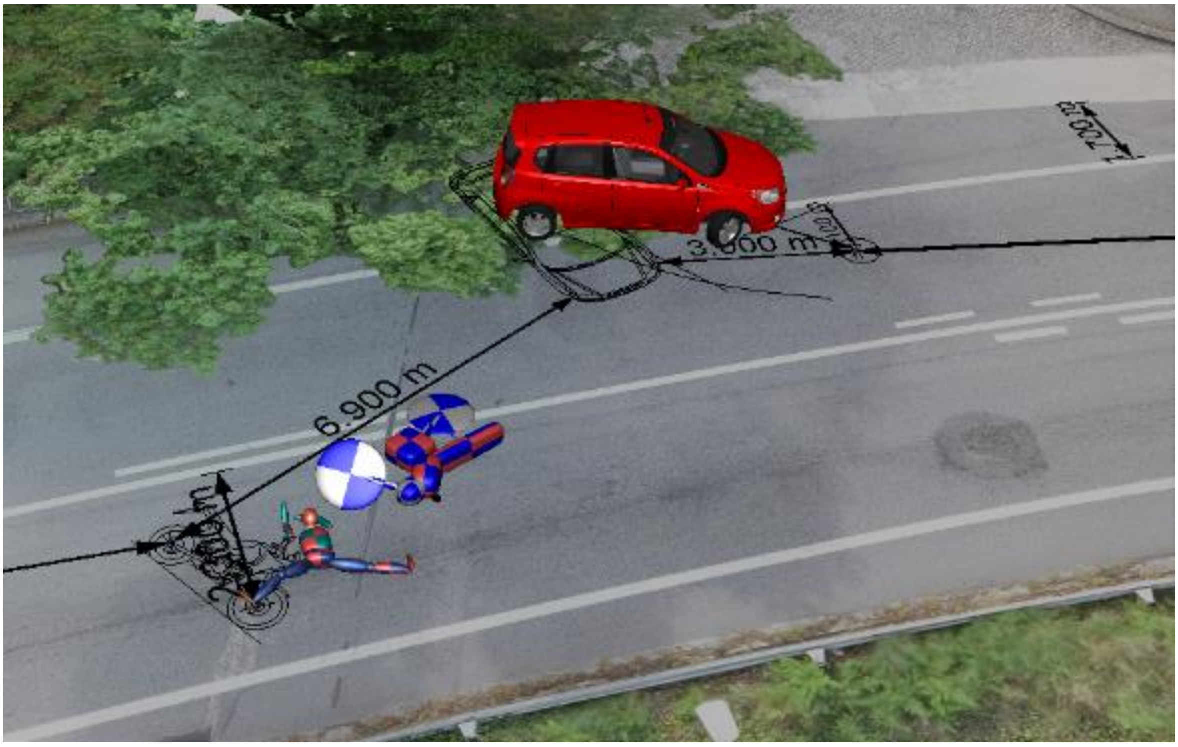


Figure 5.11 - Collision's simulation at t=1.0s

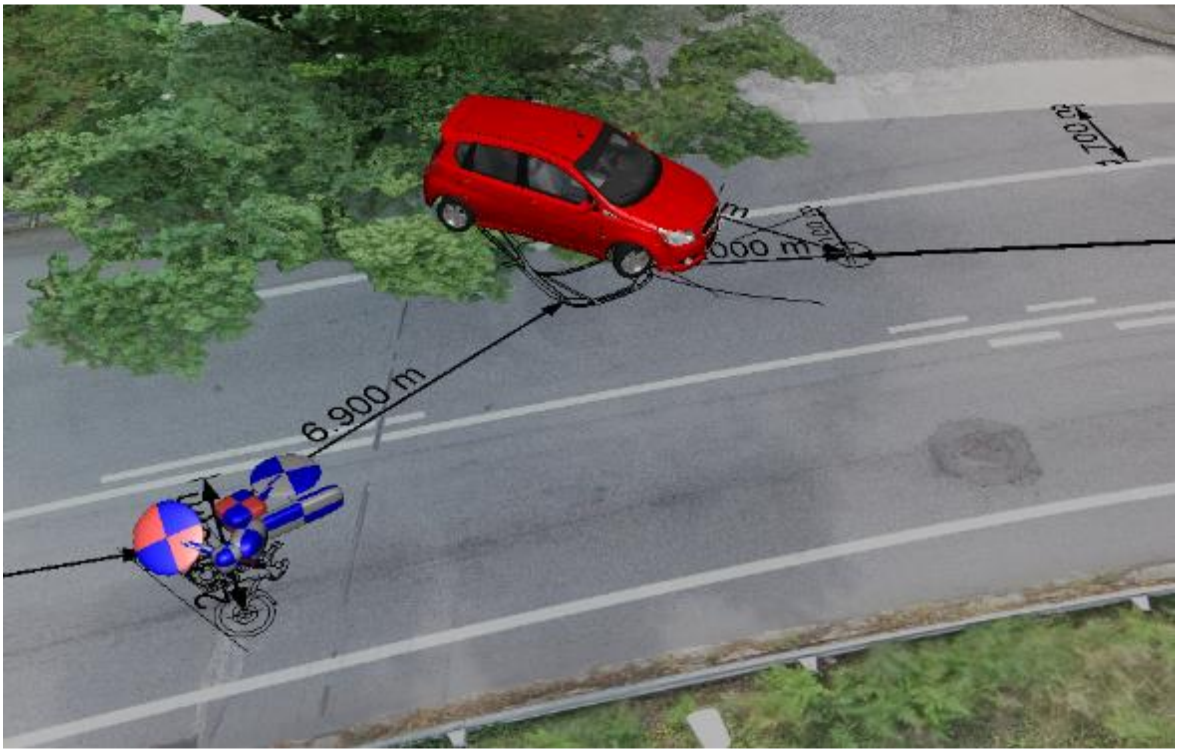


Figure 5.12 - Collision's simulation at t=2.0s

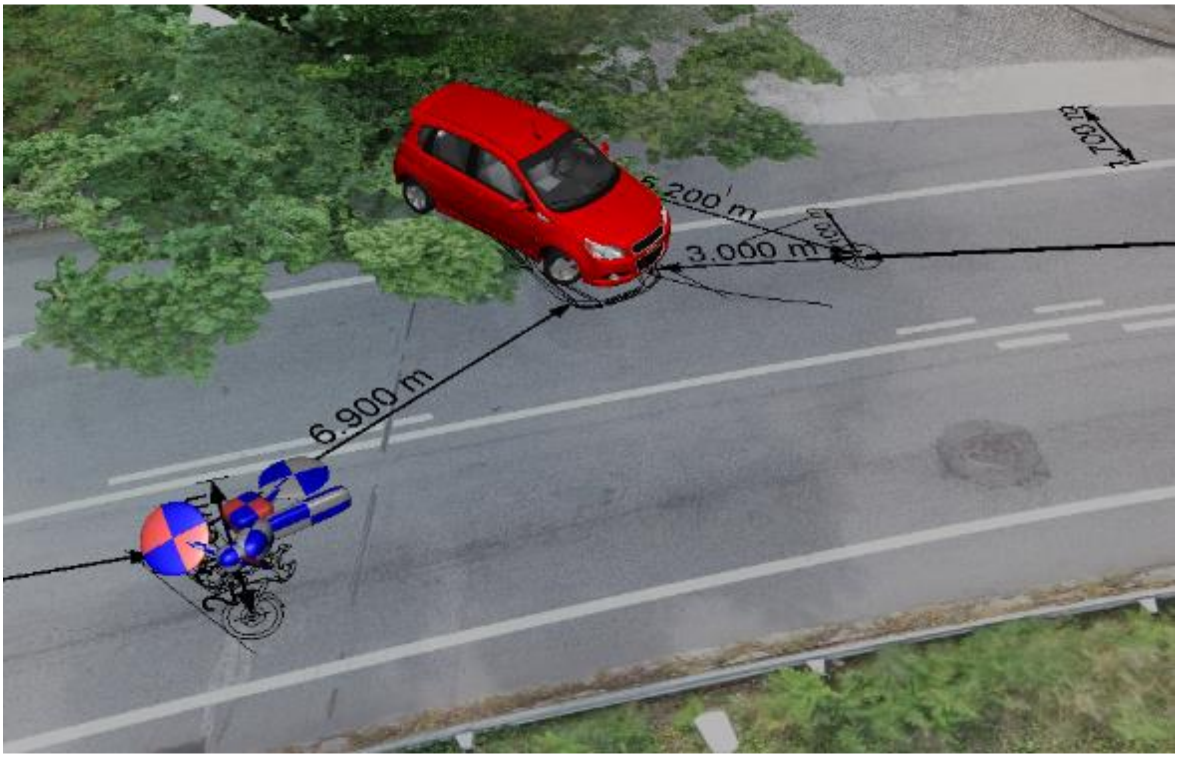


Figure 5.13 - Collision's simulation at t=3.6s (final)

5.4. Dynamic data outputs

Having the road accident reconstruction finalised, it is possible to extract diagrams which describe, on a time basis, the vehicles' dynamic variables which were determined by the software's calculus routines. Since the motorcycle multibody system's dynamic is very complex to define on a summary manner, the passengers' vehicle dynamic data is more relevant to the present study. Besides, higher emphasis is given to the variables which are recorded by the EDR, as well.

Once the passengers' vehicle suffers a lateral impact which promotes a spinning motion, it is predictable that it registers mainly lateral accelerations and yaw angular displacements. The motorcycle's impact on the vehicle's right side promoted a lateral acceleration peak of 64.37 m/s^2. Besides, due to the vehicles' positions at the moment of impact, the motorcycle also promoted a deceleration on the vehicle's longitudinal movement, contributing to its motion reversing. The impact induced two sequential peaks of negative longitudinal acceleration on the vehicle, with the magnitude of -22.89 m/s^2 and -24.26 m/s^2, respectively. Figure 5.14 presents the diagrams which describe the vehicle's lateral (blue) and longitudinal (red) acceleration data variables.

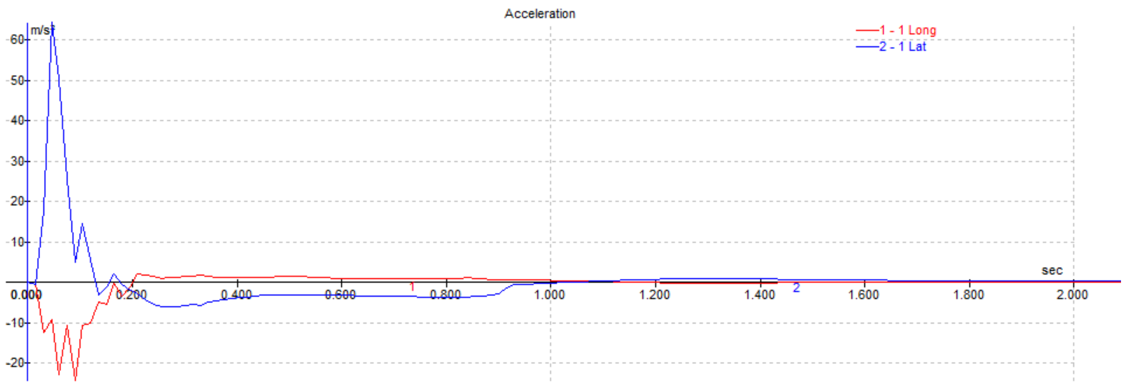


Figure 5.14 - Diagram for the vehicle's lateral (blue) and longitudinal (red) accelerations

On the EDR data elements, the vehicle's spinning motion is characterised by the yaw rate variable. According to the clockwise movement performed by the vehicle, in this case, the software presents negative values for the yaw angular velocity, as illustrated on the Figure 5.15 diagram, reaching a peak value of -2.70 rad/s, since the motorcycle collides behind the vehicle's rotation centre.

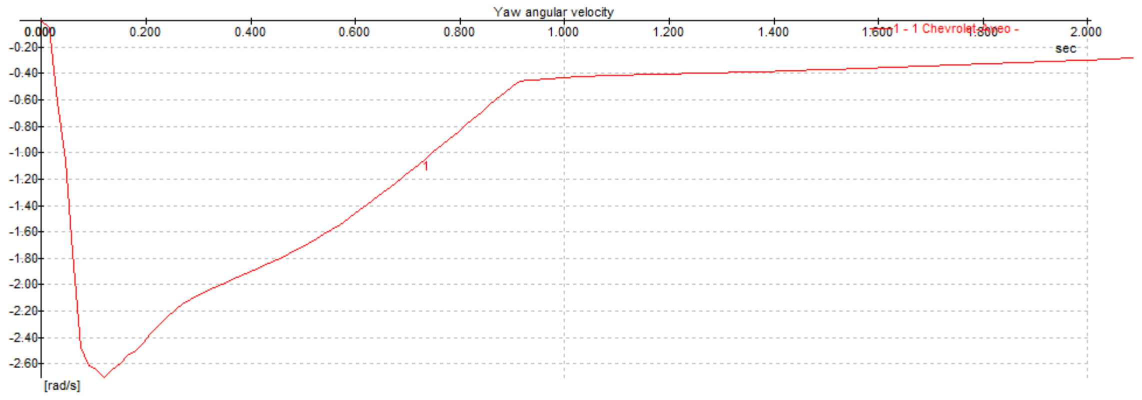


Figure 5.15 - Diagram for the vehicle's yaw angular velocity

Besides the lateral acceleration and yaw rate variables, as expected by the vehicle's movement, the motorcycle impact on the vehicle's right side also promotes a roll angular displacement on the vehicle's body, due to the tyre friction, and suspension elasticity and damping effects. The vehicle's body tilts anticlockwise, considering its traveling direction, since the motorcycle collides from the right side. The diagram presented on Figure 5.16 describes the vehicle's body roll angle resulting from the impact. The maximum roll angular displacement registered was 8.52 degrees.

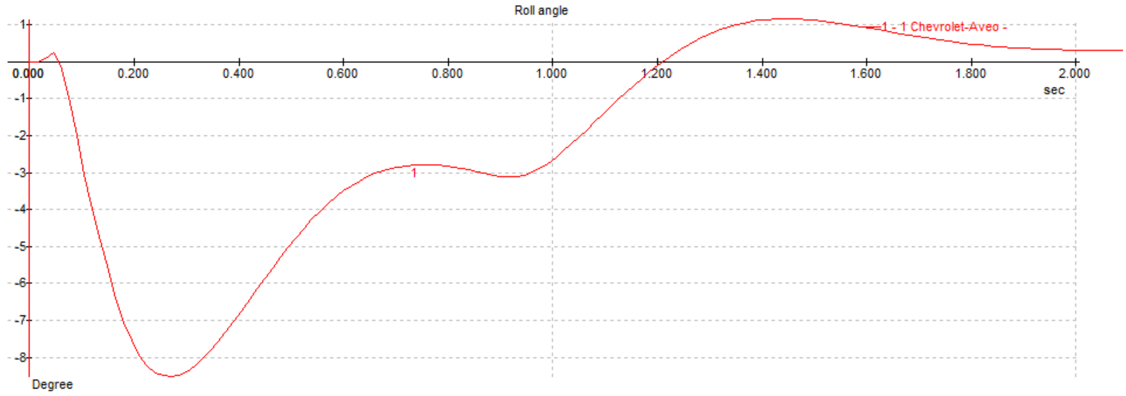


Figure 5.16 - Diagram for the vehicle's roll angle

Additionally, the Event Data Recorder (EDR) also records the vehicles' body roll rate data element regarding the rollover events' detection. This dynamic variable can be extracted from the accident's simulation too. The passengers' vehicle body's roll angular velocity outputted from the software is defined by the Figure 5.17 diagram, on which is reached the maximum roll rate peak of 1.29 rad/s with negative sign, since negative rotational direction is the anticlockwise.

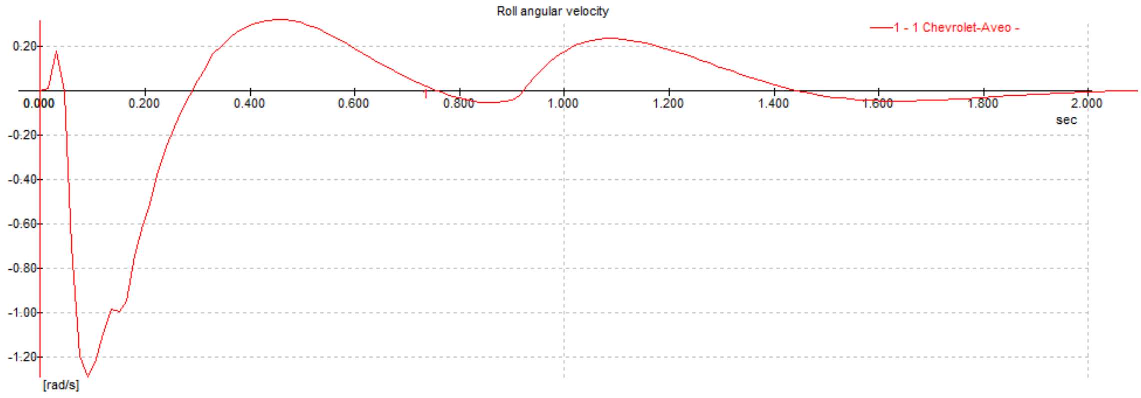


Figure 5.17 - Diagram for the vehicle's roll angular velocity

These dynamic data elements might describe the vehicles' movements and behaviour during a collision occurrence. The use of these variables as inputs for the dynamic model could consist of a valuable contribution for the efficient and accurate development of computational simulations for the road accident reconstruction forensic science. This demonstration evidences the relevance of implementing and resorting to internally registered dynamic variables for the collisions' investigation.

6. Autonomous data acquisition system

This chapter describes the development of a prototype device which is responsible for the acquisition of multiple variables. The goal is to allow the determination of the most relevant accident data elements predicted on the EDR regulations, as described earlier on the present report, section 4.3.9. The main objectives of this data acquisition system are the collection of acceleration and angular rate data for the vehicle's three orthogonal axis, to describe its dynamics, the acquisition of the vehicle's speed through GPS determination, the monitoring of the steering wheel angular displacement, the collection of some relevant data variables from the vehicle's CAN communication network, and the storage of all this information on a non-volatile memory device, such as a secure digital (SD) card. The developed data acquisition system was designated as the Vehicle Data Logger (VDL).

6.1. System development

In order to develop a prototype device, it was selected the Adafruit's Feather family of boards which included a good and versatile solution for the microcontroller and most of the needed sensor shields. Otherwise, breadboard prototyping and its less reliable connections could affect the sensors readings and communication.

The open-source Arduino® coding language, and the various libraries provided by the developers from Adafruit® and Arduino®, were used to develop and program the device's software, regarding its simplicity and versatility (Adafruit, 2022a; Arduino, 2022)

6.1.1. Identification of the VDL main components

Microcontroller

The selected microcontroller was Adafruit Feather M4 CAN Express board, Figure 6.1, which supports Arduino programming, includes the ATSAME51 32-bit Cortex M4 core that runs at a default frequency of 120 MHz, and uses the 3.3 V for logic and power. Besides it includes 512 kB of flash memory, and 192 kB of random-access memory (RAM), and multiple general-purpose input/output (GPIO) pins with ADC (Analogue to Digital Converter), DAC (Digital to Analogue Converter) and PWM (Pulse Width Modulation) functioning capabilities. This microcontroller also allows the communication with multiple peripheral devices through the SPI (Serial Peripheral Interface), I2C (Inter-Integrated Circuit) and Hardware Serial protocols. Furthermore, this board includes hardware which supports the CAN (Controller Area Network) bus communication, with a built-in transceiver and terminal connection, and the USB (Universal Serial Bus) connection for programming and serial data monitoring. (Rembor, Herrada, et al., 2022)

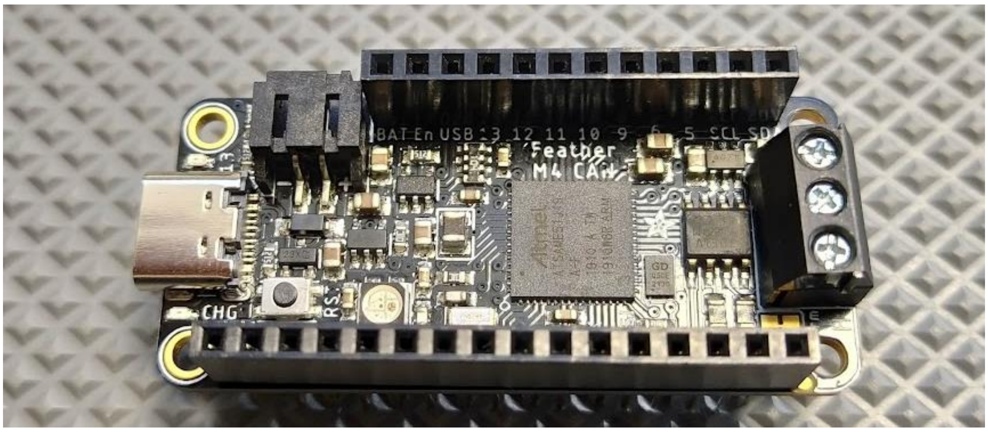


Figure 6.1 - Adafruit Feather M4 CAN Express board

Inertial Measurement Unit

For vehicle dynamics (low range acceleration and angular rate data acquisition) was selected the Adafruit LSM6DSOX + LIS3MDL FeatherWing, Figure 6.2, which consists of a shield with the LSM6DSOX, a 6 degrees of freedom IMU (accelerometer and gyroscope), and the LIS3MDL 3 axis magnetometer, which is not used in this scope. This shield's sensors communicate with the microcontroller through the I2C protocol. (Rembor, Clark, et al., 2022)

The LSM6DSOX's accelerometer has a configurable acceleration range of up to ±16 G. Besides, at the ±16 G configuration, the accelerometer has a sensitivity of about 0.000488 G/LSB. On the other hand, the sensor's gyroscope can be configured to a maximum range of ±2000 degrees/s, having a sensitivity of at least 0.07 degrees/s for each LSB (Least Significant Bit). The LSM6DSOX IMU can be configured with an update frequency which can reach up to around 6.7 kHz for both the accelerometer and the gyroscope. (STMicroelectronics, 2019)

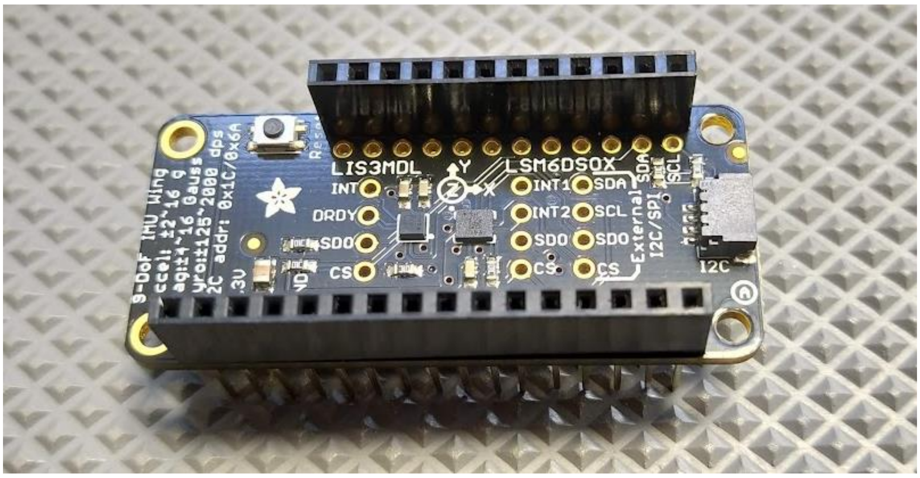


Figure 6.2 - Adafruit LSM6DSOX + LIS3MDL FeatherWing

<u>High range accelerometer</u>

Since the peak acceleration amplitudes involved on car accidents overcome 16 G, it was selected a higher range accelerometer which could be integrated into the developed device and cover the acceleration values registered on higher severity collisions. The SparkFun® triple axis accelerometer breakout - KX134, Figure 6.3, was the solution selected for the referred purpose. This board includes the Kionix® KX134 triaxial accelerometer which is characterised by a configurable maximum range of ±64 G, and a sensitivity of at least 512 counts/G, which is equivalent to 0.00195 G/LSB, as this is a 16-bit resolution accelerometer. The maximum output data rate for this sensor is 25.6 kHz. (SparkFun Electronics, 2022)

This accelerometer breakout board includes the Sparkfun Qwiic connector which is compatible with Adafruit's STEMMA QT connector. This fact allows to include the KX134 accelerometer on the Adafruit's microcontroller I2C communication bus. (Rembor, Clark, et al., 2022)

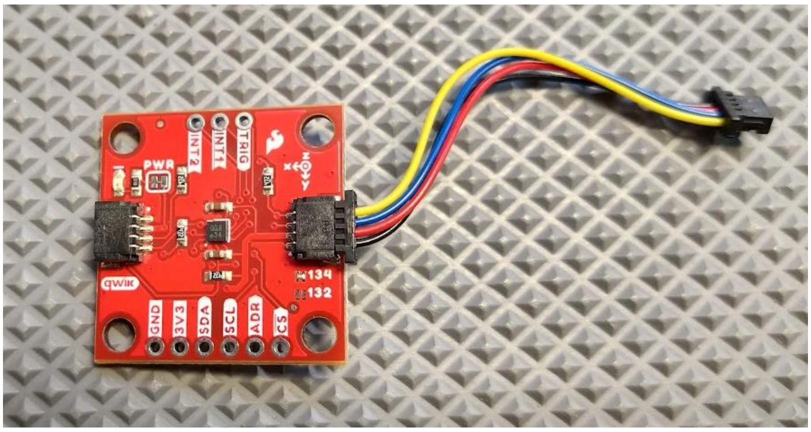


Figure 6.3 - SparkFun® triple axis accelerometer breakout - KX134

GPS shield

Regarding the independent vehicle's speed acquisition, it was decided to use a GPS sensor measuring velocities through satellite signalling. For this purpose, was selected the Adafruit Ultimate GPS FeatherWing, Figure 6.4.This board includes the MTK3339 GPS chip, giving the module the capability to connect to a maximum of 22 satellites on 66 channels. Besides, this module has its own built-in antenna, but it also allows the use of an external antenna for better accuracy and stabilization times. Furthermore, the GPS board includes the RTC (Real Time Clock) functionality to acquire and keep track of time synchronised with the satellites, with an auxiliary coin cell battery which maintains the RTC functioning and helps to minimise the stabilisation time while searching for new locations. This GPS module can be configured for update rates from 1 Hz up to 10 Hz and presents results with 1.8 meters position accuracy and 0.1 m/s for velocity accuracy. (Ada et al., 2022)

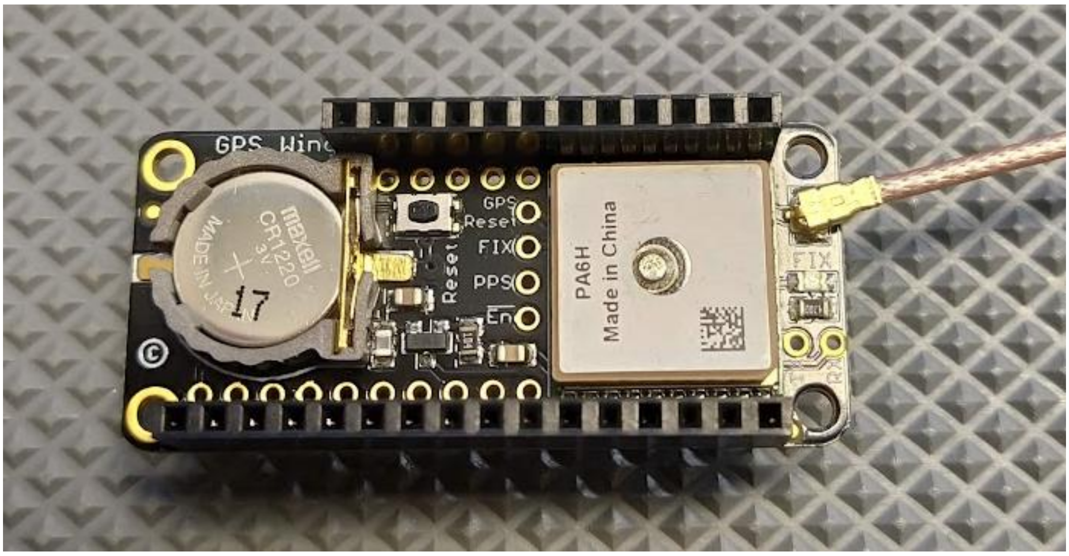


Figure 6.4 - Adafruit Ultimate GPS FeatherWing

Data logging shield

To save data, the Adafruit Feather family makes available the Adafruit® Adalogger FeatherWing, Figure 6.5. This board includes a micro-SD card socket and allows the communication with the microcontroller for reading and writing to a memory card through the SPI communication protocol. Furthermore, this module includes a RTC chip which communicates via I2C to provide date and real time data to the microcontroller. The RTC clock time is once configured to match the time on programmer's personal computer, and it is maintained counting by an auxiliary coin cell battery. (Ada & Nosonowitz, 2022)

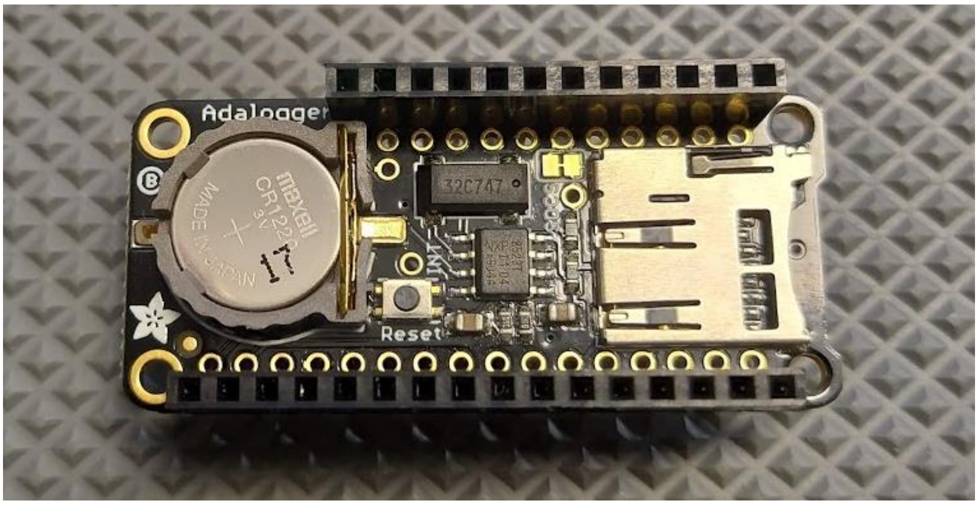


Figure 6.5 - Adafruit® Adalogger FeatherWing

Rotary position sensor

In order to acquire the vehicle's steering wheel angular displacement was selected the PSC360G2-F1A-C0000-ERA360-05K sensor, Figure 6.6, which consists of a non-contacting rotary position sensor that functions by the Hall effect principle. This sensor has endless mechanical rotational angle and it provides an analogic signal output which is directly proportional to its shaft position along the 360 degrees range. (Amphenol, 2022)

Figure 6.6 - PSC360G2-F1A-C0000-ERA360-05K rotary position sensor

6.1.2. VDL Software and Functioning

Functioning Diagram

According to the objectives defined for the VDL, the microcontroller has the described sensors, section 6.1.1, and two buttons as inputs. The micro-SD card, the computer's serial monitor and two LED lights consist of the microcontroller's outputs. Besides, to interact with the vehicle's CAN network, the microcontroller also has CAN interface capabilities. Figure 6.7 presents the VDL main functioning diagram.

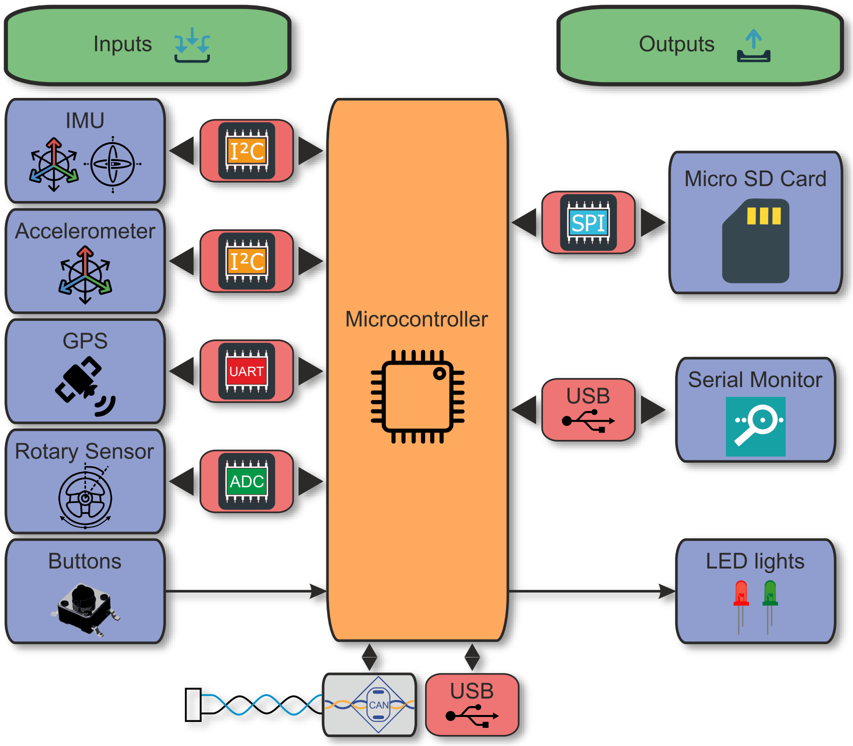


Figure 6.7 - VDL functioning diagram

Software

The VDL software was programmed with a task scheduler library (Arkhipenko, 2022) to define objective frequencies for the instructions' execution and distribute the processor's capabilities the best as possible, according to the intended data acquisition rates for the multiple variables. The main software's structure starts by including the needed libraries and defining constants, variables, objects, functions, and tasks prototypes. Afterwards, it executes the configuration setup function once, executes the loop function, which only activates the task scheduler, Figure 6.8 (right), and it transitions to the main tasks which cycle between each other according to their frequencies. Besides, the main tasks' routines may be interrupted by two interrupt service routines (ISR) associated with the buttons' inputs. Figure 6.8 (left) presents the software's main functioning flowchart.

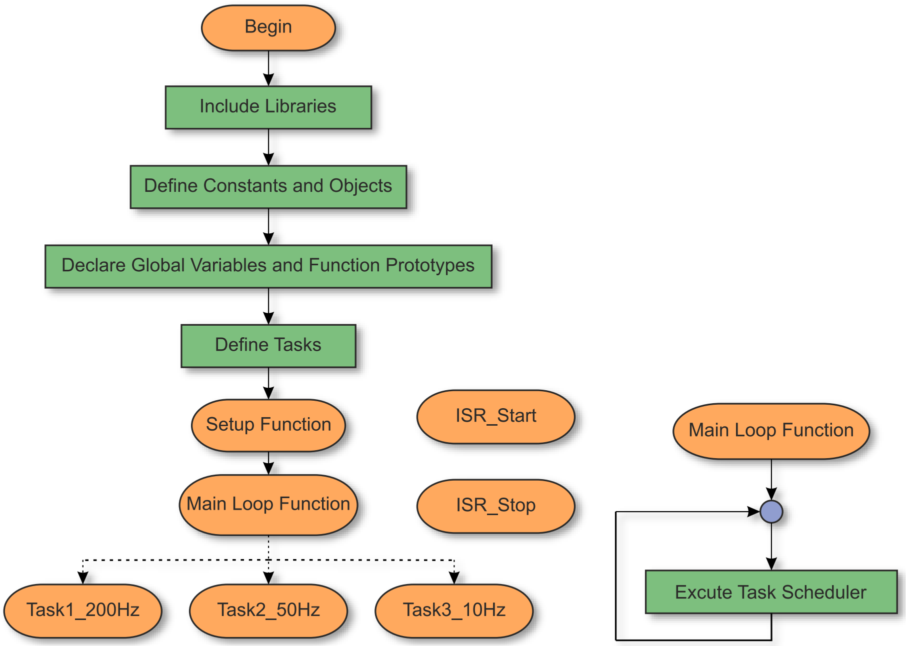


Figure 6.8 - Main flowchart (left) and Loop function flowchart (right)

The setup function is mainly responsible for the configuration and initialization of the various sensors, for the datalogging shield's initialization, for beginning the communication protocols, for configuring the microcontroller's digital pins and interrupts, and finally initialize the software's tasks, as shown on Figure 6.9. The ISR routines, which are activated by the buttons, manage the software's control variables that are responsible for the beginning and the finishing of the recording process, as presented on Figure 6.10.

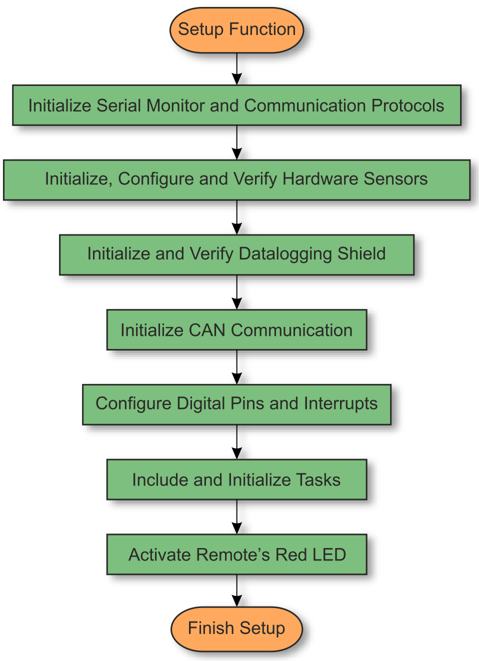


Figure 6.9 - Setup function flowchart

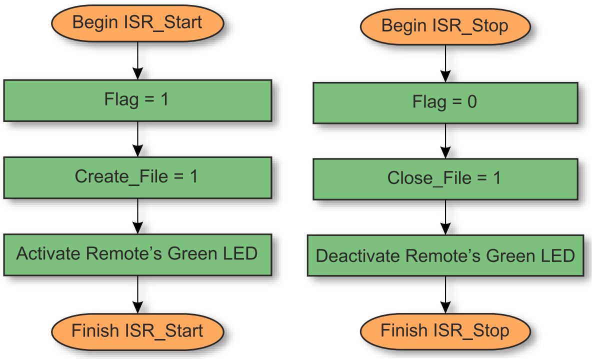


Figure 6.10 - Start interrupt (left) and stop interrupt (right) flowcharts

The first task was configured to work at a 200 Hz rate. This task performs the acquisition of the acceleration and angular velocity values from the IMU sensor and from the higher range accelerometer and writes the defined string of values and messages to the micro-SD card. Besides, it is responsible for creating and saving the recording file, depending on both interrupts' commands. Figure 6.11 illustrates the first task's flowchart.

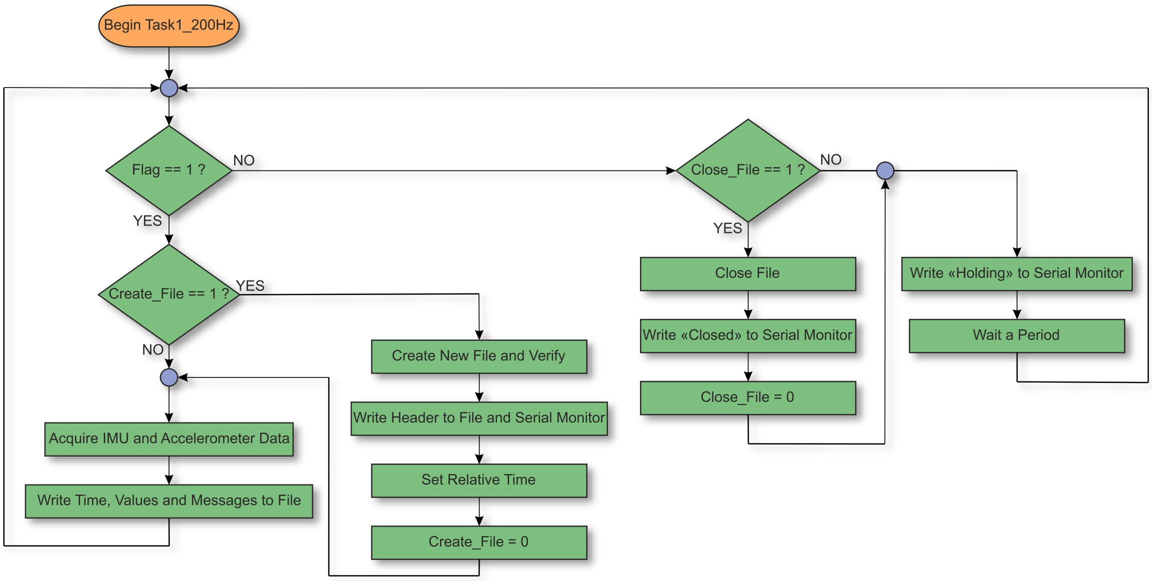


Figure 6.11 - Task 1 (200Hz) flowchart

The second task functions at a frequency of 50 Hz, it sends the multiple CAN request messages to the vehicle and receives the CAN response messages sent by the vehicle, referring to the pretended variables to acquire. The last task, working at a frequency of 10 Hz, is responsible for the acquisition of the vehicle's GPS velocity and angular position values from the GPS shield and from the rotary position sensor, respectively. Besides, this task prints the defined string of values and messages to the serial monitor. On the Figure 6.12, the flowchart for the second task is presented on the left side, while the last task's flowchart is illustrated on the right side.

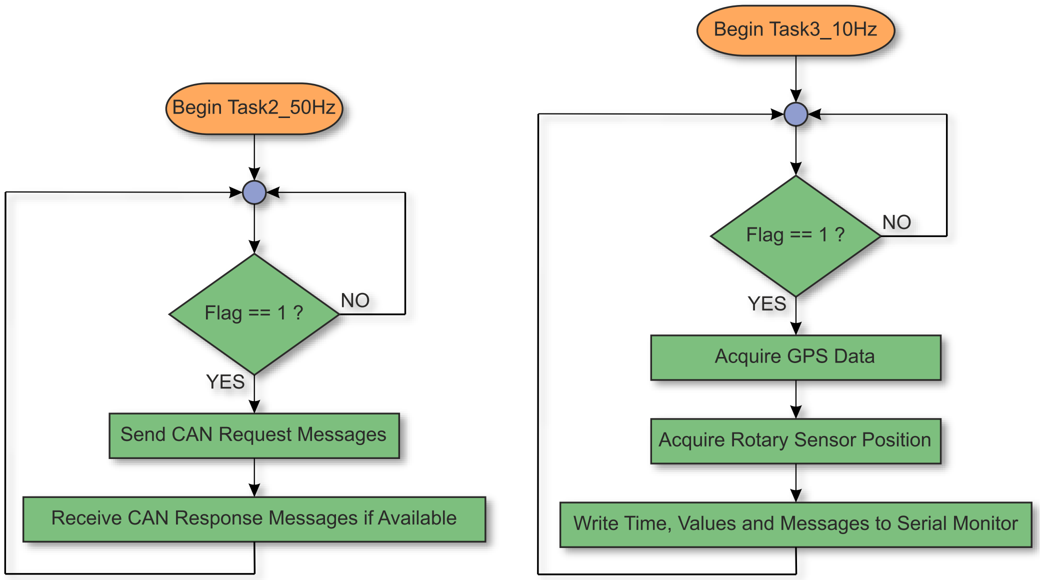


Figure 6.12 - Task 2 (50Hz) (left) and Task 3 (10Hz) (right) flowcharts

6.1.3. VDL assembly

Prototyping

On a first step implementation, the system's sensors and peripherals were tested and programmed individually to understand their functioning principles and control routines, utilizing the open-source libraries provided by Adafruit® and Arduino®.

The Feather family boards were stacked up on two layers placed side by side, through the use of the FeatherWing Doubler prototype board, which internally connects the corresponding pins from both sides to each other, allowing the availability of the Feather microcontroller pins on both stackings. (Adafruit, 2022b)

The Feather boards stacking, other sensors and peripherals were initially assembled together on breadboards to test the fully integrated system functioning, including a set of resistors for signal conditioning, press buttons for activation, and LED lights to get feedback, as presented on Figure 6.13. To test the system's CAN communication and messages acquisition, an auxiliary microcontroller and transceiver, namely the ESP32 module and the SN65HVD230 CAN board, were programmed to periodically send messages to the CAN network, with the bitrate configuration of 500 kbps.

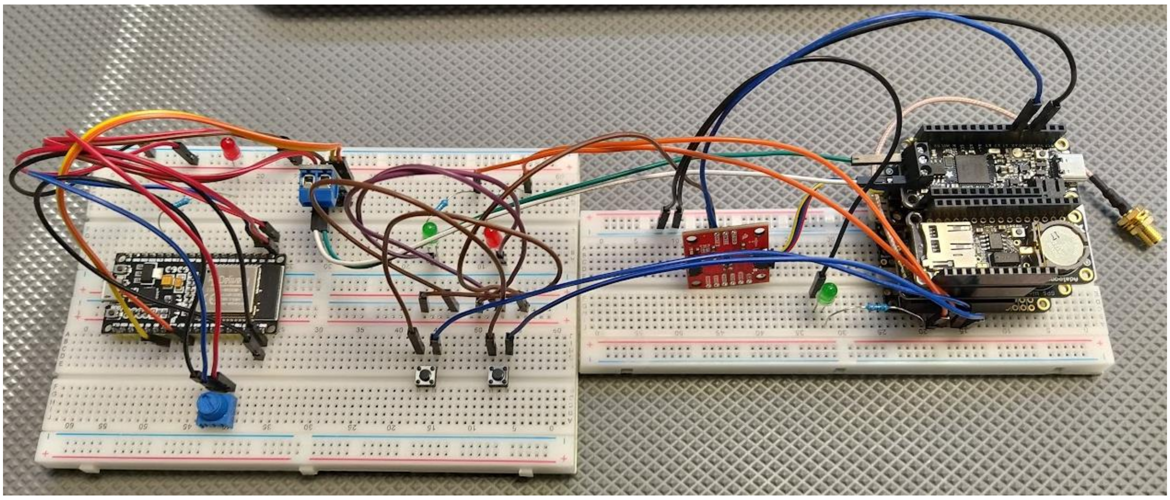


Figure 6.13 - First prototyping setup on breadboards

<u>Remote controller</u>

The device's recording start and end are managed by a remote controller with two buttons and two LED lights. The fist button functionality is to command the beginning of data acquisition and recording by opening a dedicated logging file, while the second button gives the order to stop the values' acquisition and save the respective logging file. A red LED indicates the system availability to start recording and a green LED represents that the device is acquiring and recording data. Figure 6.14 presents the referred remote controller's 3D modelling resorting to Solidworks® software, on the left side, and the resultant 3D printed object, on the right side.

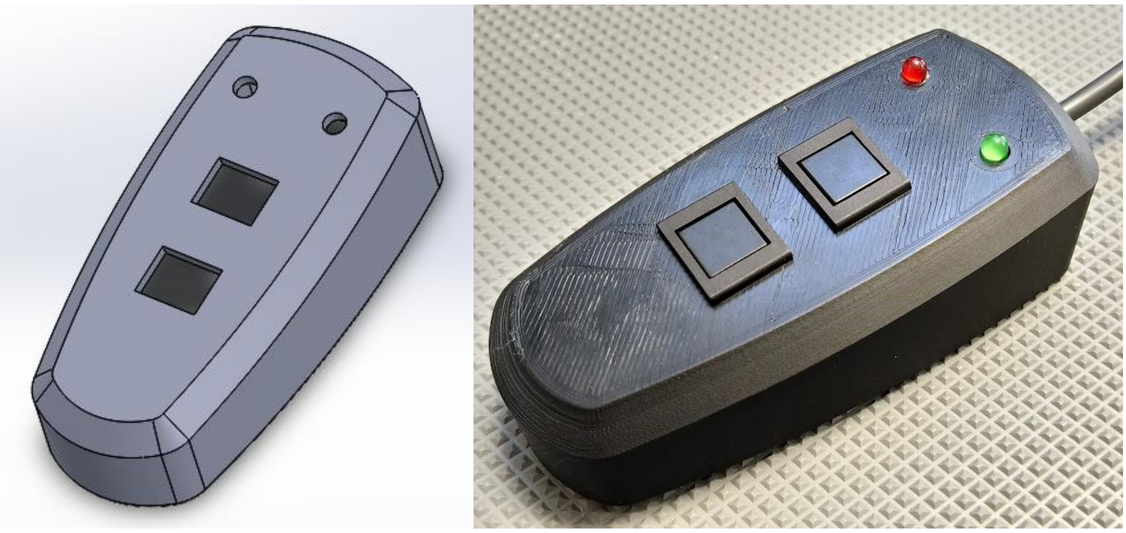


Figure 6.14 - Remote controller's 3D modelling, on the left side, and the 3D printed object, on the right side

<u>Final assembly</u>

After all the prototype testing, the system's auxiliary components and connectors were soldered to the Feather doubler protoboard, as shown on Figure 6.15.

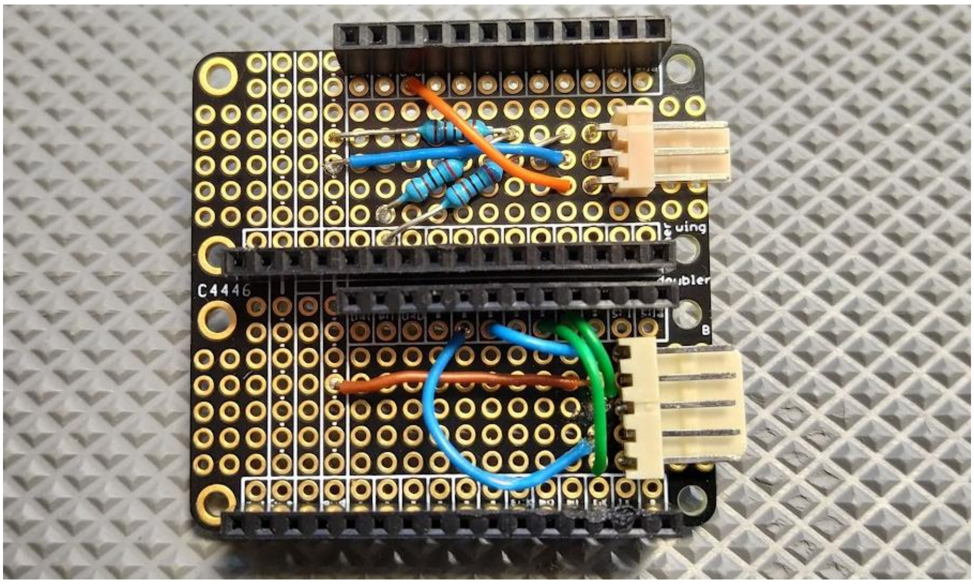


Figure 6.15 - Doubler board with auxiliary components and connectors

The system's final boards stacking, and assembling is presented on Figure 6.16.

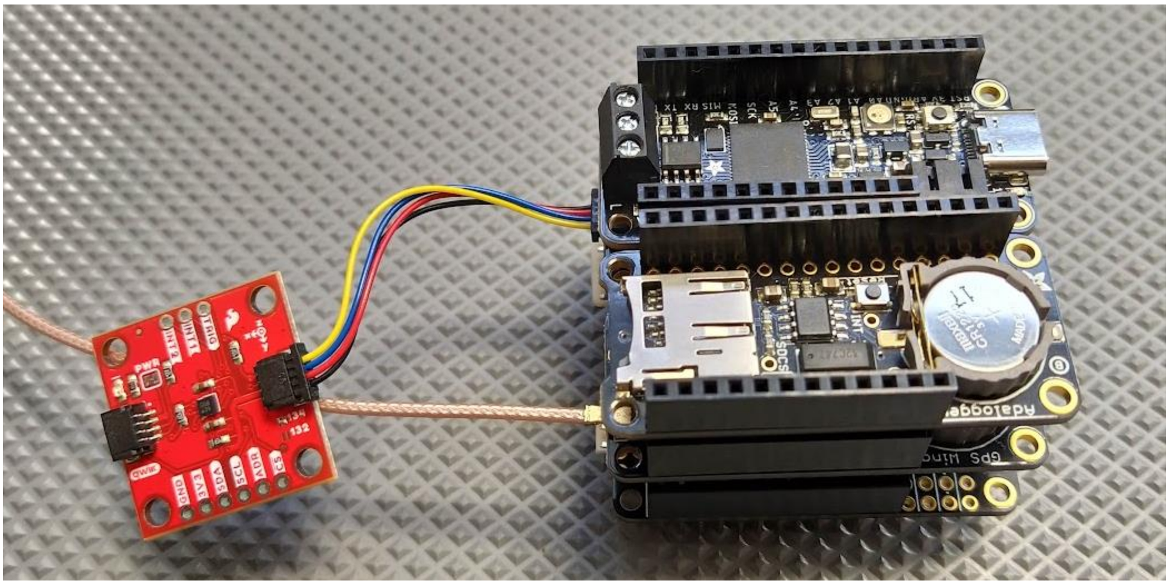


Figure 6.16 - Device's Feather boards stacking

Finally, a box and cover with fittings for the Feather boards and for the high range accelerometer were 3D modelled and printed to constitute the device's encapsulation. Figure 6.17 illustrates the box's 3D model, on the left side, and the respective cover 3D model, on the right side. The components' final assembly inside the printed box is presented on Figure 6.18.

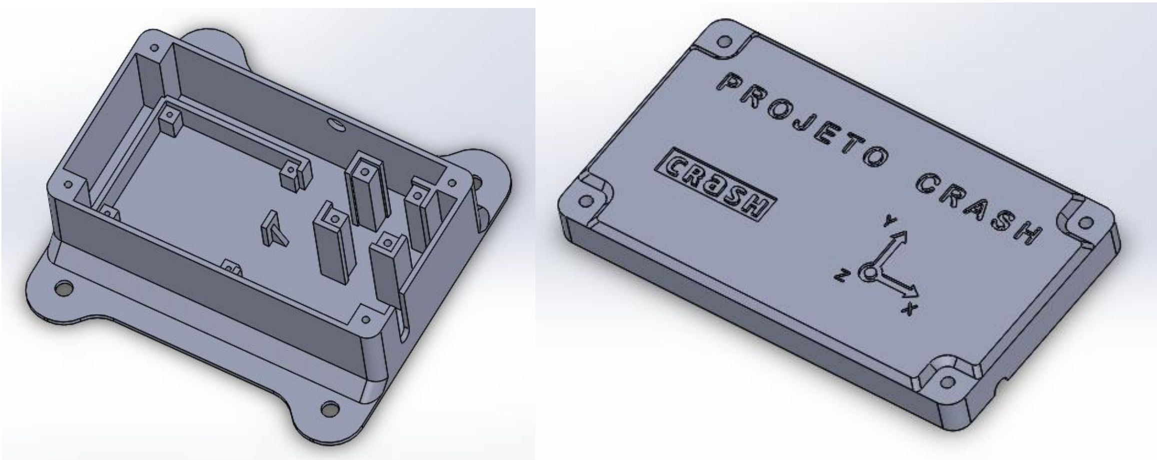


Figure 6.17 – Device's box 3D model, on the left side, and the respective cover, on the right side

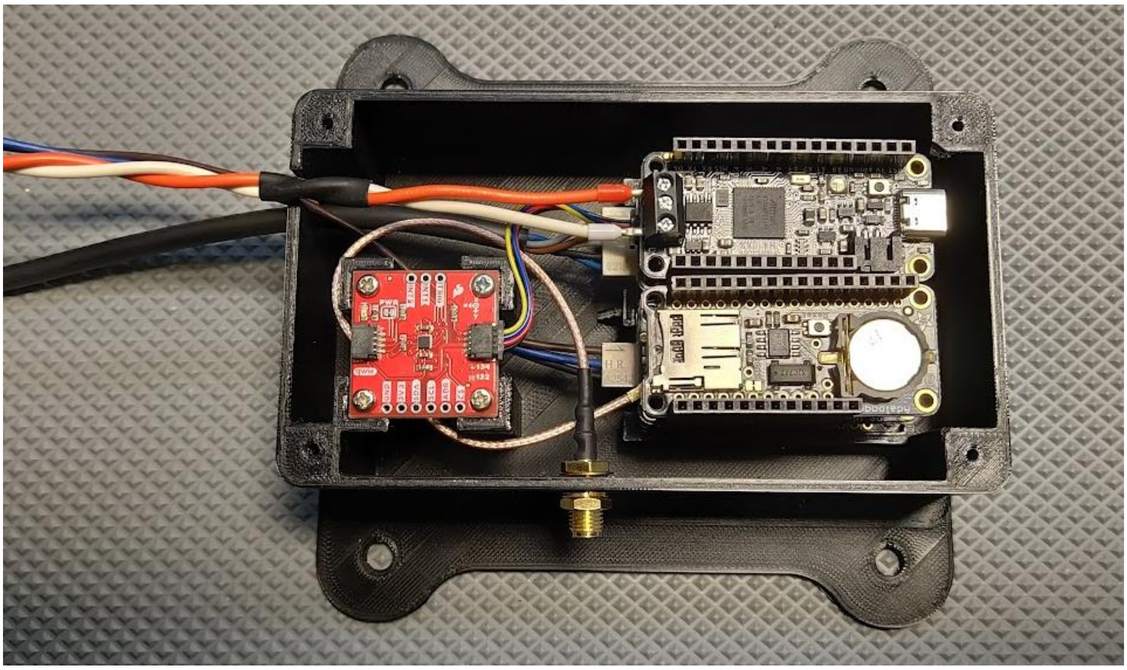


Figure 6.18 - Components' final assembly inside the printed box

6.2. Acquired data

The data recording system instrumentation, Figure 6.19, was installed on the 2019 Toyota Prius Plug-in Hybrid Vehicle (PHV), which belongs to the ESTG school's Automotive Engineering laboratory. The VDL box was assembled to the vehicle central column, between the driver's and passenger's seats, the magnetic GPS antenna was placed on the vehicle's roof, the device's CAN High and CAN Low wires were connected to the respective vehicle's CAN lines, through the OBD-II connector, and the VDL was connected to a personal computer for power source and serial data monitoring, as shown on Figure 6.20 and Figure 6.21.

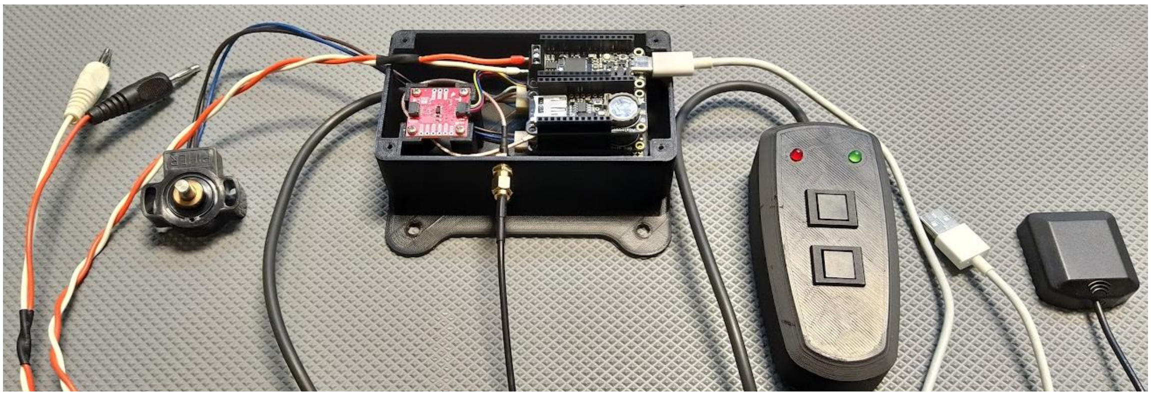


Figure 6.19 - Acquisition device's general instrumentation

Figure 6.20 - In vehicle device assembly

Figure 6.21 - In vehicle device assembly (closer look)

The experiment consisted of two laps in circuit, separated by a short pause, around the Campus 2 of the Polytechnic Institute of Leiria (IPL), as illustrated by the path on map generated with the geographic coordinates acquired by the GPS system, Figure 6.22. On both laps, the driver performed high accelerations on the main straight. On the second lap, the driver conducted one heavy braking and went around a small roundabout which is part of the circuit.

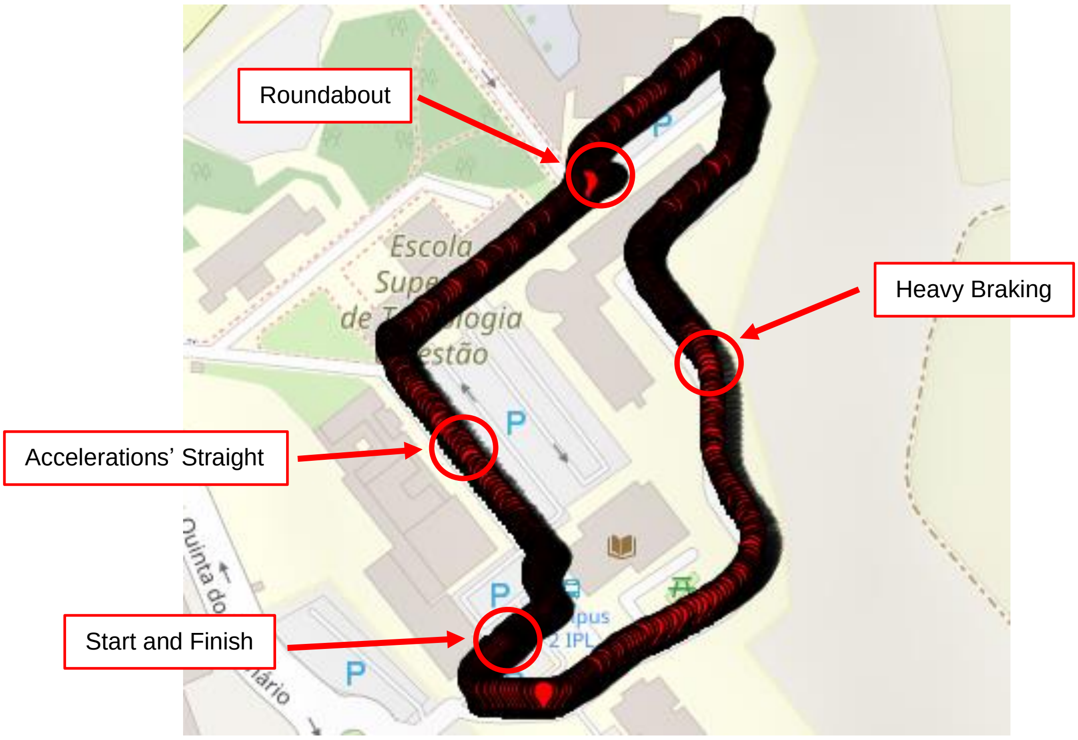


Figure 6.22 - Testing path's map (GPS Visualizer, 2022)

6.2.1. Acceleration values

The acceleration values from both accelerometers were acquired and recorded to the micro-SD card at an approximated frequency of 200 Hz, so being this the frequency for the SD card writing. This way, the accelerometers were configured for the next available update rate above the 200 Hz. The LSM6DSOX accelerometer was configured for 416 Hz output data rate, and for the ±16 G range, having the sensitivity of 0.000488 G as referred on subsection 6.1.1. The KX134 accelerometer was configured for 400 Hz output data rate, and for the ±64 G range, having the sensitivity of 0.00195 G as referred on subsection 6.1.1 as well.

Figure 6.23 and Figure 6.24 present the graphs which correspond to the acceleration values measured on the vehicle's three axis by the LSM6DSOX accelerometer and by the KX134 accelerometer, respectively.

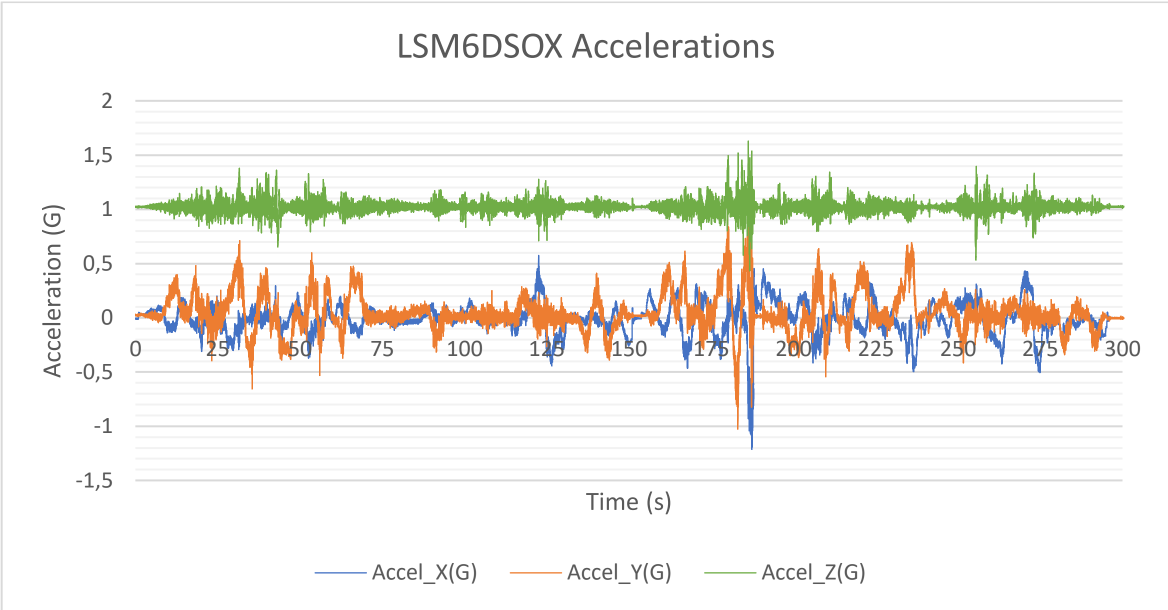


Figure 6.23 - Graph for the LSM6DSOX acceleration data

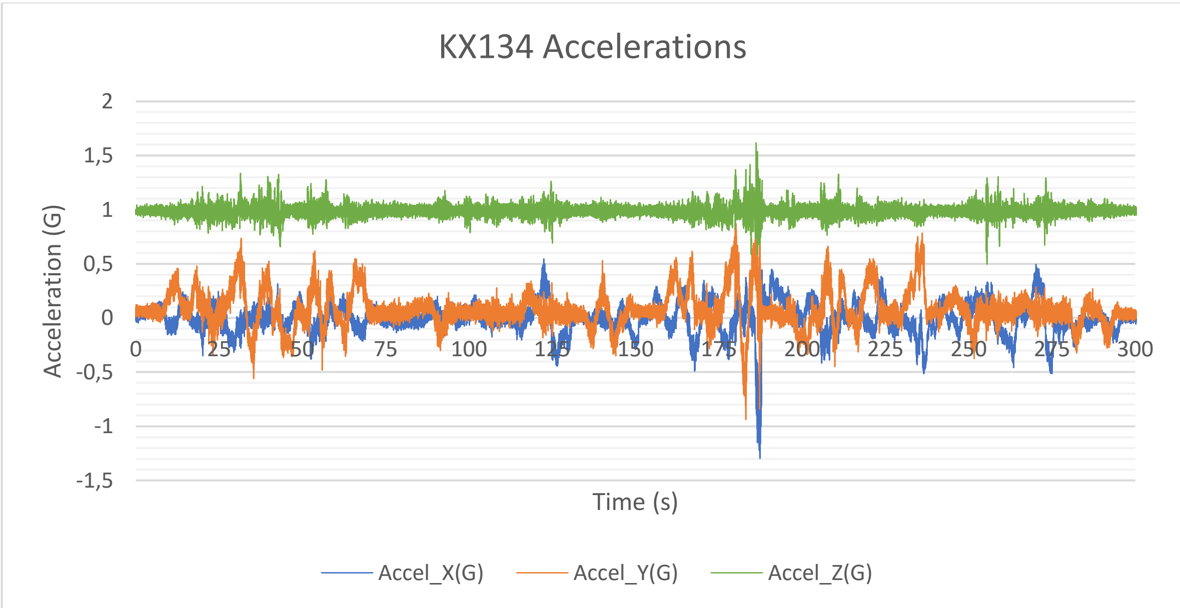


Figure 6.24 - Graph for the KX134 acceleration data

As it is noticeable both graphs present similar behaviours as there was no crash during the testing and high amplitude accelerations were not reached. Besides, the peak values registered on the X axis represent heavy accelerations and braking performed by the vehicle's driver. The acquired X and Y axis acceleration values allow the determination of the EDR's longitudinal and lateral Delta-V variables for comparison.

6.2.2. Angular rate values

The angular rate values were acquired from the LSM6DSOX sensor, as well, with a recording rate of 200 Hz. The LSM6DSOX gyroscope was configured for 416 Hz output data rate, and for the ±500 degrees/s range, corresponding to a sensitivity of 0.0175 degrees/LSB. (STMicroelectronics, 2019)

Figure 6.25 presents the graphs which correspond to the angular rate values measured on the vehicle's three axis by the LSM6DSOX gyroscope.

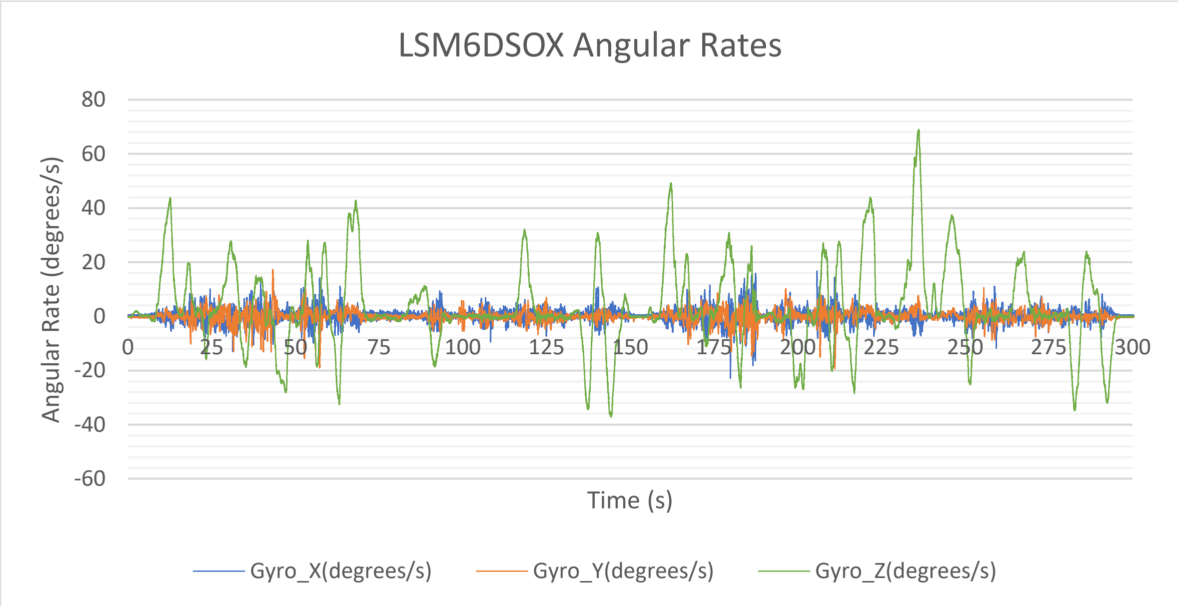


Figure 6.25 - Graph for the LSM6DSOX angular rate data

The graph for the angular rate on the Z axis reaches the highest values as it is related to the vehicle's yaw rate, which varies and can be associated with the turns performed on the defined testing path. The maximum peak value for angular velocity on the Z axis reached approximately 70 degree/s and corresponds to the roundabout included on the circuit's second lap. The angular rate values on X and Y axis present lower values as these variables are related to the vehicle's roll rate and pitch rate, respectively.

6.2.3. GPS speed values

The vehicle's GPS velocity values were acquired by the Feather GPS module configured for an update rate frequency of 5 Hz, which is already a reasonable value, since the EDR's pre-crash speed variable minimum requirements only refer to 2 Hz. The recorded values for the vehicle's GPS speed are represented by the graph illustrated on Figure 6.26.

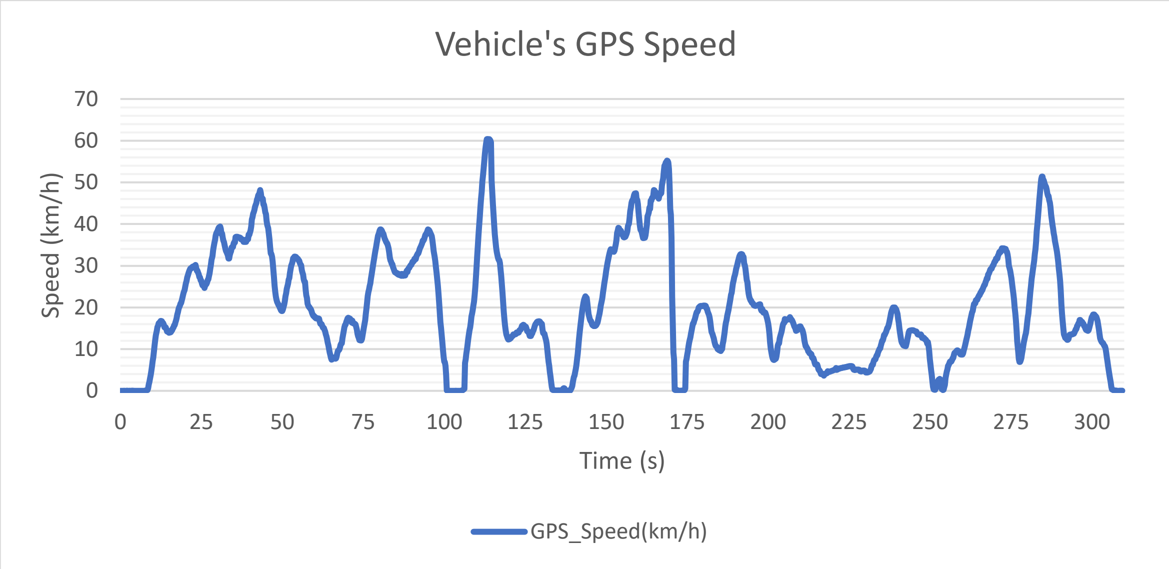


Figure 6.26 - Graph for the vehicle's GPS speed data

The verified peak values correspond to the maximum velocities reached during the testing path, on straights and descending hills. Besides, the abrupt reduction of speed until stop can be associated to the heavy braking performed by the driver, which was also registered by the previously mentioned acceleration values on the vehicle's X axis.

6.2.4. Steering angle values

To perform the steering angle acquisition testing, it was made an independent manual testing, due to the fact that there was not the opportunity to develop a mechanical solution which could connect the selected rotary position sensor's shaft to the vehicle's steering wheel. However, it was possible to acquire and record on the micro-SD card some demonstrative values for the intended variable, as shown by the graph on Figure 6.27. The steering angle values were acquired by the microcontroller through its analogue to digital converter (ADC) at an update frequency of 10 Hz, configured with a range of ±180º, and reaching a sensitivity of 0.48 degrees approximately.

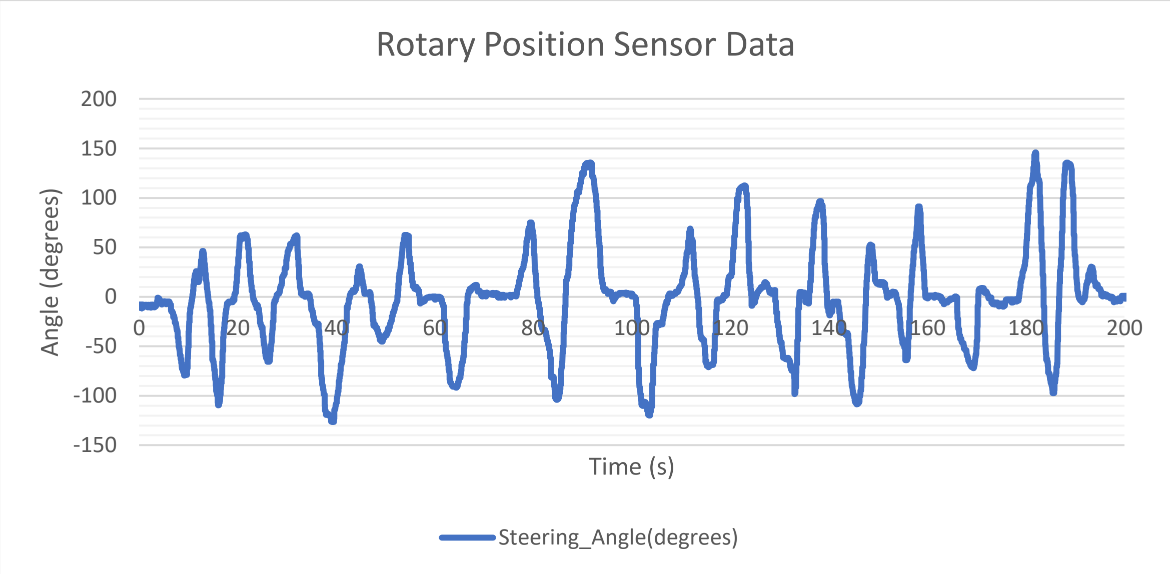


Figure 6.27 - Graph for the rotary position sensor's data

6.2.5. CAN Messages

Besides the external instrumentation implemented on the system, it was also intended to acquire variables from the vehicle's own communication network. This acquisition was performed resorting to the Feather microcontroller's CAN interface capabilities. The vehicle's CAN messages acquisition was performed by the request and response method, resorting to the On-Board Diagnostics (OBD-II) PID (Parameter IDs) codes defined by the SAE J1979 standard. (CSS Electronics, 2022a)

This way, the developed system was configured to send requests into the vehicle's CAN bus with specific message identifiers (ID) and PID codes, and to acquire the vehicle's response messages. The device was programmed to send and receive various CAN messages at a frequency of 50Hz.

The typical main structure of a CAN request message has the hexadecimal ID 0x7DF, its first byte represents the message's remaining length in bytes, the second byte identifies the mode for data acquisition, and the third byte consists of the PID code that refers to the intended variable. The response message sent by the vehicle's electronic modules are characterised by the hexadecimal identifiers from 0x7E8 to 0x7EF, the first byte refers to the message's remaining length in bytes, the second byte consists of the selected acquisition mode on the request message added by the 0x40 hexadecimal value, the third byte presents the PID code for the requested variable, and the next four bytes are dedicated to the variables' data values. On both cases, the unused message bytes are filled with random values without meaning to complete the CAN message's eight bytes data frame length, for example 0xFF but depending on the manufacturer. (CSS Electronics, 2022a)

Among the PID codes list, there are multiple variables which are not available or can only be accessed through the manufacturers' message identifiers. In order to demonstrate the functionality of the system's CAN communication, three available variables were selected from the PID codes list, which may have some relevance within the scope of the EDR variables subject. The selected variables were the accelerator pedal position, the vehicle's speed, and the engine's RPM. (CSS Electronics, 2022b)

Accelerator pedal position

To request the accelerator pedal's position from the vehicle's CAN network, the PID code corresponds to the 0x49 hexadecimal value. Furthermore, a single byte of data is required to represent the variable's full range. This way, the request and response messages' structures are defined as presented on Table 6.1. (CSS Electronics, 2022b)

Table 6.1 - Request and response CAN messages' structure for the accelerator pedal position

	ID	Byte_1	Byte_2	Byte_3	Byte_4	Byte_5	Byte_6	Byte_7	Byte_8
Request	0x7DF	0x02	0x01	0x49	0x55 (eg.)	0x55 (eg.)	0x55 (eg.)	0x55 (eg.)	0x55 (eg.)
Response	0x7E8 to 0x7EF	0x03	0x41	0x49	Data_A	0x00 (eg.)	0x00 (eg.)	0x00 (eg.)	0x00 (eg.)

The accelerator pedal position variable has a range of 0% to 100% and it is calculated by the following expression: (CSS Electronics, 2022b)

$$Accelerator\ pedal\ position = \frac{100}{255} \times Data\_A \qquad [\%]$$

The accelerator pedal position variable behaviour during the defined test path is represented on the graph of Figure 6.28. For the vehicle used on the experimental testing, this variable's range did not exceed the 15% and 70% boundaries, due to this Toyota's hybrid nature. Nevertheless, it is possible to verify on the graph that the highest peak values registered correspond to heavy accelerations intended by the driver.

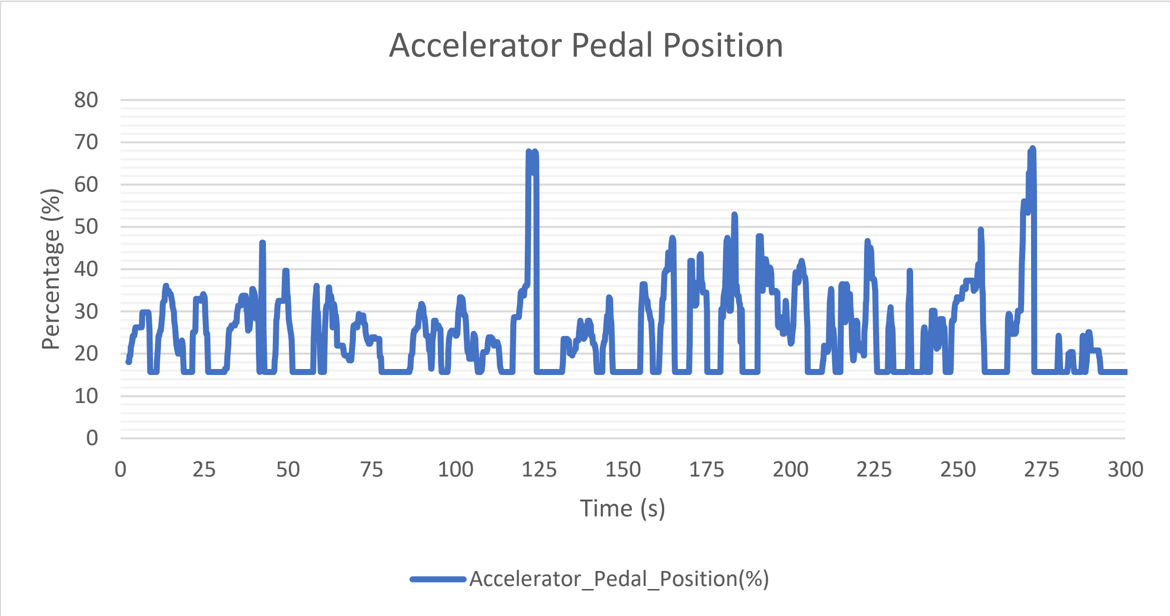


Figure 6.28 - Graph for the accelerator pedal position CAN data

CAN bus vehicle's speed

The 0x0D hexadecimal value consists of the PID code which allows to request the internal vehicle's speed variable from the CAN network. As well as for the previous variable, only one byte of data is required to define the vehicle's speed full range. The structure of the request and response messages for this variable is expressed on Table 6.2. (CSS Electronics, 2022b)

Table 6.2 - Request and response CAN messages' structure for the vehicle's speed

	ID	Byte_1	Byte_2	Byte_3	Byte_4	Byte_5	Byte_6	Byte_7	Byte_8
Request	0x7DF	0x02	0x01	0x0D	0x55 (eg.)	0x55 (eg.)	0x55 (eg.)	0x55 (eg.)	0x55 (eg.)
Response	0x7E8 to 0x7EF	0x03	0x41	0x0D	Data_A	0x00 (eg.)	0x00 (eg.)	0x00 (eg.)	0x00 (eg.)

The vehicle's speed variable is acquired in km/h, has a range of 0 to 255, and it is directly obtained from the message's fourth byte: (CSS Electronics, 2022b)

$$Vehicle\ speed = Data\_A \qquad [km/h]$$

The recorded data along the test path is presented on the graph of Figure 6.29, on which is possible to identify the straights where higher velocities are reached and the abrupt reduction of speed that corresponds to the heavy braking performed by the driver.

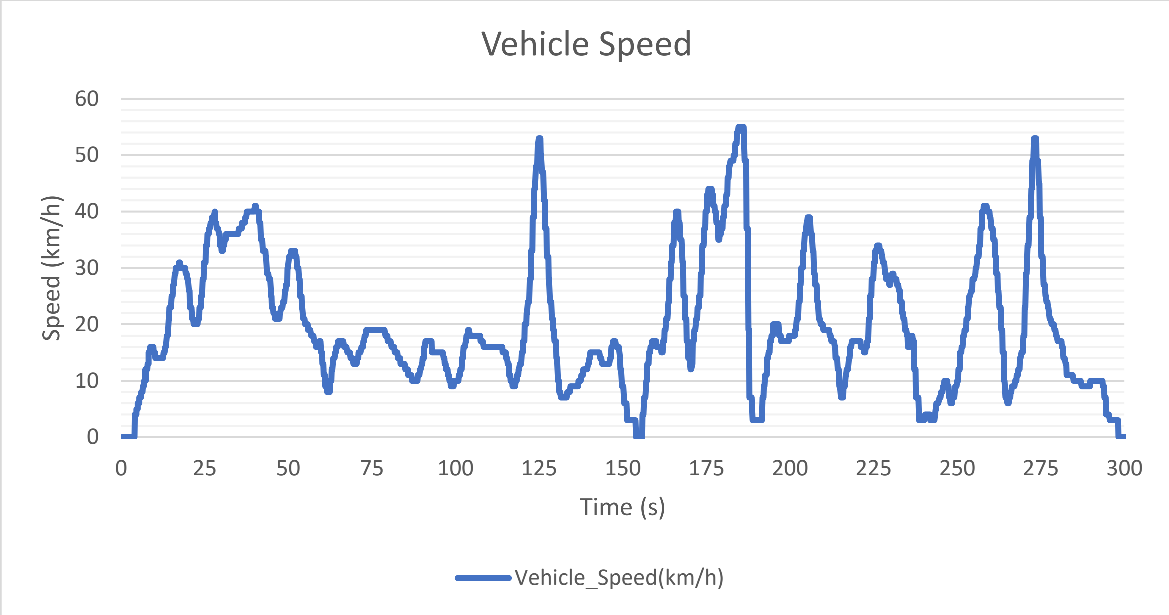


Figure 6.29 - Graph for the vehicle's speed CAN data

Engine RPM

To request the engine's RPM from the vehicle's CAN network, the PID code corresponds to the 0x0C hexadecimal value. Besides, in this case, two bytes of data are required to represent the variable's full range. This way, the request and response messages' structures are defined as presented on Table 6.3. (CSS Electronics, 2022b)

Table 6.3 - Request and response CAN messages' structure for the engine's RPM

	ID	Byte_1	Byte_2	Byte_3	Byte_4	Byte_5	Byte_6	Byte_7	Byte_8
Request	0x7DF	0x02	0x01	0x0C	0x55 (eg.)	0x55 (eg.)	0x55 (eg.)	0x55 (eg.)	0x55 (eg.)
Response	0x7E8 to 0x7EF	0x04	0x41	0x0C	Data_A	Data_B	0x00 (eg.)	0x00 (eg.)	0x00 (eg.)

The engine's RPM variable has a range of 0 to 16384 and it is calculated by the following expression: (CSS Electronics, 2022b)

$$Engine\ RPM = \frac{256 \times Data\_A + Data\_B}{4} \qquad [RPM]$$

The graph on Figure 6.30 represents the engine's RPM values acquired from the CAN network. Apparently, the recorded data has an atypical behaviour, however data is correct since the Toyota Prius consists of a hybrid vehicle which only starts its combustion engine when there is higher demand for power or when its batteries are in a low charge level.

Furthermore, sometimes this vehicle's combustion engine starts and runs at a stable RPM speed with the purpose of batteries charging. While the vehicle's batteries are charged and the demand for power is relatively low, the internal combustion engine remains stopped.

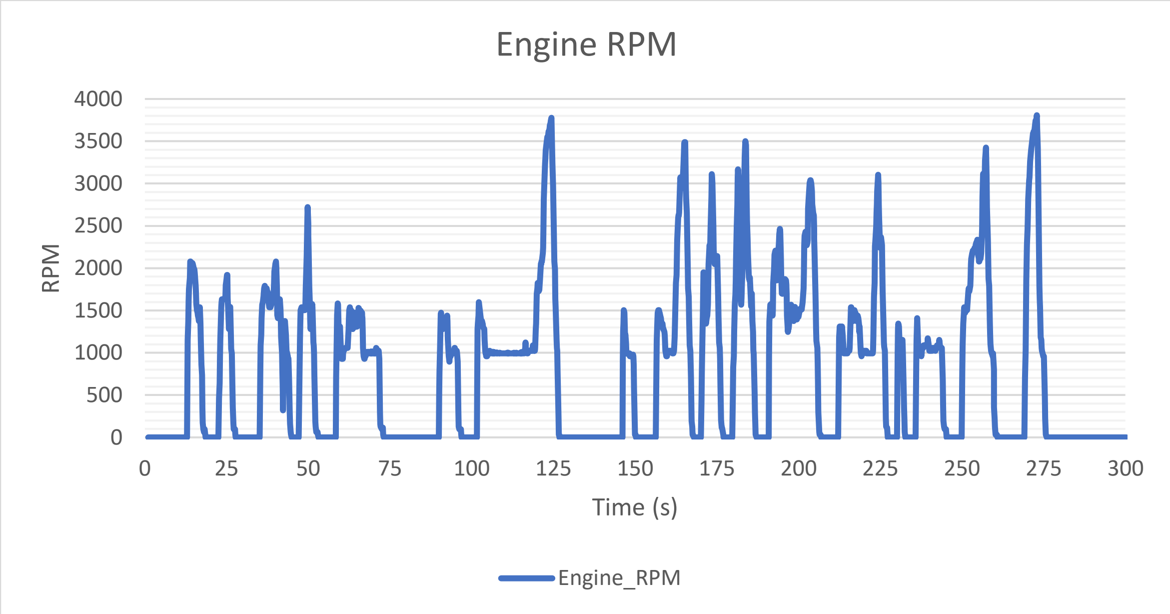


Figure 6.30 - Graph for the engine's RPM CAN data

7. Conclusions and Future Work

7.1. Conclusions

The objectives of the present work were describing the variables provided by the EDR devices implemented road vehicles nowadays, as well as its origin from the vehicle's instrumentation. Furthermore, it was intended to present the development, implementation, and testing of a prototype system capable of acquiring dynamic data elements for comparison with the information which can be retrieved from the EDR's reports, regarding a validation analysis.

From the state-of-the-art review, it is possible to conclude that the road accident reconstruction is a thorough forensic science which requires multiple, deep, and extensive data collection processes. From the collision scenario to the vehicles' deformations, every single detail and evidence is relevant and can lead to the raising of various hypotheses which, consequently, might lead to conclusions as result of the accident case's investigation.

The more information is available, more reliable can be considered the collision's reconstitution since the mostly varied data may be used to corroborate the investigators' hypotheses. With the EDR data elements' introduction, accident experts have access to variables captured by the vehicles' own instrumentation devices. These variables refer to the collisions' phases that were completely unknown previously, the pre-impact, the crash pulse, and the post-impact phases of the accident.

As result from the computational road accident simulation performed on the PC-Crash software, the extracted dynamic variables allow to conclude that the use of the same dynamic data elements as inputs for the simulation model could provide valuable help on the accident reconstruction process. This is due to the facts that these values can describe the vehicles' motion during collision and the need for an extensive iterative process based on the investigators hypotheses is minimised.

To collect the referred dynamic variables from a crash event, vehicles must be equipped with systems such as the EDR and the developed VDL. This type of devices has the capability of saving the vehicles various dynamic data on a non-volatile manner with robustness, which is essential for subsequent analysis. As was accomplished, the VDL system has the potentialities to acquire the intended dynamic variables which can be framed and consistently correlated with the expected vehicle's dynamic behaviour, according to the defined path's configuration and test routines. This fact can be concluded by the evaluation of the satisfactory results obtained from the VDL tests performed with the laboratory vehicle on the scope of the present work.

Considering all the facts, trustworthy, accurate, precise, effective, and efficient road accident reconstructions are accomplished by resorting to the use of technological methods for collision's scenario and vehicles' deformation profile data collection, and to the implementation of devices for monitoring and recording factual variables and data elements on the verge of an impact.

7.2. Future work

On what concerns the simulation case study, to conduct a valid comparison of the EDR recorded variables, it would be valuable to develop a simulation for accident reconstruction of a crash involving vehicles already equipped with the EDR. This would allow to compare the output graphs from the simulation software with the information retrieved from each vehicle's EDR.

Despite the satisfying results obtained on this work's implementation phase, the developed VDL could be enhanced to higher acquisition rates regarding better validation and accurate comparisons with the Event Data Recorder's (EDR) variables.

Besides, a solution to attach the rotary position sensor to the vehicle's steering wheel should be developed to adequately integrate the steering wheel angular position variable on the acquisition system.

To avoid using the OBD-II breakout box to connect the device's CAN wires, it would be interesting to develop a proper cable which could connect the device box directly to the vehicle's OBD-II connector.

The system, as it stands, relies on the USB connection for power source. To avoid this dependency, the solution could be the development of a strategy to provide power to the device through the use of batteries or using the vehicle's power source, which is also available from the OBD-II connector. These solutions would allow to avoid the personal computer's use during the essays, if it is not intended to visualize data through the serial monitor at that stage.

Additionally, after the final definition for all the components, peripherals and connectors needed for the VDL, a Printed Circuit Board (PCB) and a new version for the device's encapsulation could be developed to approximate the solution to a final product concept.

Furthermore, it would be valuable to acquire a vaster variety of data elements and information from the vehicle's CAN network, such as, the service brake pedal actuation, and the activity of the vehicle's multiple active safety systems, namely the ABS, the ESC and the emergency braking and steering systems, for example. These variables acquisition would involve decoding and configuring the system to acquire data from the corresponding manufacturers message identifiers.

Finally, in order to validate the data elements recorded by the EDR, it would be necessary to perform a real crash test, from which a CDR report could be retrieved and compared to the variables registered by the developed acquisition system.

Bibliographic References

Accident reconstruction. (2019). World of Forensic Science. https://www.encyclopedia.com/science/encyclopedias-almanacs-transcripts-and-maps/accident-reconstruction

Ada, Lady, DiCola, T., & Nosonowitz, D. (2022). *Adafruit Ultimate GPS featherwing*. Learn.Adafruit.Com. https://learn.adafruit.com/adafruit-ultimate-gps-featherwing/overview

Ada, Lady, & Nosonowitz, D. (2022). *Adafruit Adalogger FeatherWing*. Learn.Adafruit.Com. https://learn.adafruit.com/adafruit-adalogger-featherwing

Adafruit. (2022a). *Adafruit Industries, Unique & fun DIY electronics and kits*. Adafruit.Com. https://www.adafruit.com/

Adafruit. (2022b). *FeatherWing Doubler - Prototyping Add-on*. Adafruit.Com. https://www.adafruit.com/product/2890

Amphenol. (2022). PSC-360 Hall-Effect Rotary Position Sensor Datasheet. *PIHER Sensing Systems*. https://pt.mouser.com/datasheet/2/18/1/PSC_360_Gen2-1499168.pdf

Arduino. (2022). *Arduino - Home*. Arduino.Cc. https://www.arduino.cc/

Arkhipenko, A. (2022). *TaskScheduler - Arduino Reference*. Arduino.Cc. https://www.arduino.cc/reference/en/libraries/taskscheduler/

Auto ABC. (2022). *Chevrolet Aveo Hatchback 2008*. Auto-Abc.Eu. https://www.auto-abc.eu/Chevrolet-Aveo/g1444-2008

Becker, G., Mousel, T., & Schockmel, P. (2001). TOR (total occupant recognition) system. *SAE Technical Papers*. https://www.sae.org/publications/technical-papers/content/2001-06-0242/

Bosch. (2022a). *Accelerator-pedal module*. Bosch Mobility Solutions. https://www.bosch-mobility-solutions.com/en/solutions/air-management/accelerator-pedal-module/

Bosch. (2022b). *Steering-angle sensor*. Bosch Mobility Solutions. https://www.bosch-mobility-solutions.com/en/solutions/sensors/steering-angle-sensor/

Bosch. (2022c). *Steering Wheel Angle Sensor LWS*. Bosch Motorsport. https://www.bosch-motorsport.com/content/downloads/Raceparts/en-GB/54425995191962507.html#/Tabs=54437643/

Brake Light Switches. (2021). RepairSmith.Com. https://www.repairsmith.com/blog/brake-light-switch/

Brunt, M., & Brunt, G. (2013). Introducing conservation of momentum. *Physics Education*, *48*(5), 664–669. https://doi.org/10.1088/0031-9120/48/5/664

Campbell, L., Gotwals, D. G., Miller, P. M., Kaleto, H. A., & Winkelbauer, D. (2005). The Effect of Airbag Suppression Systems on Durability and Safety-Related Testing Procedures. *SAE Technical Papers*. https://doi.org/10.4271/2005-01-0744

Car.info. (2022). *Specifications for Chevrolet Aveo 5-door 1.2 Manual, 84hp, 2008*. Car.Info. https://www.car.info/en-se/chevrolet/aveo/aveo-5-door-12-s-tec-m5-2008-356492/specs

Chekole, S. D. (2014). Surveying with GPS , total station and terresterial laser scaner: a comparative study [School of Architecture and the Built Environment - Royal Institute of Technology (KTH)]. In *MSc Thesis: School of Architecture and the Built Environment, Royal Institute of Technology (KTH)* (Issue 3131). https://www.diva-portal.org/smash/get/diva2:715829/fulltext01.pdf

Colley, S. (2020). *Introduction to Microcontroller Timers: Periodic Timers*. Introduction to Microcontroller Timers: Periodic Timers. https://www.allaboutcircuits.com/technical-articles/introduction-to-microcontroller-timers-periodic-timers/

Continental. (2022). *Continental Automotive - Wheel Speed Sensor*. Continental Automotive. https://www.continental-automotive.com/en-gl/Passenger-Cars/Safety-and-Motion/Products/Sensors/Wheel-Speed-Sensors/Wheel-Speed-Sensor

CSS Electronics. (2022a). *OBD2 Explained - A Simple Intro [2022]*. Csselectronics.Com. https://www.csselectronics.com/pages/obd2-explained-simple-intro

CSS Electronics. (2022b). *OBD2 PID Overview*. Csselectronics.Com. https://www.csselectronics.com/pages/obd2-pid-table-on-board-diagnostics-j1979

D'Anniballe, A., Silva, J., Marzocca, P., & Ceruti, A. (2020). The role of augmented reality in air accident investigation and practitioner training. *Reliability Engineering & System Safety*, *204*, 107149. https://doi.org/10.1016/j.ress.2020.107149

Daniel, P. (2022). *What Does an Accident Reconstruction Expert Do? | Houston*. WHAT IS AN ACCIDENT RECONSTRUCTIONIST? https://www.patrickdaniellaw.com/blog/accident-reconstructionist/

Davis, G. A. (2009). Sample-based bayesian accident reconstruction. *Journal of Transportation Safety & Security*, *1*(3), 181–189. https://doi.org/10.1080/19439960903149579

Delphi Technologies. (2022). *Making sense of sensors: steering angle sensor*. DelphiAutoParts.Com. https://www.delphiautoparts.com/usa/en-US/resource-center/making-sense-sensors-steering-angle-sensor

Dima, D. S., & Covaciu, D. (2019). Vehicles Frontal Impact Analysis Using Computer Simulation and Crash Test. *International Journal of Automotive Technology*, *20*(4), 655–661. https://doi.org/10.1007/s12239-019-0062-3

DJI Phantom 4 Pro V2.0. (2022). https://www.dji.com/pt/phantom-4-pro-v2?site=brandsite&from=nav

Dustin, D., & Liscio, E. (2016). Accuracy and Repeatability of the Laser Scanner and Total Station for Crime and Accident Scene Documentation. *Journal-Association for Crime Scene Reconstruction*, *20*, 57–68. https://d1wqtxts1xzle7.cloudfront.net/79656898/Dustin-Liscio-with-cover-page-v2.pdf?Expires=1662742866&Signature=JoNvT~FZO4TGHyeHbsazxdLYdv9M94ze8rirMrIHDcVJty1ChlGNRXv0etqtEg3wmoIjlg7xtYdUe89TaunW97smxBSEXBmG9lK5yYi8qbuUrxq-FMXMdZeKXqy9dez1bcu2ZsIrb~HEjg

ELPROCUS. (2022). *Gyroscope Sensor- Working, Types & Applications*. Elprocus.Com. https://www.elprocus.com/gyroscope-sensor/

euDARTS. (2022). *EuDarts-group | Home*. Eudarts-Group.Com. https://www.eudarts-group.com/home

Evtyukov, S., Golov, E., & Rajczyk, J. (2020). Improving the accuracy of stiffness coefficient calculation when estimating the kinetic energy spent on vehicle deformation. *Architecture and Engineering*, *5*(1), 45–50. https://doi.org/10.23968/2500-0055-2020-5-1-45-50

Fei, J., & Yang, Y. (2011). System identification of MEMS vibratory gyroscope sensor. *Mathematical Problems in Engineering*, *2011*. https://doi.org/10.1155/2011/829432

Gabler, H. C., Hampton, C. E., & Hinch, J. (2004). Crash severity: A comparison of event data recorder measurements with accident reconstruction estimates. *SAE Technical Papers*. https://doi.org/10.4271/2004-01-1194

Gajjar, M. J. (2017). Sensor application areas - Steering angle sensor. *Mobile Sensors and Context-Aware Computing*, 303–330. https://doi.org/10.1016/B978-0-12-801660-2.00011-2

Gipe, S. (2015). *The Importance of the Accident Reconstruction Specialist for Your Case*. The Importance of the Accident Reconstruction Specialist for Your Case. https://www.dolmanlaw.com/accident-reconstruction/

GPS Visualizer. (2022). *GPS Visualizer: Do-It-Yourself Mapping*. https://www.gpsvisualizer.com/

Graham, C. (2022). *Seat Position Sensing*. Allegromicro.Com. https://www.allegromicro.com/en/insights-and-innovations/technical-documents/hall-effect-sensor-ic-publications/vehicle-safety-systems

Jost, D. (2019). *What is an accelerometer? | Fierce Electronics*. What Is an Accelerometer? https://www.fierceelectronics.com/sensors/what-accelerometer

Karapetkov, S., Dimitrov, L., Uzunov, H., & Dechkova, S. (2019). Identifying Vehicle and Collision Impact by Applying the Principle of Conservation of Mechanical Energy. *Transport and Telecommunication*, *20*(3), 191–204. https://doi.org/10.2478/ttj-2019-0016

KOMELON | Measuring Wheels. (2022). https://www.komelon.com/eng/html/01_product/02_read.php?idx=37&search_select=&keyword=&pagenum=0&category_idx1=3&category_idx2=0

KOMELON | Tapes. (2022). https://www.komelon.com/eng/html/01_product/02_read.php?idx=82&search_select=&keyword=&pagenum=0&category_idx1=1&category_idx2=0

Last Minute Engineers. (2022). *In-Depth: How Accelerometer works? Interface ADXL335 with Arduino*. https://lastminuteengineers.com/adxl335-accelerometer-arduino-tutorial/

Law Insider. (2022). *Malfunction indicator light Definition | Law Insider*. Lawinsider.Com. https://www.lawinsider.com/dictionary/malfunction-indicator-light

Leica FlexLine TS10. (2022). https://leica-geosystems.com/products/total-stations/manual-total-stations/leica-flexline-ts10

Leica GS18 T GNSS RTK. (2022). https://leica-geosystems.com/products/gnss-systems/smart-antennas/leica-gs18-t

Leica RTC360. (2022). https://leica-geosystems.com/products/laser-scanners/scanners/leica-rtc360

Leica Viva GS25. (2022). https://leica-geosystems.com/products/gnss-systems/receivers/leica-viva-gs10-gs25

Morales, A., Sánchez-Aparicio, L. J., González-Aguilera, D., Gutiérrez, M. A., López, A. I., Hernández-López, D., & Rodríguez-Gonzálvez, P. (2017). A new approach to energy calculation of road accidents against fixed small section elements based on close-range photogrammetry. *Remote Sensing*, *9*(12), 1219–1236. https://doi.org/10.3390/rs9121219

MotorCycleSpecs. (2022). *2012 BMW R 1200GS Adventure*. Motorcyclespecs.Co.Za. https://www.motorcyclespecs.co.za/model/bmw/bmw_r1200gs_adventure 12.htm

Neades, J. G. J. (2011). *Developments in Road Vehicle Crush Analysis for Forensic Collision Investigation* [De Montfort University]. https://dora.dmu.ac.uk/handle/2086/4935

Neades, J., & Smith, R. (2011). The determination of vehicle speeds from delta-V in two vehicle planar collisions. *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*, *225*(1), 43–53. https://doi.org/10.1243/09544070JAUTO1462

NHTSA. (2022). *Event Data Recorder | NHTSA*. Event Data Recorder. https://www.nhtsa.gov/research-data/event-data-recorder

Numata, S., Mizuno, K., Ito, D., Okumura, D., & Kinoshita, H. (2018). Validation of Crush Energy Calculation Methods for Use in Accident Reconstructions by Finite Element Analysis. *SAE International Journal of Transportation Safety*, *6*(2), 133–146. https://doi.org/10.4271/09-06-02-0009

Osman, M. R., & Tahar, K. N. (2016). 3D accident reconstruction using low-cost imaging technique. *Advances in Engineering Software*, *100*, 231–237. https://doi.org/10.1016/j.advengsoft.2016.07.007

Pádua, L., Sousa, J., Vanko, J., Hruška, J., … T. A.-I. journal of, & 2020, U. (2020). Digital reconstitution of road traffic accidents: a flexible methodology relying on UAV surveying and complementary strategies to support multiple scenarios. *International Journal of Environmental Research and Public Health*, *17*. https://doi.org/10.3390/ijerph17061868

Pagounis, V., Tsakiri, M., Palaskas, S., Biza, B., & Zaloumi, E. (2006). 3D laser scanning for road safety and accident reconstruction. In *TS 38 – Engineering Surveys for Construction Works I*. https://fig.net/pub/fig2006/papers/ts38/ts38_03_pagounis_etal_0475.pdf

Paruszkiewicz, H. (2018). Seat Belt Buckle Sensor - Reed. *Passenger Safety Sensors*. www.littelfuse.com

Reflectors | Leica Geosystems. (2022). https://leica-geosystems.com/products/total-stations/accessories/reflectors

Rembor, K., Clark, L., & Ada, Lady. (2022). *ST 9-DoF Combo Breakouts and Wings*. Learn.Adafruit.Com. https://learn.adafruit.com/st-9-dof-combo/overview

Rembor, K., Herrada, E., & Ada, Lady. (2022). *Adafruit Feather M4 CAN Express*. Learn.Adafruit.Com. https://learn.adafruit.com/adafruit-feather-m4-can-express/overview

Rose, N. A., Fenton, S. J., & Hughes, C. M. (2001). Integrating Monte Carlo simulation, momentum-based impact modeling, and restitution data to analyze crash severity. In *SAE TECHNICAL PAPER SERIES* (Vol. 1). https://doi.org/https://doi.org/10.4271/2001-01-3347

Samarins. (2021). *Brake light switch: symptoms, problems, testing, replacement*. Samarins.Com. https://www.samarins.com/glossary/brake_light_switch.html

SparkFun Electronics. (2022). *Triple Axis Accelerometer Breakout - KX13x (Qwiic)*. Learn.Sparkfun.Com. https://learn.sparkfun.com/tutorials/triple-axis-accelerometer-breakout---kx13x-qwiic-hookup-guide-/hardware-overview

Stanley Subaru. (2012). *How Does the Occupant Detection System (ODS) Work in My Subaru? | Stanley Subaru*. Stanleysubaru.Com. https://www.stanleysubaru.com/blog/2012/august/6/how-does-the-occupant-detection-system-ods-work-in-my-subaru.htm

STMicroelectronics. (2019). *LSM6DSOX Datasheet*. https://www.st.com/resource/en/datasheet/lsm6dsox.pdf

TE Connectivity. (2022). *Accelerometers | TE Connectivity*. https://www.te.com/usa-en/products/sensors/vibration-sensors/intersection/types-of-accelerometers.html

The Importance of Accident Reconstruction. (2015). The Importance of Accident Reconstruction. https://farahandfarah.com/blog/the-importance-of-accident-reconstruction/

Thivierge, B. S. (2018). *Vehicular Accident Reconstruction*. Salem Press Encyclopedia of Science. https://search.ebscohost.com/login.aspx?direct=true&db=ers&AN=89250616&site=eds-live

Throttle Position Sensor. (2022). Cars.Com. https://www.cars.com/auto-repair/glossary/throttle-position-sensor/

UNECE. (2009). *Vehicle Event Recording based on Intelligent Crash Assessment - VERONICA II*. EDR/DSSAD 1st Session - Transport - Vehicle Regulations. https://wiki.unece.org/pages/viewpage.action?pageId=87621710&preview=/87621710/87622187/EDR-DSSAD-01-10 (Secretary) veronica2_final_report.pdf

UNECE. (2017). Consolidated Resolution on the Construction of Vehicles (R.E.3). *ECE/TRANS/WP.29/78/Rev.6*. https://unece.org/fileadmin/DAM/trans/main/wp29/wp29resolutions/ECE-TRANS-WP.29-78r6e.pdf

UNECE. (2021a). Proposal for the 01 series of amendments to UN Regulation No. [XXX] on Event Data Recorder. *ECE/TRANS/WP.29/2021/58*. www.unece.org/trans/main/wp29/wp29wgs/wp29gen/wp29resolutions.html.

UNECE. (2021b). *UN Regulation No 137*. https://unece.org/transport/standards/transport/vehicle-regulations-wp29/resolutions

UNECE. (2021c). *UN Regulation No 94*. https://unece.org/status-1958-agreement-and-annexed-regulations

UNECE. (2021d). *UN Regulation No 95*. 62–129. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=uriserv:OJ.L_.2021.392.01.0062.01.ENG

Vangi, D. (2009). Simplified method for evaluating energy loss in vehicle collisions.

Accident Analysis & Prevention, *41*(3), 633–641. https://doi.org/10.1016/j.aap.2009.02.012

Wach, W., Gidlewski, M., & Prochowski, L. (2016). Modelling reliability of vehicle collision reconstruction based on the law of conservation of momentum and Burg equations. *20th International Scientific Conference - Transport Means*. https://www.researchgate.net/profile/Wojciech-Wach/publication/321071413_Modelling_Reliability_of_Vehicle_Collision_Reconstruction_Based_on_the_Law_of_Conservation_of_Momentum_and_Burg_Equations/links/5a0bfc220f7e9b0cc025c4db/Modelling-Reliability-of-Vehi

WatElectronics. (2020). *Gyroscope Sensor : Working Principle, Types & Its Applications*. WatElectronics.Com. https://www.watelectronics.com/what-is-a-gyroscope-sensor-working-its-applications/

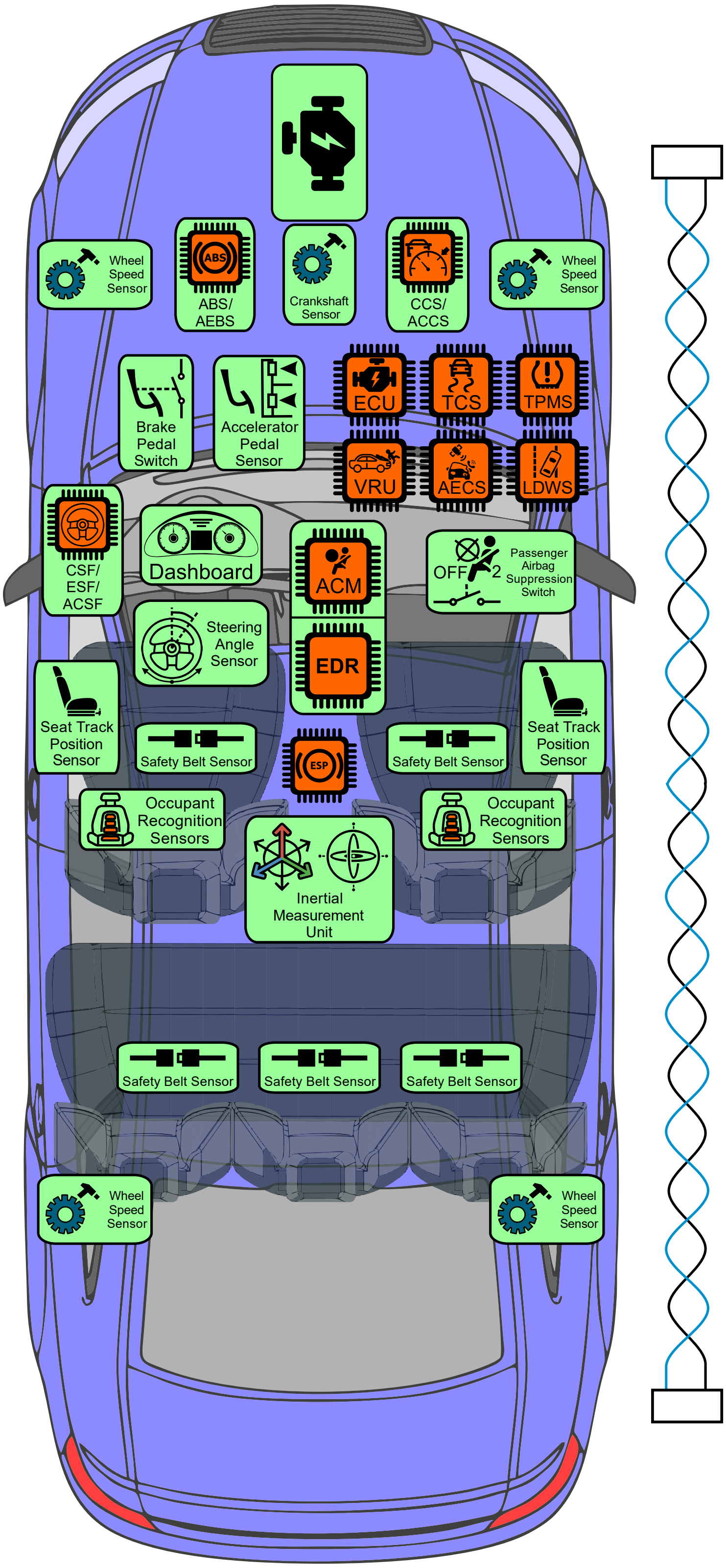
Watson, J. (2016). MEMS Gyroscope Provides Precision Inertial Sensing in Harsh, High Temperature Environments. *Analog Devices - Technical Article*. https://www.analog.com/en/technical-articles/mems-gyroscope-provides-precision-inertial-sensing.html

Williams, J. (2016). *What is Accident Reconstruction About?* Fire & Accident Causation Technical Services (FACTS). https://www.facts-1.com/whatisaccidentreconstruction.htm

Woodford, C. (2021). *Reed switches*. Explainthatstuff.Com. https://www.explainthatstuff.com/howreedswitcheswork.html

Appendices

Appendix A



Declaration

Declaro, sob compromisso de honra, que o trabalho apresentado neste relatório de projeto, com o título "Study and validation of data recorded in the vehicles' EDR in order to perform a road accident's dynamic reconstruction", é original e foi realizado pelo Estudante Francisco Gonçalo Mendes Laranjeira (2202279) sob orientação do Professor Sérgio Pereira dos Santos (ssantos@ipleiria.pt) e coorientação do Professor Carlos Daniel Henriques Ferreira (ferreira@ipleiria.pt).

Leiria, Setembro de 2022

Francisco Gonçalo Mendes Laranjeira

Francisco Gonçalo Mendes Laranjeira