

School of Engineering

DEPARTMENT OF INDUSTRIAL ENGINEERING

MASTER OF SCIENCE DEGREE IN MECHANICAL ENGINEERING

Master's degree thesis

in

MODELLING AND CONTROL OF INTERNAL COMBUSTION ENGINES AND HYBRID
PROPULSION SYSTEMS M

FEASIBILITY, REQUIREMENTS AND PRELIMINARY ASSESSMENT OF E-
HORIZON DRIVEN SPEED TARGETING ALGORITHMS, FOR ENHANCED
ADAPTIVE CRUISE CONTROL

Candidate

Simone Becci

Supervisor

Prof. Nicolò Cavina

Co-Supervisors

Eng. Alessandro Perazzo

Prof. Davide Moro

Prof. Enrico Corti

Scuola Di Ingegneria

DIPARTIMENTO DI INGEGNERIA INDUSTRIALE

CORSO DI LAUREA MAGISTRALE IN INGEGNERIA MECCANICA

Tesi Di Laurea Magistrale

in

MODELLING AND CONTROL OF INTERNAL COMBUSTION ENGINES AND HYBRID
PROPULSION SYSTEMS M

FEASIBILITY, REQUIREMENTS AND PRELIMINARY ASSESSMENT OF E-
HORIZON DRIVEN SPEED TARGETING ALGORITHMS, FOR ENHANCED
ADAPTIVE CRUISE CONTROL

Candidato

Simone Becci

Relatore

Prof. Nicolò Cavina

Correlatori

Ing. Alessandro Perazzo

Prof. Davide Moro

Prof. Enrico Corti

Abstract

According to the report from the EU, every year more than 40 000 lives are lost in a road accident. More than 90% of accidents are caused by human error. Advance Driver-Assistance Systems (ADAS) can help drivers to avoid these accidents or at least to reduce the consequence (1). Such systems use a multitude of sensors to perceive the environment around the vehicle, and act consequently. In the future, cars will be a part of an intelligent transport system where all players are connected. With these abilities, an electronic horizon is created pushing forward the sensor range. Information regarding traffic or hazard can be obtained from other cars or from the cloud.

With the use of ADAS, the driver can be assisted to avoid dangerous situations. In a near future, all this information will be elaborated and used from the vehicle itself, reducing the possibility of human error.

The thesis is a study on how and if it is possible to create an enhanced Adaptive Cruise Control (ACC) function relying on e-Horizon data. Standard ACC use a radar to keep distance from the car in front, by accelerating up to a preset speed or braking. The goal is to research if curvature can be taken into consideration to create a more comfortable and safe speed profile.

To do so, the onboard function obtains curvature information from different data sources. The first one, is the navigation data, provided in real time to the car through Vehicle to Cloud connection (V2C). The second one, is an onboard camera used for ADAS functions, which outputs the curvature. The recording from a GPS tracker is used to create an ideal path description, to be used as benchmark.

Geographic coordinates from map service provider are elaborated, with the use of Simulink models and MATLAB to obtain a curvature profile. This will be used in the test environment to create and actuate the speed profile. The parameters, used to evaluate the performance of the speed profile, are lateral and longitudinal accelerations and jerk.

Abstract in lingua italiana

Secondo un report della Comunità Europea ogni anno più di 40 000 persone muoiono in un incidente stradale. Più del 90% di questi incidenti sono causati da un errore umano. I sistemi di ausilio alla guida avanzati (ADAS) possono aiutare i guidatori ad evitarli o a ridurre le loro conseguenze (1). Per farlo usano una moltitudine di sensori in grado di percepire l'ambiente circostante al veicolo, ed agire di conseguenza. Le auto del futuro saranno parte di un sistema di trasporto intelligente, dove tutti i partecipanti saranno interconnessi tra loro. Informazioni relative al traffico o possibili pericoli potranno essere ottenute tramite connessione tra le singole auto, oppure tramite rete dati ad un servizio cloud.

Con l'uso degli ADAS i guidatori potranno essere assistiti nell'evitare comportamenti pericolosi. In un vicino futuro tutte le informazioni a disposizione dei sistemi di ausilio saranno elaborate ed attuate dal veicolo in autonomia, riducendo le possibilità di un errore umano.

Questo lavoro di tesi è uno studio sulla possibilità e le modalità per creare un controllo di velocità adattivo (ACC) che faccia affidamento su dati ricavati tramite orizzonte digitale (e-Horizon). I sistemi di controllo di velocità adattivi, attualmente in commercio, usano il radar per mantenere la distanza dall'auto precedente accelerando, frenando o attuando una velocità costante. L'obbiettivo della tesi è quello di ricercare se la curvatura associata al percorso possa essere utilizzata per creare un profilo di velocità, più confortevole e sicuro.

L'idea è che il sistema di ausilio ottenga le informazioni relative alla curvatura da più fonti differenti. La prima, riguardante le coordinate del percorso, è ottenuta tramite richieste successive nel tempo attraverso la connessione tra veicolo e Cloud (V2C). La seconda fonte deriva da una telecamera presente a bordo, utilizzata per altre funzioni ADAS, la cui uscita è direttamente un valore di curvatura. Infine, il percorso di prova è stato acquisito tramite un registratore GPS per creare un valore di curvatura ideale, da usare come riferimento per le altre stime.

Le coordinate geografiche ottenute dal servizio di mappe sono elaborate con l'uso di MATLAB e di modelli Simulink, al fine di ottenere una stima della curvatura. Questa verrà poi inserita nel modello di test allo scopo di creare ed attuare un profilo di velocità. I parametri utilizzati per misurare la bontà dell'algoritmo sono le accelerazioni laterali e longitudinali ed il jerk.

Acknowledgments

I would like to express my great gratitude to Prof. Nicolò Cavina, supervisor of this thesis, for allowing me to carry out this project and for the passion transmitted during his courses.

A special thanks to Eng. Alessandro Perazzo, who supervised my work and look after me during all the period of this thesis. I would also like to thank Marwa and Rebecca, for their help, dedication, and availability.

Last but not least, a huge thank you to my family, my friends and my girlfriend, the protagonists of my life.

Without my mother and father all of this could not be possible. They sustained me during the long course of the studies with perseverance.

A special mention for Roberta, my girlfriend, who has always been by my side. With her love has made this journey more colourful and less difficult.

Contents

Abstract	V
Abstract in lingua italiana	VI
Acknowledgments	VII
List of figures	X
List of tables	XII
Acronyms	XIII
Glossary	XIV
1 Introduction	1
1.1 Object of this work	2
1.2 What is an ADAS	3
1.2.1 ADAS classification according to SAE.	3
1.2.2 Hardware involved in ADAS functions	4
1.2.3 Connectivity	5
1.2.4 E-Horizon	6
2 Curvature definitions	8
2.1 Road design normative reference	8
2.2 Tests routes	9
2.3 Data extraction from .kml files	10
2.4 Exact curvature algorithm	11
2.5 Pratt method	12
2.5.1 Segmentation of the path for Pratt method	12
2.5.2 Curvature values and association with path position	13
2.6 Processing GPS data for the ideal curvature definition	14
2.6.1 Curvature value sensibility to different segments lengths	16
2.7 Processing data from map service provider	17

2.7.1	Curvature value sensibility to different segment length	19
2.8	Curvature comparison between map service provider and GPS recording.	20
2.9	Mobileye 6 curvature estimation	21
3	Establishing the speed profile with Simulink models	23
3.1	Variables loaded through script	24
3.2	Speed --> Distance block	25
3.3	Speed reduction block	25
3.3.1	Speed reduction function	26
3.4	Actuated lateral acceleration and jerk.	27
3.5	Actuated longitudinal acceleration and jerk.	28
3.6	Curvature for speed profile – Simulink model “Switch and hold”	28
3.7	Mobileye sensor fusion logic- Simulink Model “Sensor fusion”	31
4	Results	33
4.1	Limits on acceleration and jerk for a comfort ride	33
4.2	How advance affects the results	33
4.3	Mobileye speed estimation and comparison with map service provider	36
4.4	Speed profiles representing different driving behaviors	38
5	Conclusion and future work	41
6	References	42

List of figures

Figure 1-1 Passive Safety Systems (8)	1
Figure 1-2 Active safety systems (9)	1
Figure 1-3 Levels of driving automation according to SAE (10)	3
Figure 1-4 Tesla Model S sensor schematic- Tesla.com	4
Figure 1-5 Tesla Model 3 frontal windshield triple cameras (15)	5
Figure 1-6 e-Horizon, example of intelligent speed assist (19)	7
Figure 2-1 First test path Sant' Agata to San Giovanni	9
Figure 2-3 Test route 2- Google My Maps	10
Figure 2-2 Particular of path 2, used for the speed profile creation.	10
Figure 2-4 Curvature visualization- (8)	11
Figure 2-5 Circle through points Pratt fit	12
Figure 2-6 Curvature over segment- MATLAB Function	13
Figure 2-7 Cartesian points projection part of path 1, recorded with GPS	14
Figure 2-8 Comparison between distance of sampling points and speed of acquisition.	14
Figure 2-9 Comparison between Pratt method 30 m segment and exact curvature algorithm. Part of path 1-GPS Data	15
Figure 2-10 Curvature comparison, different segment length. Part of path 1	16
Figure 2-11 Number of points comparisons, different segment lengths	17
Figure 2-12 Points comparison between Here Maps and Google Maps. Part of path 2	18
Figure 2-13 GPS and Google Maps coordinates points	19
Figure 2-14 Curvature comparison Pratt method, increasing segment length. Part of path 2.	20
Figure 2-15 Number of points comparisons for executing Pratt method, increasing segment length. Part of path 2.	20
Figure 2-16 Curvature comparison MSP and ideal curvature from GPS recording. Part of path 1	20
Figure 2-17 Mobileye 6 Camera illustration	21
Figure 2-18 Curvature estimation comparison Mobileye vs ideal curvature. Part of path 1	22
Figure 3-1 Simulink model for creating speed profile	24
Figure 3-2 Speed--> Distance Block - Simulink Model	25

Figure 3-3 Speed reduction block - Simulink model	25
Figure 3-4 Speed target comparison with rate limiter	26
Figure 3-5 Actuated lateral acceleration block - Simulink Model	27
Figure 3-6 Actuated longitudinal acceleration - Simulink Model	28
Figure 3-7 Workflow of the curvature for speed profile creation	28
Figure 3-8 Turn index individuation and max values points	29
Figure 3-9 Curvature shifted with advance	30
Figure 3-10 Simulink model "Switch and hold"	30
Figure 3-11 Curvature for speed profile actuation and switch logic	31
Figure 3-12 Simulink model for the sensor fusion of Mobileye signal	32
Figure 4-1 Curvature and speed synchronism, 90 m advance. Part of path 2. MSP data.	34
Figure 4-2 Curvature and speed synchronism, 190 m advance. Part of path 2. MSP data.	34
Figure 4-3 Curvature and speed synchronism, 220 m advance. Part of path 2. MSP data.	35
Figure 4-4 Lateral acceleration relationship with different advances. Part of path 2. MSP data.	35
Figure 4-5 Simulation results Mobileye data from sensors fusion. Part of path 1	36
Figure 4-6 Curvature, speed and lateral acceleration comparison between Mobileye estimation and map service provider. Part of path 1	37
Figure 4-7 Speed, longitudinal acceleration and jerk and lateral acceleration. Comfort driver simulation. Part of path 2.	38
Figure 4-8 Speed, longitudinal acceleration and jerk and lateral acceleration. Balanced driver simulation. Part of path 2.	39
Figure 4-9 Speed, longitudinal acceleration and jerk and lateral acceleration. Sport driver simulation. Part of path 2.	40

List of tables

Table 1 Road Classification as DM 05/11/2001 _____	8
Table 2 Lateral friction coefficients as DM 05/11/2001 (22) _____	9
Table 3 Numerical value sensibility to segment length _____	16
Table 4 Simulation parameters, MSP data. Part of path 2 _____	33
Table 5 Simulation parameter Mobileye data. Part of path 1 _____	36
Table 6 Simulation parameter MSP data. Part of path 1 _____	37
Table 7 Simulation parameters, different driver behaviors. Comfort driver. Part of path 2_	38
Table 8 Simulation parameters, different driver behaviors. Balanced driver. Part of path 2	39
Table 9 Simulation parameters, different driver behaviors. Sport driver. Part of path 2 ____	40

Acronyms

ABS: Anti-Lock Braking System

ACC: Adaptive Cruise Control

ADAS: Advanced Driver-Assistance Systems

ESP: Electronic Stability Control

FOV: Field Of View

GPS: Global Positioning System

MSP: Map Service Provider

SAE: Society Of Automotive Engineers

V2C: Vehicle To Cloud

Glossary

Function (MATLAB): “A function is a group of statements that together perform a task. In MATLAB, functions are defined in separate files. Functions can accept more than one input arguments and may return more than one output arguments.” (2)

MATLAB: “(an abbreviation of "matrix laboratory") is a proprietary multi-paradigm programming language and numeric computing environment developed by MathWorks. MATLAB allows matrix manipulations, plotting of functions and data, implementation of algorithms, creation of user interfaces, and interfacing with programs written in other languages.” (3)

Script (MATLAB): “A script is a file that contains multiple sequential lines of MATLAB commands and function calls. You can run a script by typing its name at the command line.” (4)

Simulink: “is a MATLAB-based graphical programming environment for modeling, simulating and analyzing multidomain dynamical systems.” (5)

1 Introduction

Automotive industries always have the goal to produce a better car. In the last 30 years their improvement has focused on performance, comfort, safety, efficiency, and pollutants reduction.

Achieving such goal is not simple. Passive safety improvements require bigger crumple, this led to car bigger and heavier. To increase or maintain the same performance more power is required. Engine more powerful required more fuel, but more pressing regulations cut through the years both pollutant quantities and CO₂ emissions.

For example, this is the evolution of BMW 3 series through the years (6):

Model	320i E21	320i E30	320i E36	320i E46	330i E90	328i F30	330i G90
Year	1975	1982	1990	1998	2005	2012	2019
Length [cm]	435	432	443	447	452	462	471
Weight [kg]	1115	1050	1270	1365	1450	1575	1545
Max power [CV]	122	125	150	150	258	245	258
0-100 km/h	10.6	8.3	9.4	9.9	6.3	6.1	5.9
Fuel economy [km/l] at 120 km/h	8.7	10.4	12.3	11.6	13.1	14.3	13.8

The last model outperforms the previous ones in all the aspects, also in the safety part. It is rated 5 stars in Euroncap tests (7). In 2014 Euroncap started to evaluate Autonomous Emergency Braking and Lane Keep Assist/Lane Departure Warning. In 2021 the scoring includes a specific rating, part of the overall score, all dedicated to ADAS.

Safety improvements can be divided into two macro categories:

- **Passive safety:** under this term are classified all the systems with the aim to reduce the consequences on people in the crash event. As example: airbags, seatbelts, headrest, and crumple zones.

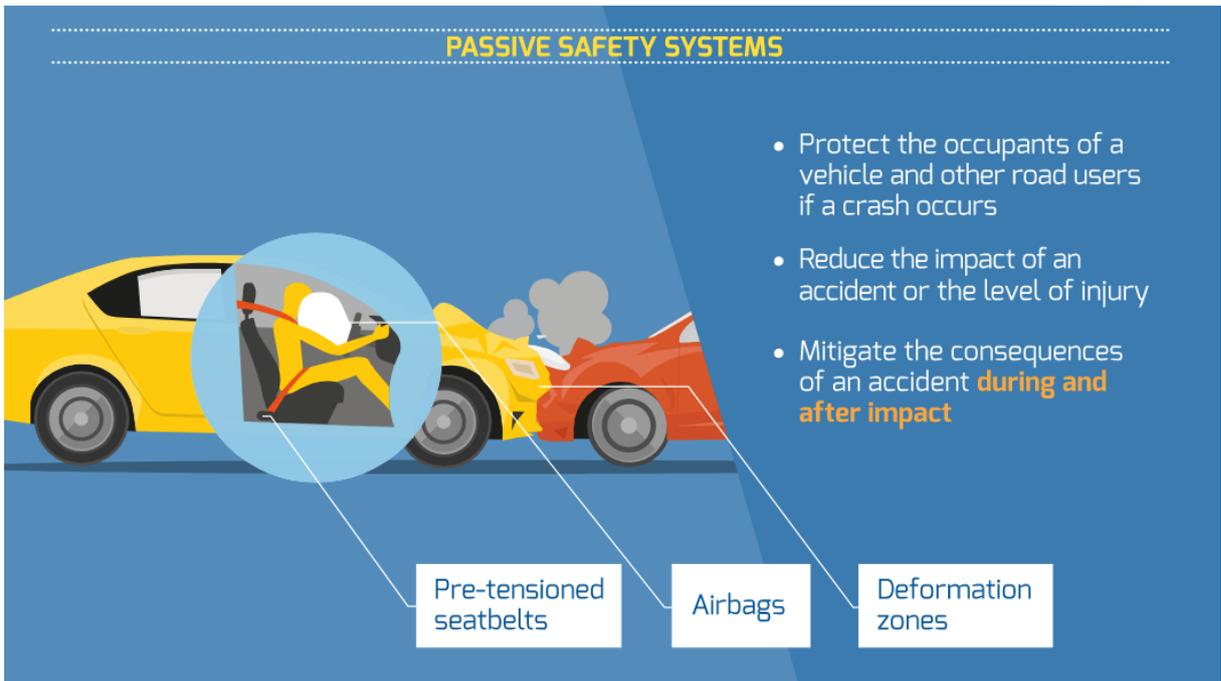


Figure 1-1 Passive Safety Systems (8)

- **Active safety:** under this term are classified all the systems that help prevent accidents. Systems like: ABS, ESP, collision warning and avoidance, adaptive cruise control, lane departure warning and driver drowsiness alert. The growth of these systems is related to the development of electronics consumer sector.

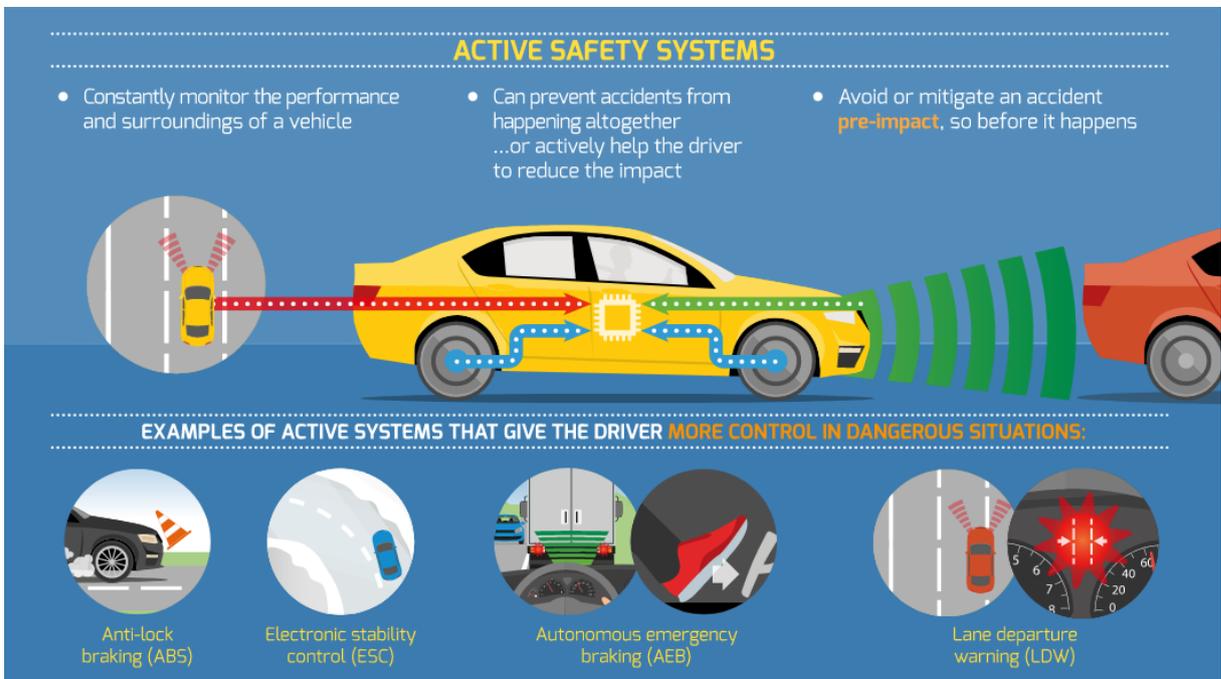


Figure 1-2 Active safety systems (9)

1.1 Object of this work

The goal of this work is to conduct a preliminary study on the improvement of existing adaptive cruise control functions (ACC). ACC is useful to reduce fatigue for the driver, improve comfort, reduce potential accident, and increase fuel efficiency. The system works by maintaining a chosen velocity and distance from the vehicle beyond by accelerating or braking. Actions include stopping and resume of the march.

The improvement object of this thesis it is the ability to use information regarding horizontal profile of the road, obtained from the map service provider through a cloud connection. From this data, a speed profile is actuated and can be optimized for different purposes like: performance, comfort, or efficiency.

Data regarding the curvature are obtained in real time from two different sources:

- **Map Service Provider:** when the driver sets the destination, updated information about the path is downloaded from the cloud through V2C connectivity. The idea is to download part of the future path, at the beginning of the journey and then along the route to make subsequent requests. This strategy ensures the possibility of reacting to road events like traffic or possible hazards.
- **Mobileye 6 Camera:** it records road view images to process them in real time to output a curvature approximation. It is also possible to estimate the curvature value ahead of the car. This approximation uses a specific formula, which takes into account the curvature derivative. The recording made by the GPS tracker is used to define an ideal curvature. The curvature is used as benchmark to evaluate the performance of other input. In the Simulink model for speed profile evaluation, the ideal curvature is used for calculating the real lateral acceleration.

Independently from the sources, data are elaborated with the use of MATLAB and Simulink.

A Simulink model is used to provide the test environment. The model simulates the car along the path from a selected starting and ending point along the route. The output is the speed target profile for the cruise control function. Which takes into account lateral acceleration threshold and speed imposed by the driver or the legal road limit. Different values are stored from the model with the aim to evaluate the performance of the control.

1.2 What is an ADAS

ADAS is the acronym for Advance Drivers Assistance Systems and includes all the electronics systems that assist the driver. It is composed by hardware components such as sensors, a central unit for elaborating data, and a human-machine interface to communicate with the driver.

1.2.1 ADAS classification according to SAE.

ADAS are categorized into different levels, based on the amount of automation in a scale provided by The Society of Automotive Engineers (SAE). The standard J3016_201806 (10) describes: “motor vehicle driving automation systems that perform part or all of the dynamic driving task (DDT) on a sustained basis [...] Six levels of driving automation are defined, ranging from no driving automation (level 0) to full driving automation (level 5), in the context of motor vehicles”.

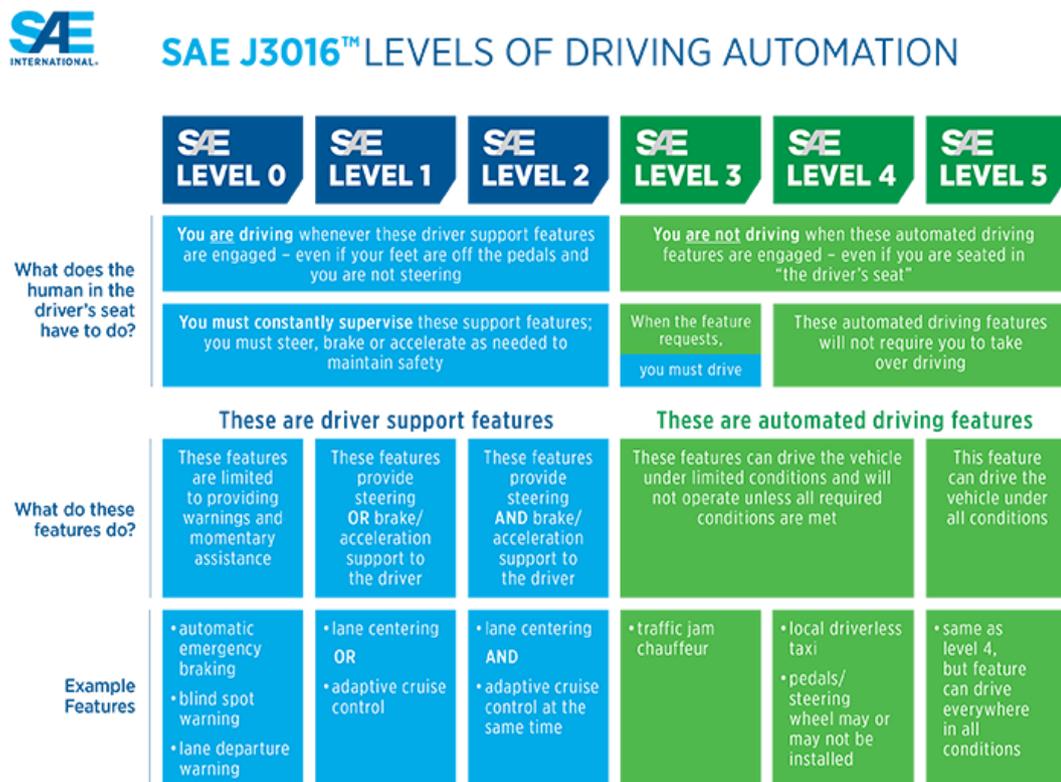


Figure 1-3 Levels of driving automation according to SAE (10)

In Europe, legislation limits cars in the market at level 2. Drivers must constantly supervise support features.

1.2.2 Hardware involved in ADAS functions

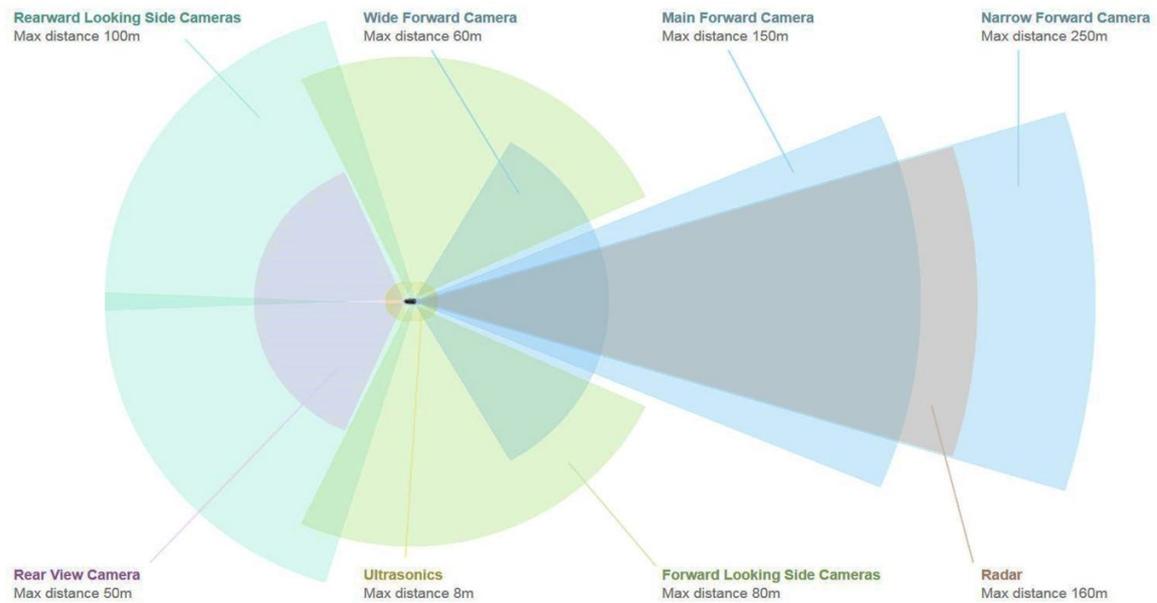


Figure 1-4 Tesla Model S sensor schematic- Tesla.com

Sensors and cameras are the key parts of an ADAS function. They can be classified based on range, field of view (FOV) and physical principles.

Some examples are:

- **Radar.** It is a detection system that uses radio waves to determine the range, angle, and velocity of objects (11). Radars can be distinguished based on range and FOV. A long-range radar is used for function related with ACC or anti-collision warning and can have a range up to 210 m with a FOV of $\pm 4^\circ$ (12). Medium range radars are involved in lane change assist and rear cross traffic alert. Two sensors, one to the left and the other on the right, are positioned inside the rear bumper of the vehicle. They are angled outward at approximately 45 degrees and can detect objects at a distance up to 80 meters (13). Short range radars are used for parking aid. They are small and light and can detect object and pedestrians up to 5.5 m (14). To achieve all the ADAS function, radars are usually combined with cameras.
- **Cameras:** multi cameras are used to scan the surrounding of the vehicle. Forward looking cameras are usually placed into the windshield, near the rear-view mirror. A module can be composed by 3 cameras. Two are used to achieve stereo vision and the other one is used for long distance images. Typical detection range can arrive at 150m and horizontal FOV can be of 150° 50° 35° .



Figure 1-5 Tesla Model 3 frontal windshield triple cameras (15)

Images are then processed by a microprocessor with image processing algorithms.

Cameras can be placed also in the B pillar for rear and lateral views.

Many of ADAS functions rely on the use of cameras. Main advantages are related to the possibility of classifying objects such as vehicles, cyclists, or road marks and rely on artificial intelligence. Thanks to machine-learning processes, cameras have learned to classify objects such as cars parked by the side of the road (16).

Some examples of functions based on cameras are: lane departure warning, road sign information, intelligent headlight control and automatic emergency braking on vulnerable road users.

1.2.3 Connectivity

In the future, cars will be able to communicate with a multitude of environmental players, that can affect the vehicle and vice versa. Progress in the telecommunications sector is creating the infrastructure necessary to set-up Vehicle-to Everything (V2x) communications. Based on the interlocutor, there are 5 types of communications (17):

- V2I “Vehicle to infrastructure”: Vehicles and infrastructures share bidirectional information regarding traffic density, speed of the car and road conditions. Components that are included in an intelligent infrastructure are traffic lights, streetlights, parking meters and sensors. For example, cars retrieve information about traffic and parking spots. On the other hand, the infrastructure elaborates variable

speed limits or changes red light duration, communicating it to the car to optimize the speed profile.

- V2V “Vehicle to Vehicle”: Cars communicate between them through a wireless protocol with a range of more than 300 meters (18). Information regarding speed, position or immediate hazard obscured by traffic, terrain or weather are communicated. The goal is to reduce the probability of accidents, ease traffic congestions and have a positive impact on the environment.
- V2C “Vehicle to Cloud”: Cars are connected bidirectionally to a web service where enhanced data are available. The ADAS object of this thesis uses data from the map service provider cloud. Advantages are related to the possibility of processing sensor data with the use of cloud-based platforms. Data are always updated since they are downloaded in real time from the cloud. Problems can arise from zones where the connection is low or absent. The evolution of cellular radio infrastructures is fundamental to express the full potential of V2C.

Other applications include Over the Air (OTA) upgrade of the software systems, diagnostic capabilities, and fleet management.

- V2P “Vehicle to Pedestrian”: Communication between personal mobile devices and the car. The aim is to improve safety in urban territory.
- V2X “Vehicle to Everything”: The technology interconnects all type of vehicles and infrastructure systems with another. For example, cars communicate with trains, ships and airplanes to get a more precise knowledge of the traffic situation across the entire road network.

1.2.4 E-Horizon

Electronic Horizon is a technology that expands the range of the car behind its sensors capability using V2X connection. Drivers and vehicles are provided with updated and predictive information about road surface condition, traffic, possible hazard, and road profile both horizontal and with respect to height.

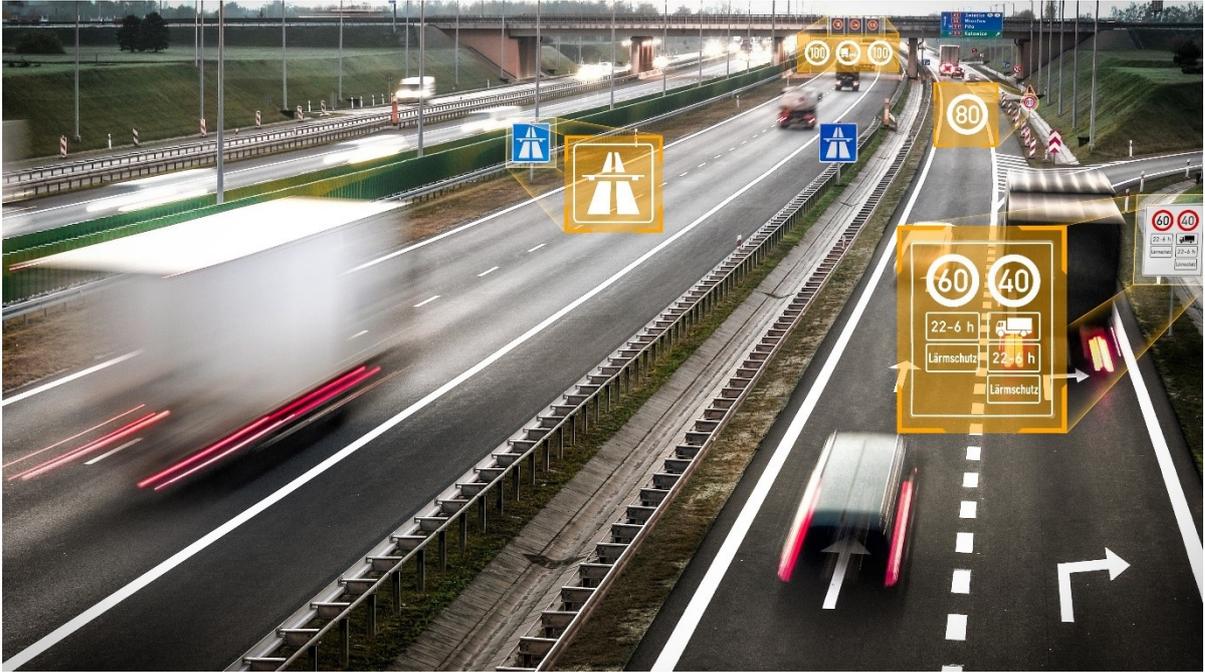


Figure 1-6 e-Horizon, example of intelligent speed assist (19)

Benefits achieved from e-Horizon concern safety, comfort, and improvement in efficiency of the journey.

An example of an e-Horizon application is the optimization of energy flow in a plug-in hybrid vehicle. When a destination is selected, inside the navigation system, the path is analyzed. Parameters such as height profile of the road and low emission zones are taken into consideration to use energy in the most efficient way. The state of charge can be preserved using the vehicle in “hybrid mode”, in high-speed road, and then switched to pure electric mode when crossing low emission zones. The information regarding the location where the switch should happen, is obtained from geo-fenced technology via GPS. (20) By doing this, the environmental performances are improved. Electric and internal combustion engines are used in their higher efficiency load conditions. Tests conducted by Quattroruote (21) with two plug-in hybrid vehicles, (Audi A3 TSFI E and Mercedes-Benz A 250e) show evidence of a reduction in consumption of both electricity and gasoline with the use of e-Horizon function. The test path is composed by 70 km of motorway and 16 km of urban roads. Results for the two cars with the use of e-Horizon shown a reduction of electricity consumption by -5% for the Audi and -15% for the Mercedes. Regarding gasoline consumption the reduction is of -16% for the Audi and -10% for the Mercedes.

2 Curvature definitions

In this chapter it is illustrated how curvature values are defined, from data acquisition to curvature definition. Different data sources are analyzed and then processed with different algorithms.

2.1 Road design normative reference

Reference to road design legislation in Italy can be found inside the DM 05/11/2001 (22) .

Road Classification		Territorial Ambit	Number of lines for each direction	Speed Limit [km/h]	Inferior speed limit [km/h]	Superior speed limit [km/h]
Motorway	A	Extra urban- Principal Road	2 or plus	130	90	140
		Urban- Principal Road	2 or plus	130	80	140
Principal Extra urban	B	Principal road	2 or plus	110	70	120

Table 1 Road Classification as DM 05/11/2001

The work of this thesis focuses on roads typology classified as A and B on extra urban territory. Type A (motorway) is characterized by 130 km/h speed limit and type B (main highway) by 110 or 90 km/h. Speed values associated with inferior and superior limits are: type A 90 and 140 km/h and for type B 70 and 120 or 40 and 100 if the speed limit is 90 km/h.

Considering the relationship from force equilibrium of a vehicle into a circular curve: (Ref. page 59 (22))

$$R = \frac{Sp^2}{(q + f_t) \times 127}$$

Where:

- **R= Radius of the curve [m]**
- **Sp=Speed project of the curve [km/h]**
- **q= transversal inclination**
- **f_t=lateral friction coefficient**

The minimum turn radius for road type A, B or C are calculated considering:

- 7% ($q=0.07$) maximum transversal inclination.
- Inferior limit of the speed project related to the type.
- Lateral friction coefficient:

Speed [km/h]	40	60	70	80	90	100	120	140
f_t for road Type A,B,C,F (extra urban)	0.21	0.17	0.147	0.13	0.118	0.11	0.10	0.09

Table 2 Lateral friction coefficients as DM 05/11/2001 (22)

Motorway (A): Speed project 90 [km/h], q max 0.07, f_t 0.118 → Minimum turn radius 339 [m]

Principal Extra Urban (B): Speed project 70 [km/h], q max 0.07, f_t 0.147 → Minimum turn radius 178 [m]

Secondary Extra Urban (B): Speed project 70 [km/h], q max 0.07, f_t 0.170 → Minimum turn radius 118 [m]

2.2 Tests routes

Two different test routes have been chosen. The first one, is a secondary extra urban road between Sant 'Agata Bolognese and San Giovanni Persiceto, for a length of 9.8 km. This path was chosen because of the facility of access in respect to the laboratory and for being characterized by two high radius curves, with good road markers.

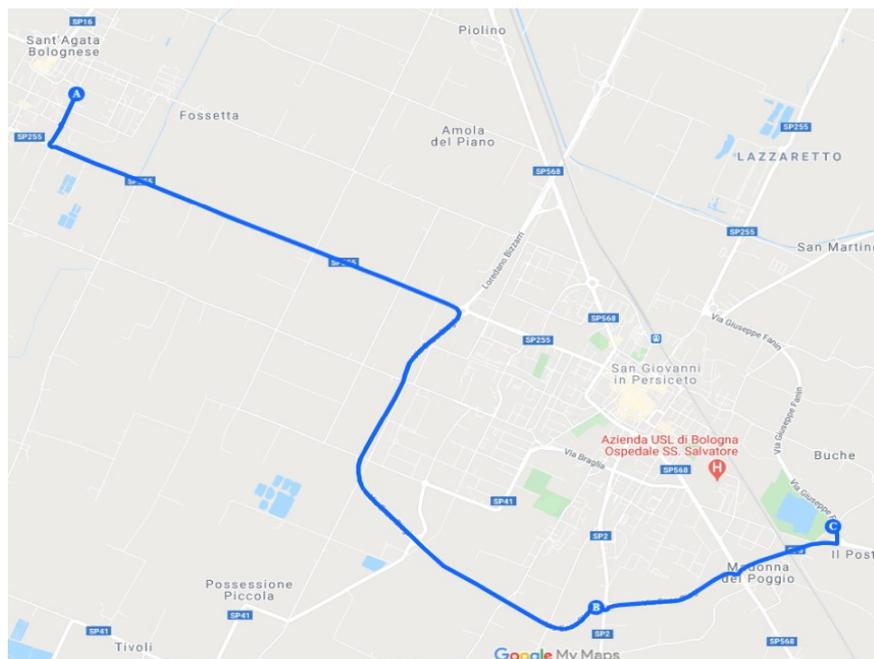


Figure 2-1 First test path Sant' Agata to San Giovanni

The second test path is more related to the work. It is a motorway segment between the exit of Rioveggio and Barberino di Mugello, for a total length of 40 km. This road in direction North→ South is along the A1 motorway in the route called “Panoramic” for its naturalistic scenery. It is well known for being “twisty” due to terrain conformation, the ideal test bench for the algorithm.

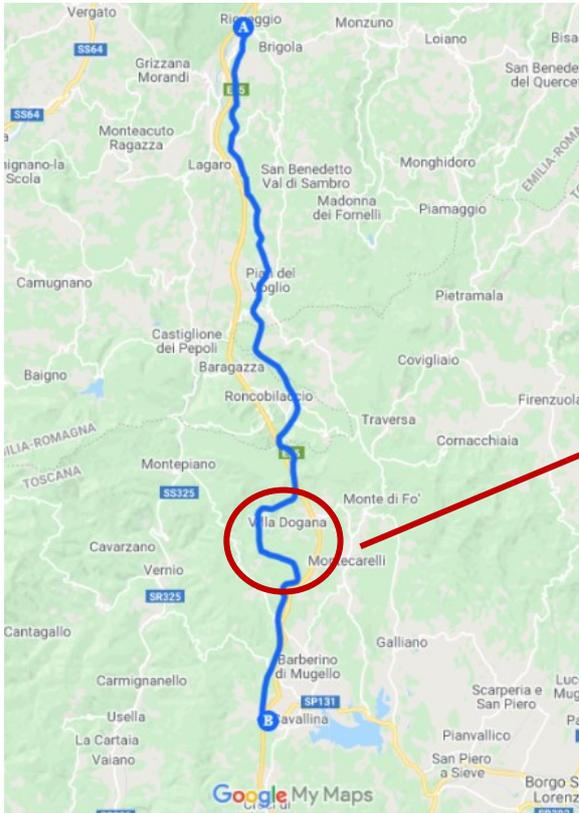


Figure 2-3 Test route 2- Google My Maps

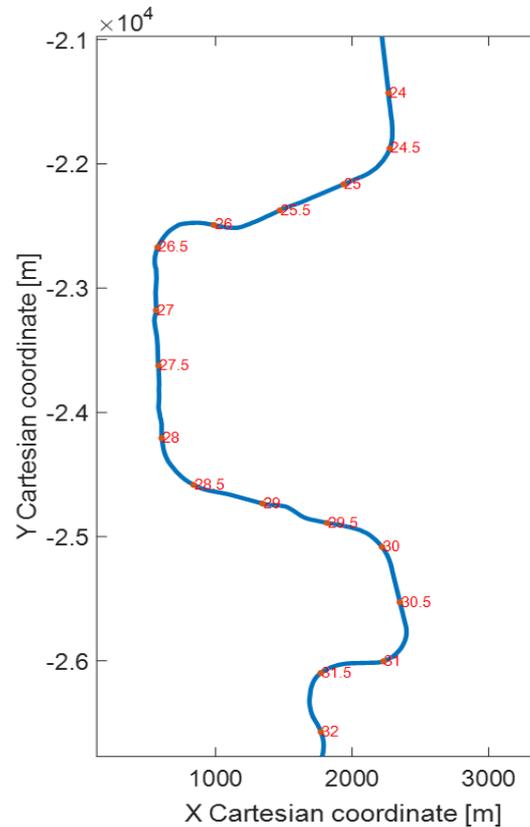


Figure 2-2 Particular of path 2, used for the speed profile creation.

2.3 Data extraction from .kml files

Routes are extracted from the map service provider with an export in .kml format. .kml is the acronym for Keyhole Markup Language (KML), an XML notation for expressing geographic annotation and visualization within maps Earth browsers. (23)

Latitude and longitude independently from the sources, are processed with the MATLAB script “Loccart FWD” (24) converting geographic coordinates into local cartesian coordinates using WGS84 ellipsoid.

2.4 Exact curvature algorithm

The first algorithm used for curvature approximation is based on the geometric statement that “for every triangle there is a circumcircle that intersects its three points”. Latitude and longitude, converted into local cartesian, are a sequence of points and it is possible to calculate the distance between them. Considering points A (x1,y1), B(x2,y2) and C(x3,y3):

$$k = \frac{2 \times |(x_2 - x_1) \times (y_3 - y_1) - (x_3 - x_1) \times (y_2 - y_1)|}{\sqrt{((x_2 - x_1)^2 + (y_2 - y_1)^2) \times ((x_3 - x_1)^2 + (y_3 - y_1)^2) \times ((x_3 - x_2)^2 + (y_3 - y_2)^2)}}$$

K is the curvature in the middle point. (25) [Stafford Roger, MATLAB Central]. The formula is based on the mathematical principle: “the curvature of a circle drawn through them is simply four times the area of the triangle formed by the three points divided by the product of its three sides”.

This method was used as a first approximation. Since coordinates points discretization is not constant, taking 3 subsequent points will lead to different distances in which the curvature is calculated. To control the distance between points, the Pratt method was introduced.

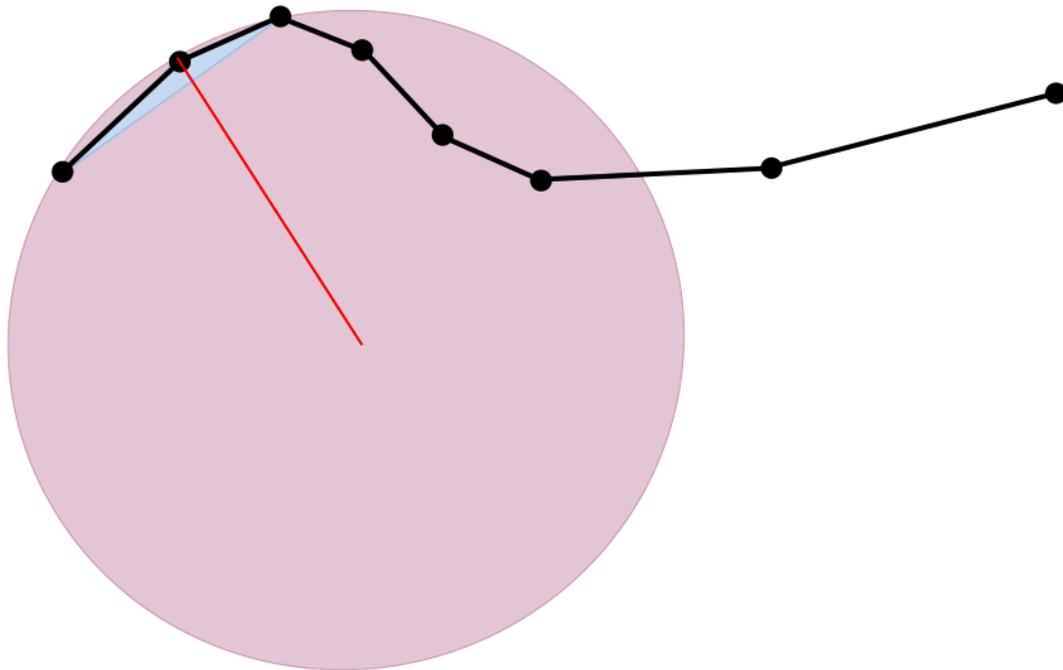


Figure 2-4 Curvature visualization- (8)

2.5 Pratt method

Circle fit Pratt method is a MATLAB function “ (26), a robust and accurate circle fit, that works with n points on a plane, and returns the circle center and radius. The circle fit was proposed by V. Pratt in his article: “Direct least-squares fitting of algebraic surfaces” (27). Such function is not a perfect fit for the three points; however, more points can be used as input. This is important because it allows more flexibility with respect to the exact curvature algorithm.

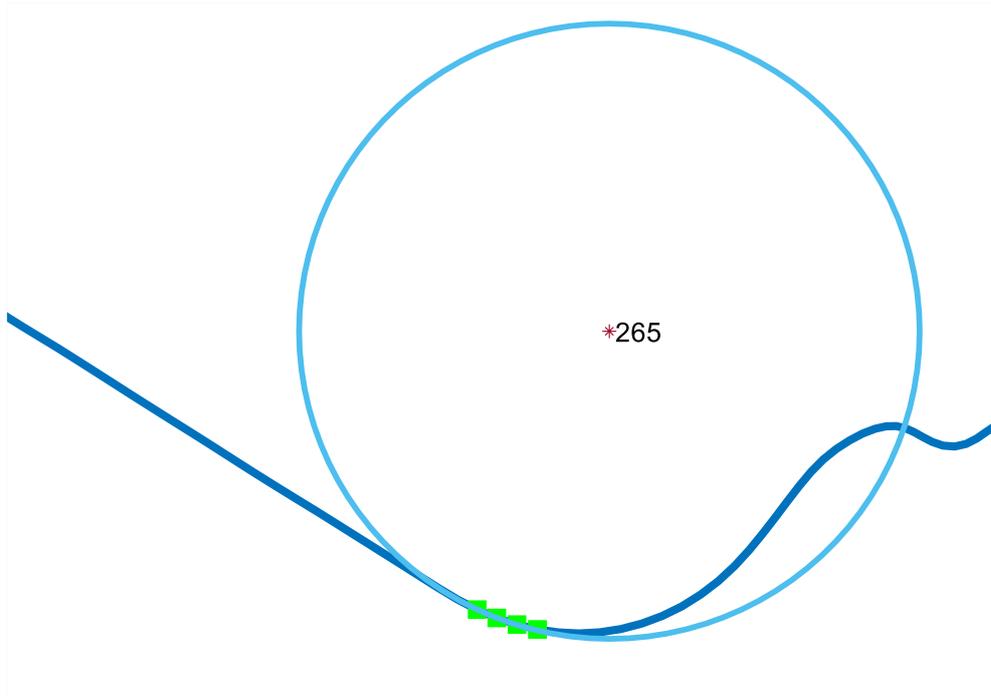


Figure 2-5 Circle through points Pratt fit

2.5.1 Segmentation of the path for Pratt method

The curvature using the Pratt method, is calculated taking into consideration a segment of a given length, for example 30 meters. The real length of the segment itself depends on two factors. The first one, is the discretization of the dataset. The minimum segment length is the one that for the entire path, after segmentation, contains at least three points to avoid errors inside the Pratt Method. A second consideration concerns the physical proprieties of the road under study. The length of the segment should be less or equal to the minimum radius of interest for the selected route. If the segment is bigger, for example 200 m to study a turn with 50 m radius, the risk is to largely underestimate the curvature value.

```

function [crv_Prt_seg,e_perc_distance,n_p_segment,center_X,center_Y]=cvtr_segment(x,y,segment)
    xr=[];%clean where i save my coordinates of points inside segment
    yr=[];
    for i=1:(length(x)
        s=i;
        totd_partial=0;
        xr=[];
        yr=[];
        while totd_partial(end)<segment
            xr=[xr x(s)];
            yr=[yr y(s)];
            s=s+1;
            totd_partial=distance(xr,yr);
            %function distance calculates distance between points inside the segment
            e_perc_distance(i)=((totd_partial(end)-segment)/segment)*100;
            n_p_segment(i)=length(totd_partial);
        end
        XY=[xr' yr'];%saving coordinates to use inside Circle Fit by Pratt
        Par= CircleFitByPratt(XY);
        crv_Prt_seg(i)=1./Par(:,3);
        center_X(i)=Par(1);
        center_Y(i)=Par(2);
    end
end

```

Figure 2-6 Curvature over segment- MATLAB Function

After user input for segment length, along all the coordinates points, the “**cvtr segment**” function is executed. As stated in Figure 2-6 the length taken into consideration for curvature processing (**totd_partial** variable) is bigger than the segment and not constant. The real length of segment used for calculating the curvature, depends on points discretization along the path. An improvement can be achieved considering the point closer to the segment distance even if it is less than the segment length. For datasets of this work this choice will lead to an insufficient number of points for the Pratt fit.

2.5.2 Curvature values and association with path position

The curvature value calculated in point n taking into consideration, for example the next 5 points, included to the segment, will result in a shift of the curvature. For high values of the segment length problems can arise with the association between the curvature value and the physical point inside the path. To mitigate the problem, the curvature value calculated in the point n is associated to the middle point of the segment. Since number of points is a discrete value, the curvature is associated to the middle of the segment by dividing by two the number of points and then rounding.

2.6 Processing GPS data for the ideal curvature definition

To assess the performance of the different estimation, it is necessary to define a curvature profile of the selected path with the best accuracy. Since it is not possible to obtain the planimetry associated with the road construction, the road profile is estimated recording using a high frequency and high accuracy GPS¹.

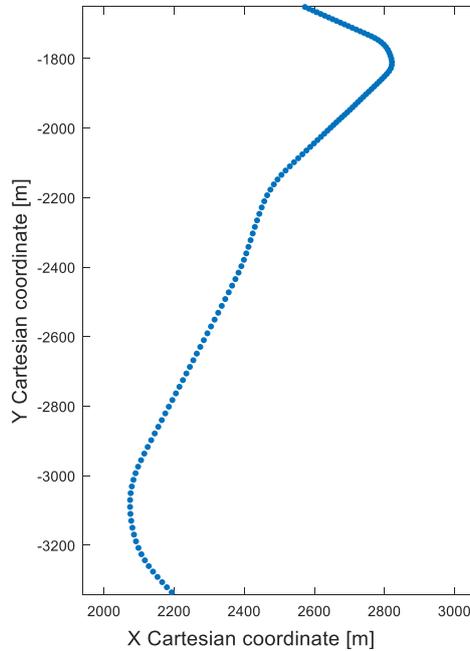


Figure 2-7 Cartesian points projection part of path 1, recorded with GPS

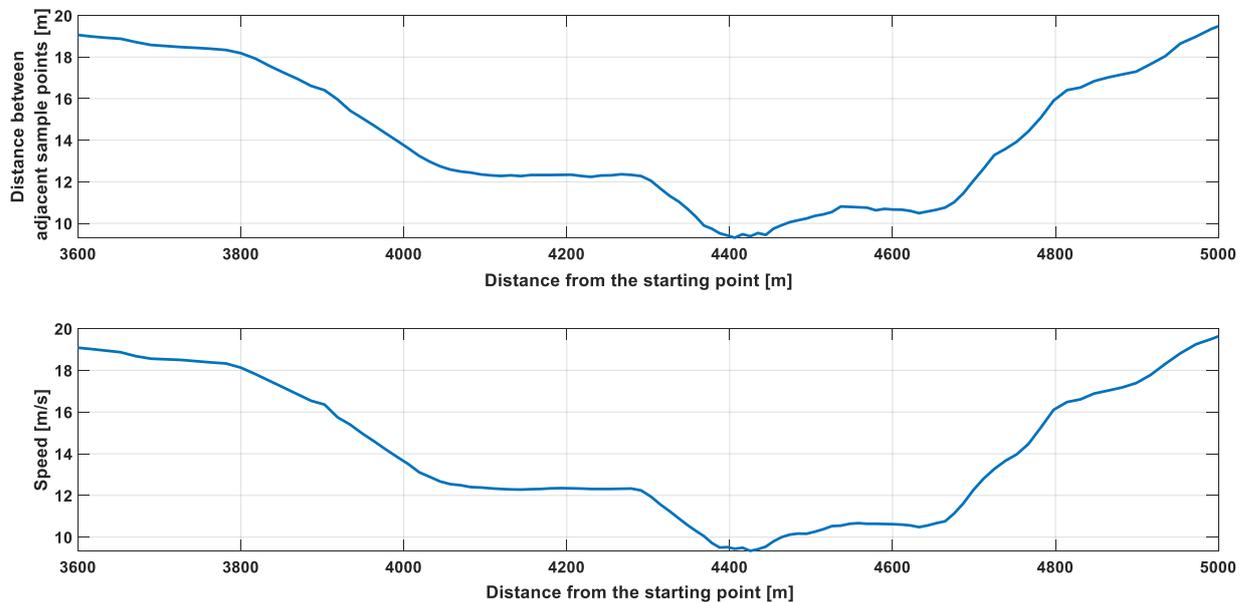


Figure 2-8 Comparison between distance of sampling points and speed of acquisition.

¹ Navilock NL-8002U-2.5 m Circular Error Probable and 1 hZ

The distance between different recording points is given by the speed of the vehicle since sampling frequency is fixed. This is notable by observing the points density in the curve and in the straight in Figure 2-7 and in Figure 2-8.

Recorded coordinates are converted into local cartesian with the **Loccart Fwd** function. Different ways of processing have been tested. In adherence to the protocol used for the data of maps service provider, the Pratt method is used. Since the path is represented with high accuracy, the exact method (2.4) results can be used as well. For minimum segment length the results between the Pratt and exact method are similar. This is because, when the input for the Pratt method it is made of 3 points it performs an exact fit.

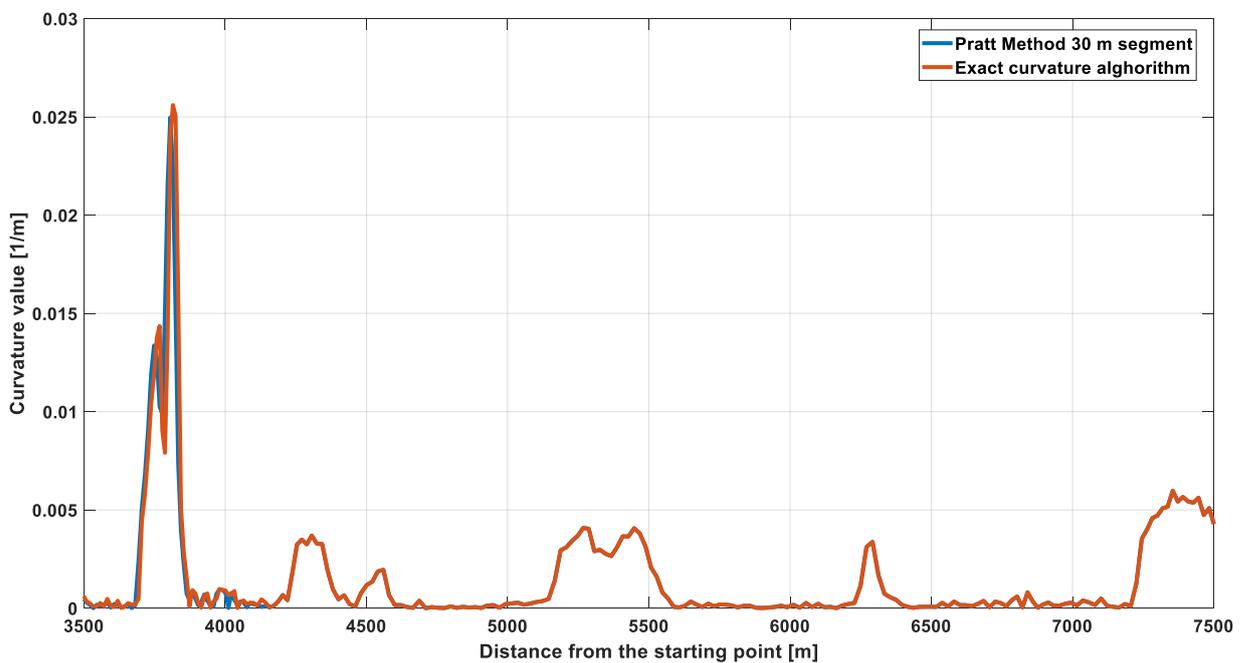


Figure 2-9 Comparison between Pratt method 30 m segment and exact curvature algorithm. Part of path 1-GPS Data

2.6.1 Curvature value sensibility to different segments lengths

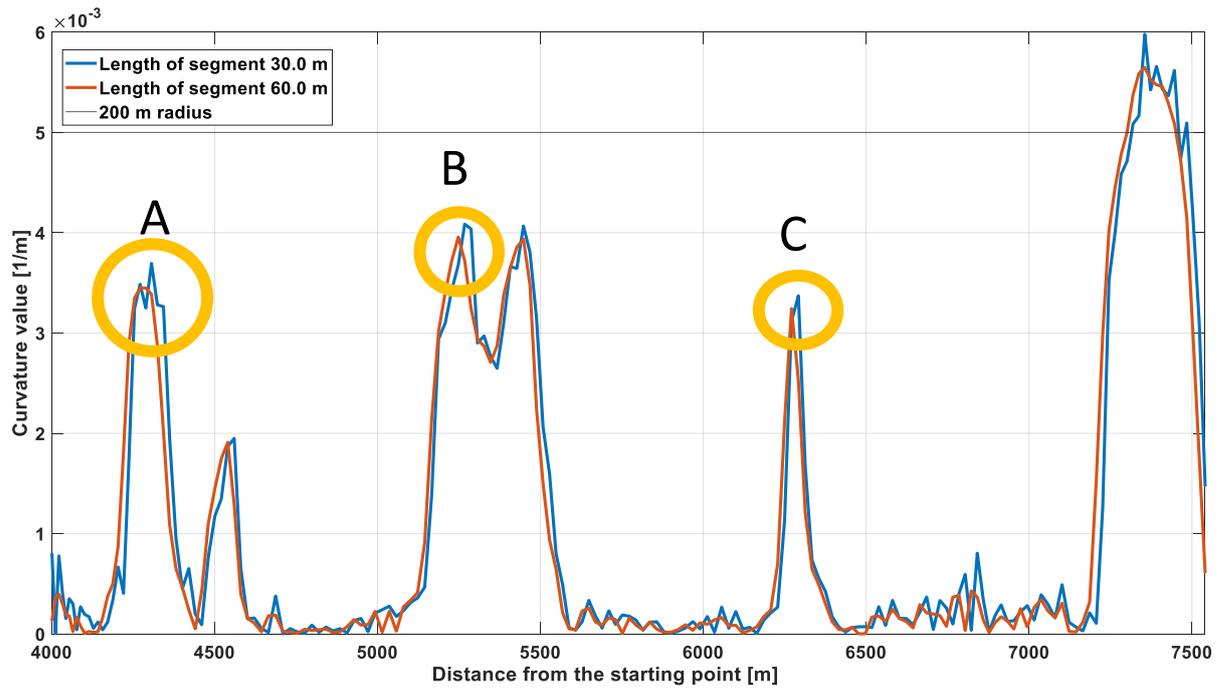


Figure 2-10 Curvature comparison, different segment length. Part of path 1

With the use of data from the GPS recording a sensibility test was conducted. The results of the tests with an increase in segment length are reported in Table 3. The results are primarily two: the shifting of the peak value closer to the starting point and the peak value decrease. Taking into consideration three curves with curvature value higher than 0.003 the numerical values are:

Curve	A	B	C
Peak shift distance from starting point segment 60 vs segment 30	-0.8% (35 m)	-0.4% (21 m)	-0.3% (21 m)
Peak value decrease segment 60 vs segment 30	-8% 0.0003	-5% 0.0002	-6% 0.0002

Table 3 Numerical value sensibility to segment length

Since 30 m is the minimum segment length for the data recorded with the GPS, it is possible to observe mainly three points inside of the segment. Clearly, increase in the segment length, results in more points in the input of the Pratt method.

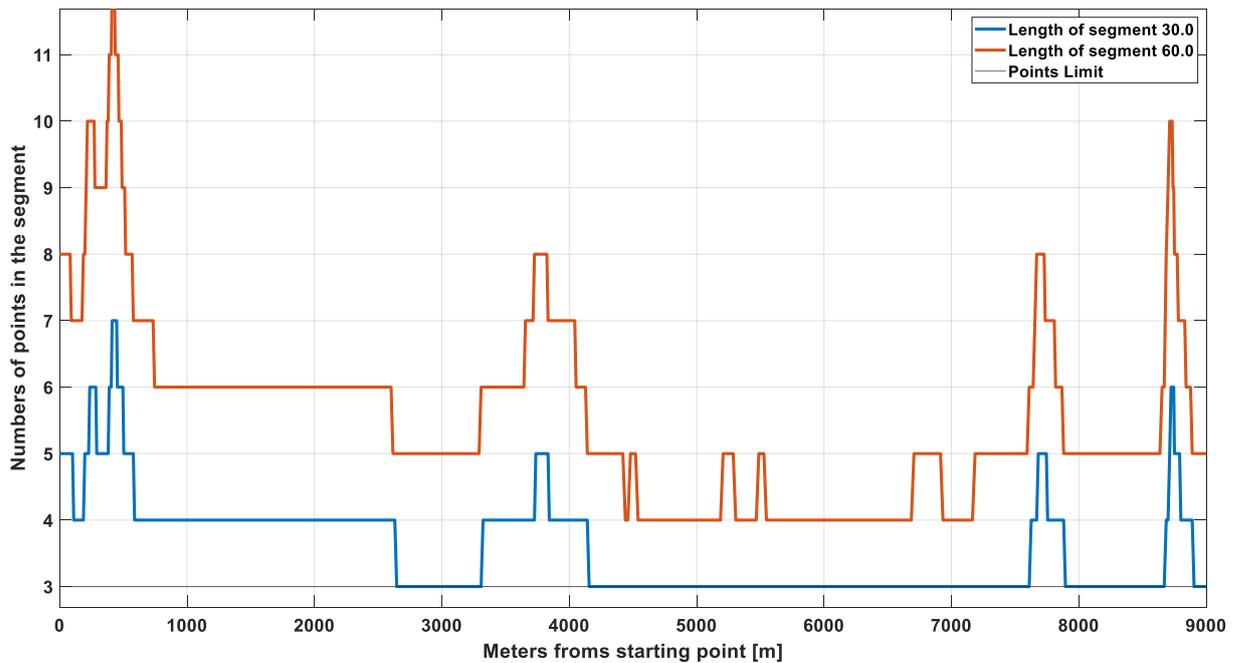


Figure 2-11 Number of points comparisons, different segment lengths

2.7 Processing data from map service provider

Using the data from the map service provider it is necessary to achieve a real time ACC function. The idea is that the car driver sets the destination from the navigation system, then the data for the next 2 km, is downloaded through a V2C connection in real time. The elaboration of the data can be performed from the car hardware or from the cloud service directly.

Two map service providers have been tested. One is Google- My Maps² and the other is Here Maps³. As showed in Figure 2-12, points from Google are closer and denser, with respect to Here's points. Mean distances are 40 meters for Google and 128 meters for Here. Comparing the results, Google Maps has been chosen as the map service provider for this work.

In Figure 2-13 the distribution of the points obtained with the GPS recording and Google Maps. While the discretization of points from GPS depends on the speed of the car during acquisition, Google Maps points are closer when the path is curvilinear and more spaced in the straights. Such optimization applied by Google is coherent with the goal of the algorithm.

² <https://www.google.com/intl/it/maps/about/mymaps/>

³ <https://www.here.com/>

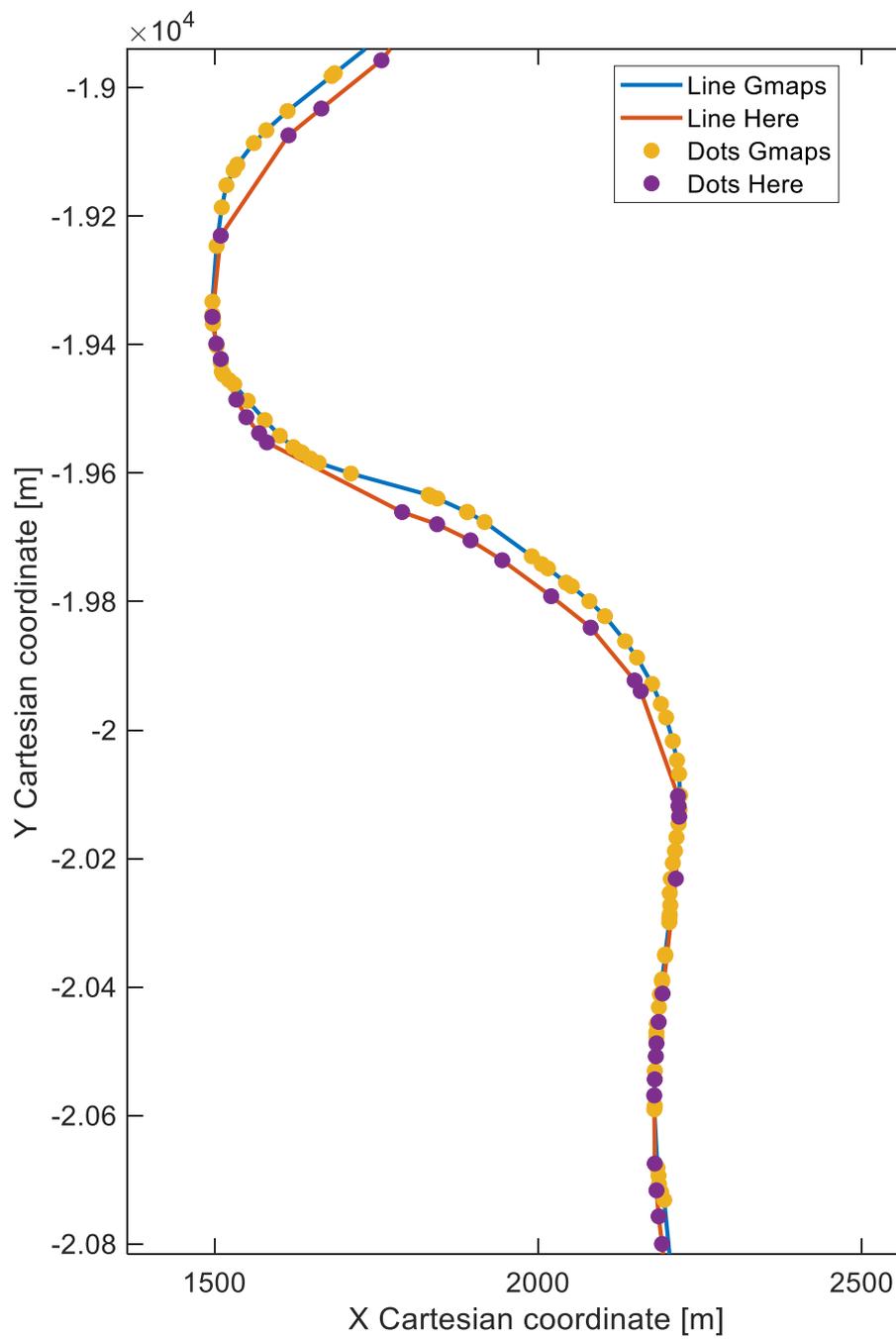


Figure 2-12 Points comparison between Here Maps and Google Maps. Part of path 2

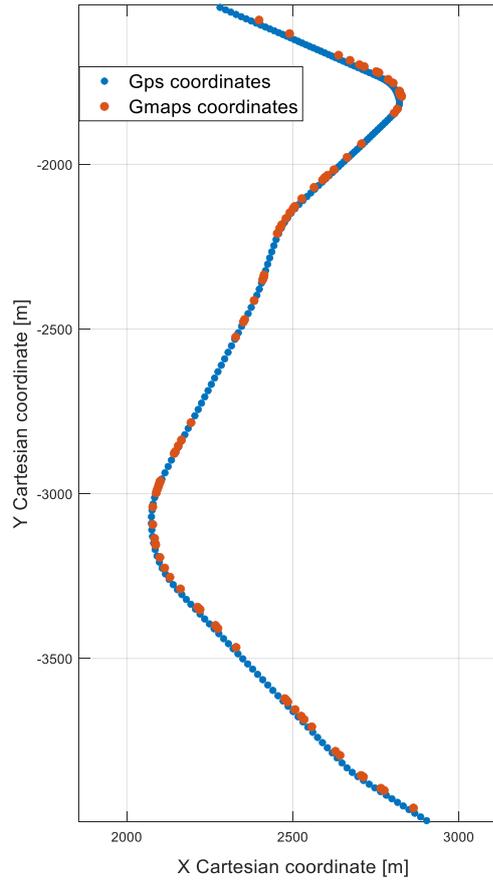


Figure 2-13 GPS and Google Maps coordinates points

2.7.1 Curvature value sensibility to different segment length

Since data from path 2 better represent the environment in which the function is used, the sensibility analysis is performed here. The results are like the one obtained with GPS data.

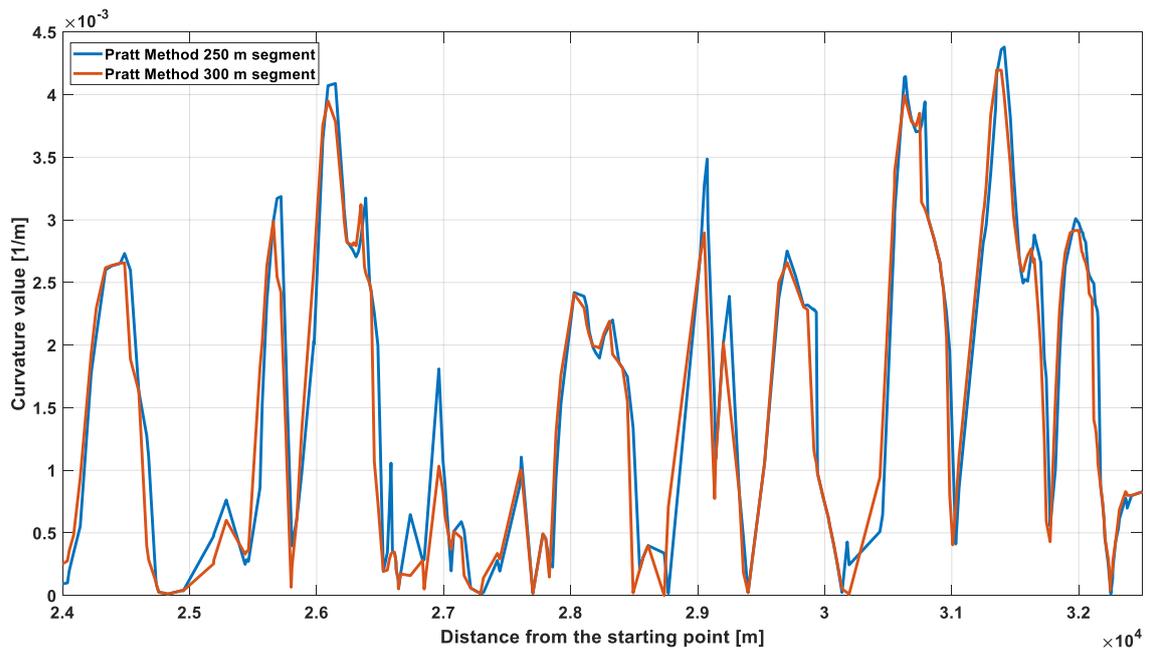


Figure 2-14 Curvature comparison Pratt method, increasing segment length. Part of path 2.

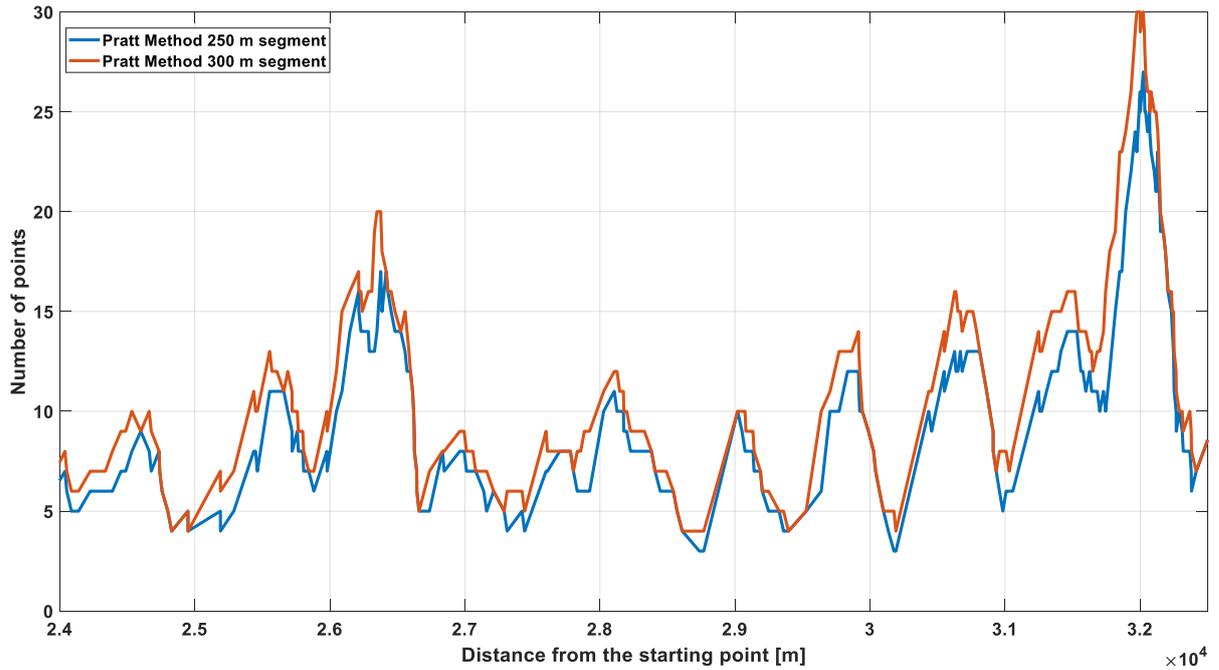


Figure 2-15 Number of points comparisons for executing Pratt method, increasing segment length. Part of path 2.

2.8 Curvature comparison between map service provider and GPS recording.

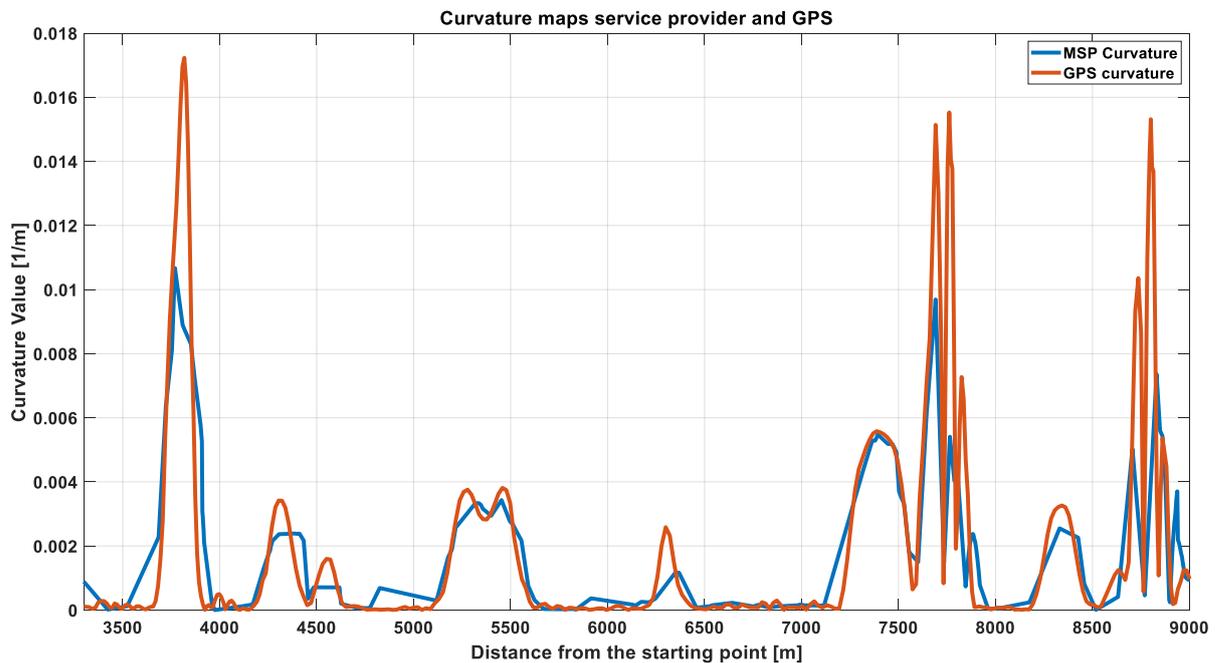


Figure 2-16 Curvature comparison MSP and ideal curvature from GPS recording. Part of path 1

For low value of curvature, the estimation based on MSP data is good. If the turn is tight, like a roundabout (as example value between 3500 and 4000 m), the value is largely underestimated. This characteristic is not relevant since tight turns are not the aim of this work.

2.9 Mobileye 6 curvature estimation

Mobileye 6 © camera is an advanced driver assistance system (ADAS). With features like forward collision avoidance system and lane departure warning. To do so, the road view is recorded by the camera placed near the rear-view mirror and then processed by the EyeQ© chip to calculate the curvature.



Figure 2-17 Mobileye 6 Camera illustration⁴

The signal is transmitted through CAN port from the camera unit and recorded with the use of a PC. The signal is elaborated with the use of the Vehicle network toolbox in the MATLAB environment. The toolbox uses a .dbc text file containing all the information for decoding the raw CAN bus data into physical values.

Messages related to the curvature are:

- **Quality:** a numeric value which describes the quality of the estimation.
- **Curvature parameter C2:** parameter C2 of polynomial model [1/m]. From its road radius can be extracted at $Z=0$. Z is the real-world longitudinal distance from camera in meters.
- **Curvature derivative C3:** parameter C3 of polynomial model [1/m²]

Lane curvature estimation is output at $Z=0$. Where Z is the real longitudinal distance from the camera. An approximation could be done for $Z>0$.

⁴ <https://www.mobileye.com/us/fleets/products/mobileye-6-collision-avoidance-system/>

The estimation is based on a visual recording of the road: visual obstacles, faded or absent road markers and sharp curves cause a drop in the signal quality. Maximum curvature reading is about 0.02 [1/m] corresponding to a turn radius of 50 m, which is enough for the aim of the research.

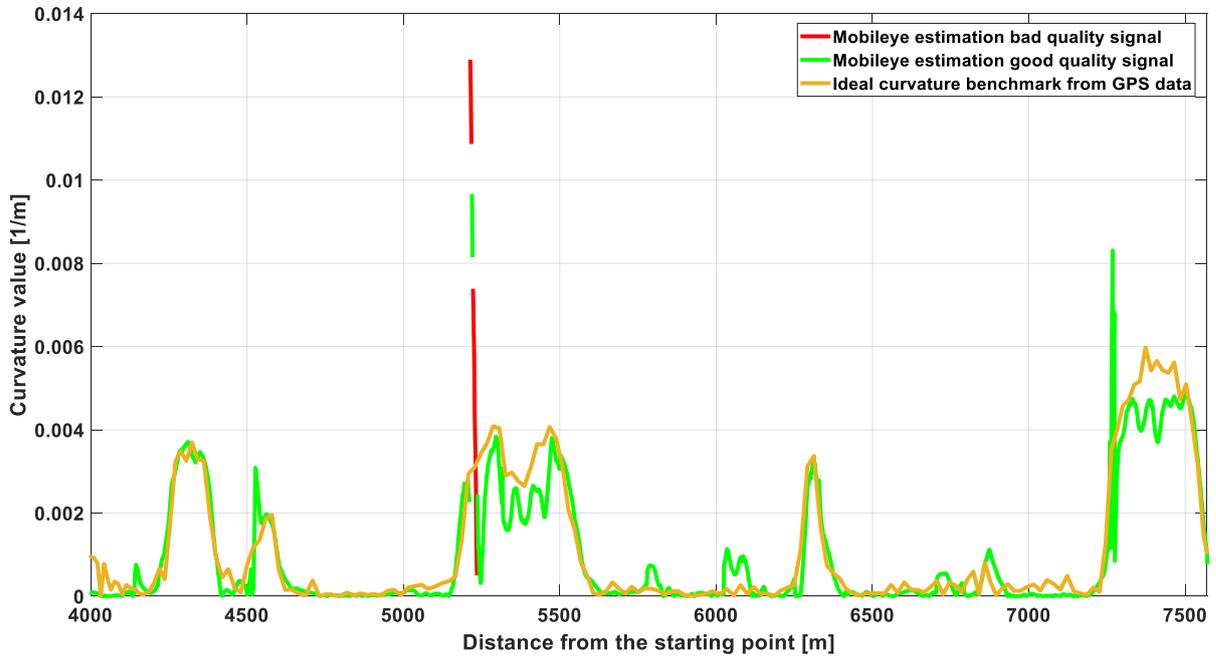


Figure 2-18 Curvature estimation comparison Mobileye vs ideal curvature. Part of path 1

3 Establishing the speed profile with Simulink models

Different models are used to elaborate data and create the speed profile. This introduction outlines the workflow for the speed profile creation, with the use of the model called “speed profile creation”.

Into the Simulink model, the vehicle along the path is simulated by imposing a constant speed equal to the speed limit as first input. When the model is running, the value of the speed used as input of the speed reduction function is the feedback from the function itself.

The speed signal is integrated in the simulation time domain, to obtain the distance from the starting point. The output is the position of the car along the path in meters. This simulates the car traveling along the route, and it is the parameter used for the interrogation of the look up tables containing curvature data.

Curvature data from the MSP are generated in advance for the path and loaded as variables inside the look up table “Curvature data input”. This procedure is studied to simulate the real function, that will be implemented in the car. Data for the onboard function are downloaded from the cloud (V2C), elaborated and the used when requested. In the Simulink model, the real time curvature output of the functions is simulated with the use of the look up table. The distance from the starting point signal, enters the look up as breakpoint and the output is the curvature of the correspondent point of the path in real time.

In the Simulink model, data for speed profiling from the Mobileye camera are loaded as variables inside the look up table “Curvature data input”. Using the distance from the starting point is simulated the real time output of the camera, which will be implemented in the onboard function.

Independently from the source curvature data are feed in the speed reduction function block. Other inputs include the lateral acceleration limit and the speed limit of the road. The output is the actuated speed which respects all the constrains.

Two auxiliary blocks compute longitudinal acceleration and jerk integrating the speed, and lateral acceleration. This is obtained by calculating the resultant lateral acceleration with the ideal curvature, where available.

3.2 Speed --> Distance block

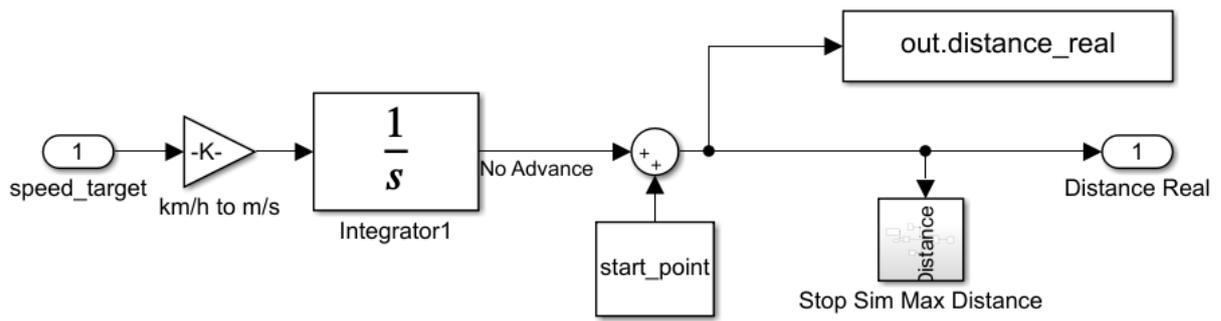


Figure 3-2 Speed--> Distance Block - Simulink Model

This block integrates the speed target, converts it in m/s and outputs the distance.

“**Distance real**” simulates where the car is along the path. It is also possible to start along the path, and not at the beginning, by loading the distance from the starting point in the variable **start_point**.

3.3 Speed reduction block

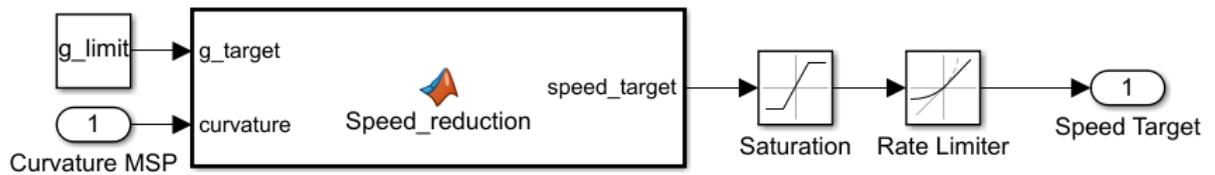


Figure 3-3 Speed reduction block - Simulink model

Using the described later **speed reduction function**, speed target is calculated. The saturation block limits the output of the speed to the speed limit.

Rate limiter: “This block limits the first derivative of the signal passing through it. The output changes no faster than the specified limit.” (28). The results can be seen inside the Figure 3-4. This block is important also the limit the values of longitudinal acceleration.

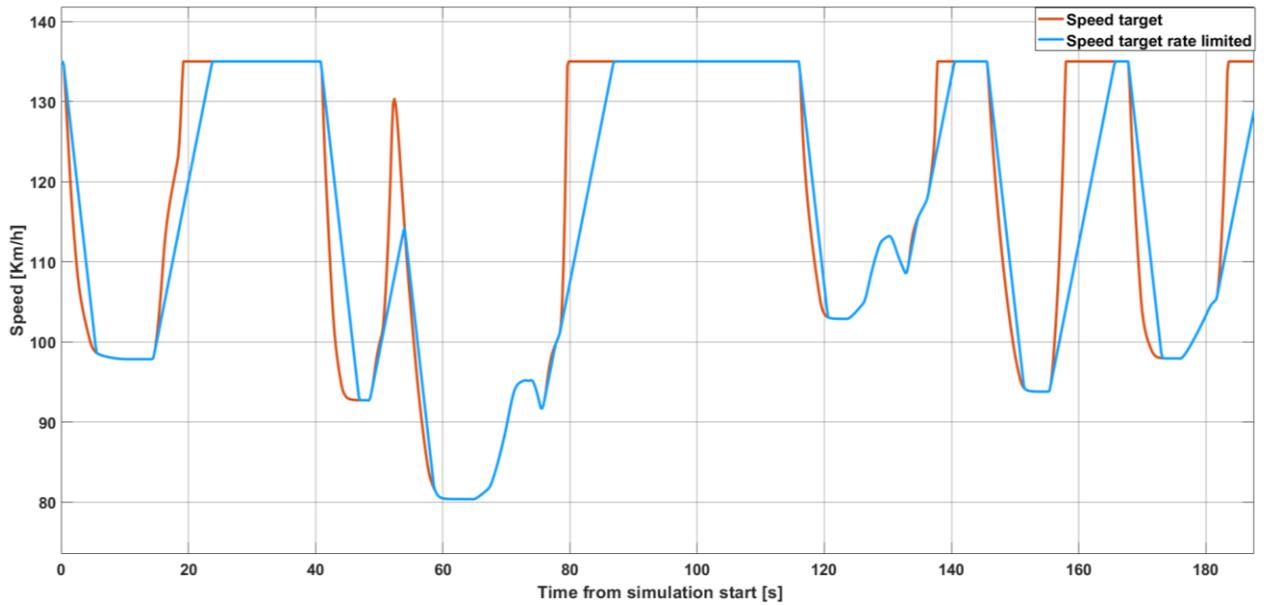


Figure 3-4 Speed target comparison with rate limiter

3.3.1 Speed reduction function

Speed is calculated in consequence of acceleration with the following formula:

$$Speed\ Target = \sqrt{Max\ Lateral\ Acceleration \times Radius}$$

Since this is a function related to the comfort, the value of max lateral acceleration is selected lower with respect to the admissible for a road car on dry tarmac. The aspects related to lateral acceleration limit are discussed in chapter 4.1.

3.4 Actuated lateral acceleration and jerk.

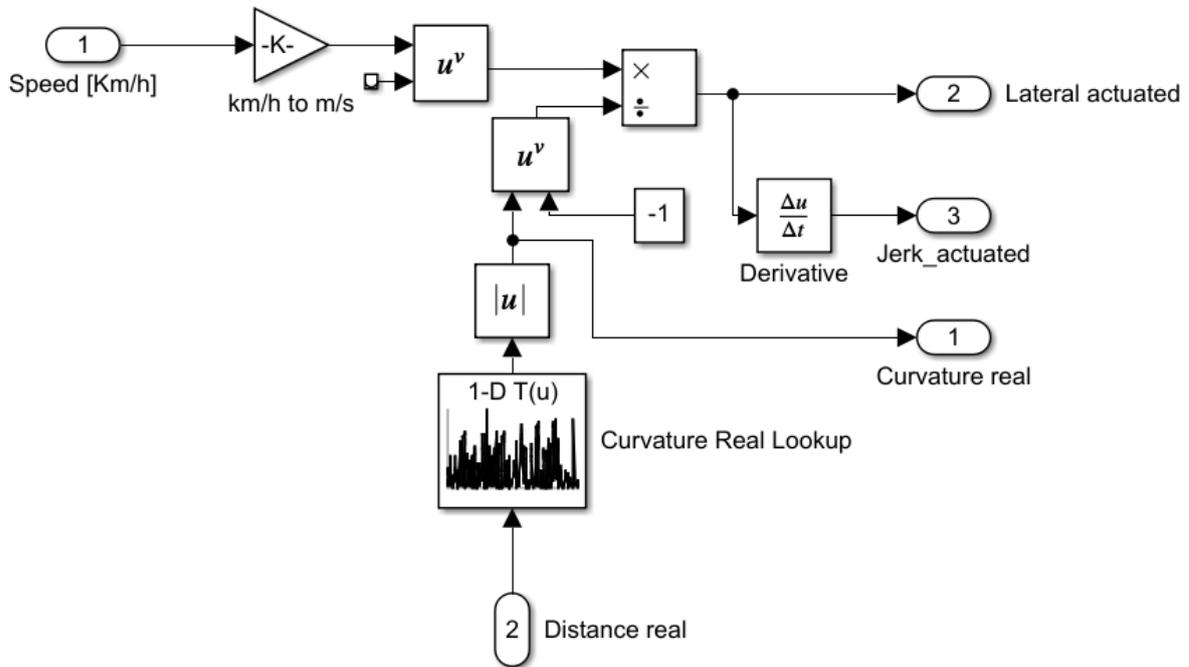


Figure 3-5 Actuated lateral acceleration block - Simulink Model

Actuated lateral acceleration is calculated using the real curvature, if available. The lookup table receives the real distance of the car from the starting point as the input and the curvature value is the output. Resultant lateral acceleration is calculated with the formula:

$$Acceleration = \frac{Speed^2}{Turn\ Radius}$$

The lateral acceleration depends also on transversal inclination of the road. In this study motorways and extra urban road are used as test paths. As state into DM 05/11/2001 (22) for this road typology transversal inclination is always higher than zero. Since it is not possible to retrieve transversal inclination from MSP and Mobileye data, the value is not considered. This assumption will lead to higher values of lateral acceleration, than the real ones.

3.5 Actuated longitudinal acceleration and jerk.

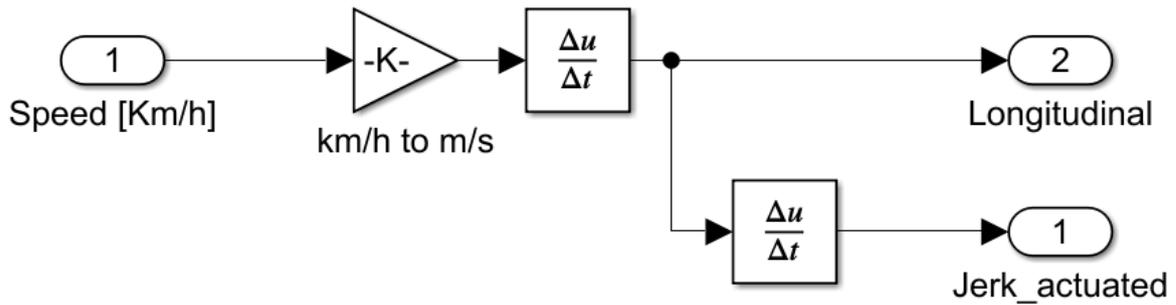


Figure 3-6 Actuated longitudinal acceleration - Simulink Model

This block outputs the longitudinal acceleration and jerk by deriving the speed target. These values are important to assess the performance of the function in terms of comfort.

3.6 Curvature for speed profile – Simulink model “Switch and hold”

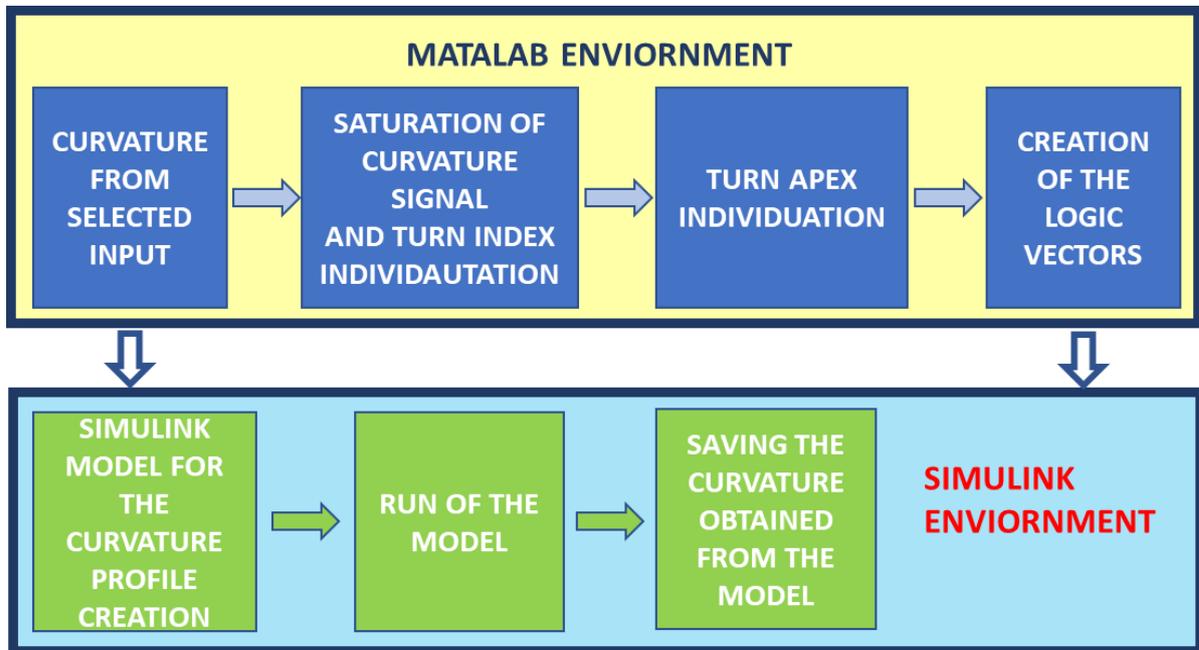


Figure 3-7 Workflow of the curvature for speed profile creation

The curvature used for the speed profile creation is elaborated with the use of the Simulink model “**switch and hold**”. The idea is to create a curvature vector which helps to slow down before the turn is reached, keep a constant speed value in the apex of the curve and then gradually accelerate. To do so the curvature profile is constructed starting from the request to the MSP, with considering a certain advance. The data elaboration is done through a MATLAB script and a Simulink model.

The test path is divided for ease of analysis in segments of 5 km each. Subsequently, the curvature is saturated at the minimum value of 0.001 (1000 m radius) to eliminate spikes that will influence the curvature index individuation. This is correct from a physical point of view. A turn with a radius of 1000 m produces less than 2 m/s^2 of lateral acceleration considering speed up to 150 km/h.

Executing the script saves points index with curvature bigger than 0.001 (1000 m radius). What is obtained is a vector (called **turn_index**) where the sequence of indexes, including all the turns of the path, are saved. **Turn index** vector is analyzed to obtain the index associated with starting and ending points of the single turn. Differences between two consecutive values of the vector are computed. If the result is more than 1, the previous value inside the cell of **turn_index** vector is saved as last point of the previous curve, and the current value as the first point of the new one. Once the turns are isolated from the path, it is possible to calculate local maximum and stored with the distance from the starting point.

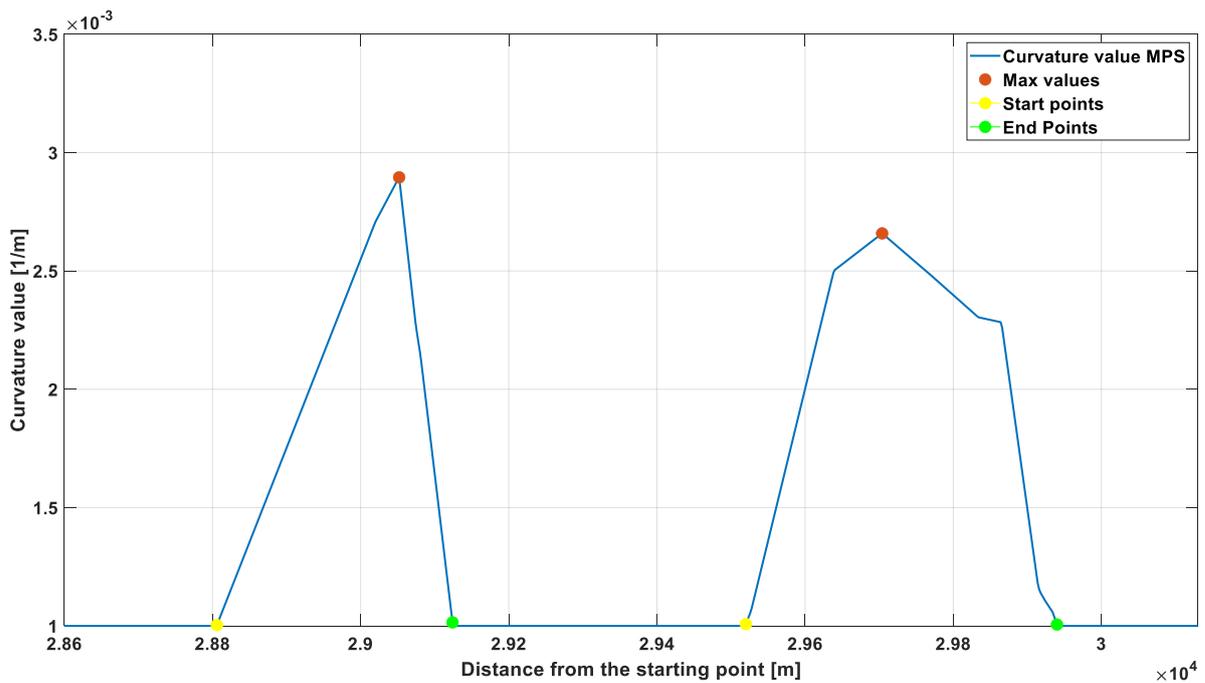


Figure 3-8 Turn index individuation and max values points

The profile is duplicated and then shifted by a distance usually referred as “advance”.

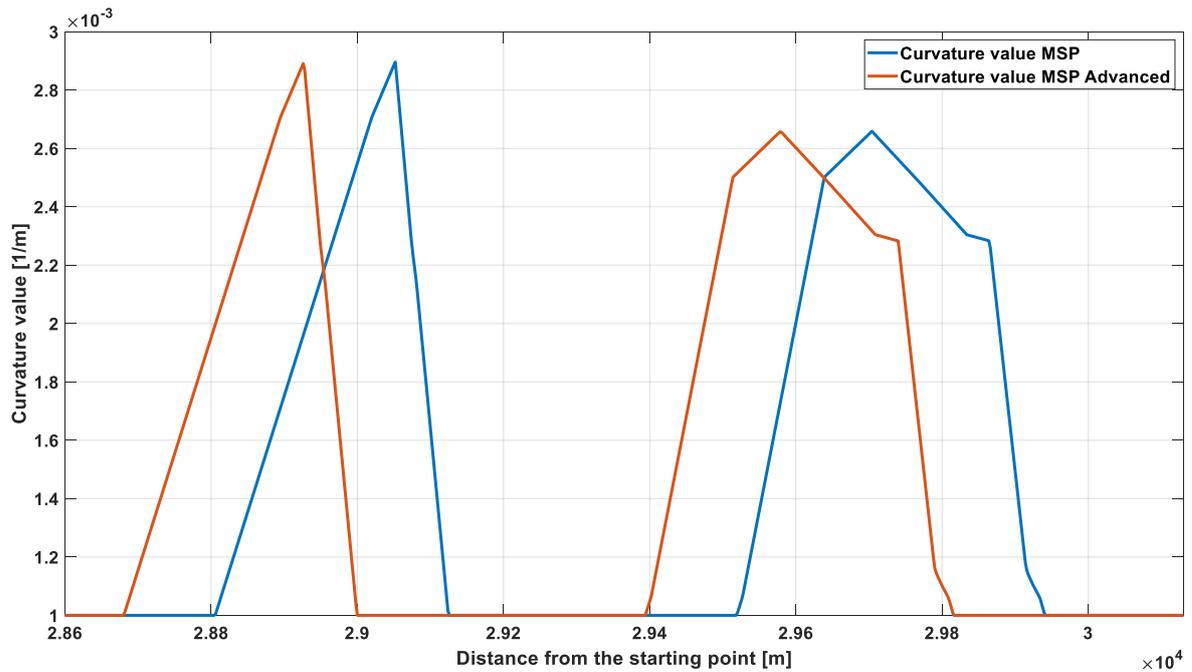


Figure 3-9 Curvature shifted with advance

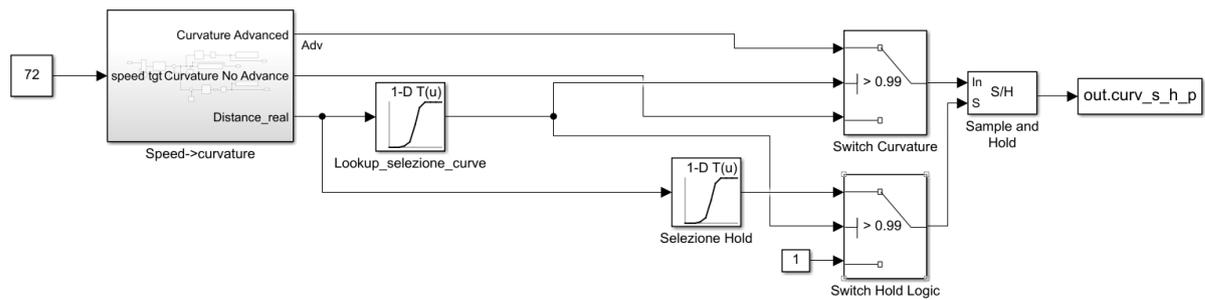


Figure 3-10 Simulink model "Switch and hold"

With the use of the Simulink model **"Switch and hold"**, peaks of the curvature profile are linked together in a single input holding the max value for the distance between peaks.

When the curvature is rising, the output from the model corresponds to the curvature value advanced. This is necessary to slow down the car with a certain advance in respect to the apex of the curvature. It is not advisable, from a dynamic point of view, to use tires for transmitting a longitudinal and lateral force at the same time.

When the peak of the advanced curvature is reached, the value is held until the peak of the curvature without advance. This is useful to maintain a constant speed in the apex of the corner.

Then output is done following the curvature without advance, for accelerating with the road curvature profile Results can be seen in Figure 3-11.

Curvature selection logic vector is created by assigning to all the elements of the vector a value of 1, for a vector length equal to the distance vector. With a for cycle, all the indexes between the max peak of curvature and end of the curve are assigned a value of 0. This will govern the “**switch curvature**” to pass the curve advanced until the peak of the curvature based on real distance is reached.

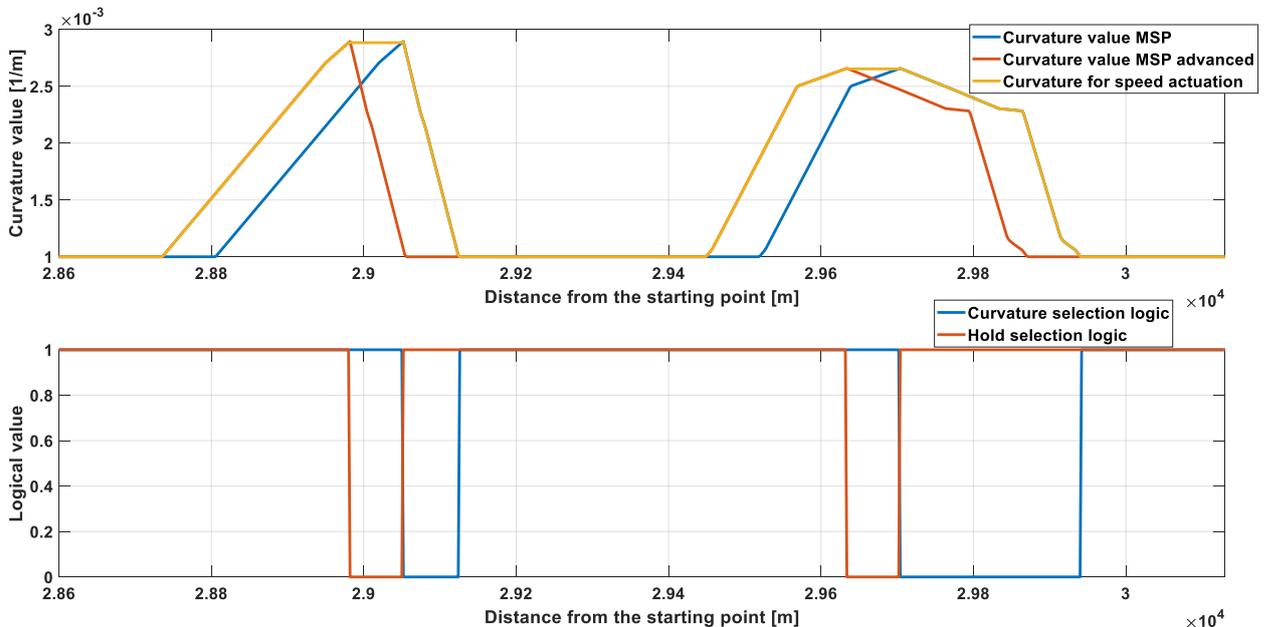


Figure 3-11 Curvature for speed profile actuation and switch logic

Hold logic vector is a copy of the **curvature selection logic**, but the associated **vector distance** for the lookup table is shifted by subtracting the advance value. This way, the output will be a 0 between the peak of the curve advanced and its end. This is just partially the output desired and to obtain the right one, another switch and the following block is used.

Sample and hold Simulink block working principal is: “the output follows input 1 (In) as long as input 2 (S) is TRUE (1). The output is held when input 2 becomes FALSE (0).” (29)

The right output to control the sample block is obtained with the **switch hold logic** block. Taking as control parameter the **curvature selection logic**, when its value drops to 0 the input to the hold block goes to 1, by the action of the **switch** hold block. This will result in the output of the curvature without advance as can be seen in Figure 3-11.

3.7 Mobileye sensor fusion logic- Simulink Model “Sensor fusion”

A quality vector is associated to the curvature value of the Mobileye signal. With an hoc Simulink model a sensor fusion logic is achieved. Synchronous curvature signals are fed into the switch block. When the quality of the signal drops below 1, the curvature from MSP is

output, if the quality value is a 1 the Mobileye curvature is output. The vector created with this method is saved and used in the same way of MSP data.

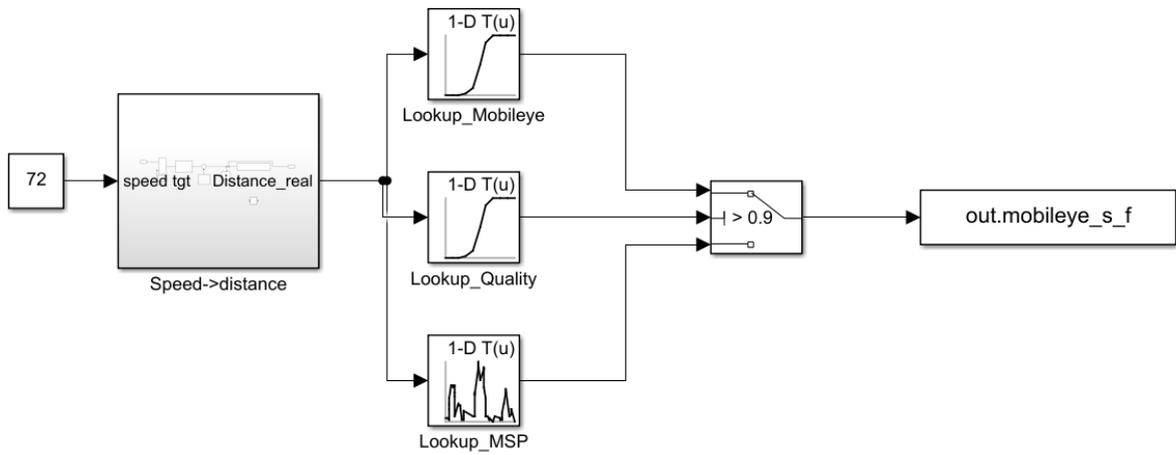


Figure 3-12 Simulink model for the sensor fusion of Mobileye signal

4 Results

An overview on the results and some sensibility analysis to parameter is proposed.

4.1 Limits on acceleration and jerk for a comfort ride

Acceleration and its derivative jerk are key factors in defining the comfort of the ride. In the literature, many values are cited and for this thesis the target limit for a comfort ride is imposed at 2 m/s^2 and a jerk of 0.9 m/s^3 (30).

4.2 How advance affects the results

The advance used in chapter 3.6 is necessary to slow down before the turn apex is reached. A sensibility analysis is proposed to evidence the importance of this parameter.

All data in chapter 4.2 are related to path 2.

Simulation Parameter	Value
Segment used in map service provider data estimation	250 [m]
Advance used in switch and hold logic Simulink model	90-190-220 [m]
Lateral acceleration limit	2 m/s^2
Speed target	135 [km/h]
Time constant low pass filter pre speed reduction block	0.5 [sec]
Time constant low pass filter post speed reduction block	1.7 [sec]
Rate limiter slew rate rising/falling	4 / -8

Table 4 Simulation parameters, MSP data. Part of path 2

Curvature data created with the use of **90 m** advance inside the switch and hold Simulink model, and speed profile associated:

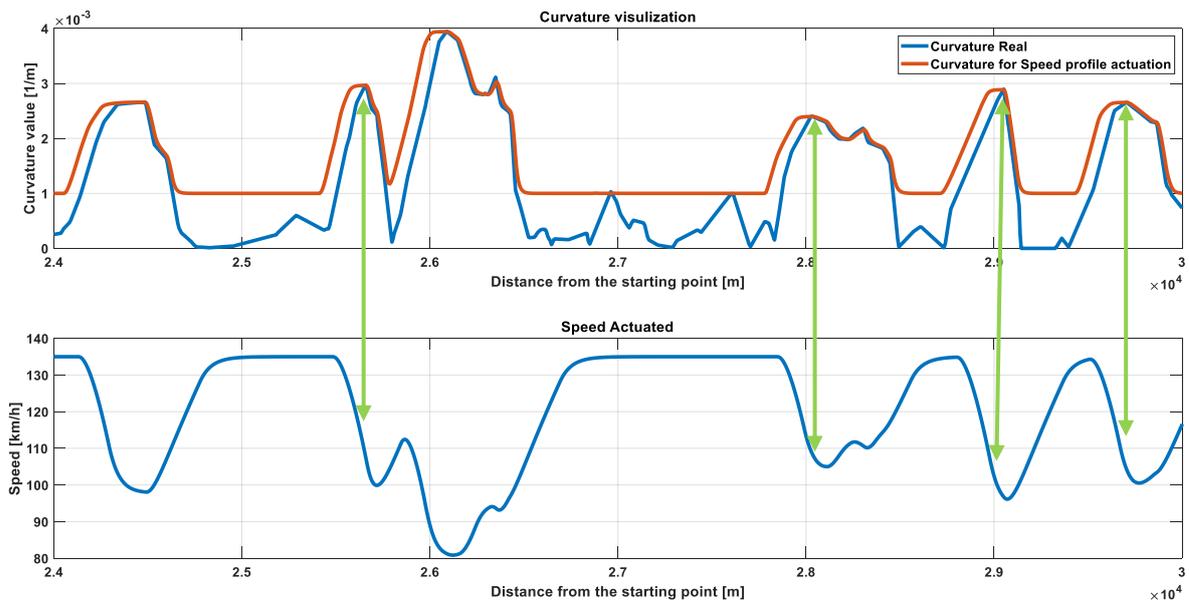


Figure 4-1 Curvature and speed synchronism, 90 m advance. Part of path 2. MSP data.

It can be noted that for some turns the car is still braking when the apex is reached. To avoid this behavior more advanced is needed.

Curvature data created with the use of **190 m** advance inside the switch and hold Simulink model, and speed profile associated:

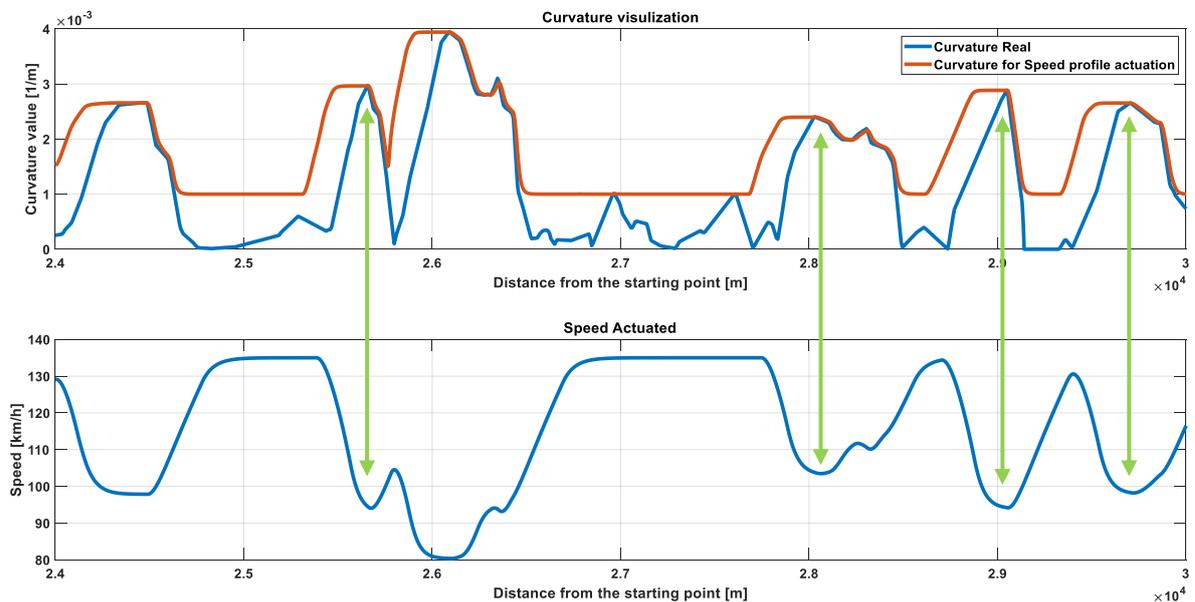


Figure 4-2 Curvature and speed synchronism, 190 m advance. Part of path 2. MSP data.

The synchronism is the right balance between not braking too early and avoiding a deceleration at the curve apex.

Curvature data created with the use of **220 m** advance inside the switch and hold Simulink model, and speed profile associated:

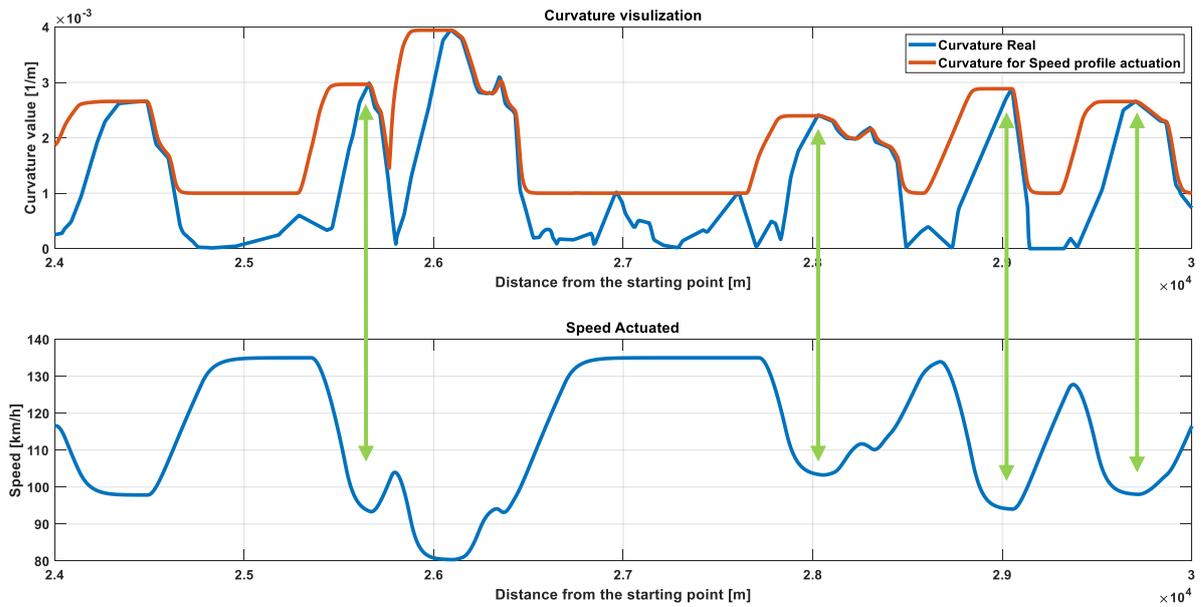


Figure 4-3 Curvature and speed synchronism, 220 m advance. Part of path 2. MSP data.

The consequence of excessive advance is the reduction of the speed too early in respect to the turn. This could be felt from the driver as too prudent and not desirable.

As shown in Figure 4-4, lower values of lateral acceleration are associated with the 190-220 m advance.

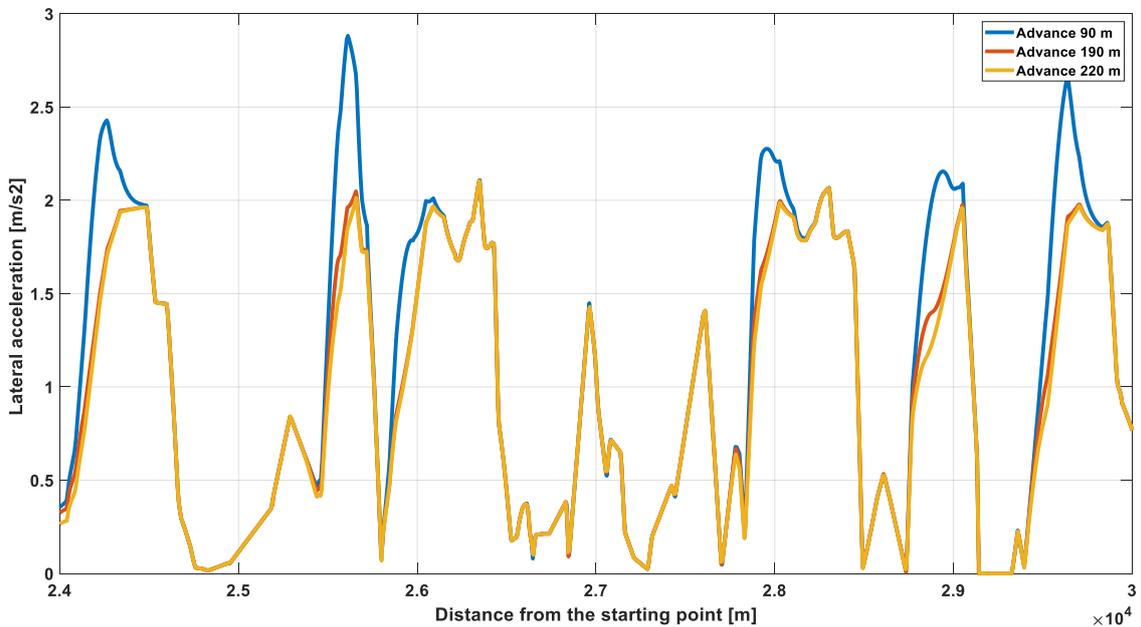


Figure 4-4 Lateral acceleration relationship with different advances. Part of path 2. MSP data.

4.3 Mobileye speed estimation and comparison with map service provider

Mobileye curvature estimation was recorded along path 1. The process for elaborating the data is like the one used for map service provider data. The only difference is the sensors fusion logic actuated based on quality parameter, explained in chapter 3.7.

Simulation Parameter	Value
Advance used in switch and hold logic Simulink model	125 [m]
Lateral acceleration limit	2 m/s ²
Speed target	95 [km/h]
Time constant low pass filter pre speed reduction block	0.5 [sec]
Time constant low pass filter post speed reduction block	1.7 [sec]
Rate limiter slew rate rising/falling	4 / -8

Table 5 Simulation parameter Mobileye data. Part of path 1

Only a selected part of the path is represented to show curvature value coherent with the aim of the project.

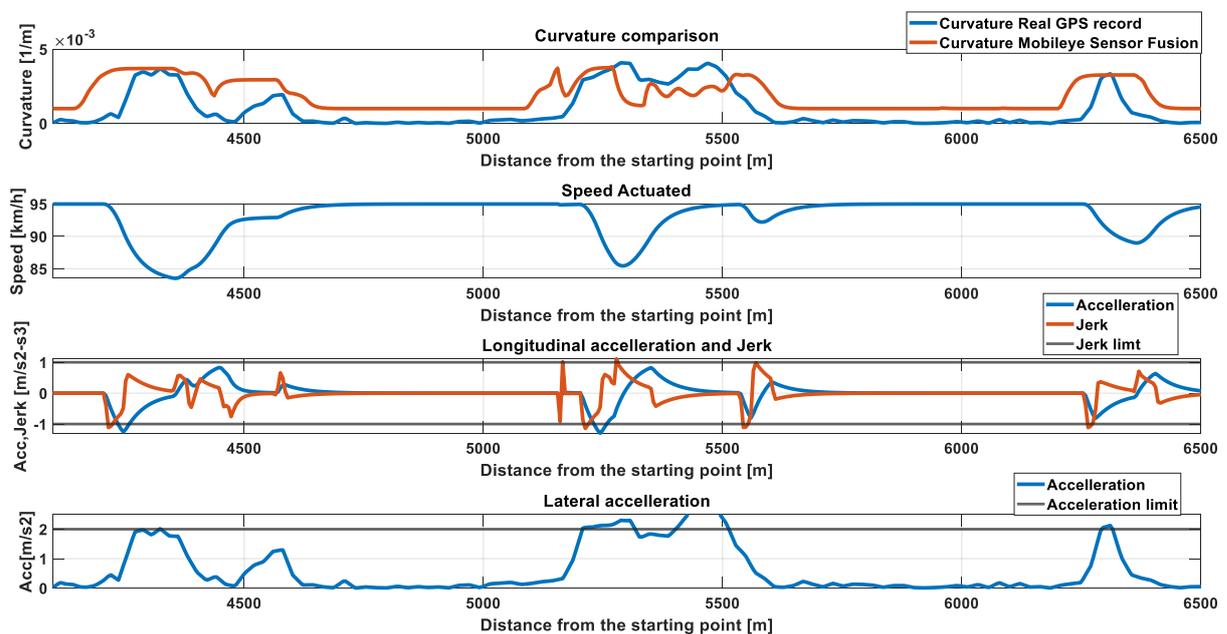


Figure 4-5 Simulation results Mobileye data from sensors fusion. Part of path 1

The problem with low quality signal and switch logic actuation (visible in Figure 2-18) is related with the turn between 5200 and 5600 m. The curvature value is underestimated and unstable with respect to the real. This results in higher lateral acceleration than threshold and poor speed control.

Simulation parameters for Mobileye data are the same of before.

Simulation parameters for MSP data are:

Simulation Parameter	Value
Segment used in map service provider data estimation	120 [m]
Advance used in switch and hold logic Simulink model	125 [m]
Lateral acceleration limit	2 m/s ²
Speed target	95 [km/h]
Time constant low pass filter pre speed reduction block	0.5 [sec]
Time constant low pass filter post speed reduction block	1.7 [sec]
Rate limiter slew rate rising/falling	4 / -8

Table 6 Simulation parameter MSP data. Part of path 1

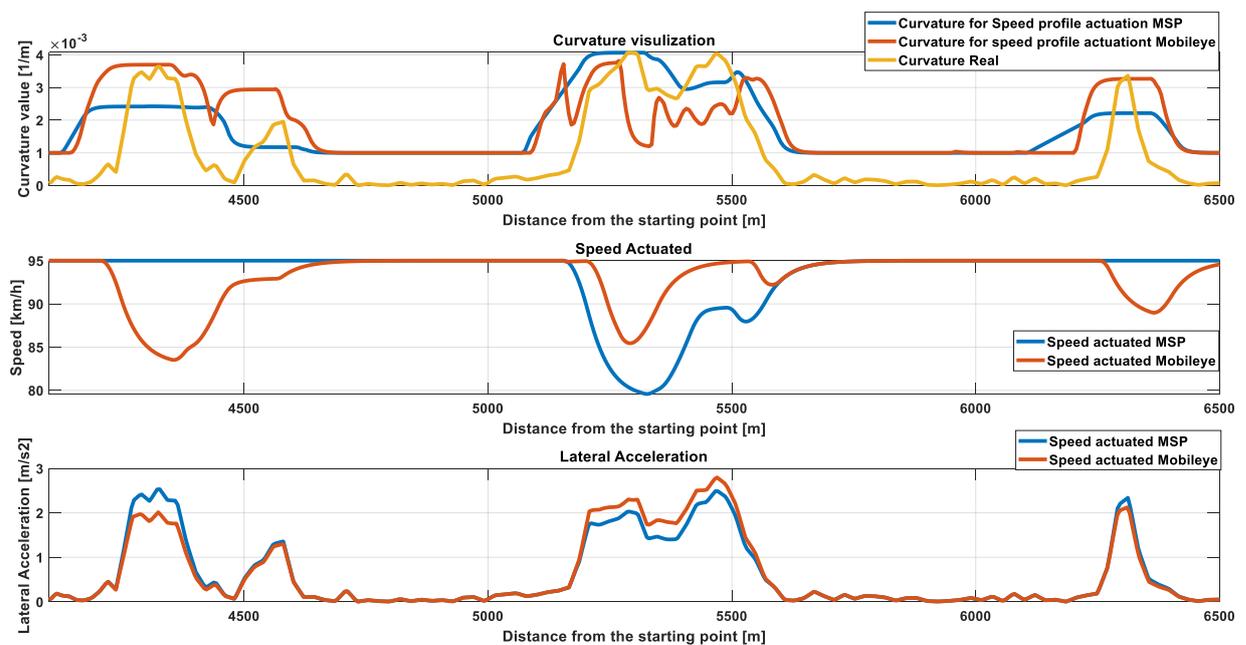


Figure 4-6 Curvature, speed and lateral acceleration comparison between Mobileye estimation and map service provider. Part of path 1

Results from MSP data seem to underestimate the curvature values for 2 turns. The possible cause is the high length (120 m) used for the segment parameter, with respect to the characteristic of the road. This will reflect in higher than threshold lateral acceleration. This comparison suggests that data from Mobileye estimation are usable, but further studies related to robustness of the signal are needed.

4.4 Speed profiles representing different driving behaviors

Three different speed targets and lateral accelerations limits are tested to represent three different driver behaviors. The aim is to demonstrate how the Speed profile prediction model reacts to different input parameters.

The first one is dedicated to a comfort driver. The parameters used for the simulation are:

Simulation Parameter	Value
Segment used in map service provider data estimation	250 [m]
Advance used in switch and hold logic Simulink model	150 [m]
Lateral acceleration limit	1.5 m/s ²
Speed target	115 [km/h]
Time constant low pass filter pre speed reduction block	0.5 [sec]
Time constant low pass filter post speed reduction block	1.7 [sec]
Rate limiter slew rate rising/falling	3/ -6

Table 7 Simulation parameters, different driver behaviors. Comfort driver. Part of path 2

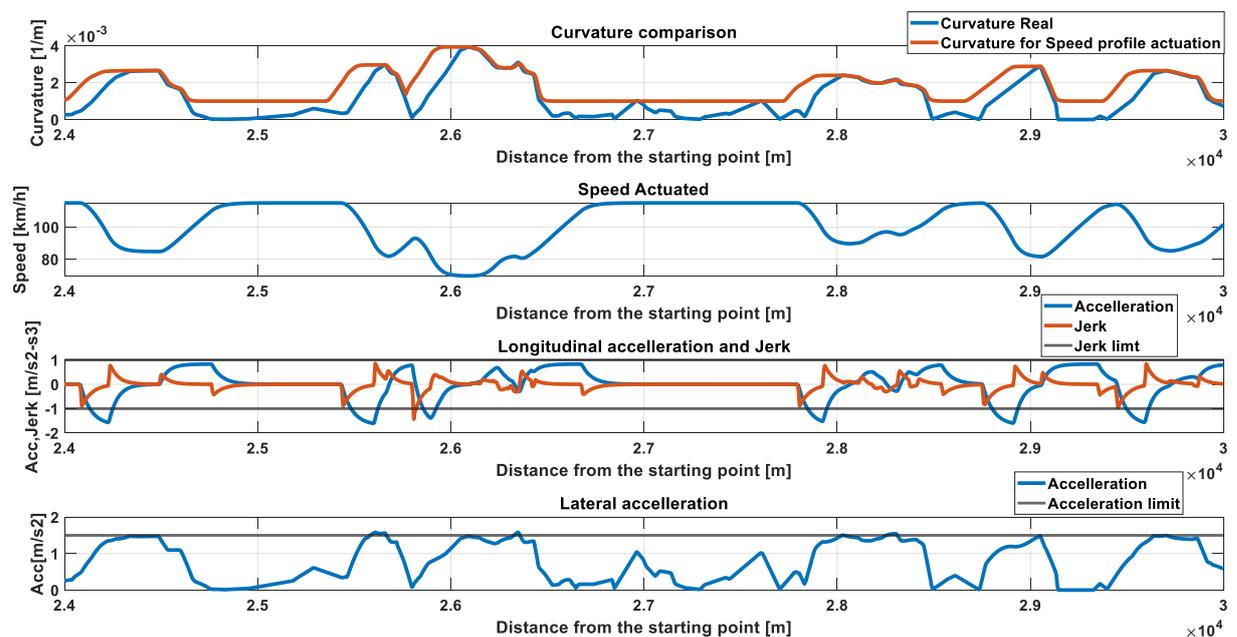


Figure 4-7 Speed, longitudinal acceleration and jerk and lateral acceleration. Comfort driver simulation. Part of path 2.

Synchronism between speed and curvature is optimal. Longitudinal acceleration is between the limits and only one jerk spike is higher than the threshold. Lateral acceleration is well constrained, with less than 5% error.

The second one is dedicated to a driver with balance between comfort and performance. Slew rates, speed limit and acceleration threshold are increased.

Simulation Parameter	Value
Segment used in map service provider data estimation	250 [m]
Advance used in switch and hold logic Simulink model	190 [m]
Lateral acceleration limit	2 m/s ²
Speed target	135 [km/h]
Time constant low pass filter pre speed reduction block	0.5 [sec]
Time constant low pass filter post speed reduction block	1.7 [sec]
Rate limiter slew rate rising/falling	4 / -8

Table 8 Simulation parameters, different driver behaviors. Balanced driver. Part of path 2

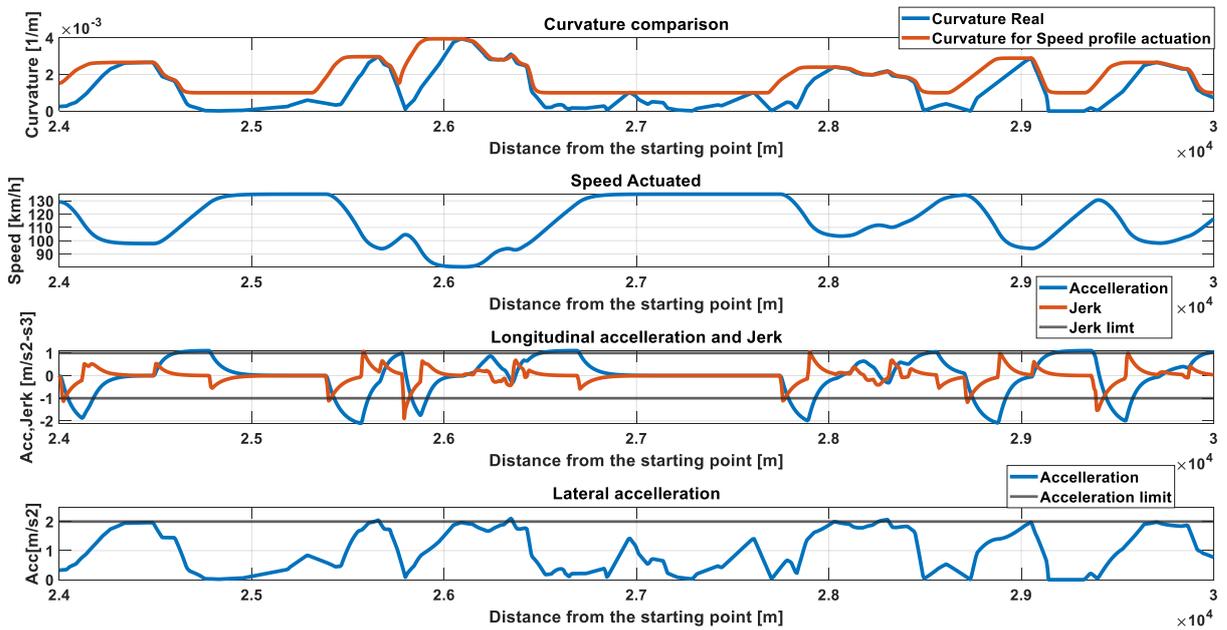


Figure 4-8 Speed, longitudinal acceleration and jerk and lateral acceleration. Balanced driver simulation. Part of path 2.

Synchronism between speed and curvature is optimal. Longitudinal acceleration is between the limits. The lateral acceleration is well constrained with less than 5% error. The jerk has two spikes outside of the limit.

The third profile is dedicated to a driver who is tolerant to accept higher values of acceleration, with an increase of the speed target. Advance is reduced from 190 to 150 m, so the deceleration is commanded more closely to the curve. Slew rates are increased to obtain higher value of longitudinal acceleration. The lateral acceleration limit is increased to 2.5 m/s² and the jerk limit to 1.5 m/s³.

Simulation Parameter	Value
Segment used in map service provider data estimation	250 [m]

Advance used in switch and hold logic Simulink model	150 [m]
Lateral acceleration limit	2.5 m/s ²
Speed target	145 [km/h]
Time constant low pass filter pre speed reduction block	0.5 [sec]
Time constant low pass filter post speed reduction block	1.7 [sec]
Rate limiter slew rate rising/falling	5 / -10

Table 9 Simulation parameters, different driver behaviors. Sport driver. Part of path 2

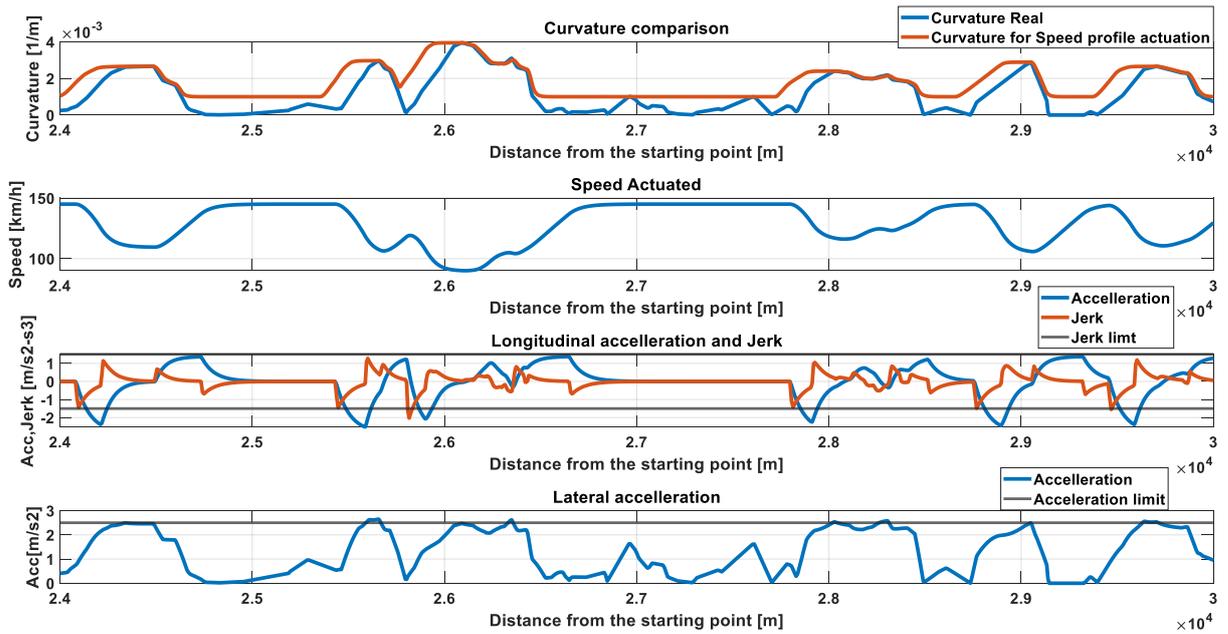


Figure 4-9 Speed, longitudinal acceleration and jerk and lateral acceleration. Sport driver simulation. Part of path 2.

Synchronism between speed and curvature is optimal. Longitudinal acceleration is between the limits. Only one jerk spike is higher than the threshold. The error associated with lateral acceleration is always under 5 %.

For all the three drivers profile good results are achieved. These results evidence the flexibility of the speed profile prediction model.

5 Conclusion and future work

In this thesis work a speed profile for actuating an enhanced version of an Adaptive Cruise Control (ACC) was presented. The aim was to create a speed profile, where the minimum speed for the turn is at the apex of the corner. Other constraints were imposed by lateral and longitudinal acceleration and jerk, to obtain a good level of comfort. The lateral acceleration was controlled, in the reference cases of chapter 4.4, with an error of maximum 5 %. The values used for the ideal curvature data is not from a GPS recording, so the data cannot be considered as real. Further tests regarding this aspect are needed.

Data were retrieved from three different inputs: map service provider, camera with built ADAS function and GPS recording. From raw geographic data a conversion into local cartesian was done. When the data in local cartesian have been obtained, different strategies for curvature definition were tested. The best one was selected in the Pratt Method and curvature was obtained and processed with MATLAB and Simulink.

The speed profile was created and tested in the Simulink environment, where both path 1 and path 2 could be executed. Sensitivity analysis to variables like as: advance used in curvature defining, speed limit and lateral acceleration level have been conducted.

Since this is a preliminary study, many possibilities are open to improve and extend this work.

One would be the research of better data from the map service provider, using commercial services. Better coordinates in terms of description of the path and discretization, will improve the accuracy of curvature estimation.

The second possible improvement would be a more extensive test campaign to better characterize the Mobileye signal. Aspect regarding robustness in respect to ambient factor, precision of estimation and synchronism would be improved.

Last proposal is an integration with a lateral adherence limit calculus. This can be predictive and actuate the minimum speed between comfort limited or adherence limited. Inside this work it was not implemented, due to the high complexity of a realistic model. Beside from this, lateral accelerations limit used in this work, for comfort, are well below the adherence limit of a road car in a motorway with dry conditions.

6 References

1. **European Commission** . Intelligent transport systems . [Online] https://ec.europa.eu/transport/themes/its/road_it#:~:text=Although%20road%20fatalities%20are%20decreasing,is%20a%20much%2Dneeded%20development..
2. **Tutorialspoint**. MATLAB-Functions. [Online] <https://bit.ly/3o0bjc6>.
3. **Wikipedia**. MATLAB. [Online] <https://en.wikipedia.org/wiki/MATLAB>.
4. **MathWorks**. Programming and Scripts. [Online] https://it.mathworks.com/help/matlab/learn_matlab/scripts.html?lang=en.
5. **Wikipedia**. Simulink. [Online] <https://en.wikipedia.org/wiki/Simulink>.
6. **Quattroruote**. 764, s.l. : EditorialeDomus, April 2019, pp. 76-77.
7. **Euroncap**. Euroncap. [Online] [Cited: April 21, 2021.] <https://www.euroncap.com/en/results/bmw/3-series/38531>.
8. **Franco, Adam**. RoadCurvature. [Online] [Cited: March 25, 2021.] <https://roadcurvature.com/how-it-works/>.
9. **Road Safety Facts** . [Online] [Cited: 20 April 2021.] <https://roadsafetyfacts.eu/>.
10. **SAE**. Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles J3016_201806. SAE International. [Online] https://www.sae.org/standards/content/j3016_201806/.
11. **Wikipedia**. Radar. [Online] [Cited: 21 April 2021.] <https://en.wikipedia.org/wiki/Radar>.
12. **Teslatap**. [Online] [Cited: April 12, 2021.] <https://teslatap.com/articles/autopilot-processors-and-hardware-mcu-hw-demystified/>.
13. **Bosch**. Medium Range Radar . [Online] [Cited: April 20, 2021.] <https://www.bosch-mobility-solutions.com/en/products-and-services/passenger-cars-and-light-commercial-vehicles/driver-assistance-systems/lane-change-assist/mid-range-radar-sensor-mrrrear/>.
14. —. Short range radar . [Online] [Cited: April 20, 2021.] <https://www.bosch-mobility-solutions.com/en/products-and-services/passenger-cars-and-light-commercial-vehicles/driver-assistance-systems/construction-zone-assist/ultrasonic-sensor/>.

15. *Tesla Owners Online* . [Online] https://teslaownersonline.com/threads/camera-locations.11375/#lg=_xfUid-1-1602773797&slide=0.
16. *Bosch. Multipurpose Camera*. [Online] [Cited: April 20, 2021.] <https://www.bosch-mobility-solutions.com/en/products-and-services/passenger-cars-and-light-commercial-vehicles/driver-assistance-systems/lane-departure-warning/multi-purpose-camera/>.
17. *Wikipedia. Connected Car* . [Online] https://en.wikipedia.org/wiki/Connected_car.
18. *NHTSA. Vehicle To Vehicle Communication*. [Online] <https://www.nhtsa.gov/technology-innovation/vehicle-vehicle-communication>.
19. *Continental . eHorizon-Intelligent Speed Assist*. [Online] <https://www.continental-mobility-services.com/en-en/ehorizon-intelligent-speed-assistance/>.
20. *Bmw. e-Drive Zone*. [Online] <https://www.bmwgroup.com/en/elektromobilitaet/ezones.html>.
21. *Risparmiare con le plug-in . Quattroruote. s.l. : EditorialeDomus, March 2021, p. 167*.
22. *Ministero delle Infrastrutture e dei Trasporti D.M. Norme funzionali e geometriche per la costruzione delle strade*. [Online] 5/11/2001. <https://www.mit.gov.it/mit/site.php?p=normativa&o=vd&id=216>.
23. *Wikipedia. KML*. [Online] [Cited: April 14, 2021.] https://en.wikipedia.org/wiki/Keyhole_Markup_Language.
24. *Geographiclib, Charles Karney. MATLAB Central File Exchange*. [Online] [Cited: March 26, 2021.] <https://www.mathworks.com/matlabcentral/fileexchange/50605-geographiclib>.
25. *Stafford, Roger. Matlab Central*. [Online] https://it.mathworks.com/matlabcentral/answers/57194-how-to-find-the-sharp-turn-in-a-2d-line-curve#answer_69185.
26. *Chernov, Nikolai. MATLAB Central File Exchange* . [Online] 2021. [Cited: April 14, 2021.] <https://www.mathworks.com/matlabcentral/fileexchange/22643-circle-fit-pratt-method>.
27. *V.Pratt. Direct least-squares fitting of algebraic surfaces. Computer Graphics. 1987, Vol. 21, pp. 145-152*.

28. MATLAB. Rate Limiter. [Online] <https://bit.ly/2QP8Ipj>.

29. —. Sample and Hold. [Online] <https://bit.ly/33pmQZc>.

30. Svensson, Jenny Eriksson Lars. *Tuning for Ride Quality in Autonomous Vehicle*. 2015.