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Master's Thesis

Real-Time Driver Advisory System for Fuel Economy based on the ADASIS data

Milan Cvetković

Supervisors: doc. Ing. Pavel Hrubeš, Ph.D.
Ing Dmitry Rozhdestvenskiy
Doc. Cristina Olaverri Monreal, Ph.D.

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CZECH TECHNICAL UNIVERSITY IN PRAGUE
Faculty of Transportation Sciences
Dean's office
Konviktská 20, 110 00 Prague 1, Czech Republic

K620...Department of Transport Telematics

MASTER'S THESIS ASSIGNMENT

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Milan Cvetković

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Guides for elaboration

During the elaboration of the master's thesis follow the outline below:

- Research of the Horizon 2020 project and ADASIS protocol
- Overview of active, current ADAS projects aimed on fuel economy improvement
- Research of existed modern State of The Art real time advisory systems for fuel Economy based advance map data
- Construct requirements to the protocol for the data structure, update frequency for the designed system
- Develop and implement algorithms in Modelica programming language
- Test and evaluate developed algorithm in terms of fuel efficiency
- Cross check algorithm behavior in terms of user acceptance (driver, follow up vehicle, other road participants)

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Accompanying report length: Minimum of 55 pages of text (including graphs and tables, which are the part of the thesis)

Bibliography:

Giancarlo Genta: Motor vehicle dynamics. Modeling and Simulation, World Scientific, 1997

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Peter A. Fritzson: Principles of object-oriented modeling and simulation with Modelica 3.3, J. Wiley & Sons, 2015

Master's thesis supervisor:
doc. Ing. Pavel Hrubeš, Ph.D.
Ing. Dmitry Rozhdestvenskiy
doc.Cristina Olaverri Monreal, Ph.D.

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L.S.

doc. Ing. Pavel Hrubeš, Ph.D.
head of the Department
of Transport Telematics

prof. Dr. Ing. Miroslav Svítek, dr. h. c.
dean of the faculty

I confirm assumption of master's thesis assignment.

Milan Cvetković
Milan Cvetković
Student's name and signature

Prague .... June 1, 2017

Declaration

I hereby declare I have written this Master thesis independently and quoted all the sources of information used in accordance with methodological instructions on ethical principles for writing an academic thesis. Moreover, I state that this thesis has neither been submitted nor accepted for any other degree.

Milan Cvetković

Milan Cvetković

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Abstract

The aim of this thesis is to develop Real-Time Driver Advisory System (RTDAS) for improving driving fuel economy of vehicles powered by internal combustion engines (ICE) and/or a hybrid energy system (HES). Model is going to be based on usage of a road map data provided in accordance with the second version of Advance Driver Assistant Systems Interface Specification (ADASIS v2) Protocol. Road map data will be transformed in a so called Electronic Horizon. As Electronic Horizon provides a preview of the road characteristics ahead of the vehicle, it will be used for development of a predictive fuel economy algorithms. System is going to be focused on static characteristics of the road ahead such as road slope, curvature, superelevation, speed limits and the traffic signs. Based on these road characteristics and vehicle configuration, system is going to use adequate algorithms to define when to send, if needed a message to the driver to release a gas pedal and to achieve higher fuel economy, comfort and safety of driving.

This thesis is an attempt to address the following issues:

- Development and usage of ADAS to improve fuel economy;
- Usage of Electronic Horizon data structure in ADAS (Advance Driver Assistant System) applications;
- Development and implementation of predictive algorithms in Modelica programming language;
- Testing and evaluation of developed algorithm in terms of fuel efficiency.
- Development of cross check algorithm in terms of user acceptance

Key words: ADAS, ADASIS v2 Protocol, Electronic Horizon, Advisory Curve Speed, Road Geometry, Hybrid Vehicle, Road Map Data, Modelica

Abstrakt

Cílem této práce je vyvinout asistenční systém pracující v reálném čase (EN: Real-Time Driver Advisory System - RTDAS) pro vylepšení spotřeby paliva vozidla poháněného spalovacím (ICE) či hybridním pohonným (HES) ústrojím. Systém je založen na využití dat o trase, která jsou poskytována pomocí protokolu ADASIS v2 (Advance Driver Assistant Systems Interface Specification, version 2). Data o trase jsou transformována do podoby tzv. “Elektronického horizontu”. Elektronický horizont poskytuje přehled o charakteristikách průjezdní trasy před vozidlem. Elektronický horizont bude použit k vývoji prediktivního algoritmu pro spotřebu paliva. Systém se zaměří na statické charakteristiky jako například sklon vozovky, křivost a klopení zatáček, rychlostní limity a dopravní značení. Na základě těchto dat a charakteristik vozidla algoritmus vyhodnotí okamžik, kdy má řidiči vyslat zprávu k uvolnění plynového pedálu vedoucí ke zlepšení spotřeby, zvýšení komfortu a bezpečnosti jízdy.

Práce se zabývá následujícími tématy:

- Vývoj a využití asistenčního systému (ADAS) pro zlepšení spotřeby paliva
- Využití dat eletronického horizontu v systémech ADAS
- Vývoj a implementace prediktivního algoritmu v jazyce Modelica
- Testování vlivu vyvinutého algoritmu na spotřebu paliva
- Ověření uživatelské přívětivosti při aplikaci výstupu algoritmu

Klíčová slova: ADAS, ADASIS v2 Protokol, Elektronický horizont, Rychlost poradní křivky, Silniční geometrie, Hybridní vozidlo, Mapové podklady, Modelica

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Abbreviation index

ADAS	Advance Driver Assistant System
ADASIS	Advance Driver Assistant System Interface Specification
Electronic Horizon	The map data, e.g. road geometry, number of lanes, speed limits, etc. provided on a vehicle bus system
VI-DAS	Vision Inspired Driver Assistance Systems
RTDAS	Real-Time Driver Advisory System
ISA	Speed Adaptation System
CSW	Curve Speed Warning
HDV	Heavy-duty vehicle
GDF	Geographic Data Files
DFCO	Deceleration Fuel Cut-Off
CAN	Controller Area Network
GPS	Global Positioning System
ECU	Engine Control Unit
MPP	Most Probable Path
HES	Hybrid Energy System
ICE	Internal Combustion Engine

Introduction

The basic ideas of modern society are to promote sustainable mobility while achieving a more efficient, safer, cleaner and secure transport of passengers and goods. Transport is widely recognized as an important factor that affects creation of conditions for economic growth and progress in modern society. On one hand, the mobility of the population and on the other the movement of goods generate constant growth of transport activities following economic growth and its improvement. According to the statistics, despite the economic recession in 2008 that primarily caused the decline of freight transport, in the period from 1995 to 2014 the average growth of total freight transport was 1.1%, passenger transportation 1.1%, while the average GDP growth was 1.6% [1]. The growth of freight and passenger transport goes primarily with negative effects on the environment by additional fossil fuels usage. The transport sector accounts for 33.2% of the total energy consumption in the European Union for 2014, of which 82% is used in road transport [2]. The transport sector generated 23.2% of overall GHG Emission for 2014, of which 72.8% comes from road transport [2]. Statistics clearly shows the negative effects of future economic growth deriving from transport.

Moreover, besides the negative impact of the road transport on environment, traffic accidents are clearly another critical issue. According to the data provided by European Commission in the period from 2010 to 2016 there was a reduction of 19% in the number of traffic accident fatalities [3]. Having in mind that European roads are the safest in the world this is not an encouraging statistics. In 2016, the European Union counted 50 road fatalities per one million inhabitants, against 174 deaths per million globally [3]. Even though this trend is appositive one, it is not sufficient to achieve the planned reduction target in number of fatalities by 50% for the period from 2010 to 2020. This requires the reduction of 11.5% annually in the years to follow in order to reach the desired target [4].

The importance and potential of ADAS applications are widely recognized, not only by the vehicle manufacturers that invest a lot of resources, but also by the state institutions. Good example is the European Union which gives considerable attention to this field through regulations related to the usage of ADAS and by financing the development projects related to this field. Horizon 2020 as the biggest EU Research and Innovation programme ever, with the fund of nearly €80 billion available for the period of about 7 years (2014 to 2020) includes, besides others, numerus projects that develop ADAS applications.

Despite the constant technological development in the field of vehicle fuel economy, emission reduction and safety, the effects of technical solutions are to some extent neutralized by mentioned constant growth of mobility and volume of freight transport. Therefore, more effort should to be directed to innovative approaches of combining existing technologies in all transport related fields to improve utilization of available potentials. One of the recognized tools are contemporary Advance Driver Assistant Systems. The focus of this thesis is development of such a system relaying on the available and upcoming technologies present on the market.

First of all, the thesis investigates opportunities of the new achievements in the development of digital maps, which contain a large number of relevant road characteristics, important for contemporary ADAS solutions. The thesis will take into consideration the latest official standard of map data provision (ADASIS v2 Protocol) defined by relevant industry stakeholders. Based on the data availability and the provision standard, Real-Time Driver Advisory System targeting driving economy, safety and comfort, will be developed. The system will provide advisory message to a driver, when to release the gas pedal in order to avoid unnecessary braking and improve usage of existing vehicle kinetic energy or its conversion to the electrical during the typical deceleration cases. As input data, the decision model will use road geometry, traffic regulation signs and vehicle characteristics. This way the model evaluates the precise timing of advisory message given to a driver. All map data will be provided for a system as Electronic Horizon. The Electronic Horizon is the new standardized interpretation of reality conditions present in front of vehicle. As such, this reality goes far beyond sensitivity range of both, human eye and related vehicle sensors. The system usage will generate fuel and energy savings and predicted time losses. The cost-benefit analysis will be estimated and expressed as an “trade off function” in this thesis. At the end, the system will be tested with a simulation software, using the segment of existing road, drive cycle obtained by test drive on simulator and relevant vehicle mode. This way the expected effects of applied model will be estimated and the model logic itself validated.

Evaluation of the user acceptance of system features and effects (follow up vehicle, other road participants, etc.) will be covered within ongoing research project “Advanced assisting systems and their UI for future EV and HEV” (SGS15/224/OHK2/3T/16).

The following parts of this master thesis are organized in 7 chapters. Chapter 1 introduces the ADAS Electronic Horizon concept and ADASIS standard. Chapter 2 gives an overview about contemporary ADAS research, trends and solutions and summarizes the most recent advancements in European research projects. In chapter 3 the Real-Time Driver Advisory System is described and logic of the models incorporated in this system explained. Also, in this chapter are explained the tools used for the purpose of study realization. In chapter 4 is provided explanation of procedure of creating deceleration models, while chapter 5 explains detailed calculation of deceleration speed profiles. Chapter 6 contains description of a system validation and the fuel/energy economy effects. In chapter 7 is presented process of estimation of RTDAD user acceptance. The last part of this thesis is the conclusion, which summarizes all results of implemented and tested system solutions and defines the future research and development steps.

1 ADAS electronic Horizon – ADASIS Standard

Contemporary predictive ADAS solutions rely on quality data from digital maps used to create digital environment of vehicle. Digital environment is presented as road ahead network with all necessary attributes requested by ADAS applications. Such a digital environment is named Electronic Horizon or ADAS Electronic Horizon. According to the purpose of ADAS applications, varying requirements can be made available from. Since Electronic Horizon provides vast variety of available data, ADAS applications are enabled to set requirements in accordance to their particular purpose. Specification of required data can be related to the road attributes, resolution, and size/length of Electronic Horizon.

In order to improve and standardize Electronic Horizon presentation for ADAS, the main ADAS industry stakeholders initiated ADASIS forum. The members of ADSIS forum are Vehicle Manufacturers, Navigation Systems Suppliers, ADAS Suppliers and Map and Data Providers. The ADASIS forum has already developed the two versions of ADASIS protocols which standardize the representation and transmission of attributes in the ADAS Electronic Horizon.

1.1 ADASISv1

The first version of ADASIS protocol was developed as a part of the MAPS&ADAS subproject of PReVENT project driven by the needs brought up in the ADASIS Forum discussions on the use of digital maps as primary and/or secondary sensors for ADAS [5]. The ADSIS Forum is established in 2001 and it is coordinated by ERTICO with aim to support and promote the development and the implementation of ADASIS communication protocol between digital map data and ADAS applications.

The ADASISv1 protocol was describing the road geometry ahead of a vehicle by using vehicle position and a digital map data. Technical feasibility of concept was tested and proven but also recognized as too complex for existing production environment of equipment manufacturers.

1.2 ADASISv2

After ending of the MAPS&ADAS subproject in 2006 additional work has been done by ADASIS Forum on further development and improvement of ADAIS Protocol. The ADASIS Forum changed the organizational structure and start functioning as open industry forum. As achievements of the first version were recognized as significant and promising ADASIS assembled more than 30 members from different sectors of the European automotive industry willing to continue further work. Result of this cooperation and activities was updated version of protocol released in 2010 as ADASIS v2 Specification now already accepted as the standard.

1.3 ADASISv3

As automated driving is being more and more reality, from 2014, the ADASIS Forum started development of new specifications ADASIS v3 focused on automated driving. It was planned to be first released by Mid-2016 and available to all ADASIS members [6]. During the 6th meeting of the Open Auto Drive Forum (OADF) in Brussels on 16 February 2017, Michael Klingsöhr, ADASIS Chairman said that 2017 will be a major milestone for the ADASIS Forum and that ADSIS Forum is committed to publish their new ADASIS v3 Specification during 2017, [7]. However, it is obvious that further development of protocol is going to be focused on contemporary automotive technologies and higher focus on automated driving.

1.3.1 ADSIS v2 System Architecture

The main element of ADAS application architecture are [8]:

- ADAS Horizon Provider (Av2HP)
- ADAS Protocol (Av2)
- ADAS Application
    - ADAS Reconstructor (Av2HR)

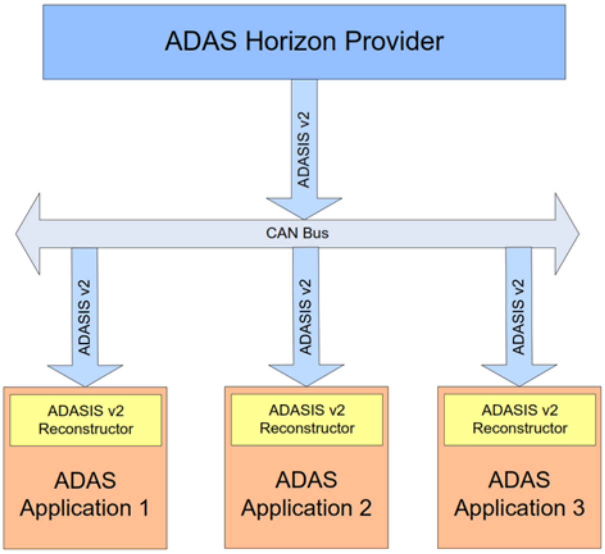

Figure 1.1 ADSIS v2 System Architecture [8]

An ADAS Horizon is created by using road related digital map data that are out of driver eyesight and vehicle sensors field of view. Digital map data are maintained by ADAS Horizon Provider and delivered to ADAS Applications by using ADASIS v2 protocol defined messages. ADAS Horizon data transfer is done via vehicle bus system as coded messages. ADAS application as a client use it’s built in component ADAS Reconstructor to received, analyse and interpret ADAS Protocol messages. This process enables reconstruction of a copy of the ADAS Horizon that will be stored in ADAS application memory.

A road network in digital maps is presented as collection of nodes and links that connect them. Since majority of ADAS applications, uses the road network data located in front of the vehicle, the ADAS Horizon is setup to consider and release only the data regarding the upcoming segments ahead. Such setup enables optimization of the data processing efficiency.

To reduce Electronic Horizon complexity, instead of network of links, the protocol introduces possible vehicle paths. Each path is considered by the application as a single element. As this approach provides several possible paths, with some common segments, it produces duplicated data. To avoid duplicated data the ADASIS v2 concept optimizes path presentation. This implies defining the Main Path and Sub-Paths attached to the Main Path. The Sub-Paths attached directly to the main path are considered to be The First-Level Sub-Paths. Their attachments are Second Level Sub-Paths and this pattern is replicated for a desired Horizon depth.

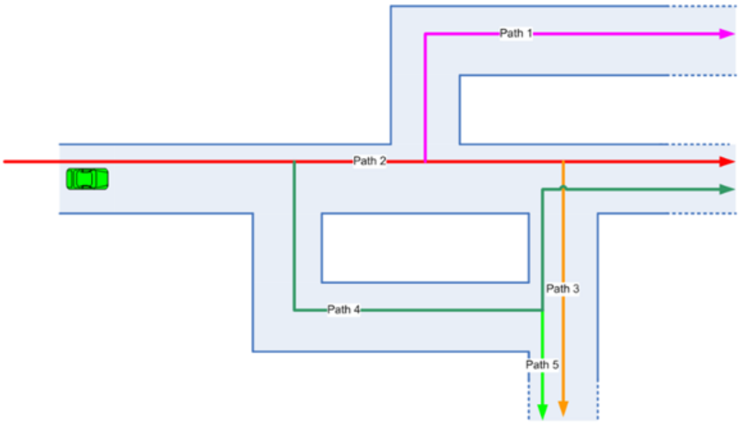

Figure 1.2 ADSIS v2 Horizon – Optimized Path Representation [8]

Based on probability of segment usage on vehicle’s route, ADAS Horizon Reconstructor’s algorithm defines Main Path. On the application developer is to define required level of ADAS Horizon robustness, which Sub-Paths Levels to include in Electronic Horizon. ADAS Horizon robustness is influenced by the application tolerance related to delayed of Electronic Horizon available data. Moreover, this occurs as system needs some time to send new main path data, when vehicle leaves the current main path, what creates the actual delay of information. Application requirements define desired and suitable Electronic Horizon structure as Single or Multiple Path Horizon.

As ADAS Horizon is a path oriented, all road data are assigned to paths and sub-paths. Therefore, a path must be considered as the main ADAS Horizon entity. Each PATH is defined with connection point, named STUB, and sections of path with same basic properties, named SEGEMENT. Each STUB represents start of a sub-path and a direct connection between this sub-path and its parent path. As such, it also presents a characteristic attached to the parent path. In addition to STUBS and SEGMENTS each path is described with POFILES. All these entities' characteristics are assigned to a path based on the path identifier and offset, distance from the path start.

The same concept is used to define vehicle status in Electronic Horizon. Vehicle status is defined with position, described as identifier of the path, and offset from the start of the path and additional characteristics such as speed and heading.

Robustness of ADAS Horizon must be arranged in accordance with client needs. Horizon provider will send messages to a client based on the arrangement. When it is sufficient for the application to have only data of the Main Path, the related Horizon data will be accordingly limited.

Some of the possible configurations are:

- Only Main Ptah
- Main Path and Stubs
- Main Path and Sub Paths
- Full Horizon

The provided Horizon configuration is defined by each vehicle installation and it has been sufficient for the most demanding application in the vehicle. If there are more than one application with different required Horizon robustness there is an option for less demanding applications to delete all redundant information on the CAN receiver interface.

1.3.2 Paths and offsets

All road characteristics are attached to the paths and their position in Horizon is defined with Path Index and Offset. The start of each path has zero offset. The ADASIS v2 Protocol defines limitation in paths numbers to 56 and offsets between 0 and 8190 meters.

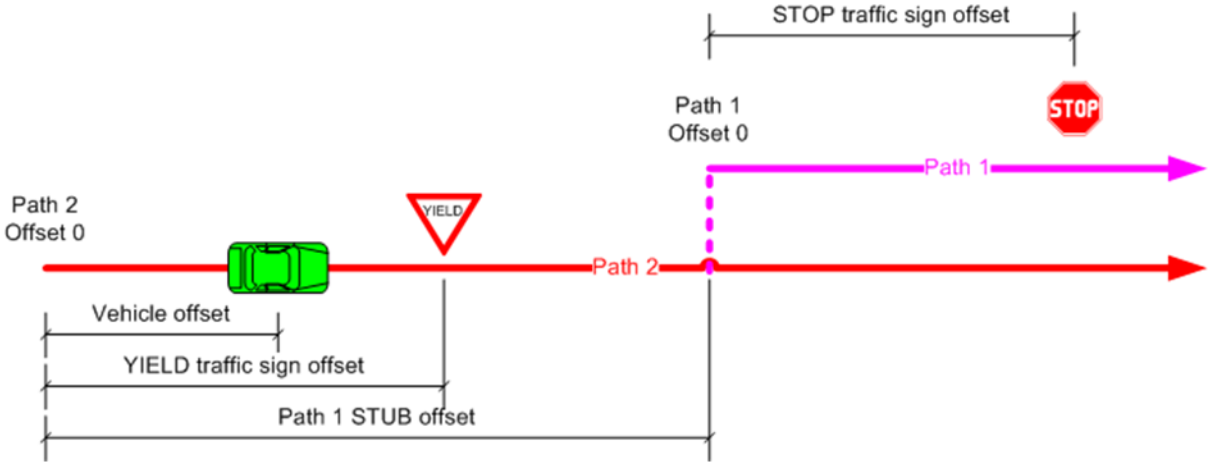

Figure 1.3 ADSIS v2 Horizon – Positioning of entities [8]

Creation of Horizon is continuous process where each new message brings new data to incorporate in existing Horizon and extend it. The Horizon configuration defines messages which are related to the data needed to be sent to a client by Horizon provider. Due to optimization of the data transferring, provider sends a message only, when some new Horizon element is available or there is some change to be updated. Client defines the length of Horizon required for proper application functioning. Horizon provider is sending only information in front of vehicle with distance shorter than maximum defined depth of view named the maximum length of transmitted path.

1.3.3 Messages

To create the full Horizon ADASIS v2 Protocol defines six types of messages. Which messages is going to be used depends of application requested information.

Massage types:

- POSITION message specifies the current position(s) of the vehicle.
- STUB message indicates the start of a new path that has origin at an existing one.
- SEGMENT message specifies the most important attributes of a part of the path.
- PROFILE SHORT message describes attribute of the path whose value can be expressed in 10 bits.
- PROFILE LONG message describes attribute of the path whose value can be expressed in 32 bits.
- META-DATA message contains utility data.

Each of six types of messages has precisely defined fixed structure. Predicted fields for each message type will be filled with data if Horizon provider has it. Required data is not always available, as some maps are not offering all attributes defined by the protocol. In addition, on some roads they are not even available. In this case, provider sends a specific message, either “unknown” for the information unknown at all on the particular road segment or “Signal not available” when required attribute is completely unavailable or not even implemented on the map.

The POSITION message is used to determine the current vehicle position in Horizon. It is described in terms of Path Index and Offset along the path. Also, message contains vehicle speed, relative heading, current lane, etc. All this data shall provide as good as possible estimation of vehicle position in created Horizon environment.

The SEGMENT message provides a set of the road attributes applied to a particular section of road, throughout which these attributes remain constant. It merges the most important characteristics of one segment. Starting position of segment is defined by a path index and a start offset, hence there is no overlapping of segments along one path. Each path consists of one or more segments. The SEGMENTS message provides functional road class, form of way, effective speed limit, effective speed limit type, number of lanes in both direction, etc.

The STUB message describes origin of the sub-path on the Most-Probable Path and it is considered to be a crossing if there are more than one stub with the same value of offset on the same path. It provides information about sub-path index, turn angle, functional road class of sub-path, form of way, etc. The continuation stub data characterizes the main path only. Moreover, it provides info describing the main path extension following the intersection.

The PROFILE SHORT message provides data about standard profiles such as: road curvature, slope, accessibility, condition, heading change etc. and system specific profiles such as: superelevation (banking), alternate radius (curve radius in meters), lane width, etc. Profile is defined with values of start and end profile spots and interpolation type for interpretation of intermediate spots between them. Position of the start profile spot is defined by offset and position of the end one is defined by distance from first profile spot to the second one. Short profile message defines maximal distance between starting and ending point that is up to 1022 meters.

The PROFILE LONG message contains data related to longitude, latitude, altitude, traffic sign, truck speed limit, etc. Message contains only one related profile spot value and interpolation type is defined by each actual profile type. The spot value may be a single value or vector containing several values for providing smooth curve representation.

The META-DATA message provides basic system info as Country Code Driving Side, Speed Units, Major Protocol Version, Speed Units, Map Provider, Map Version, etc. These data are important at the very beginning of the system operation since they configure the system itself. Therefore, configuration messages have to be sent at higher rate at the beginning of the process. Following of establishment of a stable system functioning, these massages can be reduced frequency wise. Configuration messages can be transferred to regime of low frequency. To update the system in occasions of Meta-Data modification periods of several seconds are acceptable.

An exception is at the very start of the system, during which the client should rapidly pick up some configuration data from that message. To prevent problems, it is recommended, to transmit METADATA messages after system start-up.

1.3.4 System configuration

The Real-Time Driver Advisory System (RTDAS) uses following road data to calculate advisory speed in defined deceleration cases:

- Legal speed limit
- Curve geometry
    - Radius
    - Superelevation
- Road slope
- STOP sign
- GIVE WAY sign

1.4 Vehicle approaches speed limit

Information about legal speed limits can be added to Horizon by using SEGMENT message or LONG PROFILE messages profile types Traffic Sign and Truck Speed Limits.

If information about the speed limits is acquired from SEGMENT messages, the corresponding fields of SEGMENT message are Effective Speed Limit and Effective Speed Limit Type. Effective Speed Limit will be defined as value or it will be unknown. Provided value can be already adjusted by ADASIS Horizon Provider in accordance with Effective Speed Limit Type based on time or weather conditions or it has to be done by client.

Possible Effective Speed Limits Type defined in ADASIS v2 Protocol:

- Implicit (Default speed limit in the city)
- Explicit
    - On traffic sign
    - By night
    - By day
    - Time of day
    - Rain
    - Snow
- Unknown

From the side of client, it is better to use already adjusted value of speed limit to avoid additional computing on the application side.

To improve precision of speed limit defined in SEGMENT message it can be merged with speed limit data from traffic signs that is provide as LONG PROFILE message. Related fields are OFFSET to define position, PROFILE TYPE to recognize speed limit sign and VALUE. If application is installed on truck LONG_PROFILE Message - “Truck Speed Limit” shall be used for speed limit determination. Detailed structure and defined algorithms for implementation of speed limit data from traffic signs and/or “Truck Speed Limit” can be found in appendix (Appendix I, II, II, IV, V).

1.5 Vehicle approaches curve

For estimation of advisory curve speed required data form Electronic Horizon are curvature and superelevation. These two attributes are provided by using SHORT PROFILE messages. In the ADASIS v2, Profile is a characteristic of a path that has a defined value for every location along the path. Profiles are defined by specifying profile support points and by specifying the interpolation method that is to be used to calculate the value between support points.

The important SHORT PROFILE message fields for providing road curvature and superelevation are followed:

- Path Index
- Offset
- Profile Type: Curvature/Suprelevation (Linear Interpolation)
- Value 0
- Distance 1
- Value 1

The ADSIS v2 Protocol define linear interpolation for Curvature Profile Type and it is considered to be adequate presentation as calculation of advisory safe and comfortable speed is using curve radius. Values of curvature profile are coded and after upon receipt values have to decode. Coding method is explained in detail in the protocol. After the decoding process, values are available as curvature c [1/m] from which value of radius is calculated (Equation 1.1), thus the radius of a curve is defined to be the reciprocal of the curvature c [1/m]. Positive values represent right curves, negative values left curves.

$$R = \frac{1}{C} \qquad \text{Equation 1.1}$$

For the purpose of this study it will be considered that profile is defined point-wise on each shape point. Radius of curves will be pre-calculated from curvature values by using linear interpolation with resolution of 1 meter and stored at the application memory. The advisory curve speed algorithm will use these available stored radius values.

Precision of calculation of advisory speed can be significantly improved if Horizon Provider have opportunity to provide road superelevation in curves. In this study, it is assumed that superelevation is known. ADAIS v2 defines System-Specific PROFILEs where two of profiles are related to superelevation. The Banking Profile Type defines values of super-elevation in degrees with precision of 0.05 degrees and in interval from -25.55º to 25.55º. The Banking (High Resolution) provides higher precision of 0.01 degrees but in smaller interval from -5.11º to 5.11º. Both profiles have linear interpolation type. For the study Banking Profile Type with lower precision will be used. Superelevation profile will presented at the same manner as curvature profile with pre-calculated values and resolution of one meter.

1.6 Vehicle approaches intersection

Interaction approach always requires hire driver's attention and eventually speed adjustment. Three characteristic cases when speed adjustment is required or desirable during intersection approach are recognized.

The first one is a deceleration due to STOP sign in front of the vehicle. This case can be modelled as deceleration to zero speed from current speed, as a STOP sign always means that vehicle must come to a complete stop.

The second case is deceleration because of GIVE WAY sign. GIVE WAY sign is positioned to inform a driver that he has to give way to traffic in next intersection and to be prepared to stop the vehicle if needed. To avoid cases of deceleration on STOP or GIVE WAY signs in intersection with traffic lights where traffic lights are functioning, existence and status of traffic lights should be checked.

The intersection regulated with traffic lights presents the third characteristic case. The ADASIS v2 Protocol defines traffic sign warning of light signals and traffic light location with status of lights phase. Traffic sign warning or signal ahead sign are usually placed in case of lack of adequate intersection sight distance. Hence, it will probably be absented for number of intersection. The intersection regulated with traffic lights has three phases which application will take into consideration. These are Red flashing indicting that vehicle must stop, Amber flashing indicating higher attention and consideration of traffic signs or Dark phase.

Traffic lights phase options:

- Green
- Red
- Amber
- Red + Amber
- Red flashing
- Amber flashing
- Dark

In the zone of intersection all three recognized deceleration cases will be integrated in the same intersection speed advisory algorithm. Relevant Horizon data will be acquired from Horizon provider by using LONG PROFILE messages and Traffic Sign Profile type. The indicator to evaluate desirable intersection approaching speed will be existence of intersection that can be defined with stubs or intersection sign. Using of traffic signs as intersection identifiers is less reliable approach because of their eventually lack of signs or the map data absence. More confident approach is to use STUB because STUB message brings one more important attribute. It contains turn angle between Most Probable and Main Path.

When several STUBs appear with the same path and same offset it will indicate that new intersection is positioned on Main Path and algorithm for estimation desired approaching speed will be initiated. It will take into consideration STUB offset to be an intersection location. Algorithm will check intersection approaching zone to recognize relevant data for calculation of desired intersection approaching speed (Appendix V).

Besides data needed for evaluation of a desirable speed profile, road slope, as a main factor in a deceleration model, has to be integrated as a Horizon requirement. This problem is solved by using SHORT PROFILE messages where slope value is in degrees and step type interpolated.

Final speed profile will be established by combining all three sources: legal speed limit, advisory curve speed and desired intersection speed. The final speed profile will present the minimal value for each path element.

2 Contemporary ADAS - research, trends and solutions

The improvement of mobility is one of the main goals of modern society. In developed countries, there is a strong focus on improving the quality of mobility by investing in the improvement of safety, energy efficiency, ecological and economical costs. Driver assistant systems are recognized as the tools with enormous potential for improving the quality of mobility in different segments. Driver assistance and advisory tools include wide range solutions, starting with Anti-Lock Braking System (ABS) and Electronic Stability Control (ESC) system, followed by Navigation systems, Parking Assistance systems, Lane departure warning (LDW) systems, Cruise Control and Adaptive Cruise Control (ACC) systems, Curve Speed Warning (CSW), Speed Adaptation System (ISA) etc. [9]. Most of driver assistant systems are focused on the improvement of driving safety but increase in development of solutions focused on comfort and energy efficiency is obvious. Most tools for improvements of fuel economy are primarily being designed for commercial vehicles and then the technology is being transferred to passenger cars.

The usage of ADAS applications in the automotive industry is becoming increasingly important for improvement of utilization of innovative technology built into modern vehicles. Management of driver behaviour or driving style still possess the greatest potential for improvement of fuel economy and safety. The reason is often the influence of driving style that can very often neutralize the benefits of incorporated vehicle technological solutions. If a driver doesn’t understand how modern vehicle is functioning, his behaviour can significantly influence vehicle operating performance. For instance, a very common issue is the optimal shifting strategy that is specific for each vehicle model. Therefore, the gear shift assistant system is provided in almost all modern vehicles.

Above mentioned are some of the main reasons why ADAS applications as the standard equipment of contemporary vehicles is an upward trend in automotive industry.

2.1 Advance driver assistant systems projects under the Horizon 2020 - EU Research and Innovation program

Under the Horizon 2020 challenge Smart, Green and Integrated transport, the 25 research and innovation projects will receive €198 million EU funding to make European transport greener, safer, more efficient and innovative [10]. The selected projects are related to air, rail, road, and waterborne transport. The focus of projects is on green solutions for urban transport, development of Intelligent Transport Systems (ITS), logistics and infrastructure improvements. These activities are addressed in this Work Programme by three Calls for proposals [11]:

1. Mobility for Growth
2. Green Vehicles
3. Small Business and Fast Track Innovation for Transport

From the list of covered projects, projects related to ADAS solutions and usage of Electronic Horizon are:

1. Vision Inspired Driver Assistance Systems - VI-DAS [12]

VI-DAS will be focused on development of next-gen 720° connected ADAS systems (scene analysis, driver status). It should enhance understanding of driver, vehicle and scene context, and enable one more step towards truly semi-autonomous vehicles. VI-DAS will use inexpensive and universal sensors, primarily cameras. Human error analysis will be the main goal through the study of the real accidents. The understanding of patterns and consequences of accidents will be used as an input to the future solutions. Based on predicted scene's outcomes advisory action will be provided to achieve optimal safety, efficiency and comfort behaviour. The project should improve avoidance of accidents, economic growth and continual innovation.

2. Optimal fuel consumption with Predictive Powertrain control and calibration for intelligent Truck – optiTruck [13]

The optiTruck is aimed at the improvement of Euro VI Heavy-Duty Vehicles (HDVs) (40t) energy efficiency. The improvement will be achieved by combining advanced powertrain control and ITS technologies. The result should be the global optimiser that compounds dynamic, intelligent control and prediction elements for providing optimization of powertrain management by using knowledge about the environment as transport mission, road topography, weather and road conditions and surrounding vehicles.

3. Low cots Advanced Driver Assistance Systems (ADAS): A cost affordable solution for improved road safety – SMARTCARS [14]

The SMARTCARS is focused on providing comprehensive and advanced ADAS solutions to a large part of the vehicle consumers. Improved availability is planned to be reached by using external hardware solution integral in any car manufactured after year 2000. This will offer, not just to owners of the new car of the premium-high price segment, but also to other users to use innovative ADAS applications.

4. Adaptive ADAS to support incapacitated drivers Mitigate Effectively risks through tailor made HMI under automation – ADASANDME [15]

The ADASANDME project will develop ADAS to improve safety and efficiency by combining a driver state, situational or environmental context, and adaptive vehicle and driver communication. The communication will provide automatic transfer control between a vehicle and a driver. On the characteristic driving cases, research on using algorithms for driver state monitoring, HMI and automation transitions will be carried out. It will develop robust detection/prediction algorithms for a driver state monitoring concerning different driver states, such as fatigue, sleepiness, stress, inattention and impairing emotions. It will be done by using present and innovative sensing technologies combined with traffic and weather provided via V2X. Detected or predicted driver state will be customized to individual driver's physiology and driving behaviour. Also, multimodal and adaptive strategy for generation of warnings or interventions based on predefined scenarios and estimated current state will be developed.

5. New Generation ADAS for Enhanced Driving Experience - e-Awake [16]

The goal of the project is a full development of a high performance embedded system which is able to support modern and robust ADAS and highly automated driving (HAD) solutions. The e-Awake will combine in a single device a homogenous software-centric architecture with hardware and software partitioning for functional acceleration. The new embedded computing platform shall provide significant enhancement in vehicle performance and power consumption. The cost-efficiency, scalability and flexibility of ADAS and autonomous driving solutions will be improved and significant reduction of development costs will be achieved.

6. IMplementation of Powertrain Control for Economic and Clean Real driving emission and fuel ConsUMption – IMPERIUM [17]

The IMPERIUM project is focused on reducing fuel consumption while maintaining the legal emission standards. This will be achieved through the improvement of the control strategy for the main vehicle components to maximize their performances, optimization of different energy sources in accordance with driving situation and utilization of Electronic Horizon potential. The fact that the major European stakeholders from relevant industries are part of IMPERIUM consortium creates the opportunity that results will be implemented for optimization of modern powertrain control strategies of modern trucks.

3 Real-time Driver Advisory System for Fuel Economy based on the ADASIS data

The Real-Time Driver Advisory System (RTDAS) for achieving higher fuel economy is designed to improve driving with the aspect of energy efficiency in typical situations when it comes to adjusting the vehicle speed to the road conditions. One of the most characteristic example is when the current speed has to be adjusted due to upcoming speed limit that is less than the current vehicle speed. Another case is when the vehicle is approaching a curve and speed adjustment is needed to achieve the desired level of comfort or eventually safety while passing through the curve. Other typical cases are intersections in which right of way is not applied to approaching segment and vehicle has to stop or slow down and prepare to stop if necessary and give way to all vehicles travelling in, entering or approaching the intersection with higher priority.

The system will consider lower of any relevant speeds defined as speed limit, advisory curve speed or advisory intersection speed to be required or maximal speed (3.1). In relevant cases, the system will deliver timely message to the driver to release the gas pedal and set gear in neutral which will adjust current speed without brakes usage but only existing road resistances. In this way, it increases the utilization of the existing kinetic energy of the vehicle and increases comfort and safety due to the decrease of the intensity of deceleration. Application effect will be tested on vehicle powered by ICE and HES.

Feasibility and effects of the system are evaluated based on simulation results by using verified relevant vehicle model defined in simulation software IGNITE. Simulation includes predefined scenarios that are in accordance with the estimated real deceleration situations. A detailed process of creating scenarios of deceleration cases is going to be done by merging exported real road data and driving cycle recorded from test drive on laboratory driving simulator.

The verified relevant vehicle model is defined in library of software solution IGNITE provided by Ricardo company and it is used for vehicle dynamics simulation. The road characteristics are going to be exported from available maps and used for simulation of Electronic Horizon data in accordance with ADASIS v2 Protocol as generally accepted standard in auto industry.

Generally, the main goal is to develop a reasonable model to estimate when the driver should release the gas pedal to reach the point with compulsory or advisory speed limit by using existing vehicle kinetic energy without braking. The future system development will be focused on extension of advisory messages according to the acceleration strategies. This will complement the system as comprehensive management solution for harmonizing speed fluctuation and reaching fuel efficiently and comfortable driving.

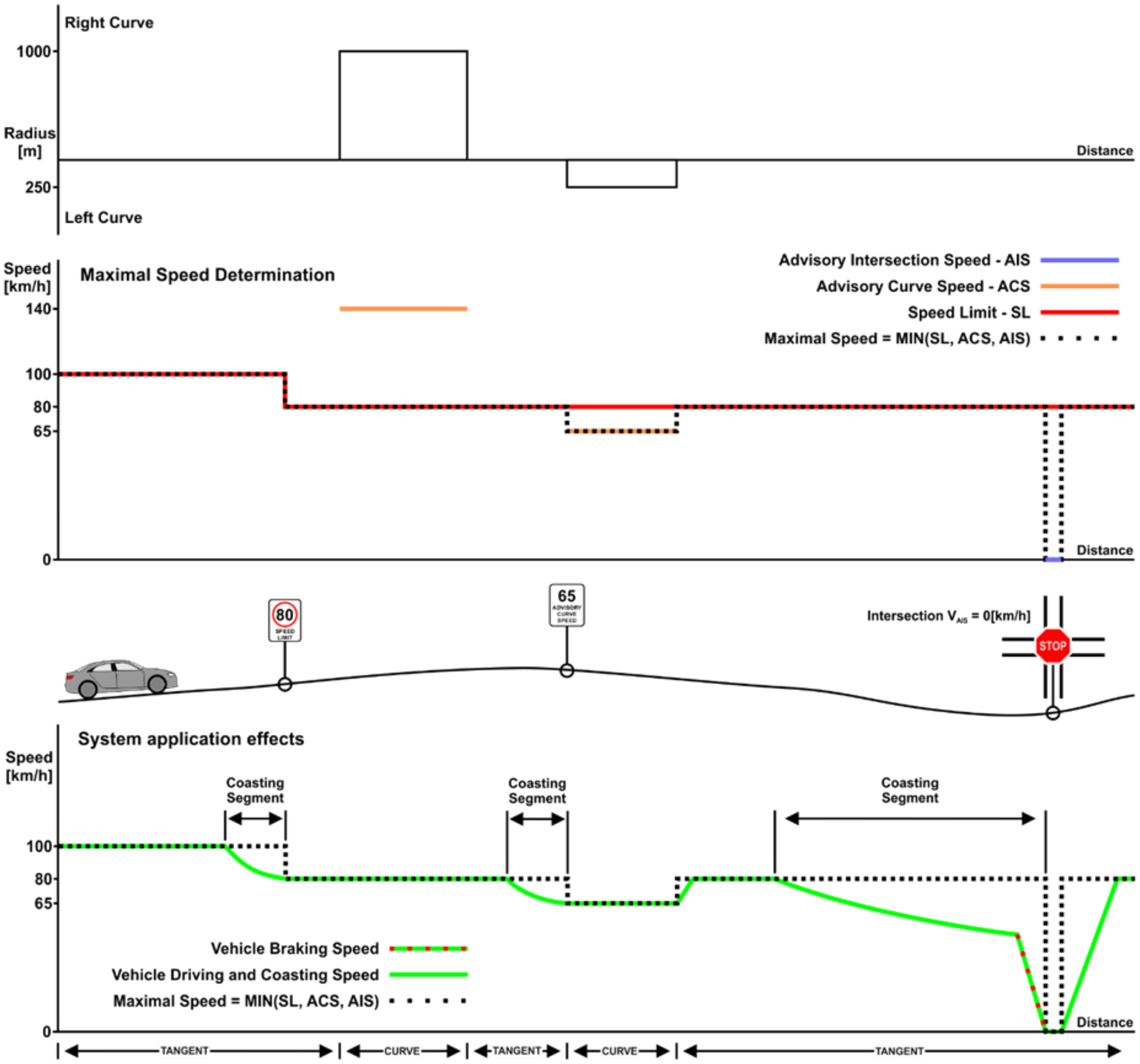

Figure 3.1 Real-Time Driver Advisory System – Typical cases of system application

3.1.1 The advisory system concept description

The advisory system is going to be embedded in the vehicle. The basic sources of data are GPS sensor, speed sensor, map data offered as Electronic Horizon delivered by Electronic Horizon provider, weather conditions and predefined vehicle characteristics (Figure 3.2). The weather conditions can be determined by using in-vehicle standard sensors [18] or taken from online weather conditions data provider such as Weather Telematics Inc [19]. In this study information about weather condition is assumed to be known.

For each driving situation, there is a maximum speed value at which the driver can manage a given task. Such “appropriate highest speed” values can be calculated theoretically for every situation based on the road friction, the slope of the road, curve radius and superelevation.

The advisory system will utilize current vehicle position, current vehicle speed, upcoming terrain (road slope), speed limits, road curvature, intersections and road signs position to calculate the precise position where a message has to be transferred to driver to release the gas pedal to save fuel and increase driving safety and comfort.

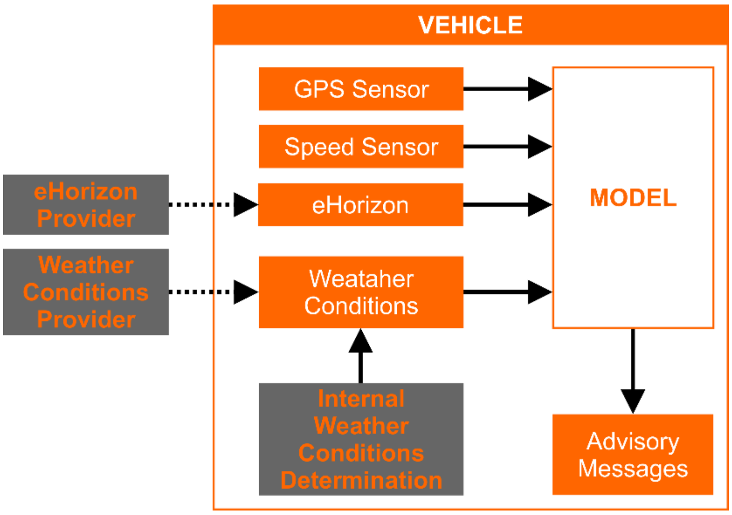

Figure 3.2 RTDAS concept

3.1.2 Vehicle Model

The purpose of the vehicle model is to calculate the vehicle translational motion (position, velocity, acceleration). The tractive force from the tyres drives the vehicle, while the aerodynamic, rolling and slope resistances and braking force act on the vehicle. In the case of HES there is additional regenerative braking force that is managed by hybrid vehicle controller.

A vehicle model is used to evaluate the coasting deceleration characteristics deceleration characteristics of hybrid vehicle that includes already mentioned regenerative braking. Evaluated results give the effects that will be used in cost-benefit analysis of system control strategy improvement in future research and development work. As the study is based on a simulation in software solution IGNITE a verified exciting vehicle model “Advanced Vehicle” from IGNITE library is used. In the case of hybrid vehicle model will be adjusted to estimate potentials of application in HES.

3.2 Vehicle Model Specification

Advanced Vehicle model presents a vehicle with 2 axles that can predict weight transfer between axels due to the acceleration and grade. The model calculates loads due to the following effects:

- Accelerating or decelerating the mass of the vehicle
- Braking forces
- Aerodynamic resistance of the vehicle
- Work done against gravity due to the elevation changes

- Rolling resistance
- External drawbar connection (Not used in the study)
- Motor-Generator Regenerative Braking (If it incorporates into HES)

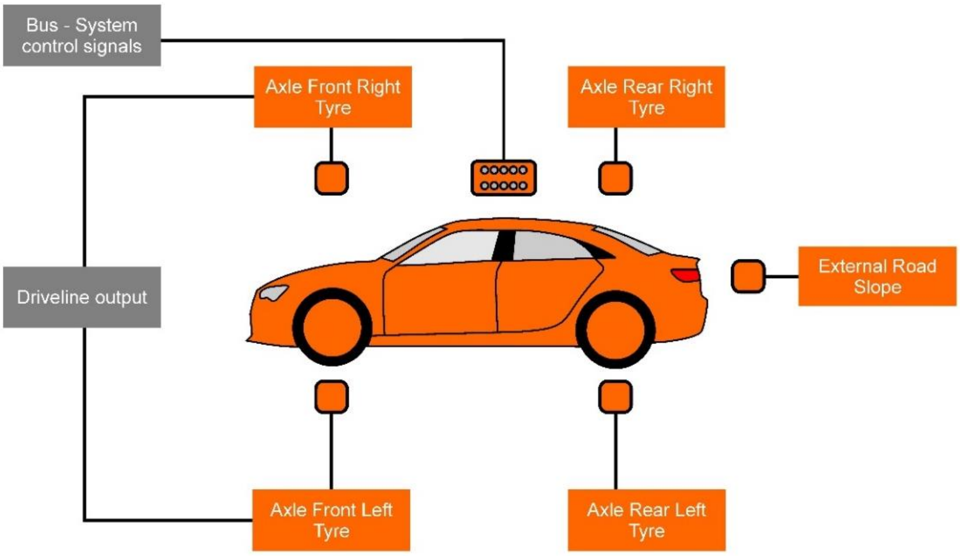

Figure 3.3 IGNITE - Advance vehicle model

Vehicle model contains all necessary features needed for evaluation of all relevant vehicle dynamics characteristics during a simulation. A vehicle model takes into consideration driveline output as traction force input, transferred onto the front wheels, and road slope data as external input. Vehicle model contains all factors needed for calculation of drag and rolling resistance. All these data enable precise modelling of vehicle dynamics (Figure 3.4).

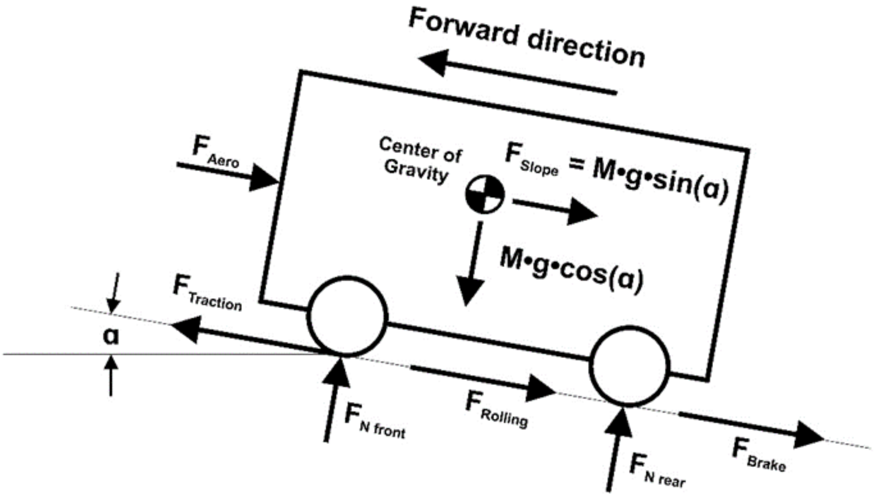

Figure 3.4 Longitudinal vehicle dynamics model - External forces acting on the vehicle

Applying Newton's second law to the direction parallel to the ground the equation of motion for the longitudinal vehicle can be defined as:

$$\sum F = F_{Traction} - F_{Rolling} - F_{Slope} - F_{Air\_Drag} - F_{Braking} \qquad \text{Equation 3.1}$$

and in the case of hybrid vehicle:

$$\sum F = F_{Traction} - F_{Rolling} - F_{Slope} - F_{Air\_Drag} - F_{Regenerative\_Braking} - F_{Braking} \qquad \text{Equation 3.2}$$

From resulting force, considering vehicle mass, vehicle acceleration is calculated as:

$$a = \frac{\sum F}{m} \qquad a = \frac{dV}{dt} \qquad V = \frac{dX}{dt}$$

where:

Forces	Description	Units
$F_{Traction}$	Traction force (Internal Input)	[N]
F_{Air_Drag}	Aerodynamic resistance force (Calculated)	[N]
F_{Slope}	Slope resistance (Calculated)	[N]
$F_{Rolling}$	Rolling resistance (Calculated)	[N]
F_{Brake}	Brake force (Internal Input - Calculated)	[N]
$F_{Regenerative\_Braking}$	Regenerative braking force Combined with Traction force (Internal Input)	Internal generator calculation based on hybrid controller strategy
Variables	**Description**	**Equation/Value**
BD	Brake demand - Defined in model deceleration strategy	Brake demand = [0 - 1]
Relations	**Description**	**Equation/Value**
a	Vehicle acceleration (Calculated)	[m/s^2]
V	Vehicle velocity (Internal Input – Speed Sensor)	[m/s]
X	Vehicle position (Internal Input – GPS Sensor)	[m]
α	Grade angle (External Input from Electronic Horizon)	[Degree]

Table 3.1 Vehicle model characteristics

Name	Symbol	Value	Units
Vehicle mass	m	1644	kg
Aerodynamic drag coefficient	C_d	0.3	/
Vehicle frontal area	A	2.3	m^2
Rolling resistance coefficient	f	0.015	/
Rolling wheel radius	R_{Wheel}	0.32	m
Air force height	H_{Aero}	0.6	m
Centre of gravity height	HCoG	0.53	m
Front axle position from CoG	X_A	1.555	m
Front axle position from CoG	X_B	-1.221	m
Maximum brake force	F_{Brake}	15000	N
Final drive ratio	FDR	3.39	/
Constants	**Symbol**	**Value**	**Units**
Ambient air density	ρ	1.293	/
Acceleration due to gravity	g	9.81	m/s2

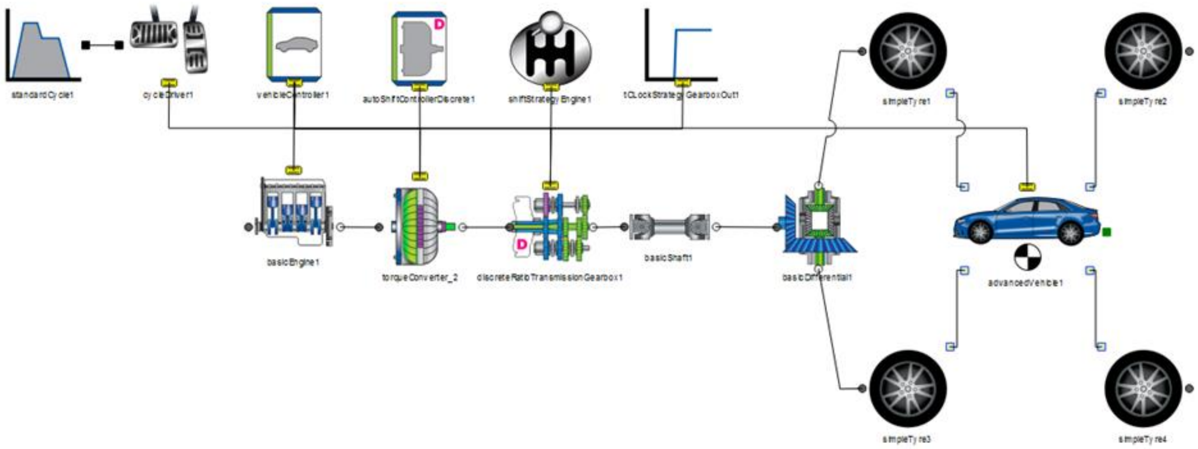

Figure 3.5 IGNITE Example of Advanced Vehicle Model (ICE)

The vehicle driveline components are also part of the model (Figure 3.5). All the necessary internal model inputs vehicle is receiving from additional model components, as driveline or as a Bus input signals. Based on brake demand and maximal braking force defined in vehicle model, applied braking force will be calculated. Model is using simplified braking model. In the case of hybrid vehicle brake demand will be distributed between regenerative braking of motor generator and mechanical braking. Incorporation of more complex model based on friction with implementation of EBS and ESP is also possible but not used in this work.

3.3 Shifting strategy optimization

The shifting strategy should be adjusted to vehicle coasting goals of minimizing fuel consumption. In modelling vehicle performance, the gear shifting strategy is defined by gear shift map (gear shift table). It defines up-shift and down-shift gear selection as a function of gearbox output speed values and driver acceleration demand signal. When a driver releases the acceleration pedal vehicle reaches injection cut-off (Deceleration Fuel Cut-Off - DFCO) and zero torque is delivered by the engine [20]. Therefore, in deceleration model the coasting distance will be travelled without fuel consumption. The shifting strategy optimization applies particularly to down-shift transmission gear selection during coasting mode, to keep longer higher gear selection during slowing down to provide lower engine speed. The lower engine speed implies lower engine braking effect and longer coasting distance. For the study, the shifting strategy in the model will be simplified and it will be presented as neutral status by disengaging clutch during coasting mode. It is considered that when driver receives advice to start with coasting he will put in neutral gear and release the gas pedal and exclude any braking action. The HES will use adopted regenerative braking strategy that will be controlled by PID controlled motor generator demand.

3.4 Tools used for RTDAS system development, testing and validation.

The RTDAS is developed by using IGNITE software tool and object-oriented language Modelica. As IGNITE is based on Modelica, all elements of RTDAS are modelled in Modelica and imported to IGNITE. Some of the system functions are coded in C++ and incorporated as external functions into models developed in Modelica. By combining vehicle model and vehicle's components models from IGNITE library, detailed presentation of ICE and HES powered vehicles are created. For the purpose of study some of the standard IGNITE models are modified by using Modelica and some of elements are completely developed. By merging all of them into models of ICE and HES powered vehicles testing of RTDAS functioning and validation is enabled.

3.4.1 Modelica

Modelica is an object-oriented language for modelling of large, complex and heterogeneous physical systems. It is suited for multi-domain modelling, for example for modelling of mechatronic systems within automotive, aerospace and robotics applications. Such systems are composed of mechanical, electrical and hydraulic subsystems, as well as control systems. General equations are used for modelling of the physical phenomena. The language has been designed to allow tools to generate efficient code automatically. The modelling effort is thus reduced considerably since model components can be reused, and tedious and error-prone manual manipulations are not needed. Modelica Libraries with a large set of models are available. Especially, the open source Modelica Standard Library contains about 1600 model components and 1350 functions from many domains.

3.4.2 IGNITE

IGNITE is a physics-based system simulation platform intended for creation of complete vehicle system models and simulating model's behaviour. It is a computational platform based on an object-oriented, equation based language Modelica. The IGNITE contains libraries of powertrain and thermofluid components that provide opportunity for creation of complex vehicle models. With the speed of simulation that is faster than real-time and optimization tools IGNITE offers solution for modelling vehicle performance, fuel economy and emissions prediction.

4 Coasting deceleration model

To assess the effects of Real-Time Driver Advisory System on adjusting speed based on the speed limit or determinate recommended curve or intersection speed, it is necessary to create a quite realistic model of driver behaviour and vehicle performance in case of existence and case of absence of such a system. To keep the focus on the events in which the greatest benefits of the system are expected, the typical driving scenario of is designed. The scenario case design is explained in detail in chapter related to model validation procedure and effects estimation.

As a specific event for speed adjustment, due to the existence of a speed limit, curve or intersection on the road, implies the event where the vehicle is moving at a current approaching speed ($V_{Current}$) and is entering next road segment with a required speed ($V_{Required}$) which is lower than the current vehicle speed (4.1).

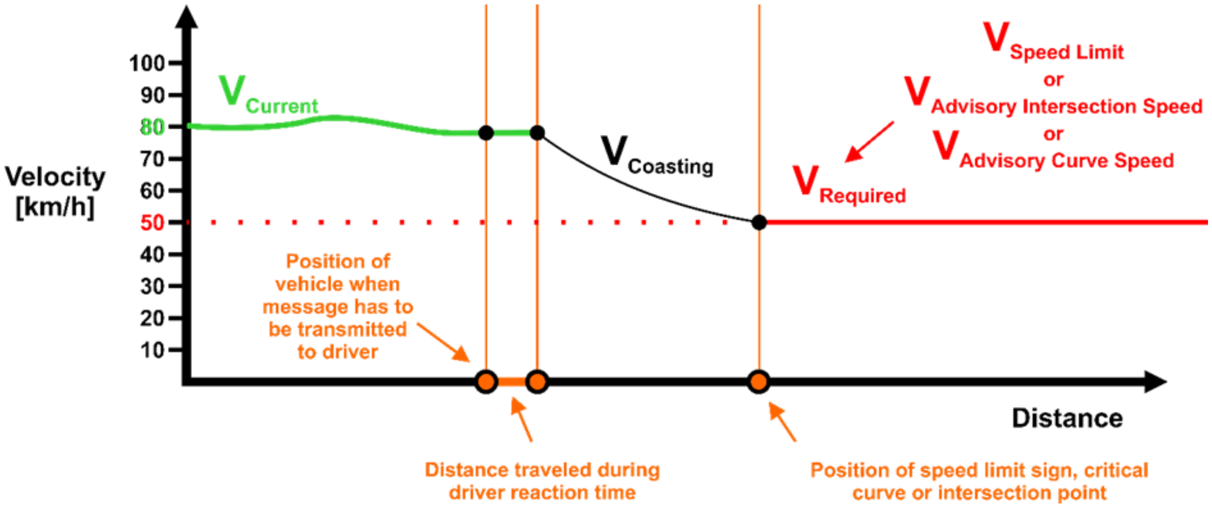

Figure 4.1 Coasting deceleration event

The coasting model uses road and vehicle characteristics to estimate coasting speed profile on approaching segment of spot where vehicle should reach required speed. Position on the road when driver should release the gas pedal is defined as intersection of current vehicle speed with coasting speed profile. The Real-Time Driver Advisory System use Electronic Horizon data for estimation of coasting profiles in advance for all spots on the road ahead for which speed has to be adjusted. This is possible as coasting speed is function of vehicle and road characteristics that are known and static for each segment of the road. The position where coasting should start depends only on vehicle current/approaching speed.

4.1 Influence of coasting deceleration model imprecision

The precision can be the main issue of deceleration model. If deceleration model has high imprecision, message is going to be sent to a driver either too late or too early. This will influence reaching defined position of speed limit sign or in curve position for which advisory speed is determined with higher or lower speed than desired. The higher speed than desired in case of curve impacts the higher is the risk of losing vehicle stability or desired comfort and in case of speed limits sign there is possibility to get a fined. It should be seriously taken into consideration in case of real world usage. Due to importance of message time window correctness a driver reaction time should be considered and added to the calculation of message transfer timing. Driver reaction time of 1.5s can be considered as adequate as represent 98% of drivers that will react in this time or less [21].

4.2 Speed limit regulation

Analysing of the existing regulations related (or relating) to the traffic safety of European countries (EU countries + Switzerland, Norway and Liechtenstein) the most common static speed limits had been identified (European Commission, 2017). The available data according to the road safety directive (Directive 2015/413 / EU) is provided by the national authorities in the country concerned (Table 4.1).

Based on the analysis, the speed limits are divided into three categories: Urban Roads, Non-Urban Roads and Motorways. From presented data, it can be concluded that in the European countries most common speed limits for motorways are 120 or 130 km/h, for rural roads 80 or 90 km/h and for urban roads 50 km/h. The most common speed limits are adopted as characteristic for each road category, and the most common speed limits of roads of higher rank are adopted as characteristic speeds on the access segment. Thus, defined the 14 the most possible real-world deceleration scenarios (Table 4.2). Some of these will be incorporated into case scenario design to test the effects of system application.

Table 4.1 Speed limits (unless otherwise stated by traffic signs) for passenger cars

Country	Speed limits [km/h]		
	Urban roads	Non-urban roads	Motorways
Austria	50	100	130
Belgium	50	70/90	120
Bulgaria	50	90	140
Croatia	50	90	130
Cyprus	50	80	100
Czech Republic	50	90	130
Denmark	50	80	130
Estonia	50	90	110
Finland	50	80	120
France	50	90	130
Germany	50	100	130
Greece	50	60	130
Hungary	50	90	130
Ireland	50	80/100	120
Italy	50	90	130
Latvia	50	90	/
Liechtenstein	50	80	/
Lithuania	50	90	130
Luxembourg	50	90	130
Malta	50	80	80
Netherlands	50	80	130
Norway	50	80	100
Poland	50/60	90	140
Portugal	50	90	120
Romania	50	90/100	130
Slovakia	50	90	130
Slovenia	50	90	130
Spain	50	90/100	120
Sweden	50	70	110
Switzerland	50	80	120
United Kingdom	48	96	112

Table 4.2 Defined possible testing deceleration scenarios

Entering urban road		Entering non-urban road					
Speed limit [km/h]	Entry speed [km/h]	Speed limit [km/h]	Entry speed [km/h]	Speed limit [km/h]	Entry speed [km/h]	Speed limit [km/h]	Entry speed [km/h]
50	80	80	100	90	110	100	120
50	90	80	110	90	120	100	130
50	100	80	120	90	130	100	140
		80	130	90	140		

4.3 Advisory curve speed determination based on road geometry

The concept of advisory speed is based on comfort and safety criteria of driving through upcoming curve based on curve geometry. The system will estimate the advisory speed and determinate position of advice message that will be sent to driver to release the gas pedal. In ideal case, it will provide speed adjustment without breaking and entering the curve with speed that guaranty defined level of comfort and safety.

Advisory curve speed estimation is an actual and challenging issue because of the variety of conditions that can influence on safety or comfort in curve driving. Most of the curves are designed based on comfort standards with respect to vehicle skidding and rollover. Nevertheless, drivers usually drive beyond the maximal safety speed guaranteed by the design safety criteria in the critical curves. This is due to a different driving style, driving experience, weather conditions, vehicle characteristics, familiarity with the road characteristics etc. Also, there is the influence of construction constraints that usually on the lower categories of roads have a considerable influence and force designers to consider usage of low radius or superelevation on some segments that lead to a very high exploitation of safety buffers or even go beyond them. Design standards for curvature and superelevation are on some roads ignored or were not in place at the time when these roads were built (Department of Transportation U.S. - NHTSA, 1999).

As the ADASIS v2 Protocol does not contain advisory curve speed which is used in model, it must be calculated. On one hand, precision and robustness of a method for advisory speed calculation is limited by available input data and on the other acceptance of provided advisory speed is influenced by relevance and precision of calculation method. Simple methods usually cannot provide sufficient precision. Usage of the more complex methods impose problem of providing relevant input data (curvature, superelevation, personal perception of comfortable lateral acceleration, weather condition, detailed vehicle characteristics, road friction factor, etc.). Trade-off between model precision and method input data availability is usually the main issue. The selection of the suitable model for application presented in this study is done based on the availability of the road geometry defined by ADASIS v2 Protocol. The ADASIS v2 Protocol predicts availability of two crucial elements of the road geometry with a high resolution (each 1 meter of road) which are the curve radius and the pavement superelevation. These data are basic for the curve design, determinate by a desirable design speed. Superelevation is tilting the roadway to help counterbalance centripetal forces acting on the vehicle as it goes along the curve. Along with friction, superelevation keeps a vehicle from sliding off the road.

Based on all the aforementioned and the analysis of the existing methods, the most appropriate method adopted for purpose of this study is the method proposed in the NHTSA (Department of Transportation U.S. - NHTSA, 1999) guidelines for the design and development of Curve Warning Systems. It defines operating performance parameters that should be take into consideration to achieve a calculation as realistic as possible. The advisory speed will be considered as lower of the maximum comfortable speed for negotiating the upcoming curve and the maximum safe speed at which the vehicle can negotiate the curve without losing control. The maximal comfortable speed will consider $f_{\text{Max-Comfortale}}$ to be relevant side friction factor defined by road design criteria. The maximal safe speed will consider $f_{\text{Tire-Pavement}}$ to be relevant side friction factor estimated based on the weather conditions.

$$V_{Advisory} = MIN(V_{Comfortable}, V_{Safety}) \quad \text{Equation 4.1}$$

The maximum comfortable/safe speed for the approaching curve should be determined from the equation:

$$V_{Comfortable/Safety} = \sqrt{R \bullet g \bullet \frac{e + f_{Comfortable/Safety}}{1 - e \bullet f_{Comfortable/Safety}}} \quad \text{Equation 4.2}$$

where:

R - Curve radius,

g - Acceleration due to gravity,

f - Side comfort acceleration/Side friction factor,

e - Road superelevation.

As mentioned, necessary input data, the values for curve radius and superelevation may be retrieved from Electronic Horizon. The side friction factor must be in case of safety speed estimated and adjusted to meet road condition influenced by weather. Model is going to consider three possible cases of dry, wet, and snow or ice road. Data related to weather is going to be delivered by external provider or it will be calculated based on internal vehicle sensors based on existing algorithms.

Determination of advisory curve speed should be done for critical portion of curve that is beginning of curve segment with constant radius as the first position inside the curve with minimal value of radius.

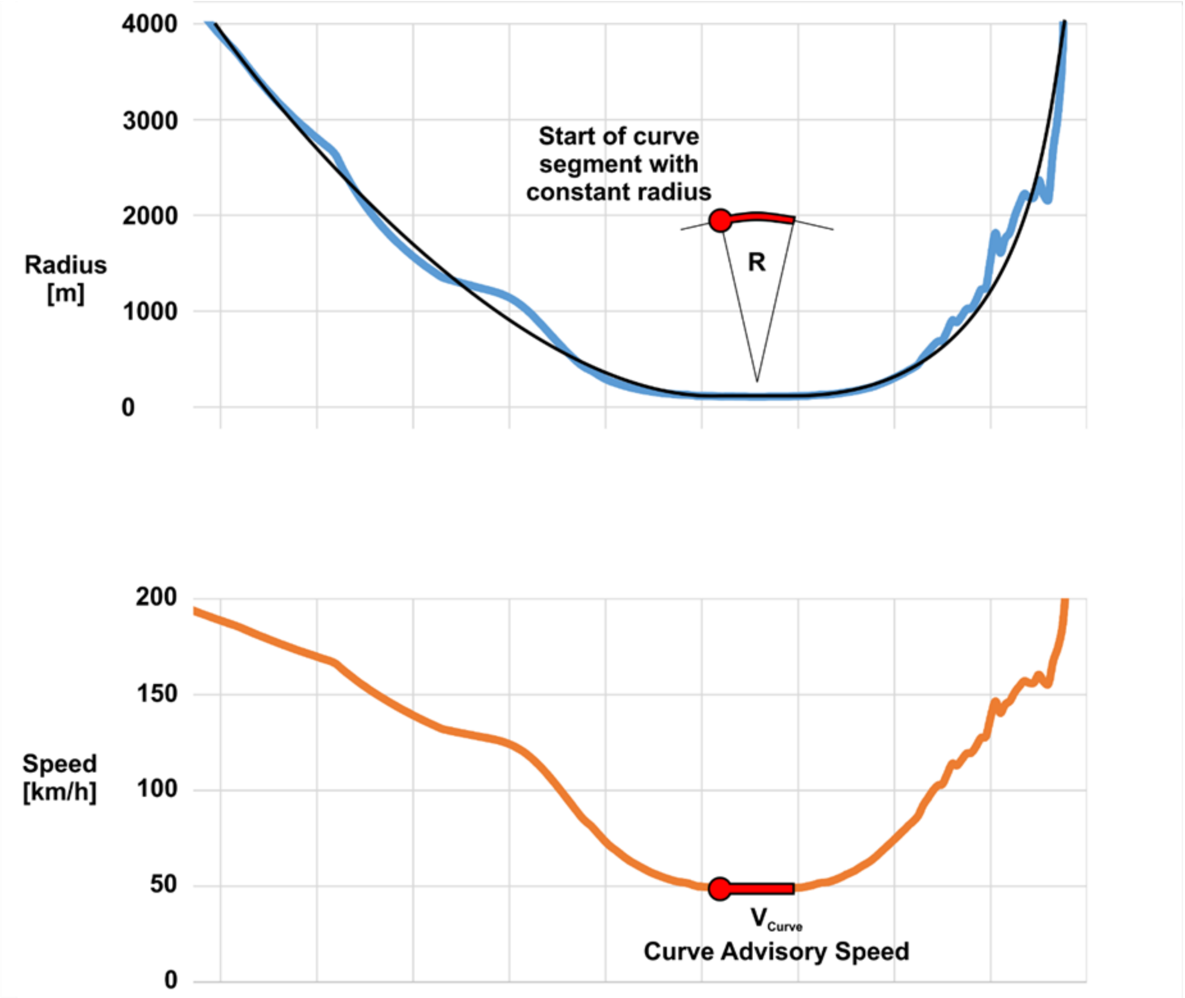

Figure 4.2 Modelling vehicle speed on curve sections [22]

4.3.1 Safe curve speed - Lateral friction factor ($f_{Tire-Pavement}$ / f_{Safety})

The lateral friction available at the tire-roadway interface is a measure of friction supply and is dependent on many factors as pavement surface type and condition, vehicle operating speed and deceleration characteristics, vehicle lane position, tire type and others. To provide precise calculation of a safe curve speed the estimation of lateral friction factor is needed. Estimating the coefficient of friction of the upcoming roadway may be the most difficult sensing function a curve warning system must perform [21]. Real time estimation of the coefficient of friction is not useful for road-ahead control applications as it provides information at a current vehicle location and the indicator of the friction in upcoming road segments stays unknown. This is the reason why in this study predefined values of the friction factor for the safe curve speed calculation will be used. The predefined values will be selected from those recognized in literature.

For the application, the critical are winter road conditions as there is decrease of available friction at the tire-roadway interface due to existence of snow and ice. When temperature drops below 0°C many undesirable phenomena can appear as black ice, condensation, frost, snow and freezing rain, snow or hail and affect vehicle stability and steerability [23]. The variety of traction coefficient values for possible road conditions and complexity of its reduction to just a few states can be perceived from Table 4.4.

Table 4.3 Traction coefficient range for different road conditions [23]

Coupling: tire – road conditions	Conditions / Traction coefficient range
Ice and tires with chains	0,12 (0°C) - 0,18 (-18°C)
Black ice	0,12 (-5°C) - 0,26 (-40°C)
Snow and ice	0,12 - 0,39
Snow and ice covered with fresh snow	0,15 (-10°C) - 0,42 (-40°C)
Compacted snow	0,24 - 0,37
Uncompacted snow	0,15 (0°C) - 0,42 (-10°C)
White frost	0,45 - 0,58
Deep snow	0,92 - 0,95
Dry asphalt	0,59 (-40°C) - 0,72 (-10°C)

As it is aforementioned, real-time estimation of available road friction is quite complicated. Still there is no implementable solution for current state of vehicle technology and data transferability among the vehicle users and other data providers. Therefore, in this study is going to be used accepted values of four characteristic road conditions based on literature review data presented in table below (Table 4.4).

Table 4.4 The friction potential ranges for different road conditions - literature review [24]

Road conditions	Source:					Accepted Value
	Bachmann	Mundl	Gustafsson	Mitschke	Barace	
Dry	1.05 -1.2	1.05	1	0.88 - 1.15	0.9-1.2	0.9
Wet	0.73-0.81	0.85	0.7	0.7 - 0.95	0.7 – 0.9	0.7
Snow	0.18-0.38	0.2	0.3	0.07 - 0.2	0.2 - 0.3	0.2
Ice		0.1	0.1		0.1 - 0.2	0.1

The accepted values for the four characteristic road conditions are adopted as the minimal rounded values from five presented in review (Table 4.4).

4.3.2 Comfortable speed - Side Friction Factor ($f_{Comfortable}$)

The limiting value for side friction, used in road design, is based on driver comfort thresholds. It depends on national road design standards and it varies from country to country. In the table below (Table 4.5) are present the curve design friction factors of some countries that are used as base for definition of acceptable comfortable friction factor.

Table 4.5 Summarize of International Practices of Side Friction Factors in Curve Design [25]

Design Speed (km/h)	Austria	Belgium	Netherland	Germany	France	Ireland	Italy	Spain
50	/	/	/	/	/	/	/	/
60	0.16	0.16	0.17	0.14	0.16	0.15	0.17	0.16
70	0.15	/	0.15	0.12	/	/	/	0.15
80	0.14	0.13	/	0.11	0.13	0.14	0.13	0.14
90	0.13	0.11	/	0.10	/	/	/	0.14
100	0.11	/	0.12	0.09	0.11	0.13	0.11	0.13
110	/	/	/	/	/	/	/	/
120	/	0.10	0.8	0.07	0.10	0.12	0.10	0.10

Design Speed (km/h)	Sweden	Portugal	Switzerland	Luxemburg	South Africa	South Korea	Canada	U.S.
50	0.18	/	0.19	/	0.16	0.16	0.16	0.16
60	/	0.16	0.16	0.16	0.15	0.14	0.15	0.15
70	0.15	0.15	0.15	0.15	0.15	0.13	0.15	0.14
80	/	0.14	0.14	0.14	0.14	0.12	0.14	0.14
90	0.12	/	0.13	0.13	0.13	0.11	0.13	0.13
100	/	0.12	0.12	0.12	0.13	0.11	0.12	0.12
110	0.10	/	0.11	0.11	0.12	0.10	0.10	0.11
120	/	0.10	0.10	0.10	0.11	0.10	0.09	0.09

As model has advisory purpose and user acceptance is influenced by compliance of calculated and perceived comfortable speed, model will provide calculation adjustment. Percentage of calculated comfortable curve speed that will be taken into consideration as advisory can be adjusted. This will be possible to be done by analysing driver’s perception of system feedback and driver’s driving style to improve acceptance. Initially defined value in the model is 100% of side friction factor accepted as relevant.

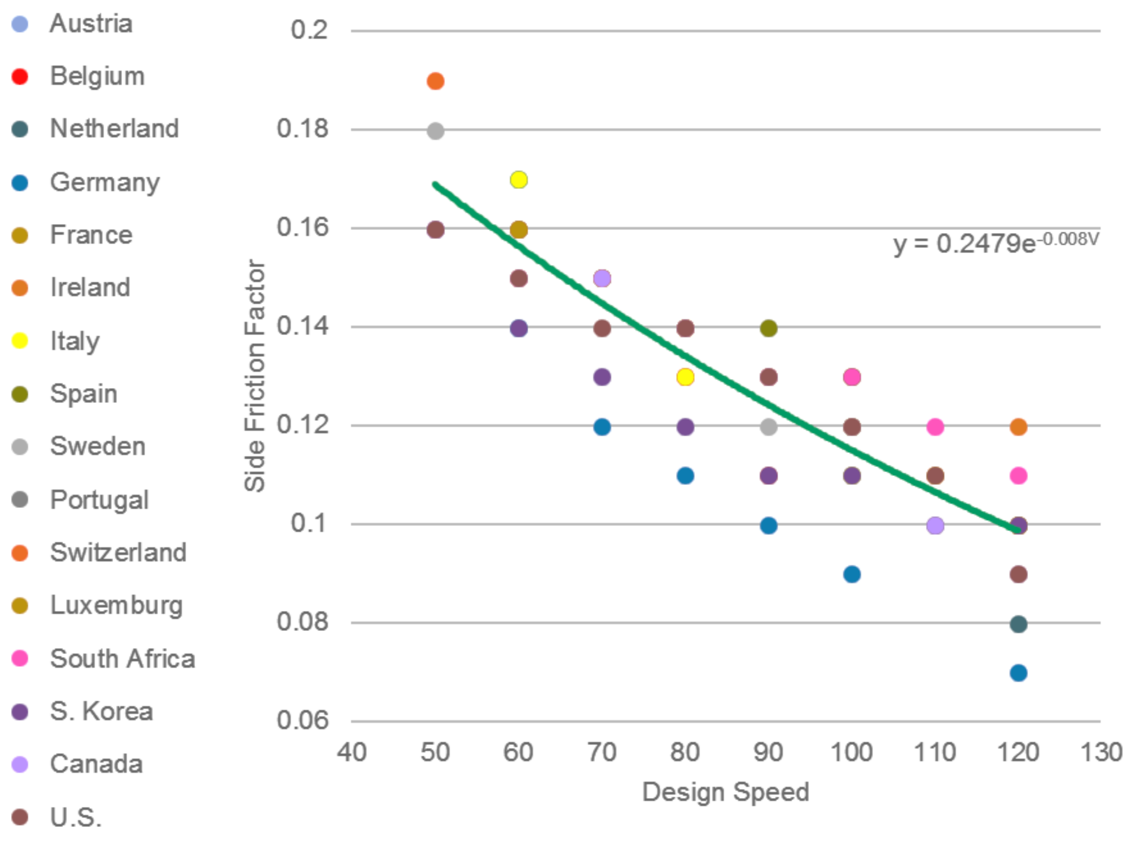

Figure 4.3 International Practices of Side Friction Factors in Curve Design

The relevant accepted side friction factor values for calculation of comfortable speed defined by formula:

$$f_{Comfortable} = 0.2479 * e^{-0.008V} \quad \text{Equation 4.3}$$

The formula is created as exponential regression model of average value of provided side friction factors in road design standards of above mentioned 16 countries (Table 4.5). The advisory comfortable curve speed has to be calculated as iteration calculus as it is function of Side Friction Factor that is function of speed to get correct value.

4.3.3 Acceptable braking deceleration rate

For implementation of RTDAS in hybrid vehicle it is necessary to select acceptable deceleration rate that will be achieved by integration of regenerative braking to adjust vehicle speed. The estimation of relevant braking deceleration rate is also a complicated procedure. Literature review provide different results and unification is complex due to different measuring methods, calculation, road conditions, vehicle conditions etc. Deceleration rates of passenger car as a result of literature review are presented in table below (Table 4.6). Here we have again the same issue as with acceptable comfortable later friction factor. The acceptable deceleration is partially question of comfort and style of driving. There are some standards as the Swiss standard model which uses a constant deceleration rate of 0.80 m/s^2 for modelling driver behaviour while driving in curves [26]. Some tests showed that driver perception of acceptable deceleration is crucial and suggest an adjustable acceptable longitudinal deceleration rate would be desirable [21].

Table 4.6 Deceleration rates of passenger car – Literature review [27]

Author	Year	Speed range (km/h)	Deceleration Rate (m/s^2)
Gazis et al.	1960	72	4.9
St. John and Kobbet	1978		1.07
Parsonson and Santiagio	1980		3
Bester	1981		0.6 - 1.9
Lee et al.	1984		0.28 - 0.96
Wortman and Fox	1994	48.3 - 80.5	2.1 - 4.2
Wortman and Matthias	1983	57.6 - 76.4	2.5 - 4
Brodin and Carlsson	1986		0.5
Watanatada et al.	1987		0.4 - 0.6
McLean	1991		0.5 - 1.47
Bennett and Dunn	1995	60 - 70	1.39
		70 - 80	1.78
		80 - 90	2.22
		90 - 100	2.34
Akçelik and Besley	2001	60	3.09
Wang et al.	2005	40 - 50	2.4
		50 - 60	2.39
		60 - 70	2.67
		70 - 80	2.52
		> 80	2.55

The optimal solution would be implementation of self-learning algorithm that can create functional dependency of acceptable comfortable deceleration rate as different deceleration cases and adjust to each driver preferences. This is the possible field for further research of system improvement. In defining initial system setup of hybrid vehicle, value of maximal acceptable deceleration rate is set to 1.5m/s^2. This value is characteristic of driver aggressiveness and driving style and present author’s initial estimation that should be confirmed in future application testing.

5 Deceleration speed profiles calculation models

The calculation models for determination of deceleration speed profiles for both vehicle concepts are developed considering characteristics of Electronic Horizon data. The most important characteristic is discrete nature of data. This determined calculation as a step based, where step is determined by Horizon resolution.

5.1 Internal combustion powered vehicle model – Coasting speed estimation

For the purpose of these study, it is considered that ICE powered vehicle in coasting mode doesn't use engine braking in order to utilize as much as possible vehicle kinetic energy. Therefore, the resistances which influence the coasting deceleration are aerodynamic drag, rolling resistance and resistance due to gradient of a slope (Equation 5.1).

The procedure of determining the dependence between the velocity and distance is calculated from basic vehicle forces equation:

$$ma = -F_{air\_drag} - F_{rolling} - F_{slope} \qquad \text{Equation 5.1}$$

where resistances are defined as:

$$F_{slope} = m * g * sin\,\alpha \qquad \text{Equation 5.2}$$

$$F_{rolling} = f * m * g * cos\,\alpha \qquad \text{Equation 5.3}$$

$$F_{air\_drag} = 0.5 * A * C_d * \rho * V^2 \qquad \text{Equation 5.4}$$

m - Vehicle mass
g - Acceleration due to gravity
α - Segment slope
f - Rolling resistance coefficient
A - Vehicle frontal area
C_d - Aerodynamic drag coefficient
ρ - Ambient air density
V - Vehicle speed

By substituting:

$$0.5 * A * C_d * \rho = K \qquad \text{Equation 5.5}$$

$$m * g * cos\,\alpha - f * m * g * sin\,\alpha = C \qquad \text{Equation 5.6}$$

Equation 5.1 is defined as:

$$m * a = -K * V^2 - C \qquad \text{Equation 5.7}$$

The Equation 5.9 is obtained by expressing a as speed derivative $\frac{dV}{dt}$ and multiplying with $\frac{ds}{ds}$ in Equation 5.7.

$$m * a = m\,\frac{dV}{ds} = m\,\frac{dV}{dt}\,\frac{ds}{ds} = m\,\frac{ds}{dt}\,\frac{dV}{ds} = m\,V\,\frac{dV}{ds} \qquad \text{Equation 5.8}$$

$$m\,V\,\frac{dV}{ds} = -(K * V^2 + C) \qquad \text{Equation 5.9}$$

Furthermore, it is converted to:

$$-m * \frac{VdV}{K * V^2 + C} = ds \qquad \text{Equation 5.10}$$

Next step is definite integration of Equation 5.10, where the limits on the left side integral are V_i and V_{i+1} and on te right side S_i and S_{i+1}. Where V_i is the entering and V_{i+1} exiting speed of the segment i. The variables S_i and S_{i+1} present the distance of beginning of segment i and segment $i + 1$ from the route starting point. The exiting speed of the segment i is at the same time the entering speed of the segment $i + 1$.

$$-m * \int_{V_i}^{V_{i+1}} \frac{VdV}{K*V^2 + C} = \int_{S_i}^{S_{i+1}} ds \qquad \text{Equation 5.11}$$

Solution of this integration generates:

$$\frac{m}{2 * C} * ln \frac{C + K * V_{i+1}}{C + K * V_i} = S_{i+1} - S_i \qquad \text{Equation 5.12}$$

The value of the segment entering speed can be calculate by expressing V_i dependacy from Equation 5.12 as:

$$V_i = \frac{1}{K} * \left((C + K * V_{i+1}) * e^{\frac{2*C*(S_{i+1} - S_i)}{m}} - C \right) \qquad \text{Equation 5.13}$$

5.2 Hybrid vehicle deceleration model – Deceleration speed estimation

HES provides much more potential to optimize vehicle deceleration model. The reason is possibility to control deceleration by using regenerative braking demand. By managing available regenerative braking force, it is possible to recover some percentage of vehicle kinetic energy and at the same time control vehicle deceleration speed while vehicle approaching to critical point on the road. Also, deceleration rate can be higher that generates lower time losses and it is more acceptable for the driver.

By using electro motor and deceleration relevant vehicle characteristics it is possible to estimate at any vehicle speed available regenerative braking force (Figure 5.1). The maximal regenerative braking force of electro motor is characterized in two generator angular speed segments. The first one is segment with constant maximal torque (T_{Max}). This segment generates the constant maximal available regenerative braking force (F_{RBmax}) that can be calculated considering defined vehicle model in IGNITE by using equation:

$$F_{RBmax} = \frac{T_{Max} * R_{Gear} * FDR}{R_{Wheel}} \qquad \text{Equation 5.14}$$

where:

- T_{Max} - Maximal generation torque defined as electric motor characteristic
- R_{Gear} - Gear ratio of currently engaged gear

- FDR - Final drive ratio (Ratio of differential element)
- R_{Wheel} - Radius of vehicle wheels

The second segment characterized braking force limited by maximal power of electro motor/generator that can be calculated by using equation:

$$F_{RBmax} = \frac{9.548 * 0.10472 * P_{Max}}{V} \qquad \text{Equation 5.15}$$

where:

- P_{Max} - Maximal power of generation defined as electric motor characteristic
- V - Current vehicle speed

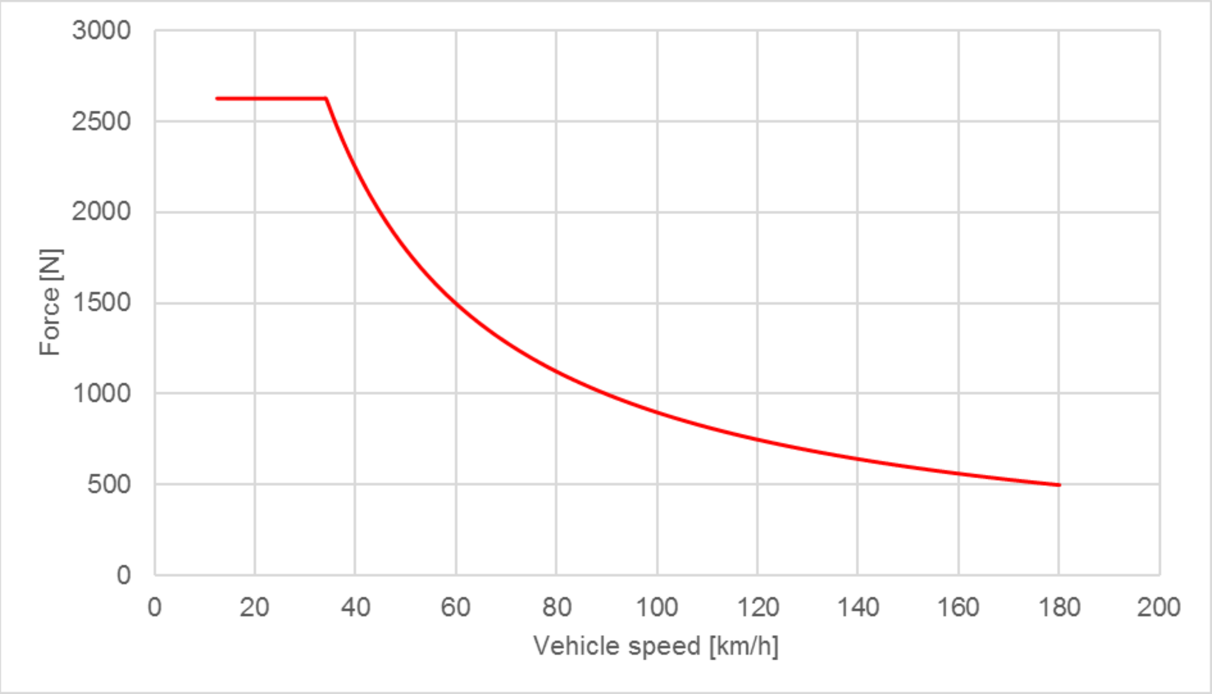

Figure 5.1 Regenerative braking characteristic of electric motor generation mode (Max Power 25kW and Max Torque 100Nm)

The proposed deceleration model of hybrid vehicle in this study takes into consideration generator and vehicle aerodynamic characteristics to estimate vehicle speed dependent available deceleration resistances. The main idea is to adopt minimal combined resulting deceleration force, in relevant vehicle exploitation speed section (0 – 180 km/h), which is generated by available regenerative braking and air drag (Figure 5.2). The maximal deceleration rate will be limited to 1.5 m/s^2 in accordance with explanation provided in chapter 4.3.3. The case scenario implemented for validation and testing of RTDAS in HES uses electric motor which generation characteristics are present in Table 5.1.

Table 5.1 Electro motor generator mode characteristics

Characteristic	value	Unit
Maximal Power	25000	[W]
Maximal Torque	100	[N]

Speed dependent deceleration forces, defined by declared electric motor generation and vehicle model characteristics, are present in Figure 5.2. The figure also contains the estimated usage of regenerative braking to achieve the constant deceleration rate dependent on speed dependent resistances.

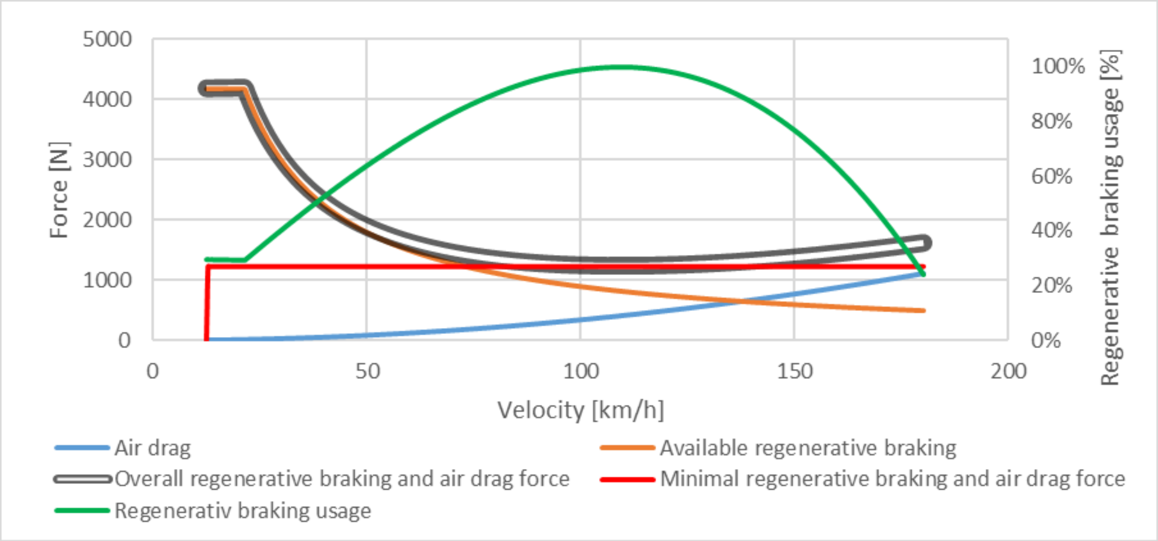

Figure 5.2 Speed dependent deceleration forces

To these resistances, model will add rolling and slope resistances which are dependent on road slope. By merging all mentioned resistances, the equation for calculation of deceleration rate will be completed.

The deceleration rate determination:

$$ma = -F_{rolling} - F_{slope} - F_{air\_drag} - F_{regenerative\_braking}$$ Equation 5.16

where resistances are defined as:

$$F_{slope} = m * g * \sin\alpha$$ Equation 5.17

$$F_{rolling} = f * m * g * \cos\alpha$$ Equation 5.18

$$F_{air\_drag} = 0.5 * A * C_d * \rho * V^2$$ Equation 5.19

$$F_{regenerative\_braking} = D_{RB} * 9.548 * 0.10472 * \frac{Pmax}{V}$$ Equation 5.20

m - Vehicle mass
g - Acceleration due to gravity
α - Segment slope
f - Rolling resistance coefficient
A - Vehicle frontal area
C_d - Aerodynamic drag coefficient
ρ - Ambient air density
V - Vehicle speed
D_{RB} - Regenerative braking demand

The regenerative braking demand is expressed as percentage of maximal available regenerative braking torque for current vehicle speed. Demand is controlled by hybrid vehicle controller developed by using Modelica and imported in IGNITE Powertrain library. The control logic uses PID controller to follow pre-calculated deceleration vehicle profile. Estimated value of regenerative braking demand is presented in Figure 5.2 as regenerative braking usage.

The air drag and regenerative braking forces are merged, for the purpose of deceleration speed profile calculation, in constant force F_{Const} (Figure 5.2). Constant force F_{Const} presents minimum of overall combined force in the interval of vehicle speed from 0 to 180 km/h. This value will be adopted as relevant for deceleration rate determination.

$$F_{Const} = MIN(F_{air\_drag} + F_{regenerative\_braking}), \qquad for\ 0 < V < 180\ km/h$$ Equation 5.21

By substituting:

$$0.5 * A * C_d * \rho = C_{AD}$$ Equation 5.22

$$9.548 * 0.10472 * Pmax = C_P$$ Equation 5.23

in Equation 5.21, constant force is redefined as:

$$F_{Const} = MIN\left(C_{AD} * V^2 + \frac{C_P}{V}\right)$$ Equation 5.24

The vehicle speed which generates the minimal F_{Const} is speed that satisfies the condition:

$$\frac{d\left(C_{AD} * V^2 + \frac{C_P}{V}\right)}{dV} = 0$$ Equation 5.25

$$\frac{d\left(C_{AD} * V^2 + \frac{C_P}{V}\right)}{dV} = 2 * \mathrm{C_{AD}} * \mathrm{V} + \frac{\mathrm{C_P}}{\mathrm{V^2}}$$ Equation 5.26

From Equation 5.26 vehicle speed that generates the minimal combined deceleration force is:

$$V = \sqrt[3]{\frac{C_P}{2 * C_{AD}}} = \left(\frac{C_P}{2 * C_{AD}}\right)^{\frac{1}{3}}$$ Equation 5.27

Based on Equation 5.27 constant force is:

$$F_{const} = C_{AD} * \left(\frac{C_P}{2 * C_{AD}}\right)^{\frac{2}{3}} + \frac{C_P}{\left(\frac{C_P}{2 * C_{AD}}\right)^{\frac{1}{3}}}$$ Equation 5.28

The deceleration rate can be now calculated from equation:

$$a = \frac{1}{m}\left(- m * g * \sin\alpha - f * m * g * \cos\alpha - C_{AD} * \left(\frac{C_P}{2 * C_{AD}}\right)^{\frac{2}{3}} - \frac{C_P}{\left(\frac{C_P}{2 * C_{AD}}\right)^{\frac{1}{3}}}\right)$$ Equation 5.29

As slope is constant at the level of one segment, calculation of deceleration rate defined by Equation 5.29, will provide value that is constant on whole segment. Therefore, we can consider that all resistances at the level of segment are constant and that overall resistances will generate constant deceleration based on equation (Equation 5.29). For segment with constant deceleration the calculation of speed at the beginning of segment by knowing the speed at the end is defined as:

$$\mathrm{V}_i = \sqrt{{V_{i+1}}^2 - 2 * a * \ (S_{i+1} - S_i)}$$ Equation 5.30

Where:

V_i - Speed at the beginning of a segment

V_{i+1} - Speed at the end of a segment (beginning of next segment)

S_i and S_{i+1} - Distances of segment i and segment $i + 1$ from the route starting point.

Deceleration speed profile will be determinate by implementing presented calculation from the ending to the beginning point of the route, segment by segment. Every time when algorithm recognize critical point with lower speed than calculated deceleration speed it updates speed with critical speed defined for this point and continues. This provides that each critical speed is taken into consideration.

6 System validation and effects estimation

To check the compliance of Real-Time Driver Advisory System with predefined application purpose and functions the process of validation is done. For this purpose, specific scenario is created that simulate real world case. The system performance and effects are analysed through comparing obtained simulation results of simulated real-world case scenario with and without Real-Time Driver Advisory System application.

To create as realistic simulation scenarios as possible, the three fundamental tasks were: creation of vehicle environment, vehicle model, and driver behaviour. The environment presents the real road which characteristics are exported into input data set, in accordance with ADASISv2 protocol. For the purpose of validation, the realistic vehicle model, with all relevant components, was created in IGNITE software that is also used as a simulation tool. The realistic driver behaviour is defined as drive cycle obtained from the driving simulator. The driving on simulator was done by using the road characteristics of preselected route that will be used in the study. The driving simulator is part of the laboratory of the Faculty of Transportation Sciences, Technical University in Prague.

Figure 6.1 Driving simulator - Faculty of Transportation Sciences

The initial scenario, for ICE and HES performance estimation, is created by combining environment, vehicle and driver models. The acquired results from simulation of initial scenario, in IGNITE software solution, are considered as performance of ICE and HES powered vehicles, without Real-Time Driver Advisory System usage.

For estimation of results of RTDAS usage, the same models of environment, vehicle and driver are used with applied developed control logic of driver and vehicle behaviour during coasting/deceleration. For simulation of system usage, the internal IGNITE elements are developed to control driver and vehicle behaviour during identified deceleration segments. These elements simulate actions, predicted to be done by real driver and vehicle controllers, when the advisory system sends the message that gas pedal should be released.

The obtained simulation results with and without RTDAS usage were analysed, compared and used for system validation procedure and effects estimation.

Simulation model in IGNITE combines standard models of vehicle components from the library and the additional ones created for the purpose of RTDAS testing (Figure 6.2). The driver behaviour is represented with distance based drive cycle recorded by driving simulator. This drive cycle is part of the Driver Model element and it provides speed based on input data related to the vehicle position. The vehicle position is acquired from the Vehicle Bus element. This element provides two important vehicle states, speed and position. The PID controller of the Driver Model uses speed from recorded drive cycle, defined for the current vehicle position, and current vehicle speed to control lateral acceleration and deceleration of vehicle.

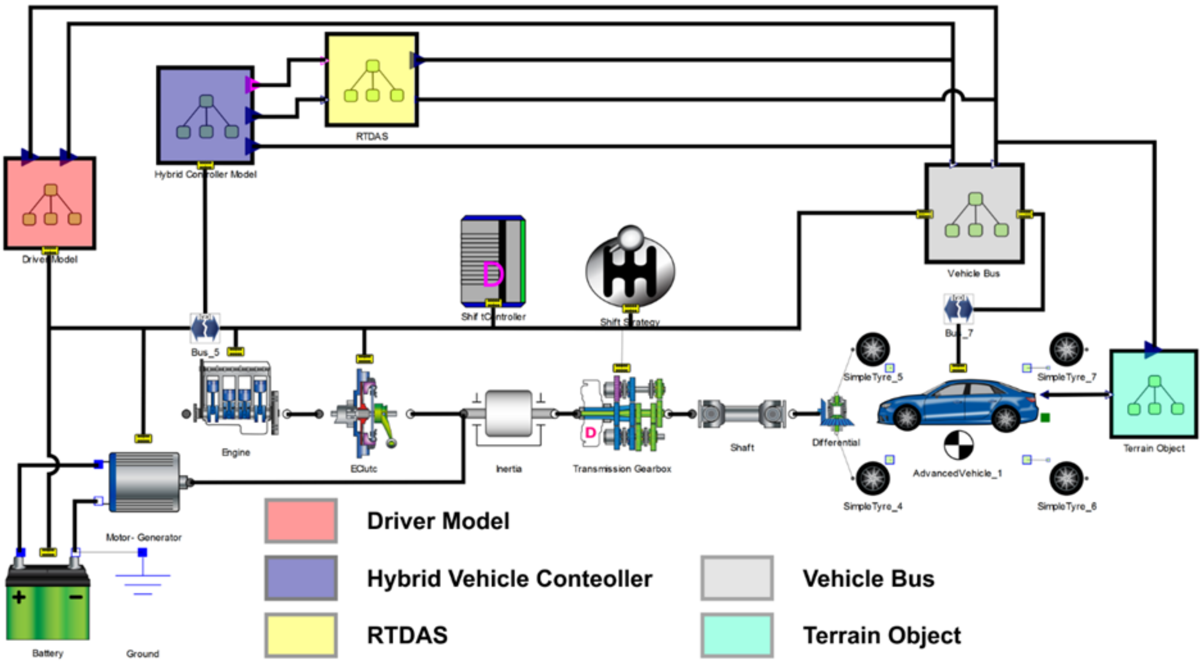

Figure 6.2 Complete IGNITE simulation model of HES powered vehicle

RTDAS element contains the model logic that, based on vehicle position and speed, recognises the moment when it should send the message to a driver. The message is created when vehicle speed is equal or higher than coasting speed. This is the trigger condition for sending a message to driver. In the simulation, the message signal is sent to the hybrid vehicle controller. The hybrid vehicle controller has two control modes, the standard mode and RTDAS mode. If the message is active, the controller switches to RTDAS mode that includes following the deceleration speed profile that comes from RTDAS. The RTDAS element at the beginning of simulation calculates and stores the deceleration profile. While message is active, controller sends zero demand to engine and braking system, disengages the clutch, and controls regenerative braking demand. This action should simulate driver behaviour when RTADS sends the message. The driver will release the gas pedal, activate neutral gear and avoid braking. The deceleration speed control is done by internal PID controller by comparing current speed and deceleration profile speed, which is provided by RTDAS element. Terrain object will generate slope resistance based on slope profile exported from map. As the slope profile is distance based, the terrain element uses current vehicle position as an input.

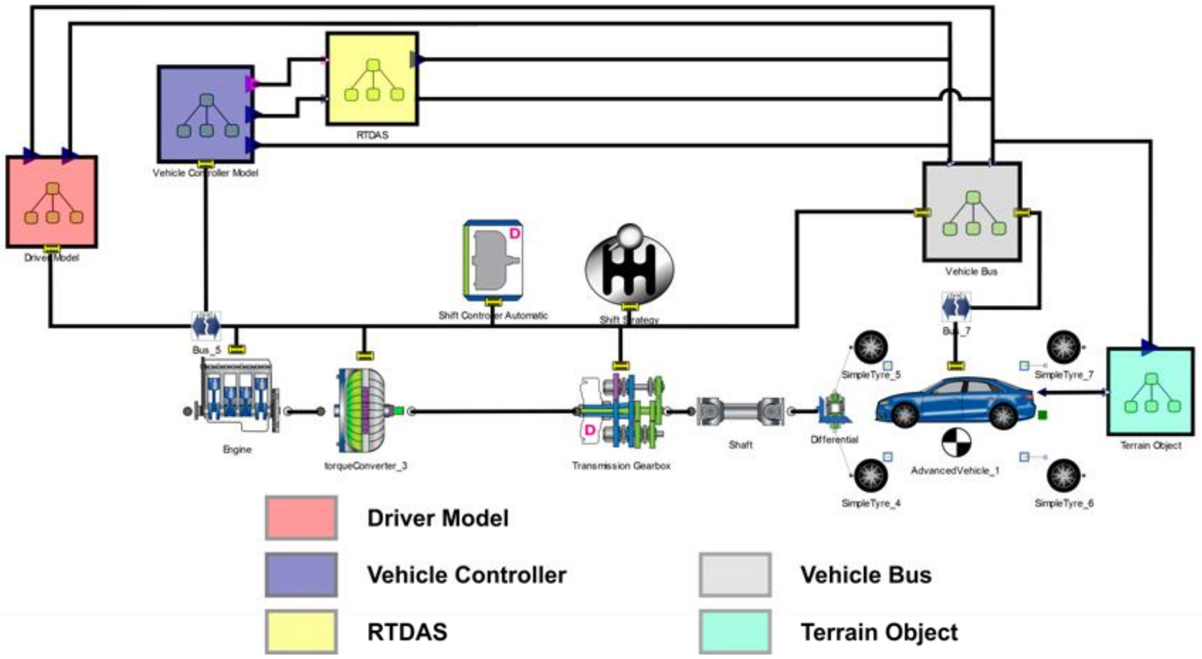

Figure 6.3 Complete IGNITE simulation model of ICE powered vehicle

In the Figure 6.3 is presented concept ICE powered vehicle. The Terrain object, Driver model, Vehicle bus and RTDAS are the same as in the HES powered vehicle. The difference is in the deceleration speed calculation model, which is part of RTDAS. The vehicle controller in this case has the same functionality as hybrid to simulate desired driver actions in accordance with coasting status message

6.1 Real-world environment

Creation of real world environment is done by exporting real road data of chosen route presented with X, Y, Z coordinates. Based on exported rad data by pre-processing procedures required road characteristics (curvature, slope, speed limits, traffic signs, etc.) are obtained. All road characteristics are implemented in simulation road input data set with the resolution of 1 meter. The same road characteristic data set is used during driving cycle recorded from driving simulator in laboratory and during simulation in IGNITE software solution. The figures below present the three main road characteristics of route that creates environment of defined case scenario such as curvature, speed limit and slope.

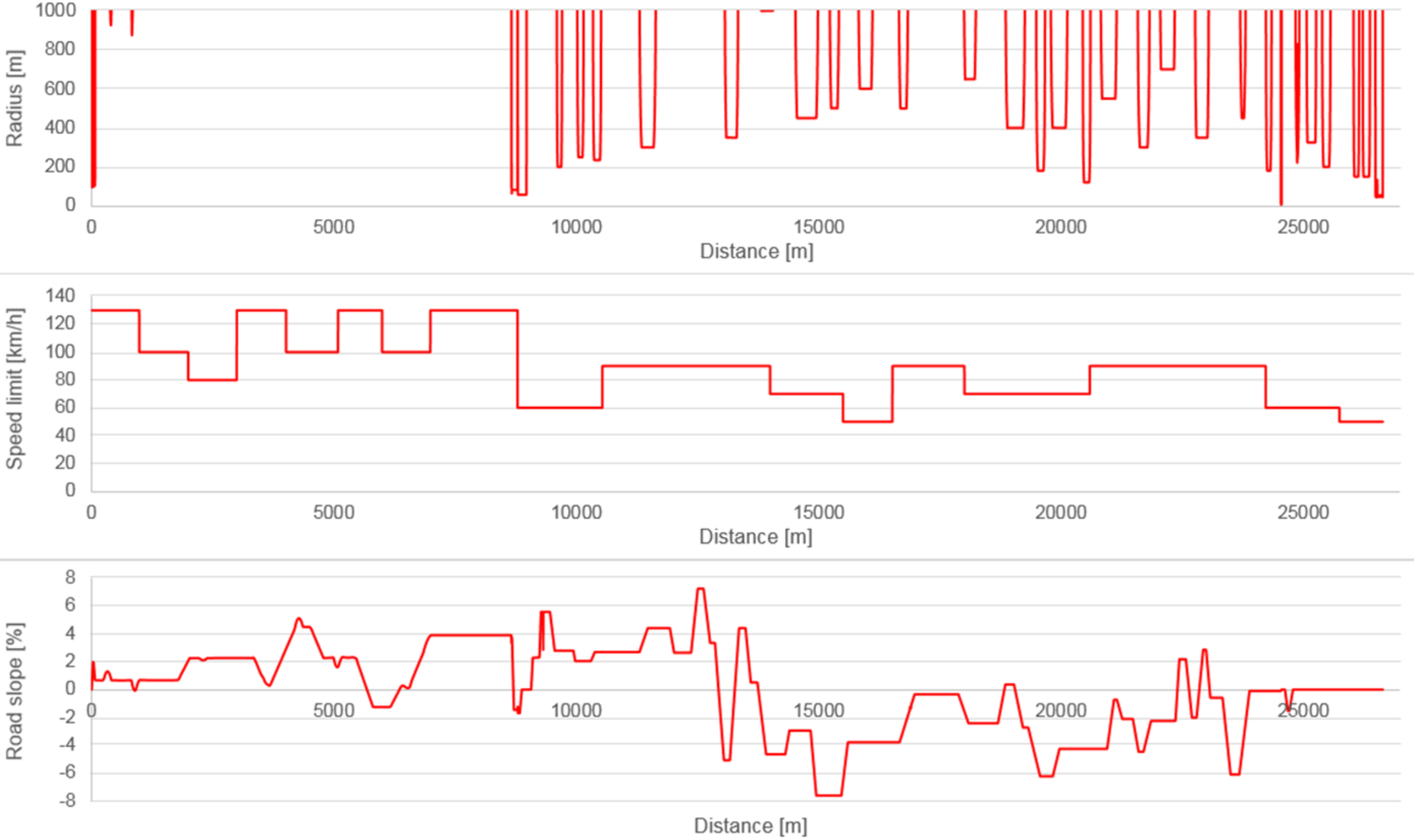

Figure 6.4 Real world environment - Curve radius, Speed limit and Slope

6.2 Driver behaviour model

In order to acquire realistic driver behaviour data, with all real world driving stochasticity, driving cycle was recorded from laboratory driving simulator, during test drive. The test drive wasn't familiar with road characteristics of the chosen route. This provides realistic effects of speed adjustments according to road curvature, traffic signs and speed limits.

The driving cycle was exported from driving simulator with high sample rate of 125 samples per second. Due to high sample rate recording, drive cycle had to be smoothed to avoid the high frequency noises which make a driving cycle difficult to be followed. The smoothing is done by using simple averaging method defined by the following equation:

$$\mathrm{V}_{\mathrm{Smoothed}}(\mathrm{t}) = \frac{1}{2\mathrm{l}+1}\sum_{\mathrm{s}=-\mathrm{l}}^{\mathrm{l}} \mathrm{V}\,(\mathrm{t}+\mathrm{s}) \qquad \text{Equation 6.1}$$

Where:

$$\mathrm{l} = 120\mathrm{ms}$$

After time-based drive cycle smoothing, it is transferred to distance-based drive cycle, for the purpose of presenting the driver behaviour model (Figure 6.5).

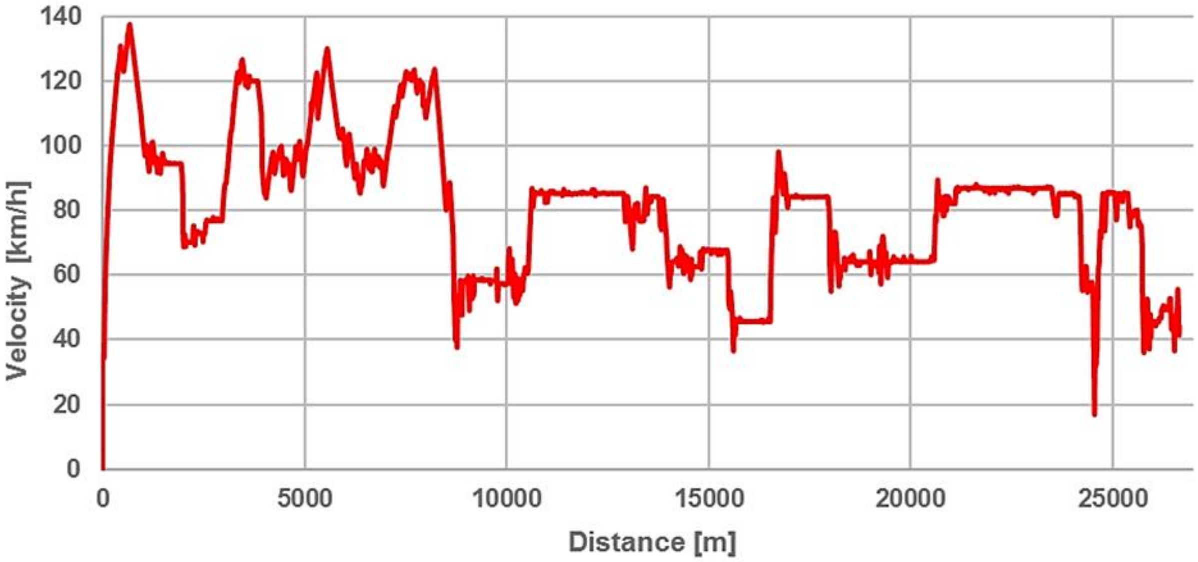

Figure 6.5 Driver behaviour model – Basic case scenario driving cycle

6.3 Real-Time Driver Advisory System effects – ICE powered vehicle

The simulation of defined case scenario with applied RTDAS in ICE powered vehicle presents the classic coasting deceleration scenario. From simulation results 16 events of coasting, without engaging the mechanical vehicle brake, were recognized based on controlled coasting model logic (Figure 6.6).

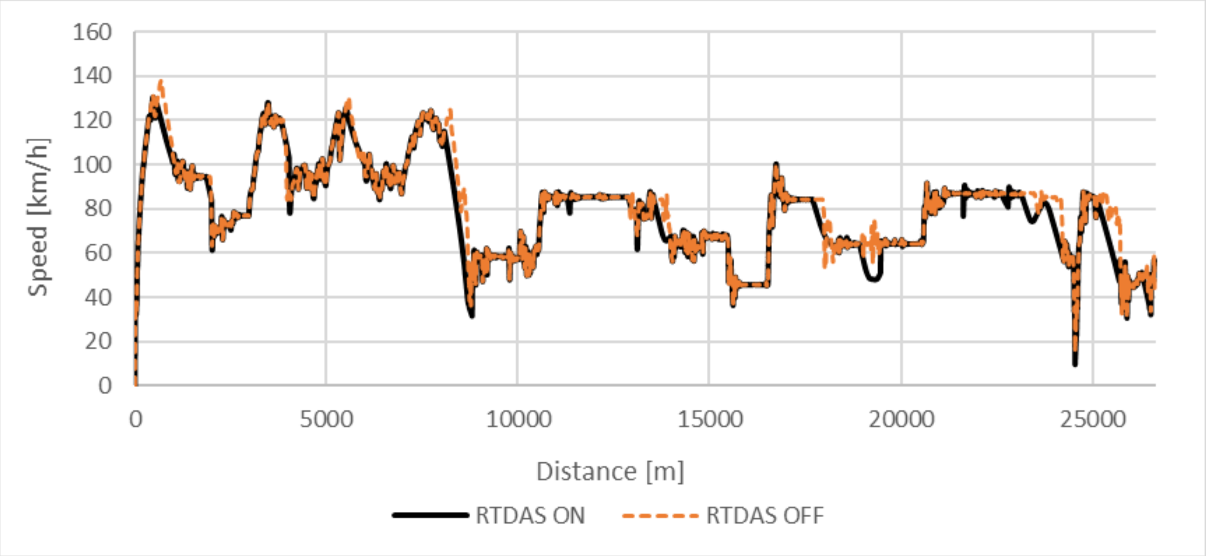

Figure 6.6 Speed profiles ICE powered vehicle

The first step in validation is the precision of system estimation. It is done based on comparing reached and desired speed of the critical point for all segments. Speed inaccuracy is defined as the speed difference expressed in km/h and percentage of desired speed. The speed inaccuracy is defined as the measure of quality of the RTDAS.

By applying the RTDAS control logic, vehicle reached critical positions with average absolute inaccuracy of 4.72%. From 16 segments 10 have higher vehicle speed than desired and 6 have lower. The occasions of higher vehicle speed in critical points are inaccuracies that influence safety and comfort driving. The events of lower vehicle speed in critical points, influence driver acceptance and unnecessary time losses. The highest positive inaccuracy of 5.69 km/h, 5% higher from desired speed, appeared in segment number 1, and highest negative of -4.84, 9% lower than desired, appeared in segment number 11 (Table 6.1). The average absolute imprecision is 3.07 km/h and presents speed difference that can be easily corrected by additional driver intervention through engaging the mechanical brake.

The higher values of system imprecision in some of segments show model logic weaknesses, which will be improved through detailed analyses of segment characteristics and future application development, in order to cover as many as possible cases that can appear in real world driving with higher precision.

Table 6.1 RTDAS coasting deceleration control logic precision

Control deceleration segment	Final speed inaccuracy	Final speed inaccuracy [km/h]
1	5%	5.69
2	1%	1.23
3	5%	4.04
4	4%	3.55
5	0%	0.41
6	-13%	-4.74
7	6%	4.47
8	1%	1.59
9	-3%	-1.90
10	-7%	-4.81
11	-9%	-4.84
12	3%	2.48
13	-6%	-3.41
14	2%	1.19
15	2%	0.52
16	8%	4.31
Average Absolute Inaccuracy	4.72%	3.07

Results related to fuel consumption and state of charge are exported from simulation done in IGNITE and used for estimation of fuel and electric charge savings. For both vehicle concepts, ICE and HES, the results are obtained for driving with and without using the RTDAS used. The fuel consumption and savings are computed for each recognized coasting segment of road. In Table 6.2 each coasting segment is presented by length of coasting, fuel consumption for both cases, fuel savings achieved and time losses. The time losses present difference between traveling times on considered segment in both cases. The overall coasting distance achieved by using RTDAS is 6014.35 meters and present 23% of total route length (26.64 km). This is the result of route slope characteristic, where the first part of drive is uphill and the second part of route is downhill with extensive slopes on some segments. This generated longer segments of coasting in second part of the route (Figure 6.7).

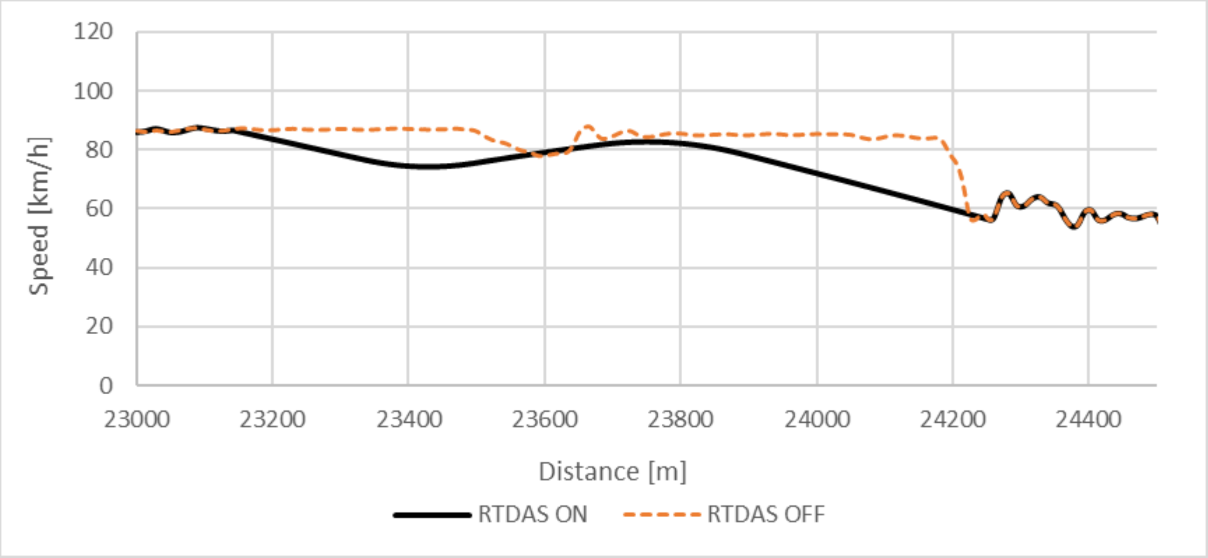

Figure 6.7 Long coasting segment

In some cases, additional assistance by engaging of mechanical brake to follow desired drive cycle is needed. Overall amount of fuel savings is 359.40 grams (0.428 litres) with accompanied overall time losses of 36.75 seconds. These results are converted to equivalent energy consumption to be comparable with HES (Table 6.3).

Conversion of diesel saved fuel in grams to kWh, including engine energy efficiency, enables comparison of energy effects of two different vehicle propulsion concepts (Table 6.4). After conversion of fuel saving in grams to kWh the consumption saving is also corrected for ICE efficiency, as just 35% of it goes to driveline [28], [29].

Table 6.2 RTDAS coasting deceleration savings

		ICE - Fuel consumption [g]			
Deceleration Segment	Length [m]	RTDAS	Simulator	Savings	Time Loss [s]
1	36.07	1.36	9.89	8.53	0.00
2	418.79	14.60	39.79	25.19	1.15
3	137.38	4.80	11.62	6.82	0.20
4	194.58	6.80	19.40	12.60	-0.45
5	487.38	16.98	39.71	22.73	0.25
6	725.17	29.64	99.32	69.68	9.80
7	65.16	3.26	9.25	5.99	0.10
8	212.82	10.73	22.70	11.97	-0.15
9	437.58	22.06	194.36	23.70	2.40
10	606.01	30.65	67.34	36.70	1.25
11	549.60	27.73	260.65	46.66	7.80
12	164.22	8.32	12.32	4.00	0.30
13	1111.69	56.21	126.77	36.00	5.55
14	627.52	38.35	72.19	33.84	6.80
15	207.62	10.56	23.24	12.68	2.10
16	32.77	1.70	4.02	2.32	-0.35
Overall	6014.35			359.40	36.75

Table 6.3 Fuel energy density and engine efficiency

Fuel	Fuel Energy Density	Unit
Diesel automotive	1.182	Litre/kg
	10.6	kWh/litre
ICE efficiency	0.35	/

Table 6.4 Fuel – Fuel consumption savings conversion to electric charge

Equivalent energy savings during coasting [kwh]	
Diesel consumption	Diesel energy equivalence to electric charge
359.40 [g]	ICE efficiency: 0.35 4.54 * 0.35 =1.59
0.428 [litre]	
4.54 [kWh]	
Electric charge equivalent to saving	1.59 [kWh]
Specific saving per time loss	0.043 [kwh/s]
Time Loss	36.75 [s]
Specific saving per km of coasting	0.264 [kwh/km]
Length of controlled segments	6.01 [km]

6.4 Real-Time Driver Advisory System effects - HES

For validation of RTDAS usage in hybrid vehicles, the same procedure is done as for ICE powered vehicles. For HES validation, calculation based on battery state of charge is added. This present regenerated or spent amount of electric energy during deceleration segments controlled by RTDAS. The system precision results, achieved in case of HES are much better, as this concept has direct real-time control of regeneration braking. This provides possibility, in some extension, for mismatching correction of vehicle deceleration speed, based on real-time feedback (Table 6.6). Usage of RTDAS in HES, recognized 17 deceleration segments of controlled coasting.

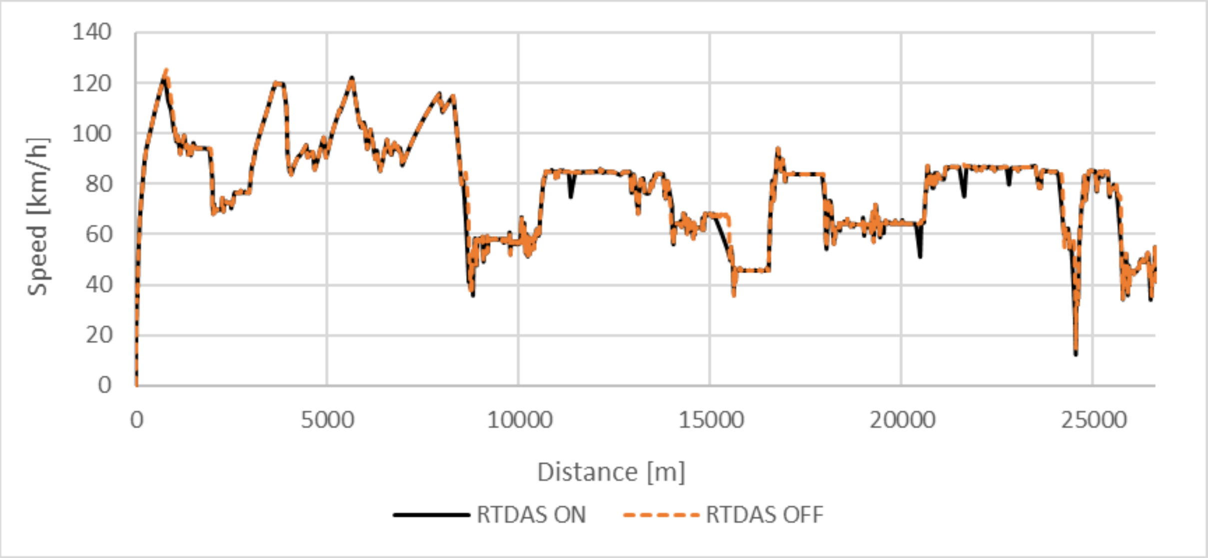

Figure 6.8 Speed profiles HES powered vehicle

Average acquired imprecision is 1.95% and it is more than 2 times lower than imprecision in case without possibility for correction, estimated as 4.72%. Also, the final average HES inaccuracy of 1.03 km/h is around three times better, compared to 3.07 km/h achieved in case of ICE power vehicle. For the concept of hybrid vehicle, we can conclude that, considering the worst segment results with maximal error in reaching desired speed at the end of controlled coasting of just 1.41km/h, RTDAS usage provide high precision.

Table 6.5 RTDAS coasting deceleration control logic precision

Deceleration Segment	Final speed inaccuracy	Final speed inaccuracy [km/h]
1	1%	1.26
2	2%	1.37
3	1%	1.14
4	3%	1.30
5	2%	0.80
6	2%	1.21
7	2%	1.21
8	2%	0.78
9	2%	1.41
10	2%	1.02
11	2%	0.79
12	2%	1.38
13	-2%	-1.27
14	0%	0.03
15	6%	0.77
16	2%	1.04
17	2%	0.79
Average Absolute Inaccuracy	1.95%	1.03

The overall coasting distance achieved by using RTDAS is 2150.40 meters and presents 8% of total route length (26.64 km). After estimation of fuel and electric energy consumption and savings presented in Table 6.7, the conversion in comparable measure of kWh is done. Overall fuel consumption saved is 359.40 of fuel grams (0.428 litres) and 0.291 kWh of energy charge saving, with accompanied time loss of 6.30 seconds (Table 6.7).

The comparison of specific savings per time loss shows that HES, with 0.082 kwh of savings per one second of loss generated during coasting, has better efficiency than ICE power vehicle with specific saving per time loss of 0.043 [kwh/s]. This measure shows that one second of time loss is more valuable for users of RTDAS of HES powered vehicles. The coasting length of route is shorter for HES almost three times which is result of higher average deceleration rate of HES vehicle, achieved by using regenerative braking.

Table 6.6 RTDAS controlled deceleration savings

		ICE -Fuel consumption [g]			Battery Motor-Generator Energy consumption/regeneration [kwh]			
Deceleration Segment	Length [m]	RTDAS	Simulator	Savings	RTDAS	Simulator	Savings	Time Loss [s]
1	241.7	1.44	5.80	4.36	0.03	0.01	0.02	0.40
2	80.6	0.60	1.80	1.20	0.02	0.00	0.01	0.10
3	28.3	0.18	0.67	0.49	0.00	0.00	0.00	-5.30
4	140.0	1.48	6.22	4.74	0.04	0.00	0.03	1.70
5	49.2	0.75	6.75	6.00	0.01	0.00	0.01	0.10
6	53.8	0.43	2.82	2.39	0.01	0.00	0.01	0.10
7	129.2	1.12	4.84	3.72	0.03	0.02	0.01	-0.30
8	435.4	4.93	24.92	19.99	0.11	0.10	0.02	2.80
9	99.7	0.84	2.07	1.24	0.02	0.01	0.01	0.00
10	48.4	0.50	1.32	0.81	0.01	0.01	0.00	0.10
11	117.7	1.35	2.28	0.93	0.03	0.01	0.02	0.70
12	136.2	1.12	2.30	1.17	0.03	0.00	0.03	0.50
13	69.7	0.54	1.58	1.04	0.01	0.00	0.01	0.10
14	174.5	1.65	4.70	3.04	0.03	0.01	0.03	0.50
15	128.2	2.39	3.89	1.50	0.04	0.01	0.02	3.70
16	152.0	1.56	4.47	2.92	0.04	0.01	0.03	0.80
17	65.7	0.99	3.34	2.35	0.02	0.00	0.01	0.30
Overall	2150.4			57.90			0.29	6.30

Table 6.7 Fuel – Electric charge combined energy savings

Equivalent energy savings during coasting [kwh]		
Diesel consumption	Diesel energy equivalence to electric charge	Electric charge
57.90 [g]	ICE efficiency: 0.35 0.731*0.35 = 0.256 [kWh]	Electric motor efficiency: 0.90 0.291*0.9 = 0.262 [kWh]
0.069 [litre]		
0.731 [kWh]		
Electric charge equivalent to saving	0.256 + 0.262 = 0.518 [kWh]	
Specific saving per time loss	0.082 [kwh/s]	
Time Loss	6.3 [s]	
Specific saving per km of controller deceleration	0.241 [kwh/km]	
Length of controlled segments	2.15 [km]	

7 Development of cross check algorithm in terms of user acceptance

The system implementation and usage is strongly connected with user experience. As it has advisory nature, driver at the end has the key role to react in accordance with system's advice. By timely accepting the advice and taking predicted actions, driver directly influences the system efficiency.

For the purpose of RTDAS user acceptance estimation, test drivers will first do a test drive on the simulator with incorporated RTDAS (Figure 7.1). Results from test driving will be used for estimation of compliance of driver actions with system advices. The measure of compliance will be defined as delay or frequency of absence of driver action. The correct driver action is considered total releasing of the gas pedal after sound and visual signal.

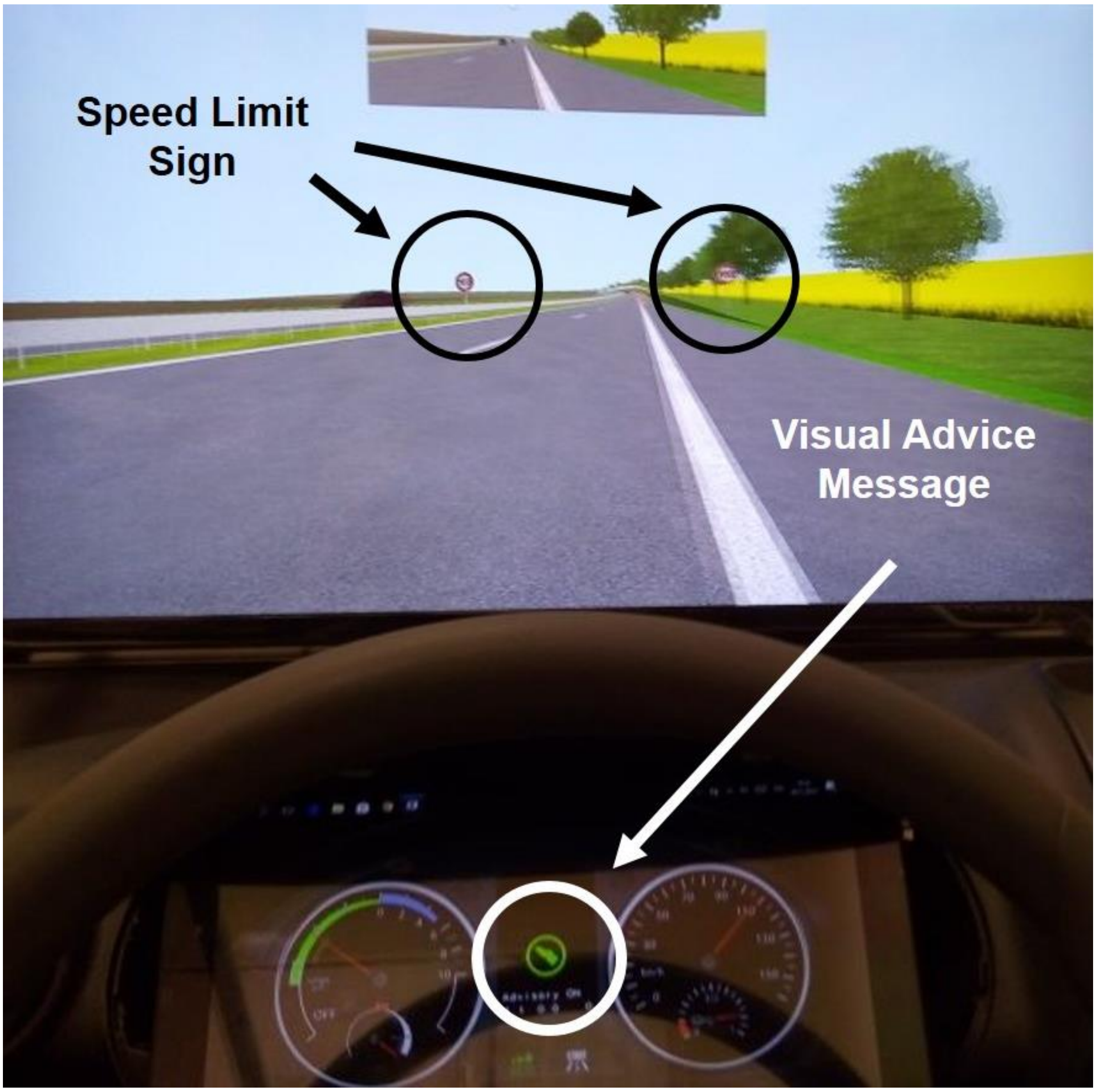

Figure 7.1 Driving simulator with incorporated RTDAS - Faculty of Transportation Sciences

The driver impression and preference will be examined through the survey based on questionnaire (APPENDIX VI). The questionnaire is focused on driver understanding of RTDAS functioning principles and perception of RTDAS efficiency, usability and deceleration suitability on different road types, advice distraction and benefits. Results will be used for optimization of system and identifying user acceptance, at the current level of testing relevance, achieved by using driving simulator.

The both parts of user acceptance estimation, driving on simulator equipped with RTDAS and following survey based on defined questionnaire, is going to be realized through the ongoing experiments which are the part of ongoing research project “Advanced assisting systems and their UI for future EV and HEV” (SGS15/224/OHK2/3T/16).

Conclusion

Research work covered by the scope of master thesis confirms the strong potential of utilization of detailed digital map road data for future development of contemporary ADAS applications.

The theoretical part of the study analyses and defines the basic requirements for ADAS applications, including RTDAS, based on ADASISv2 Protocol. It gives explanation of data structure that will be sent to the application from electronic horizon provider. This provides information for understanding the opportunities for ADAS applications development and additional applications in modern vehicles based on Electronic Horizon data.

The practical part of the thesis covers development of RTDAS system by creating system elements by using object-oriented, declarative, multi-domain modeling language Modelica. the The elements created in this way are compatible to be used in IGNITE, a physics-based system simulation package focused on complete vehicle system modeling and simulation.

Also, the practical part of the study validates initial idea and concept of coasting deceleration potentials, considering fuel and energy economy improvements, achieved by using designed RTDAS. On the other side, study identifies the dimness of approach and fields for system improvements that will be covered in future research and development work.

Acquired result considering RTDAS precision, indicates better performance of HES concept, with average absolute error of 1.03 km/h that is around three times better than average error of 3.07 km/h, achieved in case of ICE powered vehicle. Ability to use electric motor regenerative braking for managing deceleration definitely improves considerably RTDAS precision. Besides higher precision, energy flows analyses show advantage of the HES concept also in the field of fuel and energy charge savings. For this purpose, the measure of efficiency is defined as specific energy saving per time loss. With specific energy saving of 0.082 kwh/s, comparing to 0.043 kwh/s of vehicle powered by ICE, the HES concept advantages are even more endorsed.

The results clarify the system usability in either vehicle concept, ICE or HES. The study identifies greater flexibility for development and utilization of system in HES. The current state of development of HES provides extensive opportunity for system implementation, in all levels of “hybridization”, from micro hybridized to full hybridized vehicles.

The future research and development work considering RTDAS, will cover investigation of driver’s acceptance and real-world implementation of RTDAS and its testing and validation as a scope of ongoing research project “Advanced assisting systems and their UI for future EV and HEV” (SGS15/224/OHK2/3T/16), where the author is a part of the team

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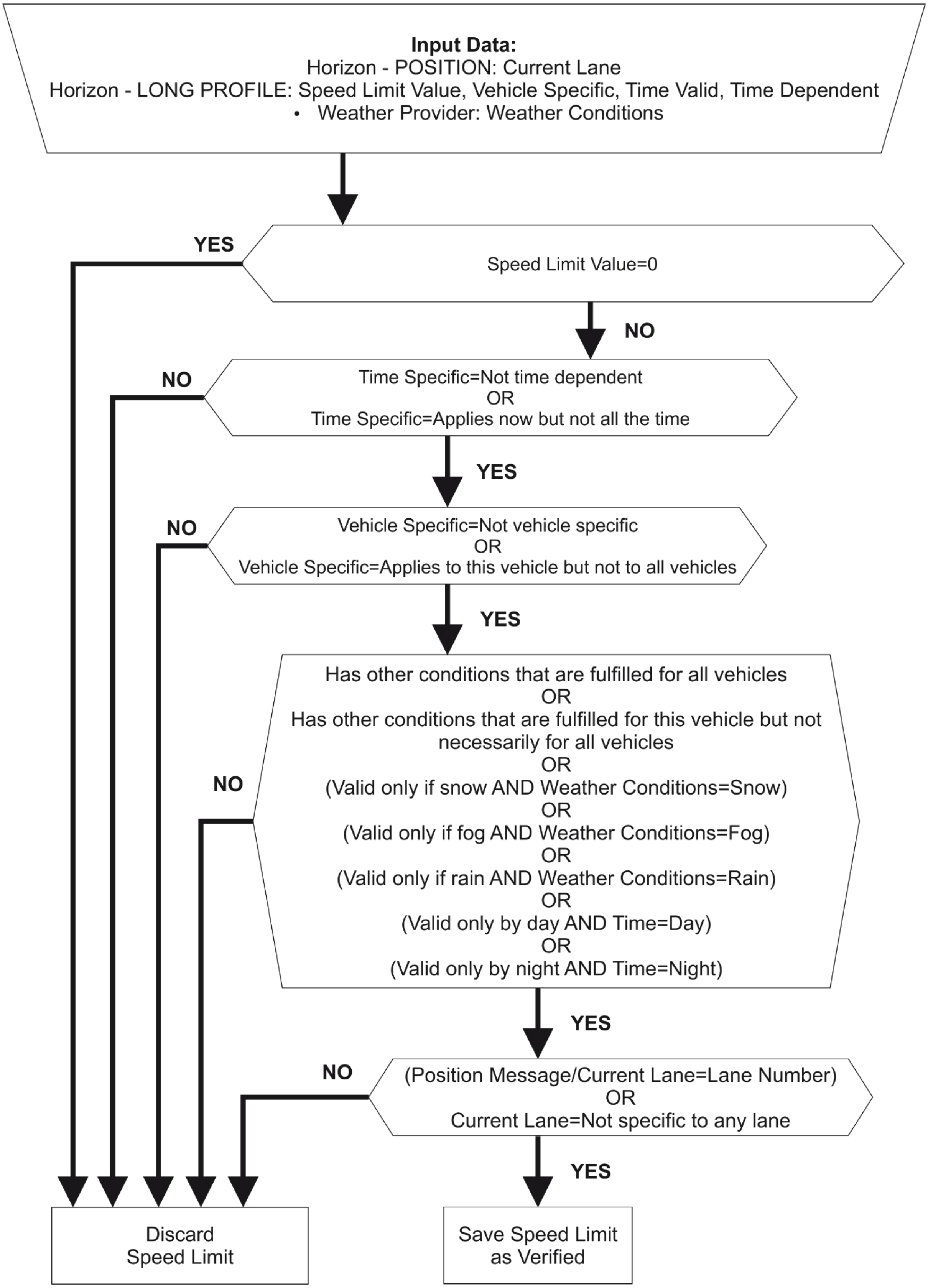
APPENDIX

APPENDIX I - The VALUE field is decomposition

- Sign Type: Speed Limit
- Value: Speed Limit Value
- Lane
  - Not specific to any lane.
  - Lane number.
  - Unknown, or N/A.
- Vehicle Specific
  - Not vehicle specific.
  - Applies to this vehicle but not to all vehicles.
  - Does not apply to this vehicle but possibly to other vehicles.
  - It’s not known whether the sign applies to this vehicle.
- Time Specific
  - Not time dependent.
  - Applies now but not all the time.
  - Does not apply now but at other times.
  - It’s not known whether the sign applies now.
- Condition
  - Has other conditions that are fulfilled for all vehicles.
  - Has other conditions that are fulfilled for this vehicle but not necessarily for all vehicles.
  - Has other conditions that are not fulfilled for this vehicle but possibly for other vehicles.
  - Has other conditions that are not currently fulfilled for any vehicle.
  - Sign is not valid at all (e.g. visible here but referring to another road).
  - Valid only if snow.
  - Valid only if fog.
  - Valid only if rain.
  - Valid only by day.
  - Valid only by night.
  - Valid depending on turn direction / future path.
  - Validity depends on conditions or combinations of conditions that cannot be adequately described by other values, and it is not known whether the sign applies.

    - Unknown whether validity depends on conditions.
- Sign Location
    - Unknown
    - Right of the road
    - Left of the road
    - Above the road
    - On the road surface
    - Sign is not physically located at this position
    - The stretch of road that a sign applies to ends at this position
    - N/A

APPENDIX II - Speed Limit Sign - Verification algorithm

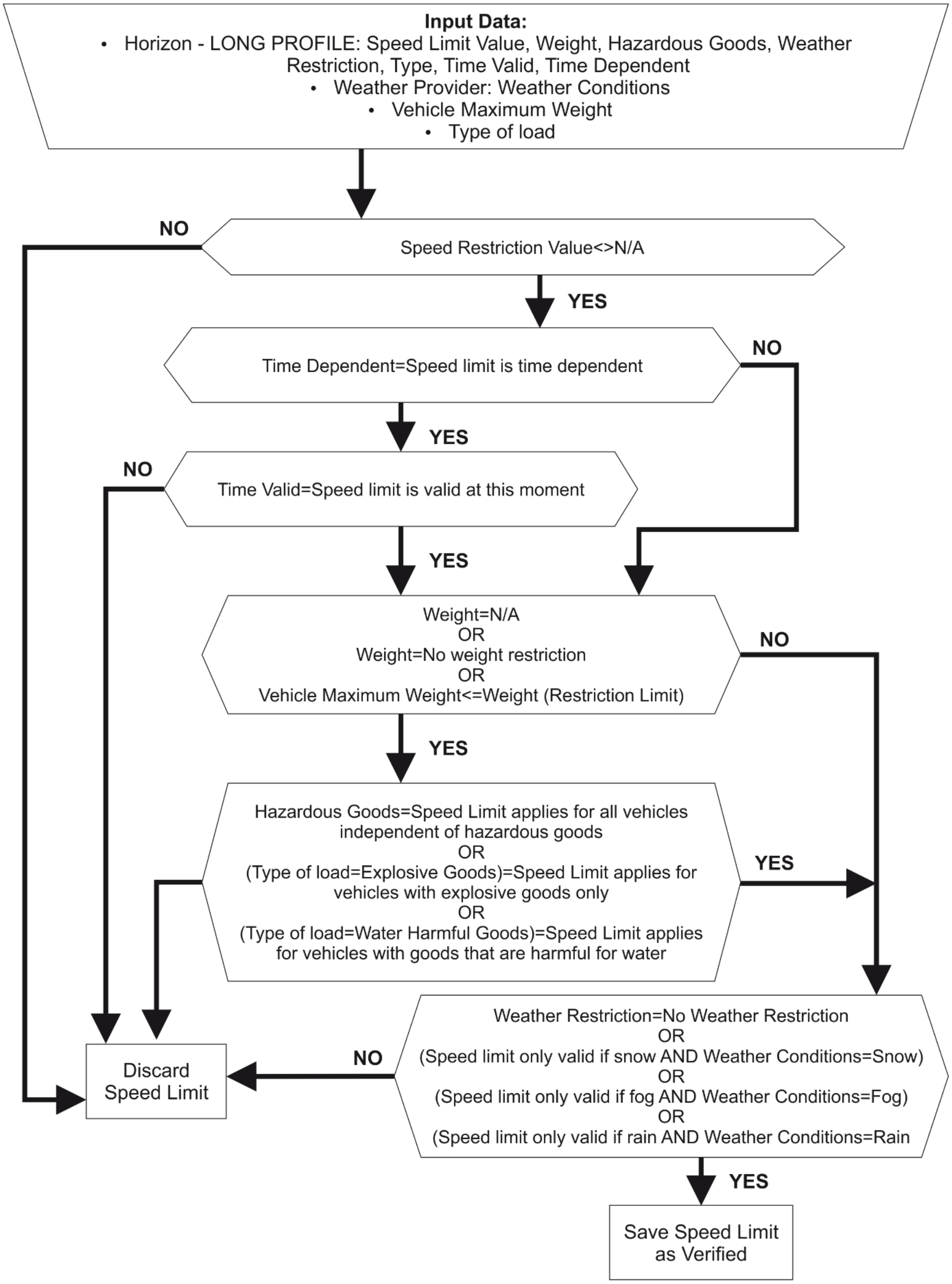


APPENDIX III - LONG_PROFILE Message - “Truck Speed Limit” – VALUE decomposition

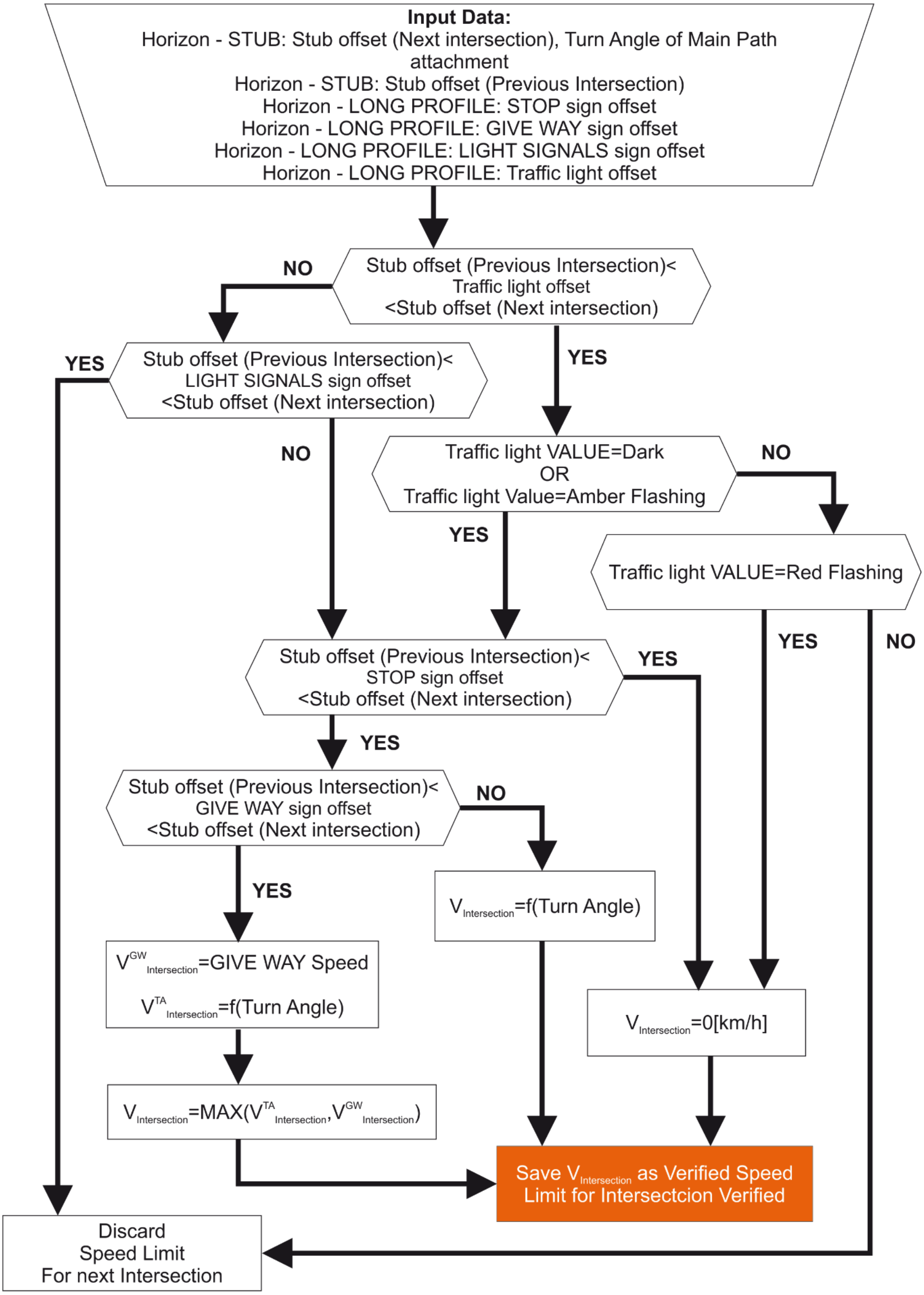
- Speed
    - Speed Restriction Value
    - N/A
- Weight
    - no weight restriction
    - 0.5 tons
    - 1 tons
    - …
    - 62.5 tons
    - >62.5 tons
    - N/A
- Hazardous Goods
    - Speed Limit applies for all vehicles independent of hazardous goods
    - Speed Limit applies for vehicles with explosive goods only
    - Speed Limit applies for vehicles with goods that are harmful for water
    - Unknown
    - N/A
- Weather Restriction
    - No weather restriction
    - Speed limit only valid if snow
    - Speed limit only valid if fog
    - Speed limit only valid if rain
    - Unknown
    - N/A
- Type
    - Explicit legal speed limit given by a sign at the road
    - Implicit legal speed limit given by road traffic regulations
    - The maximum speed limit that is allowed without distinguishing if it is explicit or implicit
    - Unknown
    - N/A
- Time Valid
    - Speed limit is not valid at this moment
    - Speed limit is valid at this moment

    - Unknown if it is valid at this moment
    - N/A
- Time Dependent
    - Speed limit is not time dependent
    - Speed limit is time dependent
- Reserved

APPENDIX IV - Speed Limit Trucks - Verification algorithm



APPENDIX V - Intersection Speed - Verification algorithm



APPENDIX VI – User acceptance estimation survey questionnaire

Survey Questionnaire	
1.	Was the system notification helpfull?
	Not helpfull at all
A	1
B	2
C	3
D	4
E	5
	Really helpful
2.	How efficient do you think was the system
A	Saved me less then 1 % of charge
B	Saved me 1 - 2% of charge
C	Saved me 2- 3% of charge
D	3 -4% of charge
E	4 and maybe even more.
3.	How diverting (distruct you) was the system?
	Not diverting
A	1
B	2
C	3
D	4
E	5
	Very diverting, could not concentrait
4.	Was system notification (visual /audio) sufficient for you?
A	Yes
B	Sound is enough
C	Visual is enough
D	Somethig else can be better (vibration)
E	Other:
5.	How likely would you use this system in real life?
	Not likely
A	1
B	2
C	3
D	4
E	5
	Very likely

6. Under what circumstances you'll use the system
A I'll never use it
B Only if I have to economise the charge (go really far)
C I'll use it all the time
D Only when the SoC (state of chage)is low
E Other:

7. Do you think the system is more helpful at
A Highway
B Rural road
C City
D Everywhere
E Never

8. Do you understend why the system signalize to release the gas pedal when there was no speed limitation?
Yes
No
I havent notice it

9. System can also help to prevent overspeeding when going downhill, will this feature be usefull?
Not usefull
A 1
B 2
C 3
D 4
E 5
Very usefull

10. Do you understend what system was doing to reduce your speed?
A Yes
B No
C Not at first
D Other: