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Highly Automated Driving on Highways based on Legal Safety

DISSERTATION

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by

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Abstract

Vehicle automation is proposed as one of the solutions to make transport safer, more comfortable and more environmentally friendly. It is gradually being introduced through Advanced Driver Assistance Systems (ADAS). ADAS started as Anti-lock Braking Systems (ABS) and have now extended to Adaptive Cruise Control (ACC) and Lane Keeping Assist Systems (LKAS). This work aims to contribute to this evolution, by discussing **how driving systems can share the road with human drivers**. It presents the legal safety concept for the design of a highly automated driving system for highways.

The legal safety concept proposes to base driving system design on **traffic rules**. This allows fully automated driving in traffic with human drivers, without necessarily changing equipment on other vehicles or infrastructure. The driving system uses traffic rules to predict legal or non-legal trajectories of objects in its perception zone and worst-case objects outside its perception zone. If all objects respect traffic rules, accidents will be avoided. If not, driving defensively will avoid most accidents. Today, international law allows highly automated driving, but not yet fully automated driving. The driving system interacts with the human driver, via **human rules**. The HAVEit project (European Seventh Framework Programme) and ABV project (French National Research Agency) propose human rules based on the horse-rider metaphor (H-metaphor). If needed, the driving system takes over control in order to avoid accidents. If the human driver cannot continue driving, the driving system brings the vehicle to a safe standstill on the emergency lane. The consequences of these human rules on driving system design are explored. **System rules** form the third set of rules of the legal safety concept. With system rules, system components respect the limitations of other system components.

The requirements on **perception, control and Human-Machine Interface (HMI) components** of the legal safety system are discussed. The **decision component**, which is the central component of the legal safety system, is completely worked out from requirements to design. The legal safety system has been implemented on PC and automotive Electronic Control Units (ECUs). The integration and validation of legal safety components on **LIVIC, HAVEit and ABV** demonstrators are presented. The work concludes that, for highway environments, legal safety decision, control and HMI can be achieved with state-of-the-art technology, and legal safety perception could be available in **medium term**.

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Lexicon

Accident	A collision that is directly related to actions of a human driver or driving system
Application zone	Environment for which the driving system is designed, e.g. road type, weather conditions and day/night conditions
Autonomous	Automation level, where longitudinal and lateral control is performed by the driving system in all application zones
Automation level	Configuration of human-system interaction: driver only, driver assisted, semi-automated, highly automated, fully automated and autonomous
Automation mode	Automation level that is active
Calculation time	Time needed for one system calculation cycle; from sensor input to control output
Decision	System component that calculates optimal subject trajectories
Configuration space	Set of all states that the subject can attain
Control	System component that keeps the subject on a trajectory
Defensive driving	Driving style that minimizes the number of accidents that are caused by non-legal behavior of other traffic participants
Demonstrator	Simulator and/or vehicle that integrates driving system
Direct trajectory planning	Trajectory planning, which directly generates (parts of) a trajectory, without the need of validation by an evaluation step
Driver assisted	Automation level, where longitudinal and lateral control is performed by the human driver, where the driving system gives feedback on optimal speed and lane, within a certain application zone
Driver only	Automation level, where longitudinal and lateral control is performed by the human driver, where the driving system is not active
Driving system	System that integrates perception, decision, control and HMI components for highly or fully automated driving
Emergency brake	Maximum deceleration till standstill
Exteroceptive sensor	Sensor on the subject that describes the environment without support of external sensors
Fully automated	Automation level, where longitudinal and lateral control is performed by the driving system, within a certain application zone
Ghost	Object that is moving in the wrong direction on highways
Growth	Maximum allowed control error on the subject speed profile
Highway	Road for motor vehicles that is structured in lanes and does not cross any road

Highly automated	Automation level, where longitudinal and lateral control is performed by the driving system, within a certain application zone. The human driver is monitoring the driving system and can be involved in the driving task
Horse-rider metaphor	Principle of using rider-horse interaction as a design model for human-system interaction
Human	Human driver in the subject vehicle
Individual speed profile	Subject speed profile that is optimal with respect to a single aspect of legal safety
Individual trajectory	Subject trajectory that is optimal with respect to a single aspect of legal safety
Interactor	Data structure communicated between system components
Lane	Longitudinal segment in which the road is structured
Lane assignment	Indication in which lane(s) an object is located
Lateral	Perpendicular on the direction of the subject axis
Left lane	First lane to the left of the subject lane
Legal safety system	Driving system that is designed according to legal safety rules
Longitudinal	In the direction of the subject axis
Minimum Risk Maneuver	Maneuver that brings the subject to standstill on the emergency lane in cases of system failure or human driver drowsiness
Not Legal and Not Safe	Situation where not all traffic participants respect traffic rules and accidents cannot be avoided
Not Legal, but Safe	Situation where not all traffic participants respect traffic rules, but accidents can be avoided
Nonholonomic	Limited in freedom of motion
Normal system functioning	Functioning without system failure
Object	Road user different from the subject
Optimal speed	Vehicle speed recommended by driving system
Optimal lane	Lane recommended by driving system
Perception	System component that describes the environment
Perception zone	Part of the environment that is described by perception
Phantom	Worst-case object outside the perception zone, according to traffic rules
Platoon	Group of vehicles following each other at close inter-distance
Proprioceptive sensor	Sensor on the subject that describes the subject state without support of external sensors
Right lane	First lane to the right of the subject lane
Safety	Lack of accidents
Safety zone	Situations that are Legal and Safe, or Not Legal, but Safe
Sampling-based trajectory planning	Trajectory planning, which directly generates (parts of) a trajectory, but needs validation of an evaluation step
Semi-automated	Automation level, where longitudinal control is performed by the driving system, within a certain application zone. Lateral control is performed by the human driver
Speed profile	Description of subject speed for a certain time horizon
Subject	Vehicle of interest
Subject lane	Lane in which the subject is located
System	Driving system

System failure	Situation wherein the system is not longer capable of driving in the application zone
System failure functioning	Functioning during system failure, where the driving system brings the vehicle to standstill with a minimum risk maneuver, unless the human driver takes over control
Target speed	Vehicle speed requested by human driver
Target lane	Lane requested by human driver
Traffic law	Law that regulates interaction of traffic participants
Traffic rules	Combination of traffic law and informal rules between traffic participants
Trajectory	Description of subject positions and speed for a certain time horizon
Trajectory space	Set of trajectories that the subject can follow
Solution space	Set of trajectories that the subject can follow, while respecting legal safety rules
Width	Maximum allowed control error on the subject trajectory
Zone description	Mathematical description of trajectories and speed profiles by minimum and maximum bounds
Zone model	Model for the zone description of trajectories and speed profiles, which can be specified by a limited number of parameters

Abbreviations

ABS	Anti-lock Braking System
ABV	Automatisation Basse Vitesse (Low Speed Automation), French ANR project
ACC	Adaptive Cruise Control
ADAS	Advanced Driver Assistance System
AL	Automation Level
AM	Automation Mode
ANR	French National Research Agency
AMD	Architecture Migration Demonstrator (HAVEit)
AS	Active Suspension
AU	Autonomous (automation level)
AUTOSAR	AUTomotive Open System ARchitecture
BAS	Brake Assist System
CAN	Controller Area Network
CC	Cruise Control
CMAS	Collision Mitigation Avoidance System
CSC	Chassis and Safety Controller
CTRA	Constant Turning Rate and Acceleration (motion model)
DA	Driver Assisted (automation level)
DGPS	Differential Global Positioning System
DO	Driver Only (automation level)
DSA	Driver State Assessment
EBA	Emergency Brake Assist
EBD	Electronic Brake force Distribution
ECU	Electronic Control Unit
ESC	Electronic Stability Control
FA	Fully Automated (automation level)
FCW	Forward Collision Warning
FIR	Far-InfraRed (camera)
FP7	European Commission Seventh Framework Programme
GPS	Global Positioning System
H-metaphor	Horse-rider metaphor
HA	Highly Automated (automation level)
HAVEit	Highly Automated VEhicles for intelligent transport, European FP7 project
HMI	Human-Machine Interface
IFSTTAR	French Institute of Science and Technology for Transport, Development and Networks
IMU	Inertial Measurement Unit
ISA	Intelligent Speed Adaptation

ISO	International Organization for Standardization
ITS	Intelligent Transportation Systems
JSD	Joint System Demonstrator (HAVEit)
LCDAS	Lane Change Decision Aid System
LDWS	Lane Departure Warning System
LIDAR	LIght Detection And Ranging
LIVIC	Laboratory on the Interactions between Vehicles, Infrastructure and Drivers
LKAS	Lane Keeping Assist System
LS	Legal Safety
LS	Legal and Safe (situation)
LSD	Legal Safety Demonstrator (LIVIC)
LSD	Low Speed Demonstrator (ABV)
MRM	Minimum Risk Maneuver
MSU	Mode Selection and arbitration Unit
NIR	Near-InfraRed (camera)
NLS	Not Legal, but Safe (situation)
NLNS	Not Legal and Not Safe (situation)
OEM	Original Equipment Manufacturer, i.e. vehicle manufacturer
PID	Proportional-Integral-Derivative (control)
PMP	Partial Motion Planning
PRM	Probabilistic RoadMap
RRT	Rapidly exploring Random Tree
RSC	Roll Stability Control
RTK	Real Time Kinematic
SA	Semi-Automated (automation level)
SI	International System of Units
SLAM	Simultaneous Localization And Mapping
TCS	Traction Control System
TOF	Time-Of-Flight (camera)
UN	United Nations
V2I	Vehicle-To-Infrastructure (communication)
V2V	Vehicle-To-Vehicle (communication)
VRS	Virtual Reference Station

Notations

Variable	c	Cost
	d	Distance
	f	State
	i	Indicator, information
	k	Type, style, tuning parameter
	l	Lane index
	l, w, g	Length, width, growth
	m, n	Active automation mode, available automation modes
	μ	Friction
	t, p, v, a, ω	Time, position, speed, acceleration, yaw rate
	ρ	Curvature
	s	Slope
	$\underline{x}$, $\overline{x}$	Minimum value, maximum value (zone description)
Subscript 1	u, w	UW-coordinate
	x, y	XY-coordinate
Subscript 2	0, 1	Start, target value
	01	Average value between start and target
Superscript	-	Subject
	F	Failure, MRM
	G, H, I	Friction limit, human limit, system limit
	J	Friction limit, human and system limit combined (extreme)
	K	Friction limit, human and system limit combined (comfort)
	L, M	Lane shape, lane marking
	O	Object
	P	Phantom
	Q	Stop
	R	Reaction time
	S	Speed limit
Name	0	Subject (normal system functioning)
	1 - 8	Object
	I - VI	Phantom
	A - C	Stop, Lane
	F	Subject (system failure functioning)

Chapter 1

Introduction

Contents

Sections 1.1 and 1.2 present the objective of this work in the general context of transport of people and goods. Section 1.3 discusses its integration in the European Seventh Framework Programme (FP7) project HAVEit and the French National Research Agency (ANR) project ABV. Sections 1.4 and 1.5 describe the research methodology and the organization of this document.

1.1 Transport of people and goods

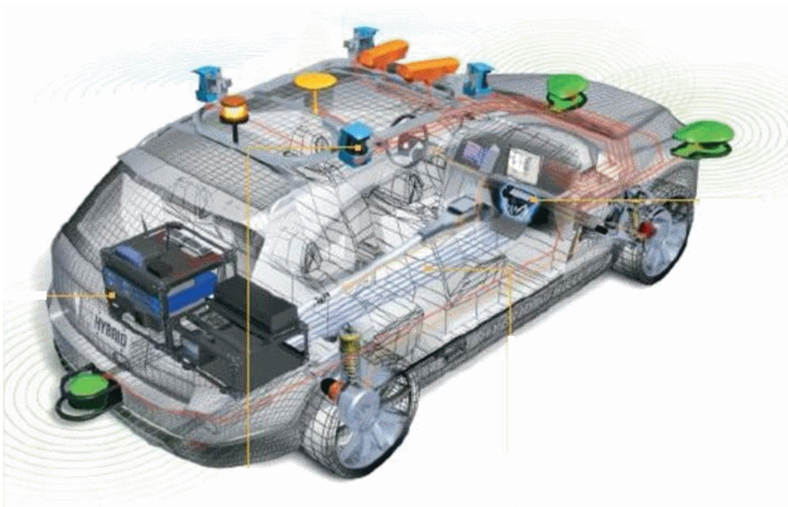
Transport of people and goods has always been crucial and challenging for society. Today, research explores **new approaches to transport**, in order to ensure its social, economic and environmental sustainability. Traffic accidents in the European Union claim around 40000 lives and leave more than 1 million persons injured annually [Eur08]. Additionally, accidents lead to an estimated annual cost of around 200 billion euros, or 2 % of the EU's Gross Domestic Product (GDP). Analysis shows that human-inherent errors by distraction, drowsiness, emotion or miscalculation are amongst the causes in 95 % of all accidents [Rum90, vK03, NDK+05, Elv05], followed by infrastructure defects, weather conditions and technical failure. Costs related to road traffic congestion and environmental pollution account for another 2 % of the EU's GDP. More important is the impact on the health of citizens; traffic pollution is believed to cause the premature death of almost 300000 EU citizens a year [Eur10]. This section motivates the development of **autonomous vehicles** as a solution to these challenges. A short comparison with other transport modes is made.

1.1.1 Digital transport, mass transport, bicycles

Since the creation of the Internet, **digital transport** exists as an alternative to physical transport, e.g. videoconferencing, teleworking and distance education [Ege07]. Still, the demand for physical transport is predicted to continue to increase in the future, not despite of, but because of the revolution in digital transport. Digital contact generally has a physical counterpart.

Mass transport (e.g. bus, train, ship) is a safe and clean alternative to individual transport (e.g. car, truck). It also allows passengers to spend time on work or leisure while moving. Still, individual transport is often preferred to mass transport; in the EU, 72.4 % of passenger-kilometers are traveled by car, and for inland good transport 72.5 % of tonne-kilometers are done by truck [Eur10]. Mass transport is fundamentally poor on time efficiency, as it operates according to limited schedules and does not bring people from a point A to B, but from C to D, while regularly halting before destination. This is especially a concern for connections that do not serve large cities, at large distances. Individual transport avoids waiting on intermodal connections and allows greater traffic flow on a same area of infrastructure.

(a) Bicycle



(b) Autonomous vehicle

Figure 1.1: Two powerful solutions for future transport: (a) bicycle and (b) autonomous vehicle

In the EU, where 75 % of all travels are less than 10 km, the **bicycle** is prized as a flexible, clean and inexpensive solution for future transport [Van10b]. Several European cities aim for a second golden age for the bicycle, after the pre-automobile period at the end of the 19th century. As an example, Figure 1.1.a shows the Vélib' bicycle of Paris, which is rented and driven between stations throughout the city, 24 hours a day, 7 days a week. The bicycle is less expensive than metro, proves to be nearly as fast. It has the merit of keeping people in, instead of under the city. This makes trips more pleasurable and contributes to the health of citizens and economy.

1.1.2 Autonomous vehicles

A future with **autonomous vehicles** [CHKW06, Van10b] would combine advantages of today's vehicles with advantages of mass transport, as sketched in Figure 1.2. Whenever the human driver wants, the driving system takes over vehicle control. Autonomous vehicles would offer the flexibility of individual transport, while significantly increasing safety; the driving system could analyze more data than the human driver and would never be subject to distraction, emotion or fatigue. Time efficiency would be optimal as the user can spend time on work or leisure while being brought directly from A to B, 24/7. At destination, autonomous vehicles could park, go on maintenance or fuel independently. They would make mobility accessible to people of all ages [BC10] and to people disabled by a physical handicap or intoxication. Short system reaction times would also enable peloton or platoon driving, i.e. a train of individual vehicles, leading to strong increases in energy efficiency and traffic flow. Figure 1.1.b gives a concept image of an autonomous vehicle, which is designed to the image of the human driver, with perception (e.g. camera, radar), decision (e.g. microprocessor) and control (e.g. steering wheel actuators, brake and throttle actuators) components.

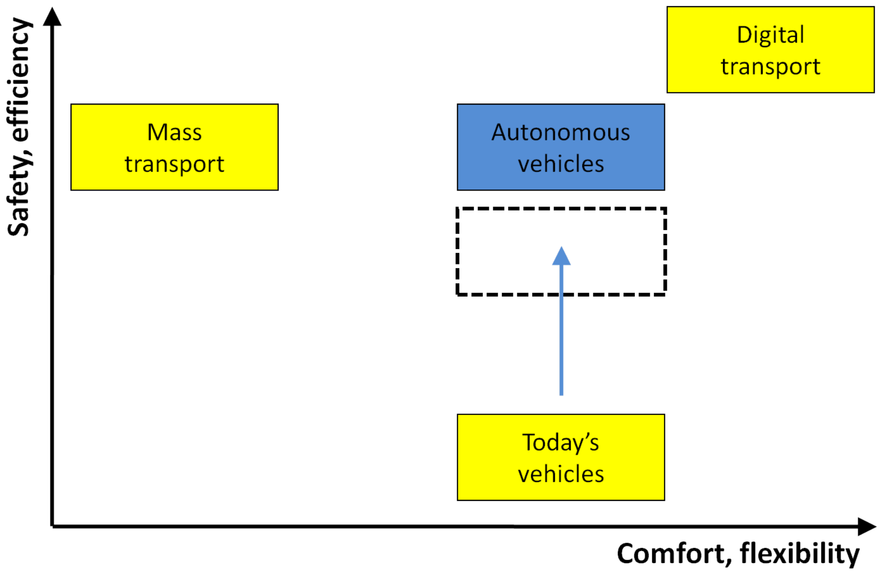


Figure 1.2: Autonomous vehicles combine the advantages of today's vehicles with advantages of mass transport. The target of this work, highly automated driving and fully automated driving, is indicated with dashed lines

Autonomous driving can already be demonstrated today, with **highly equipped vehicles under human supervision**. The VaMoRs experience [DZ87], ARGO experience [BBFC99], DARPA Grand Challenges [Def07, MBB+08, UAB+08], CyberCar [Par07] and CityMobil [Cit11] demonstrations presented autonomous vehicles on a dedicated infrastructure with limited interaction with other vehicles. For example, in the DARPA Urban Challenge (2007), vehicles drove simultaneously on a closed track for an entire day, at speeds till 50 km/h. They operated autonomously and respected a set of traffic rules. The DARPA officials could pause individual vehicles in the race in order to minimize the risk on collisions. Six vehicles successfully completed the race. Research on autonomous vehicles is rapidly developing. Recently, promising progress on autonomous driving on public road has been shown by the VisLab, Stanford and Google teams [BBB+11, LAB+11, TU11]. For demonstrations with autonomous vehicles, there are few requirements on reliability and budget; the extensive suite of sensors and computers generally comes at a cost which is a multiple of that of the original vehicle.

For economical, legal, psychological and technical reasons, autonomous vehicles are not brought to market directly. Policy makers and vehicle manufacturers choose for an evolution instead of a revolution. Vehicle automation is introduced incrementally, through **Advanced Driver Assistance Systems (ADAS)**. With a limited number of simple and safe software and hardware components, partly automated driving on the public road in cooperation with the human driver is possible. Anti-lock Braking Systems (ABS) and Electronic Stability Control (ESC) are now standard safety equipment on new vehicles. Consumer interest has increased significantly since the introduction of systems that combine safety with comfort, e.g. Adaptive Cruise Control (ACC), Intelligent Speed Adaptation (ISA), Lane Keeping Assist Systems (LKAS) and Lane Change Decision Aid System (LCDAS). These intermediate steps are worthwhile, before autonomous driving is reached. ADAS create considerable safety benefits [VPS07], and bring vehicle control to a higher level, relieving the human driver from monotonous tasks and assisting on complex tasks.

The topic of this work, **highly automated driving on highways based on legal safety**, is situated between driving with ADAS and autonomous driving, as indicated with dashed lines in Figure 1.2. Section 1.2 presents the work objectives and concept.

1.2 Highly and fully automated driving on highways based on legal safety

The objective of this work is to discuss an intermediate step between ADAS-equipped vehicles and autonomous vehicles. It presents the design of a close-to-market system, which allows **highly and fully automated driving** in a **certain application zone**, based on a concept called **legal safety**.

1.2.1 Application zone

Instead of offering a set of specific functionalities, as current ADAS do (e.g. distance keeping, intelligent speed adaptation, lane keeping and lane changing), a legal safety system allows **fully automated driving within a certain environment**. Compared to ADAS, a system with complete driving functionality increases **safety**. It also ensures the consistency between different functionalities, e.g. distance keeping can only be combined with lane changing if both functionalities are managed by a single system. Fully automated driving allows the human driver not to spend **time** on driving for a certain time. This meets a criticism on today's ADAS, which must be monitored by the human driver. This increases comfort, but does not reduce driving time. Non-active monitoring of ADAS is found to be sleep-inducing [FNG+10], which partially cancels safety benefits. Today, monitoring the driving system is required by law; the human driver must be able to take over control at all moments. Even in the case that law does not change, a system *capable* of fully automated driving has the advantage of making the **cooperation** with the human driver more powerful and simpler. A driving system with a comparable level of driving intelligence is the best partner of the human driver. Such system is also able to correct mistakes by the human driver, and bring the vehicle to a safe standstill, when needed.

In order to make automated driving quickly feasible technically and economically, the application zone of the *fully automated system* is limited to **highways**. In contrast, an *autonomous system* would cover all possible environments. The application zone **includes entrance and exit ramps, but excludes parts of the highway that are not structured in lanes**, e.g. zones around toll stations and rest areas. Figure 1.3 illustrates a highway environment with subject (i.e. the vehicle of interest), lanes, traffic signs and objects (i.e. non-subject vehicles and other objects in the environment). The highway is probably the easiest environment for fully automated driving as its simple lane structure and unidirectional flow of large objects facilitate environment perception, decision making and vehicle control. This could allow having the driving system on market in **medium term**; a rough estimate might be a market introduction in a decade (2022), as a 1000 euro option. The highway is also one of the more **relevant** environments for vehicle automation, as it often implies monotonous situations (e.g. long distances, congested traffic) and few alternatives exist compared to cities (e.g. bicycle, bus, metro). Short system reaction times allow decreasing vehicle inter-distances on highways, which improves **traffic flow**. Further reducing inter-distances would allow driving in platoon (i.e. highway train), which significantly reduces **energy consumption**. In the text, notes will be given on challenges that environments, other than highways, represent. In those environments, the system could not be used for fully automated driving, but could assist the driver, like ADAS today. A discussion on driver assistance in other application zones is however not in the scope of this work.

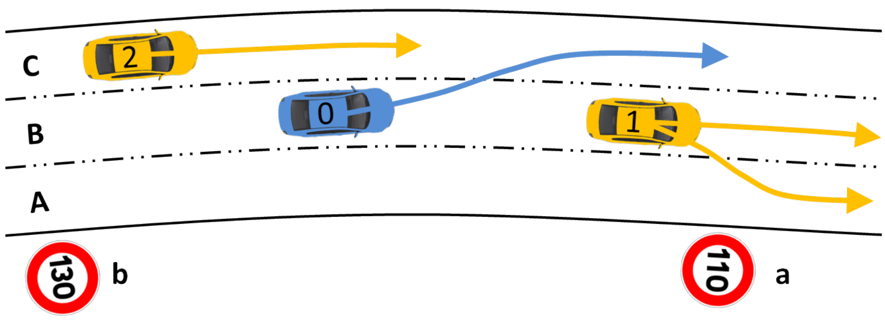


Figure 1.3: Highway environment with subject (*0*), lanes (*A*, *B*, *C*), traffic signs (*a*, *b*) and objects (*1*, *2*)

1.2.2 Legal safety

Driving systems and human drivers are essentially different in nature. But, when systems begin driving autonomously, they will likely need to **share the road infrastructure with human drivers**. Similarly, human drivers with different personalities, formation and capabilities share the road today. In a hypothetic future where all vehicles drive autonomously, driving systems could have the same intelligence, i.e. driving systems could exactly predict decisions of other driving systems. This would imply making vehicle automation compulsory, which might be unreasonable. This future would be preceded by a transient period where autonomous and non-autonomous vehicles coexist. One alternative to sharing the infrastructure would be to assign a part of existing infrastructure (e.g. one lane) exclusively to autonomous driving. Another alternative is to create an entirely separated infrastructure for autonomous vehicles. Both alternatives would come at a large cost, reduce the application zone of autonomous driving (e.g. excluding rugged environments, environments with pedestrians and cyclists) and could be difficult to implement [Shl10]. A solution where driving systems and human drivers share the road seems preferable. The aim of this work is to discuss the possibility of such solution.

This thesis states that mixed traffic with human drivers and driving systems can be managed by **traffic rules**, in the same way as traffic with only human drivers. The concept of basing system design on traffic rules, is referred to as **legal safety (LS)**. This document describes a legal safety system for highways, with traffic rules of the **1968 United Nations Vienna Convention on Road Traffic**. Within its application zone, a legal safety system is **capable of fully automated driving** based on traffic rules, whether it actually offers fully automated driving or only assists the human driver with information. Legal safety implies that the system is designed to operate without necessarily changing equipment of other vehicles or infrastructure. This makes the system development **independent** from third party developments (e.g. other vehicle manufacturers, infrastructure administrators, legislative bodies). It also allows extending legal safety principles to environments where equipment is difficult to change. For example, even in the future, not all pedestrians or cyclists will wear communication devices. The system *can* cooperate with vehicles equipped with compatible Vehicle-To-Vehicle (V2V) communication and with infrastructure equipped with Vehicle-To-Infrastructure (V2I) communication, but safety does not depend on it. This work indicates additional conditions on driving system design required for the independent approach (i.e. not relying on communication), which are not required for the cooperative approach (i.e. relying on communication). The cooperative approach can be seen as a specific case of the independent approach. For example, V2V can decrease the uncertainty on future object trajectories.

This work shows that system design based on legal safety ensures **safety** when traffic rules are respected by all traffic participants. In everyday traffic, however, traffic rules are not always respected. Integrating traffic rules in the system not only allows predicting legal behavior of traffic participants, but also detecting and anticipating on non-legal behavior; i.e. **driving defensively**. When traffic rules are offended by a traffic participant, a legal safety system prevents from an accident if possible and does an emergency brake to mitigate the accident, if not. In the case of fully automated driving, the ethical question concerning the acceptability of an accident between a legal safety system and a human driver who does not respect the traffic rules remains open. Fully automated driving also brings a legal question on the liability in the case of damage. Currently, the human driver or vehicle owner are most of times liable, even if damage is caused by technical failure of the vehicle. The question whether this is still the case for a fully automated system gains importance and is now being studied by vehicle manufacturers [BC10, HAV11p]. A detailed discussion on the legal consequences of fully automated driving system is not in the scope of this work.

Except for autonomous systems, which would cover all environments, a driving system always needs cooperation with the human driver. The interaction between driving system and human driver is specified in **human rules**. This is the second aspect of legal safety, as indicated in Figure 1.4. In the case of *fully automated driving*, human rules can be simple. In the application zone, the driver can activate the driving system. When the application zone is left (e.g. on an exit ramp of the highway), the system invites the driver to take over control. If the driver fails to act, the system brings the vehicle to a standstill before the end of the application zone, in preference on the emergency lane. A similar strategy is followed in the case of system failure (e.g. caused by a hardware problem). In the case of *driver assisted* or *highly automated driving*, there is a continuous interaction between driving system and human driver. The European Seventh Framework Programme (FP7) project HAVEit and the French National Research Agency (ANR) project ABV, which are presented in Section 1.3, propose a complete interaction scheme between human driver and driving system for various automation levels below fully automated driving. The human rules in this work follow the HAVEit and

ABV interaction schemes. The consequences of these human rules on driving system design are discussed.

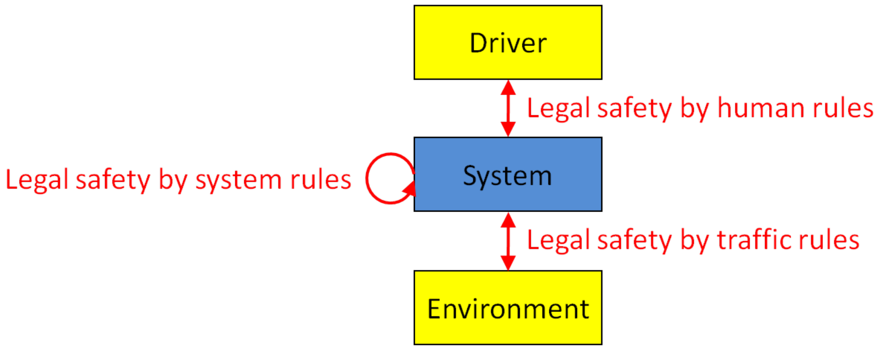


Figure 1.4: The three aspects of legal safety: interaction with the environment (traffic rules), interaction with human driver (human rules), interaction between system components (system rules)

In addition to traffic rules (i.e. the interaction with the environment) and human rules (i.e. the interaction with the human driver), the system integrates **system rules**, which must be respected by each system component in order to assure the integrity of other components. For example, subject trajectories calculated by the decision component must be feasible for the control component and accuracy of control and perception components must be within bounds to assure the consistency of trajectories. System rules form the third aspect of a legal safety system, as indicated in Figure 1.4.

Figure 1.5 positions legal safety with respect to the ADAS mentioned in Section 1.1. While current ADAS offer separate longitudinal and/or lateral functionalities, the legal safety system increases driver assistance by offering highly and fully automated driving in the application zone, based on traffic rules, system rules and human rules. The design of the legal safety system will be presented in Chapters 2 and 3. Results will be discussed in Chapter 4.

1.3 Highly and fully automated driving on highways according to the HAVEit and ABV projects

Policy makers promote ADAS, in order to make transport safer, more comfortable and more environmentally friendly. The European Commission (EC) set vehicle automation development and deployment as one of its strategies for reaching zero casualties in road transport in the European Union and cutting emissions of Green House Gasses (GHG) by 60 % between 2011 and 2050 [Eur11]. The EC encourages ADAS-equipment on vehicles or makes it mandatory, e.g. on new passenger cars sold in the EU, ABS is mandatory since 2007 and ESC since 2012. Additionally, the EC launches Framework Programme (FP) projects, which team up private and public research during several years, for the development of new solutions for transport.

1.3.1 HAVEit project

The Seventh Framework Programme (FP7) **HAVEit** project (Highly Automated VEhicles for intelligent transport) presents highly automated driving as the next step towards the long-term vision of safe, comfortable and efficient transport for people and goods [HAK+08, HAZ+09,

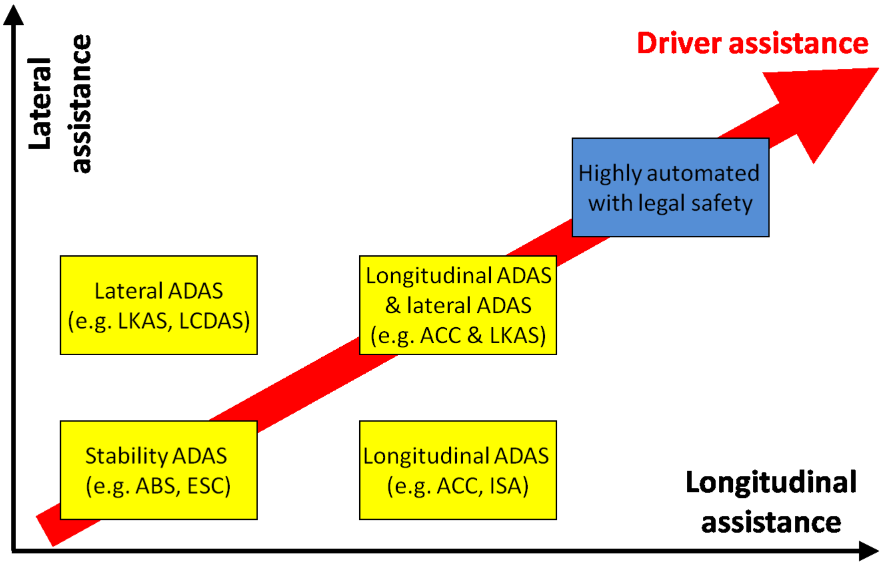


Figure 1.5: The position of the legal safety system with respect to current ADAS

FNG+10, HAV11q]. HAVEit, project number 212154 under the unit "ICT for Transport" of Directorate-General Information Society and Media (INFSO) of the European Commission, is the biggest initiative taken in this area in Europe. The intensive collaboration with a multidisciplinary team from universities, research institutes, suppliers and manufacturers in the HAVEit project has been essential for the development of this work. The principles of the project can be summarized in three points.

First, the aim of the project is to **increase ADAS functionalities** in highway environments. In this context, the **traffic rules** and **system rules** of the legal safety concept were applied, giving the system the technical capabilities for fully automated driving on highways.

Second, the HAVEit system combines the driving intelligence of the legal safety system with a HAVEit human-system interaction scheme. The human-system interaction scheme is organized along different **automation levels** from *driver assisted* to *highly automated*, presented in Figure 1.6 [HAV11f, HAV11g]. The HAVEit system does not offer fully automated driving. During all automation levels, the human driver is involved in the driving task. Consequently, the HAVEit system is compatible with today's law; it gives a step between current ADAS and systems for fully automated driving. Table 1.1 gives a short description of the HAVEit automation levels. On the naming of automation levels, no ISO standards exist. In this work, the HAVEit terminology will be used. The list in the table is not exhaustive; automation levels which are not relevant in this context (e.g. driverless vehicle, teleoperated vehicle) are not represented. Intermediate automation levels could be defined (e.g. between the automation levels highly automated and fully automated), but are not discussed. In the project, the **automation mode** (i.e. the automation level which is activated) is managed by a Mode Selection and arbitration Unit (MSU) [HAV11h]. The automation mode is dynamically adapted by human driver or driving system, depending on the situation, as is suggested in Figure 1.7. Higher levels of automation are especially useful in monotonous (driver underload) and complex (driver overload) situations. The **human rules** of the legal safety system presented in this work are a simplified description of the automation levels and automation mode transitions of the HAVEit system.

The third project objective is to demonstrate that highly automated vehicles are **close**

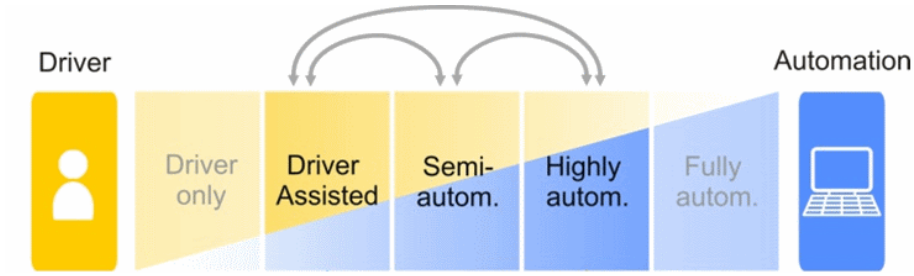


Figure 1.6: The HAVEit automation levels are situated between *driver only* and *fully automated*: *driver assisted*, *semi-automated* and *highly automated* driving. The ABV automation levels also include *fully automated*, at low speeds in congested traffic. Source: HAVEit Deliverable D33.3 [HAV11h]

to series production. Research was done on a failure tolerant architecture with redundancy management on hardware level. Decision and control components of the legal safety system have been implemented on automotive Electronic Control Units (ECUs) in Controller Area Network (CAN).

The project delivers 2 demonstrator simulators and 7 demonstrator vehicles; 4 passenger cars, 2 trucks and 1 bus. The decision (calculates optimal subject trajectories) and control (keeps subject on trajectories) components of the legal safety system were integrated in the **HAVEit Joint System Simulator**, **HAVEit Joint System Vehicle** and **HAVEit Architecture Migration Vehicle**. The demonstrators were presented during the HAVEit final event on the Volvo test track in Hällered in June 2011. A discussion on the implementation and results will be given in Chapter 4.

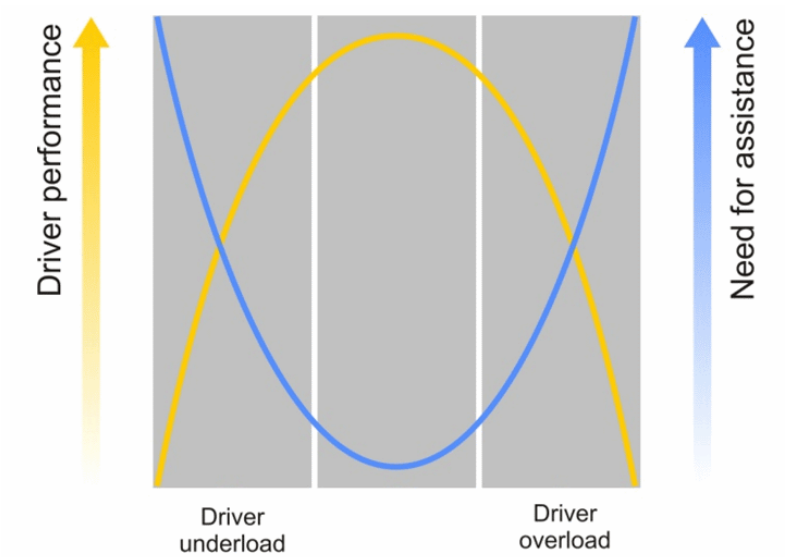


Figure 1.7: The HAVEit automation mode is dynamically adapted: higher automation levels for monotonous (driver underload) and complex (driver overload) situations. The ABV higher automation levels are for congested traffic, which corresponds to monotonous situations. Source: HAVEit Deliverable D33.3 [HAV11h]

Automation level	Description
Driver only (DO)	Human driver performs longitudinal (speed-related) and lateral (steering-related) control. Driving system is not active.
Driver assisted (DA)	Human driver performs longitudinal and lateral control. Driving system is active and gives feedback to the human driver (e.g. visual information, haptic feedback). Examples: LDWS and LCDAS.
Semi-automated (SA)	Human driver performs lateral control. Driving system performs longitudinal control. Human driver must monitor continuously and be prepared to take over longitudinal control at any time. Example: ACC.
Highly automated (HA)	Driving system performs longitudinal and lateral control. Human driver must monitor continuously and be prepared to take over control at any time. If human driver is not monitoring (which is detected with a Driver State Assessment (DSA) component) or in the case of system failure, the system brings the vehicle to a standstill with a Minimum Risk Maneuver (MRM). Example: HAVEit system, legal safety system.
Fully automated (FA)	Driving system performs longitudinal and lateral control in an application zone. Human driver does not need to monitor, but must take over control at the end of the application zone. If human driver does not take over control, or in the case of system failure, the driving system brings the vehicle to a standstill with an Minimum Risk Maneuver. Example: ABV system, legal safety system.
Autonomous (AU)	Driving system performs longitudinal and lateral control in all application zones. Example: an automated door-to-door taxi. Not described.

Table 1.1: Description of automation levels

1.3.2 ABV project

The legal safety system is now being integrated the **ABV** project (Automatisation Basse Vitesse, Low Speed Automation), launched by the French National Research Agency (ANR). The ABV project builds on the HAVEit philosophy of offering higher levels of automation on highways and organizing the cooperation between human and system along novel automation levels. It differs from HAVEit by focusing on **congested traffic** at speeds below $50\,km/h$ and adding **fully automated driving** to the automation spectrum. By automatically following congested traffic, the ABV system relieves the human driver from monotonous tasks, as in Figure 1.7. During fully automated driving, the human driver is not required to monitor the system, but has to take over control at the end of the application zone.

The legal safety concept is used as a basis for the ABV project [ABV13a]. Specifications on perception, decision, control and HMI components are in line with legal safety principles. The decision and control components of the legal safety system are integrated in the project demonstrators, which are presented at the project final event in April 2013. Intermediate integration work and results on the **ABV Low Speed Simulator** and **ABV Low Speed Vehicle** are presented in Chapter 4.

1.4 Research methodology

The goal of this section is to present how the research work has been organized and why the research methods being used have been chosen.

1.4.1 Objective

Sections 1.1 and 1.2 presented the aim of this work in the general context of transport of people and goods. The objective of the work is to discuss the design of a **close-to-market system for highly and fully automated driving in a limited application zone**; highways. The system offers different automation levels derived from the human-system interaction schemes of the HAVEit and ABV projects, presented in Section 1.3. In this context, *close-to-market* implies that technology can be available in medium term, and that system performance does not depend on adaptations of other vehicles (driven by either human driver, driving system or both) or infrastructure.

The legal safety concept has been proposed as **scientific hypothesis** [Wik12a], for achieving the objective. **According to legal safety, driving system design based on traffic rules, human rules and system rules** (described in Chapter 2) **allows human drivers and driving systems to share the infrastructure. It guarantees safety if traffic rules are respected by all traffic participants, and allows defensive driving in order to avoid accidents, if not**. The logic behind the concept is that a good way to insert driving systems in traffic made for and by humans, is to let the system imitate human beings.

The focus of this work is on **driving system technology**. In vehicle design, other aspects are important, e.g. legal issues, cost, usability, aesthetic beauty (e.g. sensor integration) and hardware reliability. Some of these aspects will shortly be referred to.

1.4.2 V-cycle

The legal safety system is developed along a V-cycle model [Wik12b], shown in Figure 1.8. In V-cycle development, **design is top-down**, from objective to system requirements to component design to implementation. **Validation is bottom-up**, from component validation to system validation to validation of the objective. The V-cycle is a classic method in automotive industry and is in line with the ISO standard 26262 on functional safety for road vehicles, which is currently under development [ISO12].

Figure 1.8 indicates the corresponding chapters in this document between parentheses. The chapters describe the work as a single process from design to validation. In reality, V-cycle development is **iterative**; each validation step is followed by a new design step, as suggested by the right-to-left arrows in the figure. For example, in the beginning of HAVEit, the theater-system technique was used, which consists in letting a second human driver act as the driving system [SHS+09]. The second human driver pilots forces on steering wheel and pedals, according to preliminary system specifications. This allows a fast validation of system principles before working out details and before programming. Since the first versions of the legal safety system in 2008, continuous refinements, simplifications and extensions have been made after testing on LIVIC, HAVEit and ABV simulators and vehicles. The feedback on this document will give material for a next development cycle.

1.4.3 System requirements

The objective, application zone and concept described in Chapter 1, can be seen in the upper left corner of the V-cycle in Figure 1.8. They are translated into system design requirements in Chapter 2. System requirements by legal safety are specified in the form of traffic rules, human rules and system rules. Section 2.2 presents **traffic rules** of the 1968 United Nations Vienna Convention on Road Traffic, which sets the international standard. Legal safety is illustrated with traffic rules of the convention that apply to the application zone, the highway.

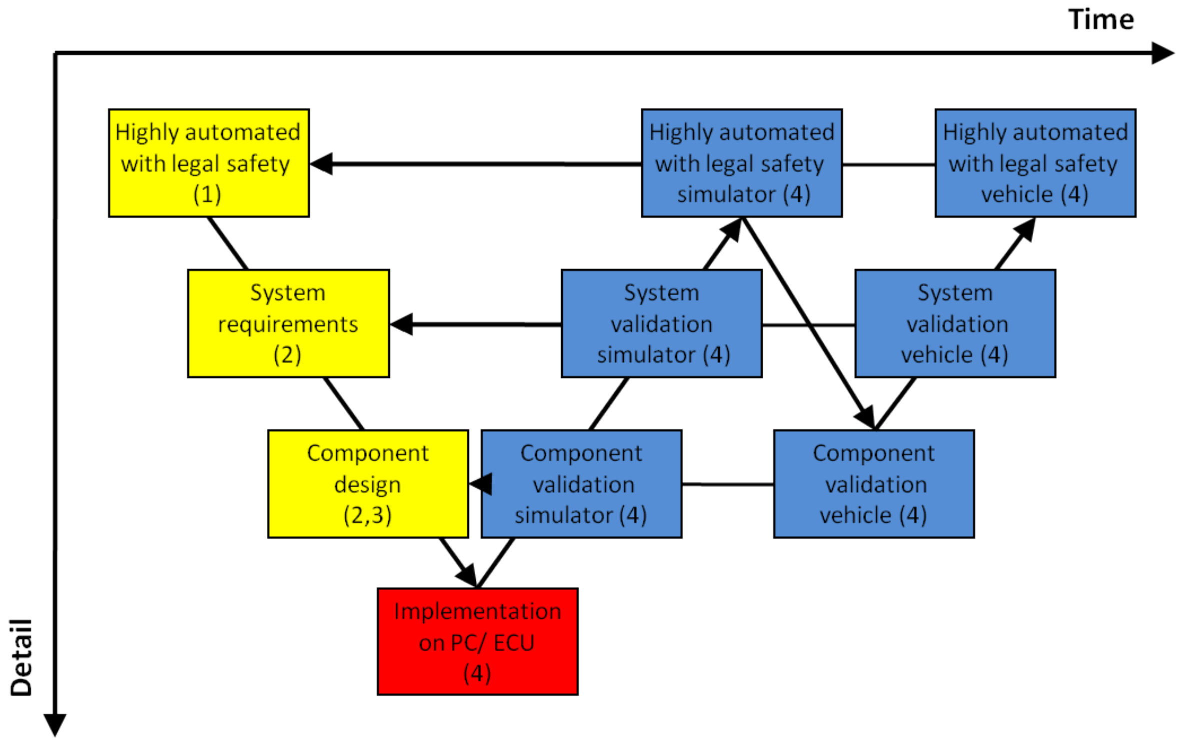


Figure 1.8: The V-cycle development of the legal safety system (indication of the corresponding chapter between parentheses)

National variations in traffic rules are not discussed. Nevertheless, the results of this work should remain valid under local legislation for two reasons: (a) the international legal principles of the convention are used by most countries as a basis for local legislation, (b) the convention gives fundamental statements, which do not radically change under local variations of the legislation. For easiness of understanding, the description throughout the work assumes that driving is on the right side of the road, translation for left-side driving is straightforward. Traffic rules, which are fundamentally written for humans, will be directly applied to the system. Legal-technically this is not obvious, but the differences between civil law and technological regulations are assumed non-relevant in the description of this work. The interaction between driving system and human driver is specified in **human rules** in Section 2.3. The human rules in this work are a simplified description of the HAVEit and ABV human-system interaction schemes. When the application zone is left, the human driver takes over vehicle control. If the human driver does not take over control, the system brings the vehicle to a safe standstill. Section 2.4 presents **system rules**, which regulate the interaction of system components. System rules allow each component to take into account performance limits of other components. For example, in the calculation of optimal subject trajectories, the decision component takes into account the accuracy and limits of perception and control.

System requirements in the form of traffic rules, system rules and human rules, lead to a **functional system architecture**, presented in Section 2.4. The system architecture consists of a perception component (which describes the environment), decision component (which calculates optimal subject trajectories in this environment), control component (which keeps the subject on the trajectory) and HMI component (which manages the interface with the human driver). The *functional architecture* allows making abstraction of the *hardware architecture* until the implementation phase of the V-cycle, which is discussed below. Section 2.5 motivates the use of a **subject coordinate system**, which avoids the need of accurate global positioning.

1.4.4 Perception, control and HMI component requirements

After system requirements, the top-down phase of the V-cycle leads to design of perception, control and HMI components. Requirements on these components are discussed in Sections 2.6, 2.7 and 2.8 respectively. Section 2.6 presents the list of variables that describe **subject state, lanes and objects**, which must be delivered by perception. These variables are needed in order to implement all traffic rules and system rules. Section 2.7 describes the **subject trajectories** that the control component must follow. The list of variables for **human-to-system** and **system-to-human** communication, which allows the implementation of human rules is given in Section 2.8.

Sections 2.6, 2.7 and 2.8 compare legal safety requirements with **state-of-the-art** perception, control and HMI components. Perception, control and HMI components on the LIVIC, HAVEit and ABV demonstrators delivered by colleagues and project partners are referred to in Chapter 4. This work keeps the description of perception, control and HMI components on the *requirement* level; it does not aim to contribute to the actual *design* of these components. Different possible designs of perception, control and HMI components should in principle give identical results, as these components are **objective** by nature; their performance can be measured with respect to a single truth. This motivates to keep their description on the requirement level.

1.4.5 Decision component design

In contrast to perception, control and HMI components, the decision component is **subjective** by nature. In a certain situation, several *optimal*, suitable trajectories exist, think of drivers with different characters and capabilities. The decision component is described completely **from requirements to design**, in Chapter 3. The decision component is the central component in the legal safety concept. It calculates the optimal subject trajectory that takes into account **traffic rules, human rules and system rules**.

Chapter 3 introduces a curvilinear **lane coordinate system**, which is a natural universe for trajectory calculations in a lane-structured environment. After this, a **zone model for trajectories** is presented. A zone model allows a more correct (i.e. safer) representation of subject and object trajectories, in comparison to an exact model for trajectories. The lane coordinate system and trajectory zone model provide the mathematical tools for predicting object trajectories and calculating subject trajectories according to legal safety. The decision component combines **analytical** and **sampling-based** techniques for trajectory calculations. The subject target speed and speed profile are calculated analytically, which is fast and precise in the continuous solution space between zero and maximum speeds. The subject target lane is calculated with a sampling-based approach, which proves powerful in a discrete solution space; keeping the lane, changing lanes to the right or changing lanes to the left. The existence **at least one subject trajectory** that respects all traffic rules, human rules and system rules is guaranteed; keeping the lane and keeping a distance to the object ahead. In all situations, decision **calculation time** stays below $1\,ms$ on a standard PC and below $25\,ms$ on automotive ECU.

1.4.6 System implementation and validation

LIVIC Legal Safety Demonstrator

The next step in the V-cycle is the **software and hardware implementation** of system components, described in Chapter 4. The legal safety concept has first been implemented and evaluated on the LIVIC Legal Safety Demonstrator. All components on the LIVIC Legal Safety Demonstrator have been implemented in C-code. The perception component on the LIVIC Legal Safety Demonstrator has mainly been designed and implemented by LIVIC colleagues, a part has been designed and implemented in this work. Decision, control and HMI components have completely been designed and implemented in this work. As mentioned above, this document presents actual component *design* only for the decision component, in Chapter 3. The document does not aim to discuss the additional *design* of perception elements, control and HMI components by this work, it only discusses *requirements* on these components. Chapter 4 discusses to which extent the current development status of the LIVIC Legal Safety Demonstrator meets legal safety requirements.

First, all system components were integrated on **PC** with the RTMaps prototyping software [Int12]. The RTMaps platform manages the communication between components and the connection with simulator or vehicle. Additionally, it delivers efficient tools for debugging and tuning. Later, **decision and control components were integrated on automotive ECUs**. This demonstrates their functioning on series production platforms, which have limited calculation power and memory. The ECUs were developed by HAVEit partner Continental and are based on the AUTomotive Open System ARchitecture (AUTOSAR) standard [HAV11b, HAV11c]. On ECU, AUTOSAR fulfills a similar function as RTMaps on PC. It encapsulates the algorithms and makes abstraction of the communication between ECUs and the connection to simulator or vehicle. This allows using the same C-code on PC and ECU, on simulator and vehicle. Only interfaces and demonstrator-related parameters change. Lauterbach Power Trace II [Lau12] and Vector CANape [Vec12] are the tools used for debugging and tuning on ECU. The ECU implementation of perception and HMI components of the legal safety system could be subject of future work. For the **perception**, this can be straightforward by combining *high-level* sensors (which perform most of perception calculations on the sensor ECU) with a simple sensor data fusion component on ECU. The **HMI** is less safety critical than perception, decision and control; if a failure occurs the vehicle can still be controlled by either human driver or driving system. Additionally, communication from and to HMI is limited. It can be handled by state-of-the-art automotive hardware. This makes demonstrating the implementation of the HMI on ECU instead of PC less relevant.

The V-cycle continues with a bottom-up **validation** of component and system functioning with respect to requirements. After each finding in the evaluation phase, system requirements and component design are adapted, implemented and reevaluated, as Figure 1.8 indicates with the right-to-left arrows. Chapter 4 presents validation scenarios for the legal safety system, which cover the different aspects of legal safety. The validation scenarios are inspired on HAVEit scenarios, ABV scenarios and ISO standard test procedures. In order to accelerate development, the bottom-up validation is done in two sub-cycles; one in **simulator** and one in **vehicle**, as Figure 1.8 illustrates. The advantage of integration on simulator before integration on vehicle is that components can be replaced by exact equivalents. This allows parallel development of different system components. For example, before the perception component is available, the decision component can be tested with an exact environment description, which is known in the simulator. In a first design and validation phase on simulator, main issues can be solved, before testing on vehicle. For the legal safety system, the simulator SiVIC [CIV12] is used, which implements a model of the Satory test track in Versailles, France and of LIVIC test vehicles. In what follows, the LIVIC Legal Safety Demonstrator (LSD) refers to both **LIVIC Legal Safety Simulator** and **LIVIC Legal Safety Vehicle**.

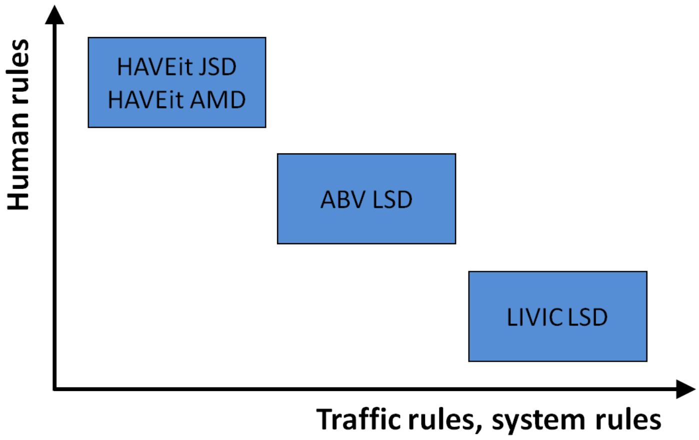


Figure 1.9: Comparison of demonstrators (i.e. vehicle and/or simulator) that integrate (parts of) the legal safety system

HAVEit and ABV demonstrators

The development of the HAVEit and ABV demonstrators follows the same V-cycle as the LIVIC Legal Safety Demonstrator, Figure 1.8. The LIVIC, HAVEit and ABV demonstrators have a common goal and application zone: highly (and fully) automated driving on highways. Their differences lie in the interaction between driving system and human driver. All demonstrators share a similar strategy: (a) using perception, decision and control components of a fully automated system, for maximizing driving intelligence and (b) adapting the HMI component to the more demonstrator-specific human-system interaction scheme. As **perception, decision or control components share the common goal** of fully automated driving, they can be shared over the different demonstrators. Chapter 4 describes the integration of legal safety perception, decision and control components in HAVEit and ABV. The project demonstrators complement the LIVIC demonstrator. Project demonstrators integrate a complete human-system interaction scheme (human rules), which is validated with user acceptance studies. The LIVIC demonstrator focusses on the driving functionality of the system (traffic rules and system rules). This is illustrated in Figure 1.9.

Table 1.2 gives an overview of the demonstrators that integrate (parts of) the legal safety system. The **LIVIC Legal Safety Demonstrator (LSD)** consists of LIVIC Legal Safety Simulator and LIVIC Legal Safety Vehicle. It implements all components of the legal safety system, both on ECU (decision and control components) and PC, and integrates a simple human-system interaction scheme from driver only to fully automated driving. The **HAVEit Joint System Demonstrator (JSD)** consists of HAVEit Joint System Simulator and HAVEit Joint System Vehicle. The **HAVEit Architecture Migration Demonstrator (AMD)** corresponds to the HAVEit Architecture Migration Vehicle. The HAVEit Joint System Simulator and LIVIC Legal Safety Simulator were used as simulator environments for the preliminary development of the HAVEit Architecture Migration Vehicle. Both HAVEit demonstrators are complementary on functionality and hardware architecture; the JSD integrates full HAVEit functionality (e.g. including lane changing) on standard PC, while the AMD illustrates the possibility of migrating on ECU with reduced HAVEit functionality (e.g. no lane changing). The HAVEit demonstrators implement automation levels from driver only to highly automated. They combine the complete HAVEit human-system interaction with legal safety decision and control components developed in this work. Perception, HMI components and additional decision and control components were delivered by project partners. The **ABV Low Speed Demonstrator (LSD)** comprises the ABV Low Speed Simulator and ABV Low Speed Vehicle. The ABV system offers automation levels from driver only to fully automated. The ABV demonstrator integrates decision and control components developed in this work. Perception, HMI components and additional decision and control components are delivered by LIVIC colleagues and project partners. All components of the ABV system are integrated on PC.

The **legal safety decision component**, which is the central component in the legal safety concept, is shared by all demonstrators. It is implemented on a single C code file; only interfaces and parametrization change between simulators or vehicles of different demonstrators.

Demonstrator	Automation components	Human component	Automation levels	Hardware
LIVIC LSD	LS perception, decision, control	LS HMI	DO, DA, SA, HA, FA	ECU, PC
HAVEit JSD	LS decision, control	HAVEit HMI	DO, DA, SA, HA	PC
HAVEit AMD	LS decision, control	HAVEit HMI	DO, DA, SA, HA	ECU
ABV LSD	LS perception, decision, control	ABV HMI	DO, DA, SA, HA, FA	PC

Table 1.2: Overview of demonstrators (i.e. vehicle and/or simulator) that integrate (parts of) the legal safety system

1.5 Document organization

The document is organized as follows. Chapter 2 discusses **system requirements** according to legal safety, and compares with state-of-the-art ADAS. Traffic rules, human rules and system rules are introduced and a functional system architecture is presented. Chapter 2 also discusses **requirements on perception, control and HMI components**. Chapter 3 works out the **design of the decision component** and compares with state-of-the-art trajectory planning algorithms. Chapter 4 presents the **implementation and validation** of the legal safety system on PC and ECU, on simulator and vehicle in LIVIC, HAVEit and ABV demonstrators. Chapter 5 discusses the contribution of this work and provides a **perspective** on future work.

Chapter 2

System requirements based on legal safety

Contents

This chapter begins with a discussion of legal safety design on system level. Section 2.1 compares legal safety systems with state-of-the-art systems. Sections 2.2, 2.3 and 2.4 specify **system requirements**, in the form of traffic rules, human rules and system rules. Sections 2.4 and 2.5 present the **system architecture** and coordinate system that is used by all system components.

After the discussion of requirements on system level, the chapter continues with a discussion on component level, in correspondence to the V-cycle (Figure 1.8). System requirements are translated in **component requirements of perception, control and HMI** in Sections 2.6, 2.7 and 2.8 respectively. Traffic rules, human rules and system rules specify the required input and output signals (i.e. interactors) and functionality of each of these components. This work does not contribute to the actual component design for perception, control and HMI, but compares component requirements with **state-of-the-art technology**. Requirements and actual design of a legal safety decision component will be worked out in Chapter 3.

2.1 State of the art

This section compares state-of-the-art ADAS for **driving on highways** with the legal safety concept. As indicated in Section 1.2, a legal safety system is capable of fully automated driving. Existing ADAS can be seen as partial implementations of it. The section also makes a comparison between the legal safety system and autonomous driving systems that are currently being demonstrated. Systems which do not directly relate to driving intelligence, or which do not have highways as application zone are not discussed, e.g. passive safety systems, automatic emergency call, automatic parking, pedestrian detection and navigation systems. The focus of this section is on complete systems; reference to state of the art of perception, control, HMI and decision components will be made in Sections 2.6, 2.7, 2.8 and 3.1 respectively.

Control of systems driven by human beings is usually separated into a longitudinal (speed-related) and lateral (trajectory-related) part. In vehicles, this is done with pedals and a steering wheel respectively. This natural division has usually been respected by ADAS; the driver assistance is either on the longitudinal or lateral axis. Figure 2.1 gives an overview of the ADAS discussed in this section, with indication of the type of assistance; information or control. The naming of ADAS follows ISO standards, if available.

2.1.1 Stability assistance

Stability assistance systems came first on market. These systems help the human driver to keep the vehicle in control during extreme maneuvers. Systems that improve the connection of vehicle and road surface lead to a significant increase in safety. The connection vehicle-road is completely assured by friction forces between tires and road surface. The main principle of stability assistance systems is to avoid or reduce slipping and rolling, which greatly decrease the maximum force that can be transferred from tires to road.

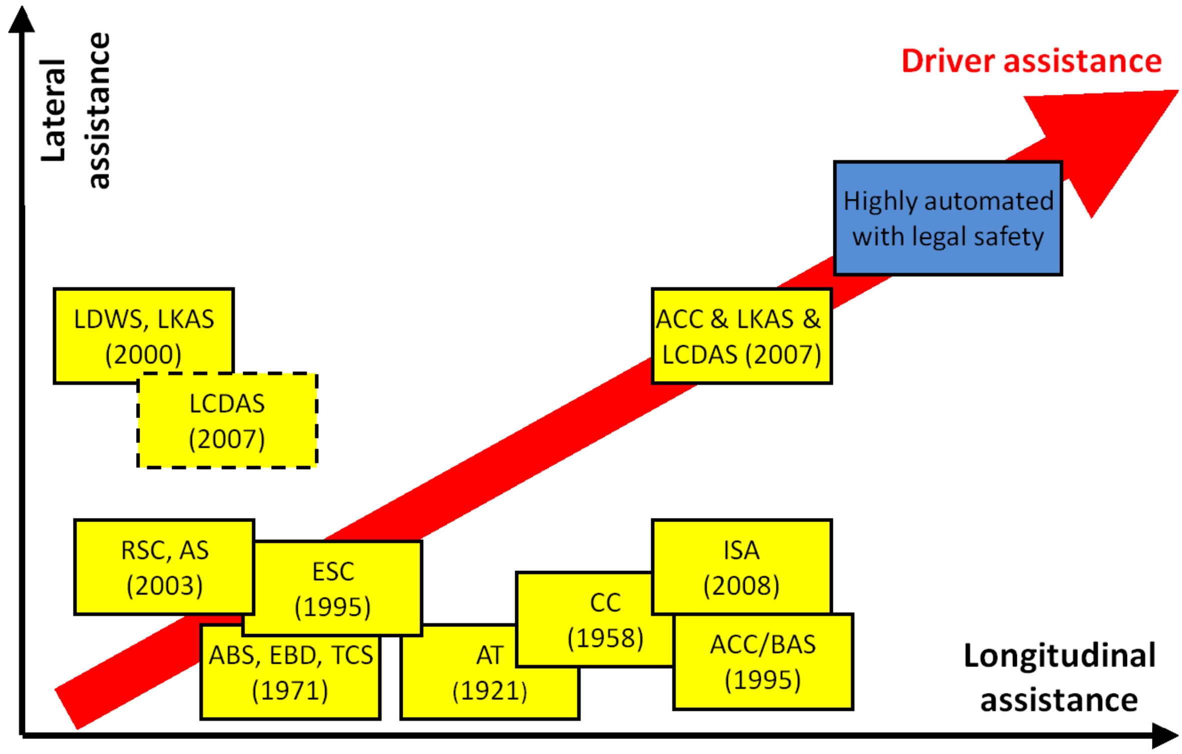


Figure 2.1: An overview of existing ADAS (the year of first market introduction is indicated between parentheses). ADAS that only give information to the driver are indicated with dashed line. ADAS that also perform vehicle control are indicated with continuous line

Anti-lock Braking Systems (ABS) prevents wheels from locking up when the vehicle is braking, by continuously applying and releasing braking pressure. This leads to improved vehicle control and shorter stopping distances. ABS is estimated to reduce multiple vehicle crashes by 18 percent and run-off-road crashes by 35 percent [BDN+04]. ABS can be extended with **Electronic Brake force Distribution (EBD)**, which adapts braking forces on each wheel to the actual weight distribution in the vehicle. The ABS equipment, which avoids slipping during deceleration, can also be used to avoid loss of traction during acceleration, as **Traction Control System (TCS)**. TCS brakes slipping wheels, which causes power to be transferred to non-slipping wheels, through the differential.

ABS, EBD and TCS help to keep traction while braking or accelerating. **Electronic Stability Control (ESC)** avoids skidding while steering. ESC systems are an evolution of the ABS concept. Minimally, two sensors are added: a steering wheel angel sensor to measure the driver's intended trajectory, and a gyroscopic sensor to measure the vehicle's actual trajectory. If both trajectories do not correspond, which indicates a loss of control, the ESC system brakes the individual wheels, so that the vehicle takes the direction wished by the driver. Additionally, engine power can be reduced until control is regained. Compared to the typical human driver, ESC detects skidding much faster and corrects more effectively, often before the driver is even aware of the imminent loss of control. One-third of crashes could be prevented by ESC [Dan04]. ESC technology is seen as one of the most important advances in vehicle safety in recent years.

ESC is the basis for new systems as **Roll Stability Control (RSC)**, which operates in the vertical plane, as ESC does in the horizontal plane. When RSC detects rollover, it applies brakes, decreases throttle and creates understeer. **Active Suspension (AS)** systems control the vertical movement of the vehicle by applying independent forces on the suspension or by dynamically changing the damping coefficient of shock absorbers. The system significantly reduces variations in vehicle roll and pitch during steering, accelerating, and braking. RSC and AS bring a higher comfort level and also improve vehicle grip and control by keeping the tires perpendicular to the road during steering.

Stability assistance represents a fundamental evolution in the **relationship between human drivers and driving systems**; the systems change the speed and trajectory of the vehicle. They outperform the human driver in many situations (e.g. ESC corresponds to operating four braking pedals at high frequency, something a human being could never do) and are widely accepted. ABS and ESC bring safety gains that are so important that the EU decided to make these systems mandatory on new passenger cars. ABS is mandatory since 2007 and ESC since 2012. Mass production of these systems facilitates the acceptance and development of other ADAS, e.g. it reduces the costs of calculation power on automotive ECUs.

While these systems improve the connection between vehicle and road surface, they do not consider the environment (i.e. lanes, traffic signs and objects), as Figure 2.2 suggests. The legal safety system supposes that the vehicle is equipped with state-of-the-art stability assistance; minimally **ABS and ESC**. Stability assistance helps the legal safety system control the vehicle trajectory in extreme situations, in the same way as it helps the human driver.

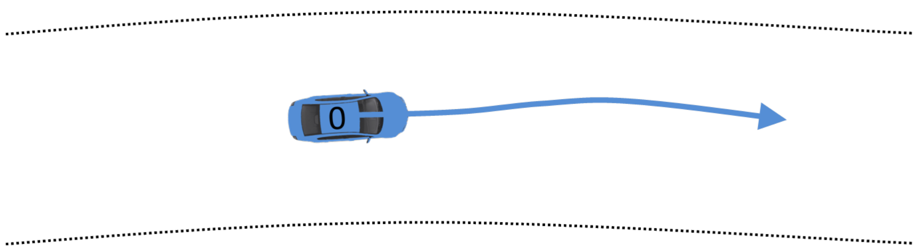


Figure 2.2: Environment model of stability assistance systems. Subject is described. Lanes, traffic signs and objects are not described

2.1.2 Longitudinal assistance

Stability assistance systems only deliver assistance for situations where the limits of vehicle stability have been reached. The systems in the remainder of Section 2.1 deliver continuous assistance; longitudinal (i.e. speed-related) and/or lateral (i.e. trajectory-related). Longitudinal assistance has first been developed, as for partial longitudinal assistance no knowledge of the environment is required. An early example is **Automatic Transmission (AT)**, which relieves the driver from repetitive gear changing. The legal safety system assumes that vehicles are equipped with AT; it does not deal with gear management. **Cruise Control (CC)** automatically keeps the vehicle on the target speed set by the human driver. With AT and CC, the driver performs longitudinal control on a higher level. Instead of continuously adapting gears, throttle and brakes, the driver adjust vehicle speed in correspondence to the environment. This is particularly useful in situations where the environment does not vary a lot; e.g. on highways with little traffic.

On highways with dense traffic, CC is not convenient as it requires the human driver to continuously adapt target speed to the presence of vehicles ahead. **Adaptive Cruise Control (ACC)** adapts vehicle speed in order to keep a certain distance to a vehicle ahead [MMY09].

If no vehicle is present, ACC keeps vehicle speed on the value chosen by the driver, like CC. In contrast with the systems discussed before, ACC interacts with the environment, i.e. with the object ahead. In principle, it relieves the driver from the task of keeping target speed and keeping distance to vehicles. Early systems on market only operated at medium and high speeds. Now, ACC includes stop-and-go functionality, e.g. in congested traffic. For continuous distance control with ACC, the perception and discrimination of the object that is to be followed is required at quite large distances, which is not yet possible in complex environments. **Brake Assist Systems (BAS)** have been developed, which do not offer continuous assistance, but assist the human driver in an emergency situation at short distance of an object [KSD09, Eid11, SB11]. Brakes are precharged and/or automatically applied in order to avoid or mitigate an accident with an object. Additionally, the system can adapt head rest position, inflate passenger seats, tension seat belts and activate airbags in preparation for the accident. BAS are on market under different names; e.g. Emergency Brake Assist (EBA), Precrash system or Forward Collision Warning (FCW). As more generic term, Collision Mitigation Avoidance System (CMAS) could be used, which integrates *steering assistance* in addition to *braking assistance*.

A discussion on gains in safety with ACC and BAS equipment is given in [VE03]. Figure 2.3 shows the environment model of ACC and BAS. ACC and BAS react to objects ahead which have a predicted trajectory that is in line with the predicted subject trajectory. The prediction of subject and object trajectories is done without knowledge of lanes, e.g. based on the measurement of the subject front wheel angle or the extrapolation of subject and object movement. The correctness of this kind of prediction depends on the situation. For example, on highways, where road curvature varies slowly, the accuracy is quite good when both subject and object keep lanes. It is worse when either subject and/or object change lanes. With respect to these systems, legal safety improves prediction of object trajectories by using lane information, additional object information (e.g. indicator status) and traffic rules. For example, based on the object position in the lane and indicator status, the legal safety system predicts and reacts to an object lane change before the object reaches the subject lane. Not only objects on the subject lane (i.e. the lane in which the subject is located), but also objects on the lane to the left are considered in order to avoid right overtaking. ISO test procedures for ACC involve stopping behind an object that decelerates at $-2.5\,m/s^2$ till standstill [ISO09a, ISO09b, ISO10]. However, traffic rules require being able to stop behind an object that performs an emergency brake, around $-8\,m/s^2$, till standstill. The legal safety system manages a safety distance from the object at all times, so that an accident can be avoided when the object performs an emergency brake.

With **Intelligent Speed Adaptation (ISA)** vehicle speed is automatically adjusted to speed limits [Tho03]. Speed limits can be obtained by camera, by digital map (if updated regularly) or by a combination of both. Making ISA mandatory, which would make impossible for vehicles to exceed speed limits, would save 20 % of accidents with injury and 37 % of fatal accidents [CT05]. While ACC provides first interaction with objects, ISA implicitly takes into account limits imposed by the road itself, e.g. curves and visibility. However, speed limits that are specified for an extended zone do not always reflect the appropriate speed on each road segment in that zone, e.g. in curves [GNL07, Lee08]. Additionally, speed limits are usually fixed, while the appropriate speed varies with day/night and weather conditions, i.e. visibility [GHG10]. The legal safety system respects speed limits, but also considers these additional environment parameters, e.g. road friction, lane curvature, and visibility.

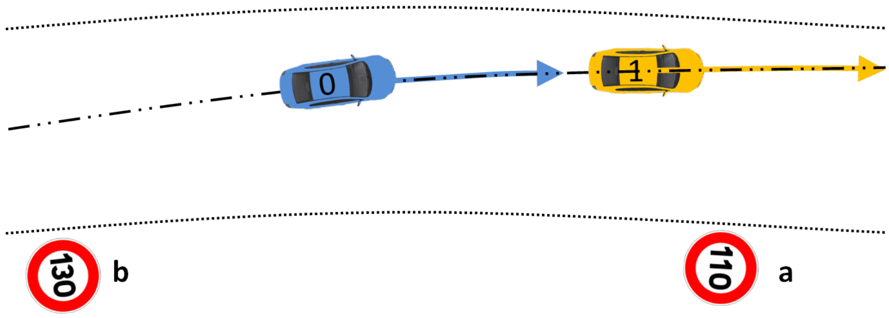


Figure 2.3: Environment model of longitudinal assistance systems. Subject, object ahead and traffic signs are described. Other objects and lanes are not described

2.1.3 Lateral assistance

In order to facilitate the interaction between traffic participants, the road environment is divided in lanes, each intended to be used by single line of vehicles [Uni68]. Lateral assistance, which detects lane markings and controls the vehicle within the lane, is a next step in driver assistance. A **Lane Departure Warning System (LDWS)** warns the driver when the vehicle leaves the lane, unless the driver signals that this is his intention, e.g. by activating indicators [VSPS08]. **Lane Keeping Assist Systems (LKAS)** actively prevent a lane departure, by acting on the steering wheel or applying brakes on one side of the vehicle [WCP+08, EMNL10, BNM11]. Originally, LKAS only intervene when the vehicle is actually leaving the lane, and deactivate when the vehicle is brought back into the lane. Without intervention of the human driver, such system would in principle be able to keep the vehicle in the lane, zigzagging from one lane border to the other. A new generation of LKAS can continuously control the vehicle in the center of the lane.

When the driver does not indicate his intention to change lanes, LDWS and LKAS help keep the vehicle in the lane. A next step is to assist the driver during lane changes. When the driver does indicate to change lanes, a **Lane Change Decision Aid System (LCDAS)** system warns the driver when the lane change is unsafe, e.g. if it detects other vehicles in the target lane [TVDVVAT07]. This is illustrated in Figure 2.4. A discussion on costs and benefits of LDWS, LKAS and LCDAS is given in [VSPS08]. Systems that actually control the vehicle during lane changes will probably come on market in the coming years.

In contrast to LKAS and LCDAS, a legal safety system performs continuous control of the vehicle during lane keeping and lane changing. During lane changing, it does not only take into account objects which are *visible*, but also objects which are *predictable*, e.g. it takes into account the possible presence of a fast vehicle coming from behind, outside the perception zone. ISO test procedures for LCDAS define target objects according to their position *with respect to the subject*; they do not require the perception of lane markings [ISO08]. The legal safety system benefits from a lane description ahead of and behind the subject, which allows a more precise discrimination of objects that are on the target lane, and objects that are not. In addition, the detection of object indicator status allows anticipating object lane changes.

2.1.4 Stability, longitudinal and lateral assistance combined

Each of the systems for stability, longitudinal and lateral assistance described previously, delivers one specific functionality. Today, they are often offered together in one **ADAS package**. This is

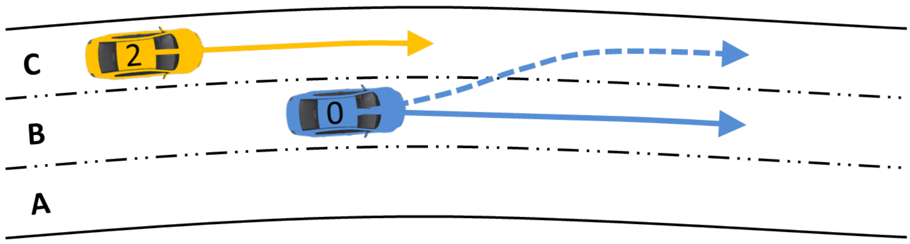


Figure 2.4: Environment model of lateral assistance systems. Subject, lanes, objects behind and objects on the side are described. Objects ahead and traffic signs are not described

already a step in the direction of automated driving. For example, continuous vehicle control by combining ACC and LKAS allows following another vehicle over long distances. Many of today's ADAS do not offer continuous vehicle control, but only act in emergency situations, e.g. BAS apply brakes for collision avoidance, as discussed above. This approach is currently (a) easier to accept by human drivers and international law, (b) easier to implement with state-of-the-art perception. For collision avoidance, the priority is to avoid unnecessary interventions (e.g. false positive object detection due to perception error), to the detriment of missed interventions (e.g. false negative object detection) in certain situations [MJS11]. In order to avoid unnecessary interventions, some collision avoidance systems mainly focus on low speed scenarios (e.g. urban traffic). At high speeds, collisions can be avoided by a steering maneuver by the human driver, instead of braking by the driving system. Executing an emergency brake in this situation could be perceived as an unnecessary intervention [KSD09, Eid11].

Compared to ADAS packages, a legal safety system both provides continuous vehicle control and takes over in emergency situations. It **extends functionalities** of existing ADAS towards fully automated driving on highways. As the legal safety system is designed for fully automated driving, it must avoid missed interventions, at the cost of (a minimum number of) unnecessary interventions. This requires additional studies on human-system interaction and additional development on perception technology. A legal safety system **combines ADAS functionalities** in **one system**. This assures the consistency between different functionalities. For example, lane changing can only be performed safely if actions in longitudinal and lateral direction are calculated together. Additionally, each system functionality benefits from a complete environment model (Figure 2.5), rather than a partial environment model. For example, the ACC functionality considers the object description, but also benefits from the lane description.

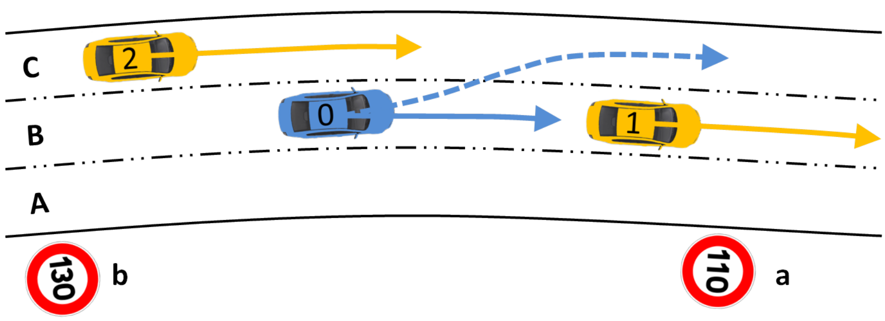


Figure 2.5: Environment model of stability, longitudinal and lateral assistance systems combined. Subject, lanes, traffic signs and objects are described

2.1.5 Highly automated driving and fully automated driving

Highly automated driving systems bring the task of the human driver on a higher level. Instead of continuously controlling the vehicle, the human driver defines target speed and target lane and monitors the driving system. Highly automated driving systems are now being studied by several European and national projects. In June 2011, the HAVEit consortium has presented the vision of highly automated driving with 7 demonstrator vehicles on **test track** [HAV11q]; the *Joint System Demonstrator*, *Brake-by-Wire Truck*, *Architecture Migration Demonstrator*, *Automated assistance in Roadworks and Congestion*, *Automated Queue Assistance*, *Temporary Auto-Pilot*, *Active Green Driving*. The *Joint System Demonstrator* and *Architecture Migration Demonstrator*, which integrate parts of the legal safety system, will be presented in Chapter 4. In April 2013, ABV vehicles and simulators will be demonstrated. The integration of parts of the legal safety system on the ABV *Low Speed Demonstrator* is discussed in Chapter 4.

Several vehicle manufacturers are considering bringing highly automated driving systems on market. This will probably be possible without changes in legislation [HAV11p]. In August 2011, BMW reported tests with highly automated driving systems over 5000 km on **public highway** [BMW11]. Tests included changing lanes for overtaking a slower vehicle or for stopping the vehicle on the emergency lane.

The legal safety system takes over the human-system interaction scheme (**human rules**) of highly automated driving systems. Compared to highly automated driving systems, it integrates the complete set of **traffic rules** as a basis for the cooperation with *human drivers in other vehicles*. This allows **fully automated driving** within the application zone and facilitates the cooperation with the *human driver in the subject vehicle* during **highly automated driving**.

2.1.6 Autonomous driving

Autonomous driving can already be demonstrated today, with highly equipped vehicles under human supervision. Several historic demonstrations of autonomous driving have been cited in Chapter 1 [DZ87, BBFC99, Def07]. Recently, impressive results have been presented by the Google car project [Thr10, TU11], which teams up main players of the famous DARPA challenge (e.g. S. Thrun, C. Urmson, M. Montemerlo, A. Levandowski). The **Google car** has logged about 300000 km of autonomous driving in city traffic, busy highways (including toll zones) and mountainous roads with only occasional human intervention. The Google car does not limit to one application zone; it targets all types of environments. This corresponds to the definition of *autonomous driving* in Table 1.1. One limitation exists: the route needs to be driven manually first, one or several times. The autonomous vehicle relies on detailed 3D maps recorded during the manual drive with a Velodyne LIght Detection And Ranging (**Velodyne LIDAR**) sensor. During an autonomous drive, the system localizes itself with the Simultaneous Localization And Mapping (**SLAM**) technique; it correlates measured LIDAR data with recorded map data. The SLAM technique based on the vast map database is the hearth of the system. Camera, radar are only used for information that cannot be obtained by LIDAR. For example, the position of a traffic light is detected by LIDAR, and camera detects its status (i.e. color).

The idea behind the legal safety concept is quite different. First, legal safety system makes safety only depend on **measured data**, not on previously recorded data. This avoids a first manual run, and covers the cases where the road structure has changed, e.g. due to road construction. The legal safety system relies on a limited perception zone, corresponding to the sensor range. Maps only assist the driving system with non safety critical information, as they assist human drivers. For example, a highway exit can be prepared earlier with the help of a map. Second, the legal safety system focuses on the **interaction** with other driving systems and human drivers, which goes beyond localization. For the interaction with human drivers on an infrastructure made for the human eye, **camera** is a central player. For example, interaction with other vehicles on highways involves the detection of indicator status and distinction of continuous and discontinuous lane markings. Estimating the intention of cyclists and pedestrians (i.e. in future development for other application zones) even involves interpreting where they are looking at. In this case, the camera is assisted by other sensors (e.g. radar) and map, rather than the opposite. Technically, autonomous driving based on-vehicle sensors only is not yet possible. This work considers the simplest environment for highly automated driving and fully automated driving; **highways**.

In following sections, requirements of legal safety on system design are specified in three sets of rules (see Figure 1.4). Traffic rules are presented in Section 2.2, human rules in Section 2.3 and system rules in Section 2.4.

2.2 Traffic rules

The word *traffic* comes from the Arabic *taraffaqa* meaning slowly walking along together. This is today certainly not the most common type of road traffic. Traffic is complex because of the diversity of its participants (e.g. driver personality, driver capacities, vehicle type) and of its infrastructure (e.g. multiple lanes, junctions, intersections). **Traffic law** has been developed as mediator between traffic participants, to promote traffic safety and efficiency. **Traffic rules** combine traffic law with non-official agreements between road users. This work uses the word *traffic rules*. It only takes into account rules present in today's traffic law, but leaves the possibility to integrate non-official rules in future development. This work does not remove, add or change any article with respect to today's traffic law. Rather, it aims to show that, with today's traffic law, highly (or fully) automated driving on highways is possible.

2.2.1 Traffic rules for human drivers

Traffic rules provide a natural way for human drivers to interact. Traffic rules keep **explicit communication** between traffic participants to a minimum, in favor of **implicit communication**. Explicit communication on highways is limited to the status of vehicle indicator and brake lights. Even with little explicit communication, human drivers know which actions to expect from other human drivers, through extensive implicit communication in the form of traffic rules. In cases that the intentions of different drivers conflict, traffic rules act as negotiator. However, with traffic rules, a human driver cannot *exactly* predict the future action of another human driver. He can only predict *bounds* wherein the future action of another lies. The prediction of future actions of other drivers could be more exact if more explicit communication were used, i.e. if drivers actively describe their future trajectories. A highway environment does however not give many possibilities for more explicit communication between human drivers. But, even during walking or cycling, when additional explicit communication with gestures and voice is possible, human beings favor implicit communication. They predict the bounds of others' actions based on common rules [Nor09]. Traffic between human beings based on (informal) rules, has proved successful during hundreds of years. Accidents do not result from the execution of traffic rules, but from drowsiness or distraction.

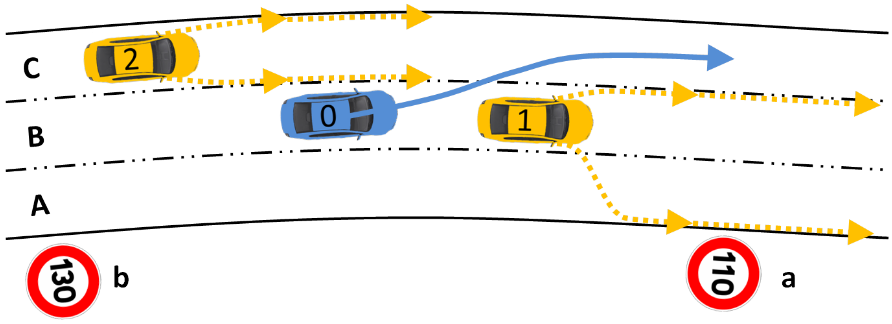


Figure 2.6: With limited explicit communication (brake and indicator status) and extensive implicit communication, a bounded uncertainty exists on future trajectories of other vehicles (dashed lines). A legal safety system is able to deal with this uncertainty

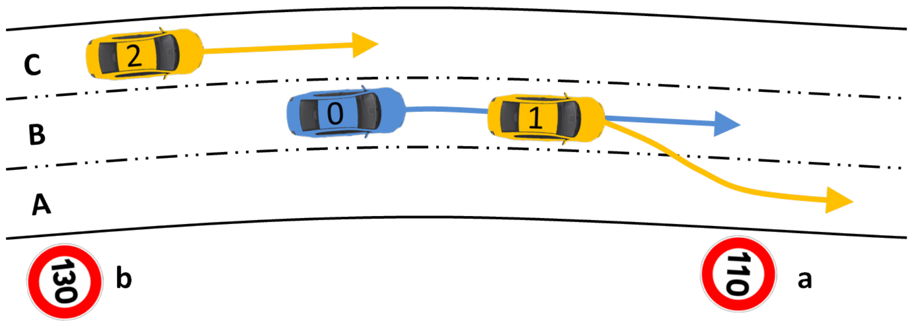


Figure 2.7: With complete explicit communication (full trajectory description), exact future trajectories of other vehicles are known (continuous lines)

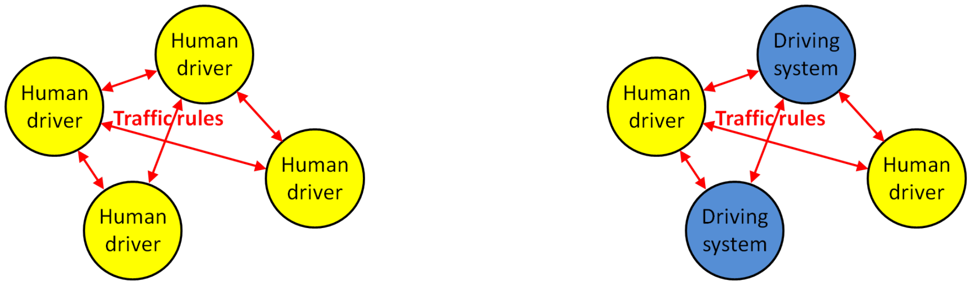
2.2.2 Traffic rules for driving systems

Legal safety means organizing traffic with driving systems in the same way as traffic with human drivers; with **limited explicit communication and extensive implicit communication**. On highways, explicit communication is based exclusively on indicator and brake light status, as for human drivers. Implicit communication is based on the integration of the complete set of traffic rules, which implies uncertainty on the prediction of actions of other traffic participants. This uncertainty is however *bounded*, as is illustrated in Figure 2.6. An alternative to legal safety would be to base traffic with driving systems on extensive explicit communication, e.g. Vehicle-to-Vehicle (V2V) and/or Vehicle-to-Infrastructure (V2I) communication. The amount of information that could be exchanged during explicit communication between driving systems is significantly higher than between human drivers. Driving systems could communicate a complete description of their *exact* future trajectories, as is illustrated in Figure 2.7. The knowledge of *exact* trajectories would help increasing safety and would simplify traffic rules.

However, legal safety does **not rely on explicit communication with V2V and V2I**, for several arguments. First, the driving system should be able to interact with human drivers in the environment. Even if in a distant future, all vehicles would drive autonomously, there would be a period where driving systems need to share the road with human drivers, as stated in Section 1.2. The idea behind legal safety is that a powerful way to let driving systems interact with human drivers is to **imitate human drivers**, as is suggested by Figure 2.8. This allows that actions of the driving system are understood by both human drivers of vehicles in the environment and by the human driver in the subject vehicle. For automation modes driver assisted, semi-automated and highly automated, the human driver and driving system share vehicle control. These automation modes are facilitated if both partners (i.e. human driver and driving system) have a same basis for decisions: traffic rules. Second, economically, **only depending on systems installed in the vehicle** seems a more attractive business model than depending on the uncertain development of equipment of other vehicles or infrastructure. On highways, communication devices could be made mandatory on all vehicles. However, in some environments, mandating communication devices for all traffic participants is unrealistic, e.g. in cities with pedestrians and cyclists. Keeping costs internal (i.e. the complete cost of the driving system is paid by the vehicle owner) also avoids the problem of distributing external costs (e.g. the costs of infrastructure adaptations must be redirected on traffic participants that benefit from it). Third, legally and psychologically, it seems preferable that **safety does not depend on information coming from third parties**. For example, if vehicles would always communicate their intention to brake, vehicle inter-distances could decrease [DGB$^+$11, vWSK11]. It seems however wiser to keep an inter-distance that is sufficient to avoid an accident in the case an unannounced emergency brake of the vehicle ahead, as specified in traffic rules. Safety then does not depend on the reliability of other actors, e.g. other traffic participants, map suppliers, satellite programmes and infrastructure administration. Forth, technically, extensive communication between vehicles, relies on accurate global positioning, which might be difficult to realize in many situations, as will be discussed in Section 2.5. Legal safety only depends on **proprioceptive and exteroceptive sensors**, i.e. sensors on the subject which describe the subject state and environment without support of external sensors.

Even if it does not depend upon it, a legal safety system is **compatible explicit communication with V2V and V2I** for additional information. The use of explicit communication can be seen as a specific case of the use of implicit communication; it eliminates or reduces the uncertainty of perception and prediction of other traffic participants. As an example, the occurrence of traffic congestion could be reported over large distances by V2V and V2I communication. This allows anticipating and braking more comfortably for still standing vehicles in the environment. The legal safety system could benefit from V2V and V2I communication in certain cases of non-legal object behavior. The legal safety system avoids accidents in the case of legal object behavior. It avoids accidents in most cases of non-legal object behavior, based on the principles of defensive driving, as will be discussed further in this section. Communication could avoid accidents in the case of non-legal object behavior that cannot reasonably be foreseen with defensive driving, e.g. a sudden lane change of an object on the side of the subject, or the approach of ghost drivers at high speeds. Benefits of avoiding these particular accidents should be weighed against the costs of equipping a large number of vehicles and infrastructure with communication devices.

This work discusses system design based on traffic rules. Legal-technically, this is not trivial [HAV11p]. Traffic law has been written as **civil regulatory law**, which by nature can only be applied to humans, not to systems. Traffic law does not have binding legal impact on the design of driving systems; i.e. driving systems that do not respect traffic rules are not in conflict with law. Today's traffic law only specifies that the human driver is responsible for safety; if a system takes over (a part of) vehicle control, the human driver must monitor system behavior and be able to take over vehicle control whenever needed. For legal safety, **technologically effective regulations** that specify driving system behavior, would be an exact copy of civil regulatory law, except for the system-specific formulation. In this work, the legal-technical differences between civil regulatory law and technologically effective regulations are not relevant. Traffic rules from civil regulatory law are directly applied to system design. The *driver* referred to in



(a) Interaction between human drivers

(b) Interaction between human drivers and driving systems

Figure 2.8: The use of traffic rules for (a) the interaction between human drivers and (b) the interaction between human drivers and driving systems

the traffic rules is interpreted as either *human driver* or *driving system*.

2.2.3 Traffic rules of the Vienna Convention on Road Traffic

Standard traffic rules are defined by an international treaty under authority of the United Nations, the **1968 Vienna Convention on Road Traffic** [Uni68]. For the presentation of the legal safety concept, traffic rules of the Vienna Convention are used. The Vienna Convention has not been signed by all countries, and local variations in practice can be found among signatories. Many of the local specificities do however not apply to driving (e.g. driving under intoxication, day lighting, seat belt use, tire equipment). Some local specificities do apply to driving, but follow the same fundamental principles as the Vienna Convention. These local variations would be integrated if the legal safety system were to be commercialized, but as the focus of this work is to discuss the principle of legal safety, they are not considered.

The **application zone** of the legal safety system indicates the environment for which the system is designed, and optionally puts additional conditions; e.g. day/night conditions, weather conditions and right-hand/left-hand traffic. As presented in Section 1.2, the application zone for the legal safety system in this work is the **highway**. The Vienna Convention defines the *highway* as a road, which (i) is for motor vehicles only, (ii) does not serve properties or cross at level with any road, railway, tramway track or footpath, (iii) separates the lanes for the two directions of traffic by a strip not intended for traffic, except temporarily, (iv) is signposted as highway [Uni68]. For the legal safety system presented here, **additional conditions on the application zone** are that (v) it is divided in lanes that are separated by visible lane markings, e.g. excluding zones without lane markings around toll stations, construction sites, or extreme weather conditions that make lane markings not longer visible (vi) include entrance and exit ramps (i.e. the system can drive from the beginning of an entry till the end of an exit), but not complex highway junctions or highway rest areas. In the document, the word *highways* denotes roads that respect conditions (i) to (vi). The description in this work assumes that driving is on the right side of the road; translation for left-side driving is straightforward.

A concise description of the articles of the Vienna Convention that apply to driving on highways is given in the **rules** below. The formulation of the rules is simplified for understandability but intends to reflect the exact article content. The original index and title of the article(s) in the text of the convention is indicated between parentheses. The word *article* is reserved to refer to the original formulation of the Vienna Convention, which can be found in Appendix A. Note that, in future work, the content of rules could be extended beyond the article content, e.g. to integrate universal non-official understandings between road users.

Rule 1 (8. Drivers) *The* ***(human) driver*** *should be in good physical and mental condition, and should always be able to control the vehicle.*

Rule 2 (7. General rules) *Traffic participants should* ***avoid damage*** *to road infrastructure or other traffic participants.*

Rule 3 (5. Status of signs, 13. Speed and distance between vehicles) ***Speed*** *must be adapted to road and weather conditions (i.e. visibility and road friction) and the presence of other vehicles. Instructions given by traffic signs, traffic lights and markings on the road must be respected and have priority on other traffic rules. Driving abnormally slowly should only be performed for safety reasons or in order to respect traffic rules. The* ***distance to other vehicles*** *must be such that a collision can be avoided if a vehicle performs an emergency brake. The driver also must be able of avoiding collisions with any* ***foreseeable obstacle*** *outside the perception zone.*

Rule 4 (17. Slowing down) ***Braking*** *should only be performed for safety reasons or in order to respect traffic rules. It must be indicated with braking lights.*

Rule 5 (10. Position on the carriageway) *Driving should be on the* ***right-most lane*** *if possible, except for overtaking.*

Rule 6 (11. Overtaking, 14. Manoeuvres) *Overtaking must be* ***on the left****, and sufficient lateral distance should be kept from vehicles being overtaken. An overtaking maneuver can only be started if the* ***vehicles behind and ahead in the same lane*** *have neither indicated nor started to overtake another vehicle and if* ***vehicles in the target lane*** *are not hindered by the maneuver. An overtaken maneuver cannot be performed if prohibited by the corresponding traffic sign and continuous lane markings should not be crossed. The corresponding indicator of the vehicle must be activated during the entire overtaking maneuver. In* ***congested traffic****, both left and right overtaking are allowed. In congested traffic, lane changes are not allowed, except for leaving the highway. Congested traffic is defined as traffic where all lanes are entirely occupied by vehicles, and where vehicle speeds are significantly lower than the speed limit.*

Rule 7 (25. Motorways and similar roads) *Only motor vehicles are allowed on highways. Vehicles shall not travel in reverse or in the opposite direction. Vehicles on the highway have priority over* ***vehicles entering*** *the highway. Exiting the highway must be done with a single lane change from the right most lane to the* ***exit ramp****, as soon as possible. If the vehicle needs to be stopped for safety reasons, this must be done on the* ***emergency lane****, if possible.*

Rule 8 (25bis. Tunnels, 32. Lamps) *The lighting of the vehicle should be adapted to the* ***visibility*** *conditions and should not hinder other traffic participants. In tunnels, vehicle lighting must be switched on.*

Rule 9 (34. Exemptions) ***Priority vehicles*** *are exempt from traffic rules, except from Rule 2 (7). Other vehicles should make the road clear and decelerate if necessary, to let pass the priority vehicles.*

Rule 10 (6. Instructions by officials) *Instructions given by authorized officials must be respected and have* ***absolute priority*** *on all traffic rules.*

Sections 2.6, 2.7, 2.8 and Chapter 3 will discuss the consequences of these traffic rules on the design of legal safety perception, control, HMI and decision components.

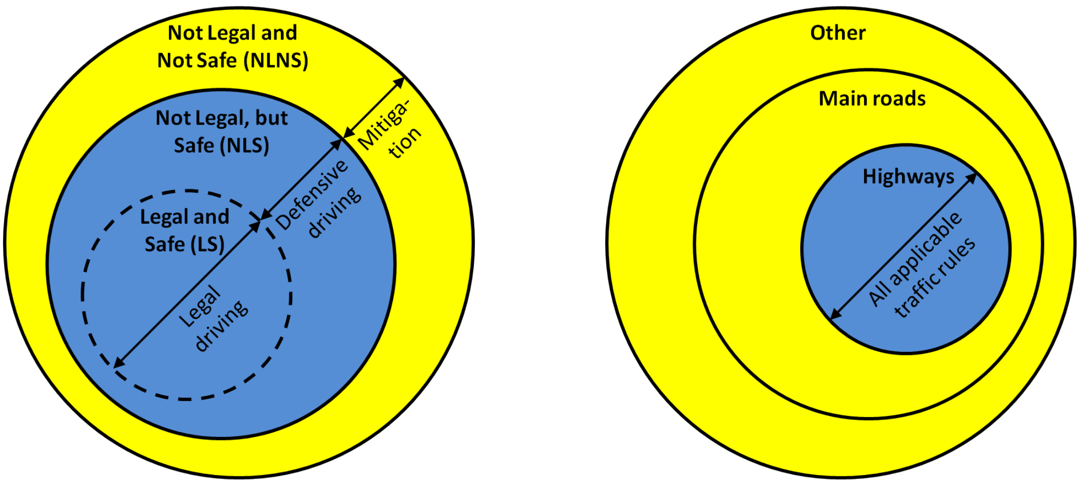
2.2.4 Legal driving versus defensive driving

In the context of this work, the term **accident** denotes a collision that is directly related to the actions of the driver (human drivers or driving systems). The discussion and prevention of accidents that cannot directly be influenced by driver decisions are not in the scope of this work. This excludes accidents caused by loss of vehicle control due to technical failure (e.g. an accident caused by the loss of a wheel), accidents caused by unpredictable external factors (e.g. falling rock, lightning impact) and accidents caused by abnormal defects on the infrastructure (e.g. road markings that would lead vehicles off the road). However, it includes accidents due to minor technical failure (e.g. fuel exhaustion), accidents due to external factors that are foreseeable (e.g. reduced visibility due to weather conditions) and accidents caused by normal dysfunctions of infrastructure (e.g. missing or poor lane markings). These accidents must be avoided. In this work, the term **safety** indicates the lack of accidents.

From Rules 1 to 10, it can be concluded that on highways, **no accidents occur if all traffic participants respect traffic rules**. Respecting traffic rules, implies the integrity of perception, decision and control of human drivers and driving systems. Rule 8 entails the perception of objects within a certain perception zone. Outside of this horizon, the system takes into account non-visible but predictable objects (e.g. objects that respect traffic rules), by Rule 3. When human drivers and driving systems respect Rules 1 and 3, they have control over the vehicle; i.e. they can perform the lane keeping or lane changing trajectories that they calculate. Drivers that *keep the lane*, keep an appropriate longitudinal distance to vehicles in the same lane, so that even in the case of emergency braking of other drivers, accidents are avoided, according to Rule 3. These drivers also keep an appropriate lateral distance to slower vehicles in other lanes, according to Rule 6. Drivers that intend to *change lanes* do not hinder drivers on the target lane, or other drivers that have first intended the same lane change, also by Rule 6. When all traffic participants respect traffic rules, the situation is **Legal and Safe (LS)**, indicated in Figure 2.9.a. Legal safety promotes LS situations, as a legal safety system respects traffic rules at all times. The legal safety system is designed never to be responsible for an accident and never to incur traffic fines.

Driving that only takes into account LS situations could be called **legal driving**. However, in everyday traffic, **traffic rules are not respected in all situations**. In come cases, drivers disobey traffic rules intentionally (e.g. speeding in order to reduce travel time, lane changing without activating indicators or lane changing abruptly in order to avoid an accident) or unconsciously (e.g. speeding by inadvertence, departing from the lane due to drowsiness). Rule 2 implicitly states that other drivers should foresee these situations, i.e. **drive defensively**. In the case non-legal situations occur, everything possible should be done to avoid accidents. The legal safety concept makes use of traffic rules, to integrate principles of defensive driving. The driving system leaves space for non-legal actions of other traffic participants (e.g. by foreseeing that objects can have a speed higher than the speed limit), predicts non-legal object actions and adapts to avoid accidents (e.g. a slower vehicle on another lane, which activates indicators towards the subject lane, is believed to change lanes even if it should give priority). The idea of using traffic rules in this context is that it helps the system to detect non-legal situations, in order to act in a different way than in legal situations. To be able to detect situations where rules are not respected, the driving system needs to know the rules. As Figure 2.9.a indicates, defensive driving converts a maximum number of non-legal situations into situations that are **Not Legal, but Safe (NLS)**. There is a great freedom in how to implement defensive driving. Law does not explicitly state which non-legal object behavior should be taken into account. For example, a driving system could implement different defensive driving strategies for different cultures, in order to adapt for traffic rules that are most frequently disregarded locally [LCJZ08]. In this work these cultural differences are not considered. The legal safety system remedies to general non-legal actions, which will be described in Chapter 3. The LS and NLS situations form the **safety zone**. The aim of legal safety is to make the safety zone as large as technologically and reasonably possible.

Not all non-legal situations can be solved with defensive driving. Situations that are **Not Legal and Not Safe (NLNS)** remain, as Figure 2.9.a indicates. Defensive driving needs limits, it should not anticipate unlikely situations. As an example, taking into account the possibility that slower vehicles can perform a sudden lane change at all times, without any indication, would preclude overtaking. Taking into account the possibility of a group of senseless ghost drivers ahead would exclude driving altogether. In the case of NLNS situations, the legal safety system cannot avoid the accident. The accident is **mitigated** with an emergency brake. An emergency brake is a legal action in NLNS situations, by Rules 3 and 4. In its current development, the legal safety system does not perform non-legal actions in order to avoid an accident, in order to simplify liability issues. In future development non-legal subject actions might be considered, e.g. performing a lane change, even when this hinders objects on the target lane. As defensive driving strategies are not regulated, different drivers deal differently with difficult non-legal situations. Some human drivers will be able to avoid accidents that some driving systems cannot avoid, and vice versa. Fully automated driving presents the novel situation where, in certain non-legal situations, life or death depends on the technological capabilities of the driving system. The question is how regulators and public will react this. There is a clear risk of overreaction, as accidents which involve humans are generally better accepted than accidents which involve systems, even if it could be shown that fully automated driving dramatically reduces the number of traffic related casualties. Generally, law requires that systems function with a quality that corresponds with state of the art at the time of introduction market. Fully automated driving might only be accepted when driving system reliability has become several times higher than reliability of the human driver.



(a) Safety zone

(b) Application zone

Figure 2.9: (a) Safety zone includes LS and NLS situations, does not include NLNS situations and (b) Application zone includes highways, does not include main roads and other environments

2.2.5 Traffic rules in other application zones

The application of the legal safety system in this work has deliberately been restricted to **highways**. Highways are among the simplest environments for driving. On highways, only a limited number of traffic rules of the Vienna Convention (Rules 1 to 10) applies. This facilitates the presentation of the general concept of legal safety. As Figure 2.9.b suggests, covering other application zones does probably not imply a completely new system concept, but an extension of system functionalities for highways in order to cover traffic rules in other environments. As the legal safety system imitates the human driver, chances are high that system functionality can be extended to other environments created for human drivers, without relying on adaptations of equipment on infrastructure or equipment of other traffic participants.

There are various reasons why an extension of legal safety to **other environments** is still far from state-of-the-art perception, decision and control. A first reason is the complexity of the **environment structure** [ABV13a]. This includes an increased variety of lane shapes. For example, the perception zone needs to be larger than on highways in order to adapt to strong curves. Often lanes are not separated by lane markings. Lanes for vehicles and lanes reserved for other traffic (e.g. public transport or bicycles) must be differentiated. Traffic coming from the opposite side constitutes a challenge for overtaking; the perception zone must be extended to detect oncoming traffic. Additionally, the space in front of a vehicle to be overtaken must be analyzed, for example, by looking through its window. Opposite traffic is also a challenge when on certain points, the road is not wide enough to let pass two vehicles. Additionally, a great variety of intersections exist, with different priority rules and traffic signs, e.g. intersections with priority for traffic from the right, intersections with traffic lights, roundabouts, pedestrian crossings and railway crossings. A second reason of the complexity of legal safety in other environments than highways is the diversity of **traffic participants**. Often, traffic participants in other environments are more difficult to recognize and their actions more difficult to predict, especially in the case of non-legal behavior. For example, understanding the intention of pedestrians or cyclists frequently implies recognizing where their attention is drawn to. A challenge is recognizing and understanding instructions given by traffic regulating officials, and recognizing vehicles that have priority. These, and other reasons, make that autonomous driving (i.e. fully automated driving on all environments) seems far from market.

Still, the basic skills for driving on highways could be helpful in many situations in other environments. The legal safety system could be used for semi-automated or **highly automated driving in other environments**, with the human driver taking over control when needed. The application zone for fully automated driving could also be extended to other simple environments. A next application zone could include **main roads** with only motorized vehicles, and only intersections regulated by traffic lights, as Figure 2.9.b suggests. The discussion on the use of a legal safety system in application zones different from highways is however not in the scope of this work.

2.3 Human rules

Before autonomous systems will be able to perform complete trips (e.g. a door-to-door taxi service), the *driver* in Rule 1 is alternatively the human driver, driving system or a combination of both. The understanding and interaction between human driver and driving system, defined by human rules, is a crucial element of legal safety. This section presents a minimal set of human rules, which specify automation levels and automation mode transitions. During **fully automated** driving, the interaction can be kept simple; vehicle control is switched from driving system to human driver at the end of the application zone. In automation modes **driver assisted, semi-automated and highly automated**, human driver and driving system share the driving task. Through human rules, the actions of the driving system are designed to match with actions of the human driver, and vice versa. The optimal design of a continuous interaction between human driver and driving system constitutes a study on its own. The human rules used in this work follow the human-system interaction scheme of the HAVEit project [FNG+10, FSS+11].

2.3.1 Human driver monitoring the driving system

Rule 1 states that a driver should always be able to control the vehicle. Under current law, the term *driver* means **human driver**. The human driver must constantly monitor the environment and always be able to take over vehicle control from the driving system when needed. For ADAS that offer either longitudinal or lateral control (Section 2.1), monitoring is natural as (a) the human driver is involved in the other part of vehicle control and (b) it is quite clear that the system does not handle all situations (e.g. ACC does not adapt to speed limits). With highly automated driving, when the driving system offers longitudinal and lateral control, monitoring the system might become a bigger challenge for the human driver. This is especially the case if driving systems reach higher levels of driving intelligence. Figure 2.10 [HAV11k] shows one of the results of the HAVEit transition study, where participants generally appreciated the system, but judged it quite sleep inducing. Related to this, is the phenomenon of **risk homeostasis**. As driving systems increase perceived safety, human drivers tend to be less attentive and to take more risk, which reduces (and sometimes neutralizes) potential safety benefits [Wil82, Wil01]. Effects such as drowsiness and risk homeostasis must be countered by system design. Two strategies can be distinguished [FNG+10]: (a) **increase the role of the human driver** so that the need for his attention is clear, (b) **increase the role of the driving system** by making the system capable of fully automated driving. Option (a) could be implemented by giving the driver a task that requires his continuous attention, e.g. give a part of longitudinal or lateral control. Human driver attention could also be increased by intentionally decreasing system performance. For example, letting the system make regular driving errors could increase safety. *Regular* system errors are found to be less dangerous than *sporadic* system errors [Fae11]. Some ESC systems let the vehicle's course deviate slightly from the driver-commanded direction, even if higher precision could be reached, in order to make the driver aware of the criticality of the situation. Collision Mitigation Avoidance Systems (CMAS) presented in Section 2.1 (e.g. Brake Assist System) only intervene in emergency situations. These systems can be parameterized with an uncomfortable deceleration and a distance from objects that feels dangerous for a human driver [Eid11]. This work is compatible with option (a), but focuses option (b).

2.3.2 The term *driver* in the Vienna Convention

The legal consequences of fully automated driving are considered crucial for the development of new driving systems. Questions such as *Is fully automated driving in accordance with law?* and *Who is liable if an accident occurs during fully automated driving?* are now being investigated by research and vehicle manufacturers (OEMs) [HAV11p]. The *Legal Consequences of an Increase in Vehicle Automation* were studied by a working group including the German Federal Highway Research Institute (BASt), BMW, Daimler, Volkswagen AG, Bosch, DLR, University of Berlin and University of Braunschweig [BAS12]. In HAVEit deliverable D67.1 [HAV11p], the results of the BASt working group are mapped on HAVEit automation levels highly automated and fully

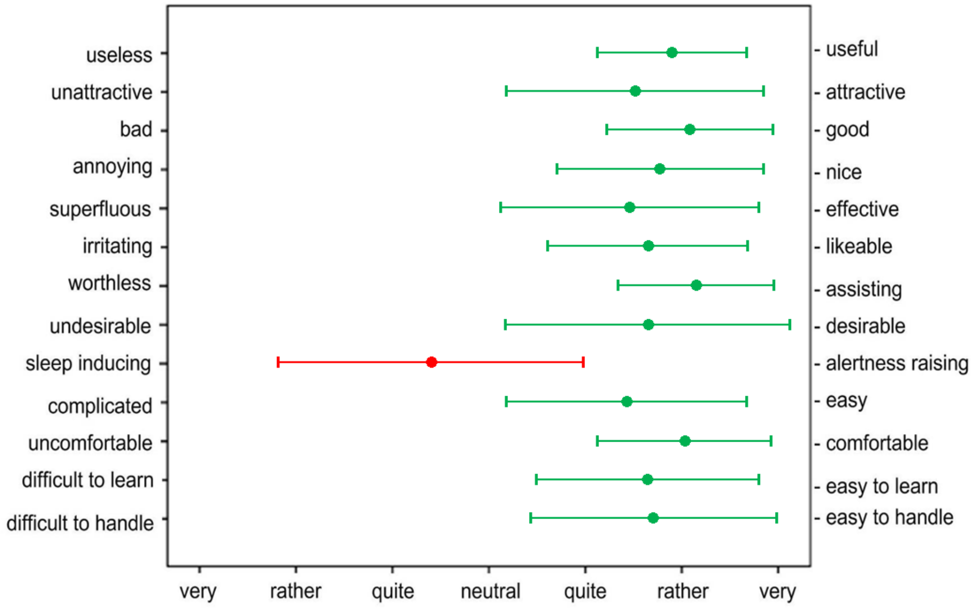


Figure 2.10: Subjective evaluation of highly automated driving in the HAVEit transition study. Source: HAVEit Deliverable D33.6 [HAV11k]

automated driving. The conclusion of the working group is that **highly automated driving** is congruent with regulatory law, as the human is constantly monitoring the system. **Fully automated driving** is generally in conflict with today's law. However, the **Minimum Risk Maneuver (MRM)**, which brings the vehicle to a safe standstill when the human driver is not any longer capable of driving (e.g. has fallen asleep or has fainted), is one special case of fully automated driving that is accepted by law. The conclusion concerning product liability law follows the same pattern. Highly automated driving is possible under current liability law, fully automated driving not. For highly automated driving, the roles of vehicle owner, vehicle driver, vehicle manufacturer as well as motor vehicle third-party liability insurance do not change radically, as long as system design uses state-of-the-art technology and avoids foreseeable misuse by the human driver. For example, the driving system must minimize the risk that the human uses the system for fully automated driving, i.e. without monitoring the system. Currently, OEMs do not have any protection against liability claims in the case that an accident occurs during fully automated driving.

In order to bring fully automated driving systems on market, adaptations to regulatory law and product liability law are needed. Insurance for fully automated driving systems should take into accounts its benefits and risks in comparison with human drivers. Whether is these changes will come through in short or medium term, or not, is subject to uncertainty. But even under current law, a system *capable* of fully automated driving, has advantages for driver assisted, semi-automated and highly automated driving. It improves safety and **facilitates the interaction with the human driver** by matching the driving intelligence of the system to driving intelligence of the human. It allows performing an MRM (i.e. fully automated driving) in order to bring the vehicle to a **safe standstill** when the human driver is not longer capable of controlling the vehicle.

From the discussion can be concluded that under today's law the *driver* in Rule 1 can only be interpreted as either the **human driver, or a combination of human driver and driving**

system. This work assumes that the *driver* is extended to **driving system** in order to allow fully automated driving.

2.3.3 Human rules for driving systems

For a driving system, a **good physical and mental condition** implies giving control to the human driver when the driving system is not longer capable of driving. For example, when the end of the application zone approaches or in the case of hardware failure, vehicle control is taken over by the human driver. If not, the system automatically brings the vehicle to a safe standstill on the emergency lane without leaving the application zone. This section presents a **minimum interaction scheme** between human driver and driving system in order to respect Rule 1, along the automation levels driver only (DO), driver assisted (DA), semi-automated (SA), highly automated (HA) and fully automated (FA), defined in Table 1.1. Legal safety takes over the HAVEit human-system interaction principles [HAV11f, HAV11g]. This work does not contribute to the actual design of human-system interaction, it discusses the consequences of human-system interaction principles on the design of the automation components of the system. Human-system interaction for a legal safety system is specified in **human rules**. Requirements from human rules on perception, control, HMI and decision components, will be discussed in Sections 2.6, 2.7, 2.8 and Chapter 3.

For **complete study on human-system interaction schemes for DO, DA, SA and HA**, reference is made to the HAVEit project [HAV11f, HAV11g, HAV11h, HAV11k, FNG+10, FSS+11]. The design of HAVEit interaction schemes is inspired by the Horse-rider metaphor (H-metaphor) [FAC+03, GSFW06, Nor09, FH10]. Under tight reins, a rider controls the horse directly. The horse can, however, resist the commands of the rider and balk when it judges a maneuver too dangerous. During loose-rein riding the horse has more autonomy, but the rider still gives some high-level instructions and corrects when necessary. Similarly, the vehicle is directly controlled by the human driver in DA (tight rein), but in emergency situations the vehicle adapts the automation mode to SA and automatically brakes (balks), as in a Brake Assist System (BAS). In HA, the vehicle is controlled by the driving system (loose rein) and the driver chooses target speed and acknowledges lane changes (high-level instructions). The HAVEit deliverables [HAV11f, HAV11g, HAV11h, HAV11k] describe the iterative interaction design process and user experiments.

Further research is needed on human-system interaction schemes for FA, e.g. on how to best invite the human to take over control at the end of the application zone. It is currently being studied by partners in the ABV project [ABV12]. Research in this field can build on findings in other sectors, for example, on the lessons learned from temporary automation in aviation [GSFW06].

Human rules for legal safety system design are presented below.

Rule 11 (Automation Level (AL) description) *In automation level **DO**, the system is not active, it is in stand-by. The automation levels **DA**, **SA**, **HA** and **FA** follow the description in Table 1.1.*

*The human specifies a **target speed**. The system indicates the **optimal speed**. If the target speed cannot be met, the system explains why (e.g. vehicle ahead, speed limit). The human specifies the **target lane**, except in FA, where the target lane is chosen by the system. The system indicates the **optimal lane**. If the target lane cannot be met, the system explains why (e.g. vehicle on the side, continuous lane markings).*

*In all situations, the human can directly **brake or accelerate** the vehicle. In DA and SA, the system gives **haptic feedback** on the steering wheel which is sufficient to avoid that the* *vehicle leaves the lane, when the human does not react. In HA and FA, the system gives haptic feedback which keeps the vehicle in the middle of the lane, but which can still be overpowered by the human.*

Optionally, the human can choose the ***driving style****, e.g. normal, sportive and comfortable.*

Table 2.1 summarizes the Automation Level (AL) description, according to Rule 11. With *speed control*, the control of an optimal vehicle speed is meant. *Lane control* means the control of the vehicle in the middle of the target lane (i.e. lane keeping or lane changing). In the proposed interaction scheme, human and system *share* speed control (i.e. only one of both is acting), but are able to *cooperate* on lane control (i.e. human and system can act at the same time on the steering wheel) [FH10].

Matching driving styles of human and system avoids the situation wherein the systems actions exceed what the human perceives as safe [Nor09].

AL	Human driver	Driving system
DO	**Speed control**, **lane control**	Not active
DA	**Speed control**, **lane control**, driving style, system monitoring	Optimal speed, optimal lane
SA	Target speed, **lane control**, driving style, system monitoring	**Speed control**, optimal lane
HA	Target speed, target lane, driving style, system monitoring	**Speed control**, **lane control**
FA	Target speed, driving style	**Speed control**, **lane control**

Table 2.1: Short description of Automation Levels (ALs)

Rule 12 (Automation Mode (AM) transitions) *The system informs on the* ***active and available automation levels*** *via a display in the human's primary field of view.*

Outside the application zone, only DO is possible. In the application zone, the system switches from DO to DA. The human can ***switch between consecutive automation levels*** *and can also directly come back to DA, from each automation mode. If the human performs a decisive* ***action on pedals or steering wheel****, he receives longitudinal or lateral control directly.*

The system automatically switches from DA to SA, in order to ***avoid a collision*** *by braking. In the case of a system failure or end of the application zone, the system automatically brings the vehicle to a standstill before the end of the application zone with a* ***MRM****, unless the human takes over control in DA. In DA, SA and HA, an MRM is also performed when the human is not longer monitoring the system.*

Figure 2.11 illustrates the automation mode transitions according to Rule 12. By respecting the human rules, the vehicle is **always controlled by a competent driver in the application zone**, in accordance to Rule 1. When *both human driver and driving system* are available, any automation mode can be chosen. When the driving system is not available, the *human driver* takes over. When the human driver is not available, the *driving system* switches to SA and keeps the vehicle in the lane through haptic feedback, or it switches to MRM. When *neither driving system nor human driver* are able to continue driving, the vehicle is brought to a standstill through an MRM, without leaving the application zone.

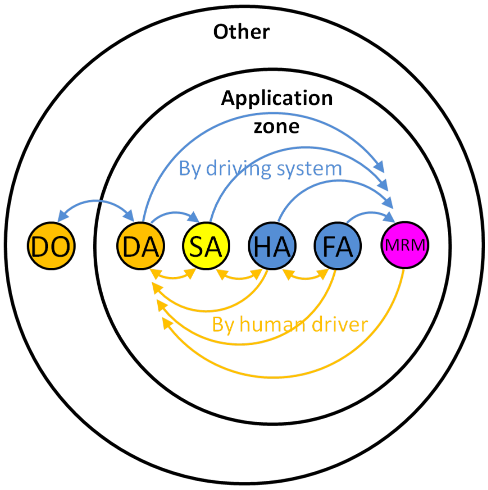


Figure 2.11: Rule 12 (Automation mode transitions): the automation mode transitions, initiated by human driver (lower part) or by driving system (upper part). The MRM is indicated as a special case of FA

2.4 System architecture and system rules

After the specification of system requirements with traffic rules and human rules, the V-cycle (Section 1.4) continues with the presentation of system architecture and specification of system rules.

2.4.1 System architecture

The driving system is first specified according to a *functional* architecture. Later, in the implementation phase of the V-cycle, the functional architecture is mapped on a *software and hardware* architecture, as will be described in Chapter 4. The functional architecture of the legal safety system is presented in Figure 2.12. The driving system **imitates the vision, decision and action of the human driver**, with a perception, decision and control component. This facilitates the interaction between driving system and human drivers in the environment (traffic rules) and the human driver in the subject vehicle (human rules).

The perception component creates a representation of the environment, with sensors such as camera and radar. The decision component calculates an optimal trajectory in the environment, in correspondence to legal safety rules. The control component keeps the vehicle on this trajectory, with actions on brakes, powertrain and steering wheel. The HMI component manages the interaction with the human driver.

Perception, control and HMI implement *objective* functions; these components have a single optimal behavior. For example, the ideal behavior of perception is to give an *exact* representation of the environment. The ideal behavior of control is to keep the vehicle *exactly* on the trajectory. In contrast, the decision component implements a *subjective* function. Different *optimal* decisions exist for one situation; think of human drivers with different personalities. The **decision component is the central component** for legal safety. It implements the negotiation with the environment (*traffic rules*) and human driver (*human rules*), as is indicated with dashed lines in Figure 2.12. As the figure suggests, legal safety decision also implements a negotiation with perception and control (regarding perception and control accuracy) via *system* *rules*, will be presented in next section.

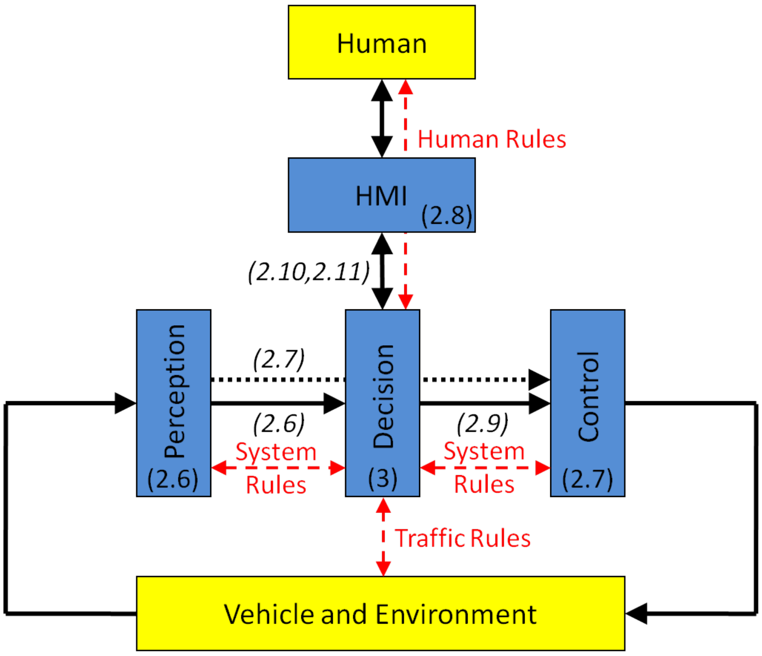


Figure 2.12: System architecture with perception, decision, control and HMI components (the corresponding section in this work is indicated between parentheses). Continuous and dotted lines indicate interactors between components (the corresponding description table is indicated between parentheses). Dashed lines indicate interaction with traffic rules, human rules and system rules

The system architecture in Figure 2.12 is **simple** and one-directional. The legal safety rule sets can easily be mapped (dashed lines), compare with Figure 1.4. Each component implements a well-defined function, with a consolidated output towards other components, vehicle and human driver. This is easier to manage than the network of separate ADAS, which implement sub-functions and have competing outputs. As the perception, decision and control are **universal driving functions**, they can be migrated to other vehicles (e.g. truck, bus, motorcycle).

2.4.2 System rules

Through system rules, the decision component takes into account **limitations of perception and control**. First, trajectories calculated by the decision component must be **feasible** for perception and control. For example, extreme lane change trajectories cannot be proposed if they cannot be followed by control, or if they compromise environment tracking by perception. Second, the decision component must take into account the **accuracy** of perception and control, in order to guarantee the integrity of its decisions.

Minimum system rules for guaranteeing the integrity of system components are presented below. System rules can be seen as a **negotiation** between perception, decision and control specifications. They have continuously been redefined during the development of legal safety components. System rules have been applied in the development of LIVIC, HAVEit and ABV demonstrators, which have perception, decision and control components designed by different project partners.

Rule 13 (Perception accuracy) *The error of subject state description by perception must be* ***within bounds****. Within a* ***perception zone****, the error of lane and object descriptions by perception must be within bounds.*

This ***accuracy*** *is such that the subject can be controlled in the lane and that objects within the perception zone are correctly assigned to their lane.*

The distance to the end of the perception zone in front does not decrease faster than the distance traveled during maximum subject deceleration.

Figure 2.13 illustrates Rule 13. The lane description by perception (dotted lines) deviates from the actual lanes (continuous lines). The uncertainty on object and traffic sign positions is also indicated with dotted lines. Due to uncertainty on the **longitudinal position** of the object, the decision component keeps additional distance from the object, as will be explained in Chapter 3. Similarly, the decision component adapts to the speed limit, in correspondence to the worst-case (i.e. closest) position of the traffic sign. In the figure, the object is correctly **assigned** to the subject lane. However, the uncertainty on the lateral position of the object, leads to a double object-to-lane assignment; the object is partly in the subject lane, partly in the left lane. In reality however, the object is located entirely in the subject lane. Due to the double lane assignment overtaking the object on its left side is not possible, as is explained in Chapter 3. Overtaking the object is not possible, but following the object is. As the subject approaches the object, the accuracy of the object detection improves and, if a single lane assignment is reached, overtaking becomes possible. Note that legal safety tolerates uncertainty on environment variables by perception, but that it requires that this uncertainty is **bounded**. This cannot yet always be met with state-of-the-art perception. If uncertainty on environment variables is unbounded (e.g. Gaussian), highly or fully automated driving is not possible. For example, like the human driver, the driving system must not be able to *exactly* describe object positions, but must be able to describe a box in which the object certainly lies.

As object lane assignment is essential for the application of traffic rules, a single perception zone is defined for lanes and objects. The perception zone is the intersection of the individual lane perception and object perception zones. Rule 13 implies that objects outside a perception zone are not necessarily detected. The decision component adapts vehicle speed to the possible presence of **phantoms**, worst-case objects outside the perception zone, discussed in Chapter 3.

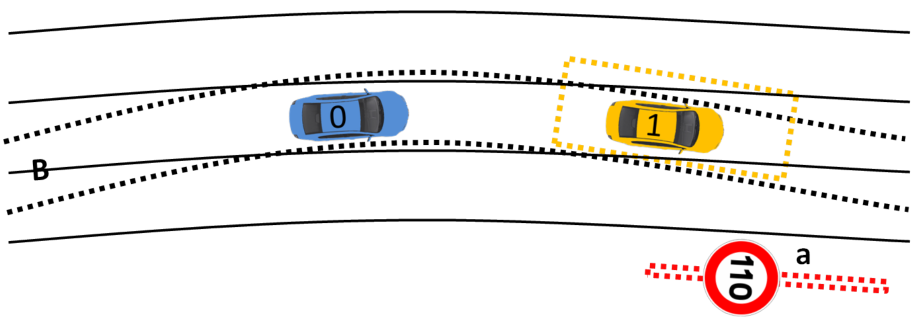


Figure 2.13: Rule 13 (Perception accuracy): the uncertainty on lane, traffic sign and object descriptions must be bounded

Rule 14 (Decision feasibility) *The subject trajectories proposed by the decision component respect the* ***integrity*** *of perception and the* ***feasibility*** *of vehicle control.*

Figure 2.14 illustrates Rule 14. The rule implies that the decision component always finds **at least one trajectory**. The feasibility of vehicle control minimally means that nonholonomic constraints are integrated, but constraints are usually stronger. For example, a control component may be designed for *slow* lane changes only. In this case, the decision must only propose slow lane change trajectories. **Constraints for the integrity of perception** are usually even stronger than constraints on control. As an example, with state-of-the-art cameras fast changes in vehicle orientation leads to a loss of lane tracking.

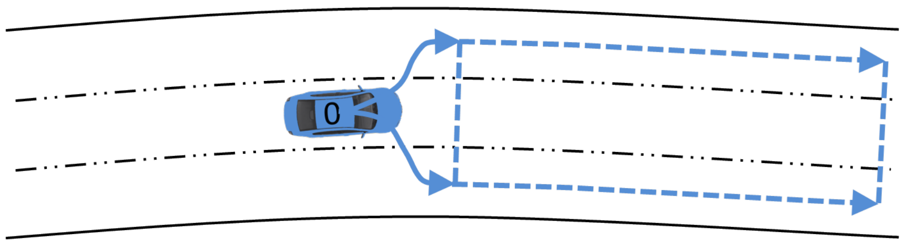


Figure 2.14: Rule 14 (Decision feasibility): trajectories must assure perception and control integrity. As an illustration, four extreme trajectories (dashed lines) indicate boundaries for trajectories calculated by the decision component

Rule 15 (Control accuracy) *The control component follows the subject trajectory with a **bounded error**. The accuracy of control is such that a **lane change** is performed within a certain distance and that the vehicle can be kept **within the target lane**.*

In literature, control error is sometimes modeled as probability distribution (e.g. Gaussian) which parameters vary with subject speed [HS11]. In contrast, Rule 15, stipulates that, while the control error can change with subject dynamics, it should always be bounded. With a non-bounded control error safety during highly or fully automated driving cannot be guaranteed. Figure 2.15 illustrates Rule 15. The decision component allows a control error that corresponds to the lane width, as the figure suggests.

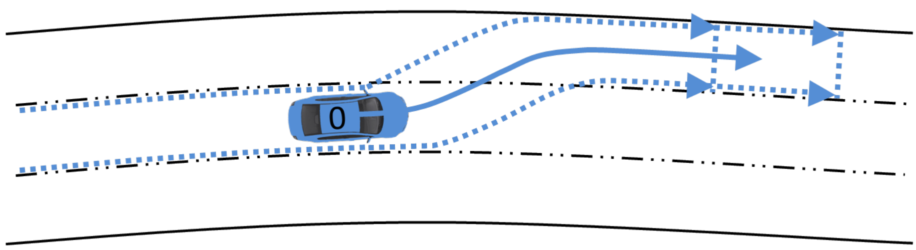


Figure 2.15: Rule 15 (Control accuracy): control must keep the entire vehicle in the lane during lane keeping. Control must complete lane changes within a predefined distance

Rule 16 (Number of elements and calculation time) *All information communicated between components has a bounded number of elements. The perception describes a maximum of **three lanes**; the left, subject and right lane. It limits objects in the environment to a maximum of **eight objects**; six of which are nearest objects ahead of and behind the subject in each of the three lanes, and two of which are objects on either side of the subject. The decision component describes a maximum of **four trajectories**; one trajectory in each lane, and one trajectory for an MRM.*

*The **calculation time** of perception, decision and control meets predefined bounds.*

Figure 2.16 and 2.17 illustrate Rule 16. The limitation of number of data elements and calculation time serves the integration on **automotive ECU**. In current ECUs, data elements have a predefined (i.e. fixed) size and the calculation time must fit in a predefined cycle time. Additionally, data transfer between ECUs (e.g. via CAN) has currently a predefined number of elements. The total calculation time for the automation loop of perception, decision, control and vehicle dynamics must also stay below a limit in order to allow a stable vehicle control.

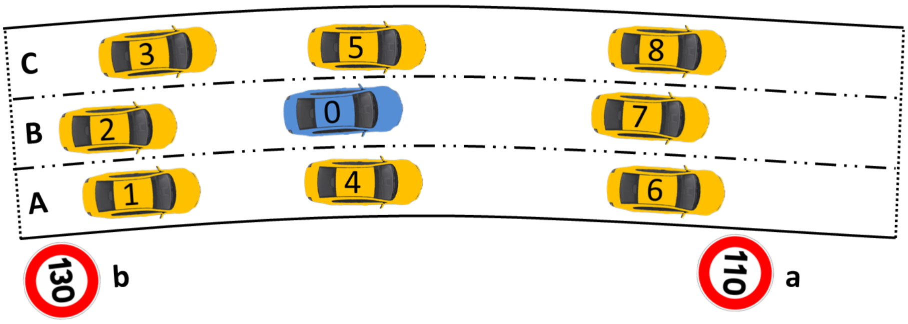


Figure 2.16: Rule 16 (Number of elements): the number of lanes detected by perception is limited to three. The number of objects detected by perception is limited to eight

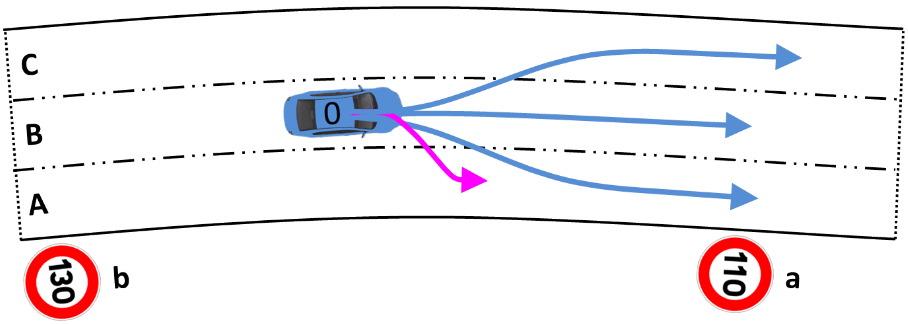


Figure 2.17: Rule 16 (Number of elements): the number of trajectories described by decision component is limited to four

The specification of system rules is an iterative process. Increases of perception and control performance leads to increases of decision capabilities, e.g. extending the perception zone leads to higher speeds. The integration of system rules by the decision component will be described in Chapter 3.

2.5 Subject coordinate system

This section discusses the coordinate system that is used by all components for the description of subject state, lanes, objects and trajectories. A first part motivates the use of a **subject coordinate system** (relative to the subject) rather than a **world coordinate system** (relative to a fixed point in the environment). The choice of a subject coordinate system implies the subject position estimation by the control component, which is presented in a second part.

2.5.1 Subject coordinate system vs. world coordinate system

The **world coordinate system** $X_W Y_W$ is indicated in Figure 2.18. It is a fixed frame of reference. The world coordinate system would be a logic choice if the subject based its movement on a highly accurate map (which can be updated by the infrastructure through Vehicle-to-Infrastructure (V2I) communication) and if objects communicated their positions through Vehicle-To-Vehicle (V2V) communication. A driving system based on an **accurate map, V2I and V2V would be technically easiest to achieve**: (a) on the perception side, it would avoid the need of proprioceptive or exteroceptive sensors (i.e. sensors on the subject that describe the environment without the need of external sensors), which is the biggest bottleneck for ADAS today, (b) the decision component could use classic trajectory planning algorithms that are based on a complete knowledge of the environment, in a fixed frame of reference, (c) the control component would also benefit from the availability of an absolute subject position at all times. But conditions for this are that (a) the world coordinate system is common to all traffic participants in the environment, (b) an accurate and reliable subject description can be given in this frame, (c) an accurate and reliable lane and object description can be given in this frame, (d) communication between traffic participants is guaranteed.

It seems difficult to meet these four conditions in the future. Positioning with commercial Global Positioning System (**GPS**) meets condition (a), but its poor positioning accuracy conflicts with conditions (b) and (c). Commercial GPS is subject to satellites ephemeris, propagation errors and noise. In best cases, an **accuracy** from five to ten meters can be met, which is not enough for driving applications. Furthermore, **delays** are difficult to handle and **reliability** is poor; the signal can be lost when buildings, trees or heavy clouds come between receiver (in the vehicle) and satellites. With differential Global Positioning System (DGPS) or Real Time Kinematic (RTK) navigation, centimetric accuracy can be reached, by the use of local, ground-based reference stations. The Virtual Reference Station (VRS) method extends the use of DGPS and RTK navigation to a complete reference station network. These and other methods can improve GPS positioning [GP11], but not completely overcome fundamental GPS issues on accuracy, delays and reliability of positioning of subjects and objects. For the description of lanes, GPS could in principle be linked to highly accurate **digital maps** containing additional attributes such as local speed limits. Here too, reliability seems an issue. The adoption of changes in environment structure (e.g. construction sites) or attributes (e.g. variable speed limits) would be difficult to guarantee, even with real-time updating services. Condition (d) implies that the infrastructure and all vehicles in the environment are equipped with compatible and reliable **communication** devices. This would be a challenge on highways, and would exclude a future extension to other environments (e.g. with pedestrians or cyclists), as was already mentioned in Section 2.2.

This work assumes that **accurate positioning, accurate maps, V2V communication and V2I communication will not always be available** for future driving systems. The legal safety system offers the possibility of fully automated driving with a perception **based on proprioceptive and exteroceptive sensors**, which delivers information in a **subject coordinate system** relative to the subject. The legal safety system however also takes into account **V2V and V2I communication**, if available. For example, early information on traffic congestion allows reducing speed earlier and braking more comfortably. All information by V2V and V2I communication, delivered in the world coordinate system, can be transferred to the subject coordinate system. This transformation is basically an Euclidean transformation, i.e. translation and rotation.

The **subject coordinate system** XYZ has its origin in the center of the subject rear

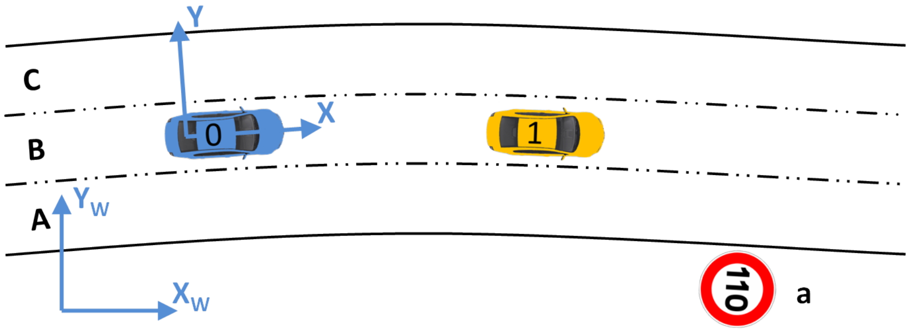


Figure 2.18: The subject coordinate system XY and world coordinate system $X_W Y_W$

wheel axle, X-axis to the front and the Y-axis to the left, as in Figure 2.18. The Z-axis (not illustrated on the figure) points upward. The subject coordinate system is in line with the ISO 8855 standard on road vehicle dynamics [ISO91]. In this work, the words *longitudinal* and *lateral* refer to the X-axis and Y-axis, respectively. The XY-plane takes the shape of the road surface, with Z perpendicular on it. This means that even on non-flat surfaces, lane descriptions have a zero Z-component. For legal safety, the variation along the Z-axis is not relevant; all objects with which the subject can collide (e.g. vehicles, but not bridges) are described by their projections on the XY-plane. As this work describes a two-dimensional problem, the term **subject coordinate system** XY (without Z) will be used. Reference to the Z-axis is only made for the description of values in the XY-plane, for example for the notation of angles and yaw rates.

In the subject coordinate system, speed and acceleration of subject and objects is given in **absolute** values. For example, still standing objects have zero speed. For the application of traffic rules, absolute values are more relevant than relative values (i.e. relative to the subject movement), in which a moving subject would have zero speed and still standing objects would have negative speed. **Exteroceptive** sensors, i.e. sensors on the subject that measure the environment around the subject without the support of external sensors, generally give information in relative values, e.g. relative speed of an object. This information is translated to the subject coordinate system by compensating for subject motion, i.e. adding subject speed. The subject motion is measured by **proprioceptive sensors**, i.e. sensors on the subject that measure the subject state without the support of external sensors.

Table 2.2 gives a comparison of the world coordinate system $X_W Y_W$ and subject coordinate system XY. Other coordinate systems exist, but do not give advantages with respect to the ones discussed. The **lane coordinate system** UW used for trajectory calculations in the decision component has been added in the overview, it will be presented in Chapter 3. The **speed profile system** TV describes the speed profile on subject trajectories.

2.5.2 Subject position estimation in the control component

At the start of a new calculation cycle, the subject coordinate system XY takes the position and orientation of the subject. During the complete system calculation cycle, the subject coordinate system XY does not change. This means that **subject coordinate system changes with discrete steps, while the subject vehicle itself moves continuously**. In XY, the subject has zero position and orientation at the beginning of the calculation cycle, but not during the complete calculation cycle (except for a still standing subject). Figure 2.19 illustrates this. At

Name	Reference frame	Coordinate system	Use
World coordinate system $X_W Y_W$	Fixed position and orientation	Cartesian	-
Subject coordinate system XY	Position and orientation of subject at start perception cycle	Cartesian	System
Lane coordinate system UW	Position of subject, orientation of lane at start perception cycle	Curvilinear	Decision
Speed profile system TV	Time at start perception cycle	NA	System, decision

Table 2.2: Description of world coordinate system $X_W Y_W$, subject coordinate system XY, lane coordinate system UW and speed profile system TV

$t = T$, when a new calculation cycle begins and XY corresponds to the subject position and orientation. During this calculation cycle, at $t = T'$, subject and object vehicle move, but XY remains on its position, till the start of a new calculation cycle, at $t = T''$, corresponding to a new subject coordinate system XY''.

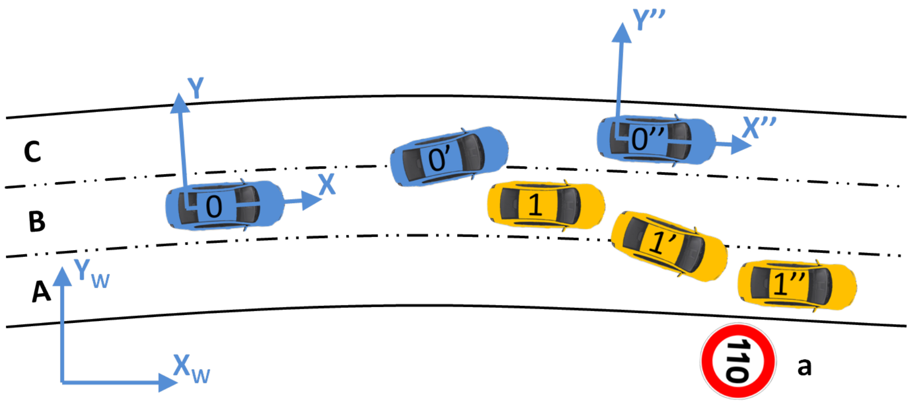


Figure 2.19: The evolution of subject coordinate system over time. At $t = T$ (subject *0*, object *1*) and $t = T'$ (subject *0'*, object *1'*) the subject coordinate system is XY. At $t = T''$ (subject *0''*, object *1''*) the subject coordinate system is XY''

Figure 2.20 explains how a legal safety system deals with this topic. It shows the flow of information through perception, decision and control components over several system calculation cycles, which are labeled from *1* to *7*. The start of the **system calculation cycle *1***, $t = T_1$, is defined as the moment that the perception component starts its calculation, i.e. when the environment signals enter the sensors. The environment description by perception, used during the complete system calculation cycle *1*, correspond to this moment $t = T_1$. A subject coordinate system XY_1 is defined, according to the position and orientation of the subject at $t = T_1$. The perception labels the environment information with the timestamp T_1 and communicates it to the decision component. The decision component calculates an optimal trajectory for the moment $t = T_1$, describes it in XY_1 and labels the trajectory description with a timestamp T_1 before communicating it to the control component. At a time $t = T_C$, the control has the task to keep the subject on a trajectory that is described in XY_1 for $t = T_1$. For this, it needs to know where the subject is located at $t = T_C$, with respect to XY_1. As mentioned before, this work assumes that no accurate world positioning is available for comparing positions and orientations at $t = T_1$ and $t = T_C$. As no exact measurement exists, the **control component estimates the subject position**. The estimation is performed by integrating measurements on subject movement from T_1 to T_C. The time T_1 is communicated from perception to decision to control, the time T_C is directly communicated to control by the clock that used for defining timestamp T_1. The difference between T_C and T_1 is called the *calculation time*; i.e. the *age* of the active calculation cycle. Note that subject position estimation is **only performed by the control component**. The perception and decision components calculate on the *old* environment model at $t = T_1$.

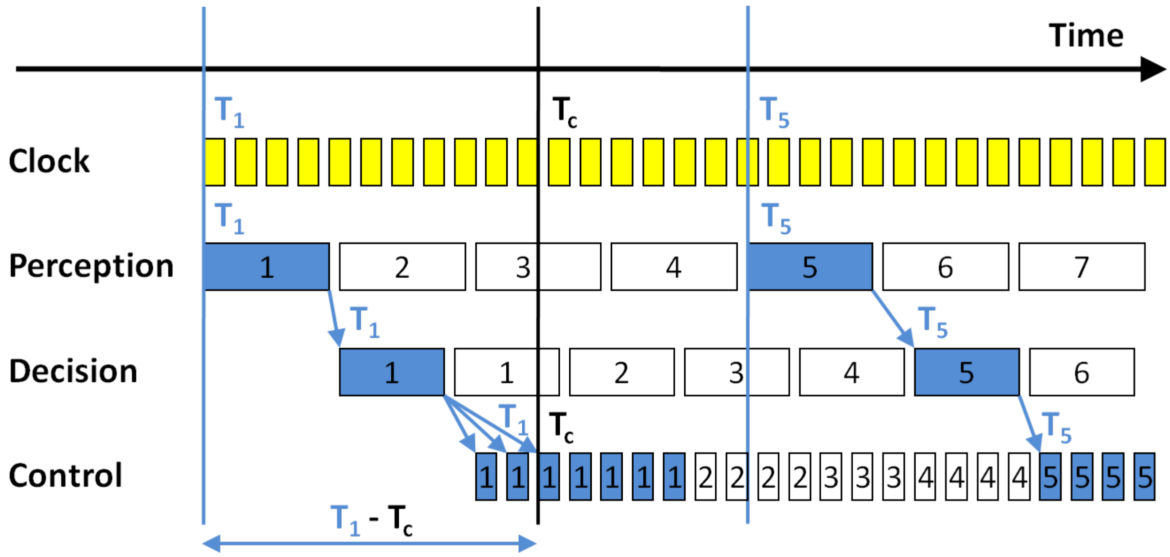


Figure 2.20: Visualization of several system calculation cycles, labeled from *1* to *7*. The subject position estimation over a time $T_1 - T_C$ is indicated. The timestamp T_1 is communicated from perception through decision to control. The timestamp T_C is communicated directly from clock to control

As Figure 2.20 suggests, system components are not necessarily synchronized. Their calculation cycles are usually independent, e.g. when components are implemented on different automotive ECUs. This causes additional **communication time**, as one component may have started, just before the arrival of new information. This situation is shown for the decision component in calculation cycle *1*. The maximum communication time caused by this phenomenon corresponds to the component calculation time; reducing component calculation times reduces communication times. Control performs estimation of the subject with respect to $t = T_1$ until it receives a trajectory based on a new environment description by the perception. This is when a new timestamp T_2 is communicated from perception to decision to control, which indicates a switch from system calculation cycle *1* to *2* and from subject coordinate system XY_1 to XY_2.

For facilitating the subject position estimation, system calculation time must be kept as small as possible. Communication delays between components can be reduced by integrating them on the smallest number of hardware modules as practically possible. Ideally, the perception, decision and control component are implemented on a single hardware module, which synchronizes component calculations. This practically eliminates communication times. **Minimizing system calculation time** allows minimizing safety margins for control errors and worst-case object behavior during system reaction time. A perception and decision calculation time of $50\,ms$, control calculation time of $10\,ms$ and total system calculation time of $200\,ms$ are examples of practical values. At highway speed of $40\,m/s$ the subject has traveled $8\,m$ during one system calculation cycle of $200\,ms$. Figure 2.19 has been exaggerated for clarity, subject and objects do not perform a complete lane change during such system calculation time.

The **timestamp** T used for the subject position estimation can usually not correspond exactly to the beginning of the sensor measurement, according to its definition presented above. It is often approximated as the beginning of the fusion of different sensor measurements within the perception component. This is due to the fact that state-of-the-art sensors usually do not deliver a timestamp, or at least not a timestamp according to a common system clock. Additionally, different sensors (e.g. odometer, camera, radar) usually operate asynchronously, i.e. the subject or environment data that they deliver correspond to different moments. In principle, the perception component could compensate for these differences by taking the timestamp of the sensor with oldest information as a basis, and estimating the information of other sensors for that timestamp, through estimations. In practice, thanks to the small sensor calculation times, differences are small and are covered by the safety margins that are integrated in the decision component.

In principle, the common **clock**, can be an *additional component*, which dictates the time to the perception and control components. The clock needs a high frequency, to allow precise timing. A more practical solution consists in using the **subject sensor** as clock, as it is part of perception and also delivers information for the subject position estimation to control. This has been indicated with the dotted line on the system architecture in Figure 2.12. An alternative, even simpler solution is to integrate the clock *implicitly*, i.e. the control component does not receive any timestamp information, but estimates the calculation time since timestamp T. On the arrival of a new timestamp, the control sets the clock at the value that corresponds to the average perception-to-control time, and increases the time at each control calculation cycle. This technique is accurate if system calculation time is not subject to large variations.

For the **subject position estimation** different alternatives exist. A trivial solution is not to perform any subject position estimation; i.e. *neglecting* the subject displacement, assuming that the subject stays on the origin of the coordinate system XY. This can be done in practice if the component calculation times are small, during **normal functioning of the system**, e.g. in the example above, $200\,ms$ with maximum displacement of $8\,m$ at highway speeds. On the LIVIC, HAVEit and ABV demonstrators, which are presented in Chapter 4, subject displacement is currently indeed neglected. Neglecting the subject position estimation does however not work when the perception or decision component fails. In the case of **system failure**, a Minimum Risk Maneuver (MRM) is performed over longer times, until the human driver takes over control, according to Rule 12. The estimation of subject position during the MRM must be accurate enough to *blindly* keep the vehicle in the lane till standstill; e.g. during $8\,s$ if the subject speed is $40\,m/s$ and the average deceleration $-5\,m/s^2$.

The subject position estimation can be based on proprioceptive or exteroceptive sensors, in combination with a vehicle model [Gil92] and the Kalman filter [Kal60] or one of its derivatives. The **reliability** of components involved in the subject position estimation, i.e. **subject sensor** (for clock and information on subject dynamics) and **control component**, is critical for safety during an MRM. Subject position estimation with proprioceptive sensors, e.g. based on subject speed and yaw rate [SRW08], is more robust than with exteroceptive sensors, as proprioceptive sensors do not depend on environment conditions.

2.6 Perception requirements by legal safety

Sections 2.2 to 2.5 discussed legal safety design on system level. Following sections and next chapter discuss design on component level. Section 2.6 discusses the perception component of the legal safety system. Perception delivers a description of **subject**, **lanes** and **objects** to the decision component. It also delivers the subject description to the control component, as has been discussed in Section 2.5.

Section 2.6 presents the *requirements* on perception according to traffic rules, human rules and system rules. The actual *design* of the perception component is not discussed. Only, some state-of-the-art technological implementations are referred to as examples. These examples solely intent to give a rough estimate of the distance of state-of-the-art technology with respect to legal safety requirements, they do not intent to prescribe the use of certain sensors or perception algorithms.

2.6.1 Subject perception

The description of the subject vehicle state is essential for decision and control components. It is also crucial lane and object perception. For example, lane tracking can be facilitated, with the knowledge of subject vehicle dynamics. Another example is subject motion compensation in object description, in order to describe object speed in the subject coordinate system XY.

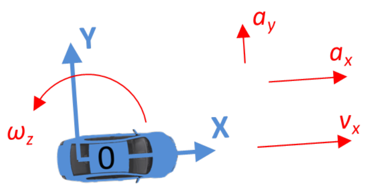


Figure 2.21: Subject perception (description in Table 2.3)

Table 2.3 presents the variables required from subject perception. The **position and orientation** of the subject are not required. As was described in Section 2.5, the subject is in the origin of the subject coordinate system XY at the moment of perception measurements. The subject position and orientation described by perception are zero. The control component performs the estimation of the subject position in XY on its own, without the need of additional position information by the perception component, as was discussed in Section 2.5.

The knowledge of vehicle **speed** is essential. Only the *magnitude* of the velocity vector (i.e. the vehicle *speed*) is assumed to be known. The vehicle *slip angle* (i.e. angle between the velocity vector and the longitudinal axis X [Gil92]) can be measured with optical sensors [Cor12], but their price is considered high for medium term series production. The slip angle could also be estimated based on variables that are easier to measure, e.g. speed and yaw rate. However, the constraints on subject trajectories in order to keep the integrity of perception and control (Rule 14), only allow moderate lateral dynamics. Under these conditions, the existence of a slip angle on highways can be neglected. The longitudinal component of the velocity and vehicle speed are considered equal, variable v_x in Figure 2.21 and Table 2.3.

The human driver uses the human sense for **acceleration and yaw rate** for driving. The driving system senses these values through a simple Inertial Measurement Unit (IMU), which integrates accelerometers and gyrometers. Three acceleration and yaw rate values are considered relevant for the application (on a total of 6 IMU values: acceleration and yaw rate in the three axes X, Y and Z); the acceleration a_x in X, a_y in Y and the yaw rate ω_z over Z . Acceleration and yaw rate are important for subject position estimation by control (Section 2.5). This is especially needed during system failure, when control only relies on subject perception in order to bring the vehicle to a standstill with an Minimum Risk Maneuver (MRM).

Rule 13 indicates that the **error on subject state perception** must be bounded. An estimation of the error is not explicitly communicated in the subject description. It is assumed to be constant, and known by the decision component.

Variable	Description	Sensor (example)
v_x	Speed	Speedometer
a_x	Acceleration in X	IMU
a_y	Acceleration in Y	IMU
ω_z	Yaw rate over Z	IMU

Table 2.3: Subject description (illustration in Figure 2.21)

As Table 2.3 suggests, the subject description can be found with **only proprioceptive sensors**. High accuracy and reliability are important, as subject perception is an essential part of the safety chain during system failure, together with the control. Sensors for this subject description are already on market at low cost.

2.6.2 Lane perception

Perception zone

The organization of the environment in *lanes* forms the basis for the interaction between traffic participants on highways. Traffic rules (Rules 5, 6, 7) make reference to the lane of the subject, and to the lane to its right and to its left. These three lanes must be described by perception. The description of additional lanes is not needed. In this work, the **right lane, subject lane and left lane** are labeled A, B and C respectively, as in Figure 2.22. The position of the origin of the subject coordinate system XY, with respect to the lane markings is used for the definition of the subject lane. For example, during a lane change to the left, the left lane B becomes the subject lane A when the origin of XY crosses the lane marking that separates both lanes.

Lanes are not necessarily separated by lane markings, according to the definitions in the Vienna Convention [Uni68]. However, Chapter 1 limits the application zone of the legal safety system to highways with lanes that are separated by lane markings. This excludes zones around toll areas and road construction sites and situations where lane markings are not longer detectable (e.g. in extreme weather conditions). In future work on environments without lane markings, lanes could be defined based on other road features (e.g. road barriers and obstacles) or virtual lanes could be created. In addition to correctly describing the **subject, right and left lane** structure and attributes (e.g. speed limits), perception should also detect **where lane markings end**, as this marks the end of the application zone of the system.

Sensors

Research on lane detection and tracking has accelerated in recent years. Lane perception could come from an accurate **map** [WCW$^+$06], Vehicle-To-Infrastructure (**V2I**) communication [SAF10, VGGM10] or Vehicle-To-Vehicle (**V2V**) communication [DLCH07], combined with accurate subject vehicle positioning (e.g. DGPS). In this case, map data is transformed from a

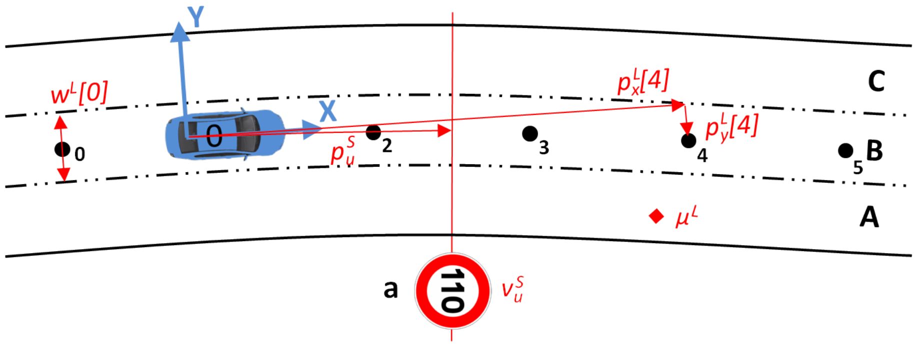


Figure 2.22: Lane perception (description in Table 2.4)

world coordinate system to the subject coordinate system XY. However, as is discussed in Sections 2.2 and 2.5, legal safety assumes that precise map information is not always available. This means that the system must perform lane perception with the use of exteroceptive sensors only.

A variety of exteroceptive sensors can be used for lane perception. LIght Detection And Ranging (**LIDAR**) bases lane perception on the detection of road borders and analysis of reflection energy (white lane markings reflect more energy than the road) [KA00, SDS01]. With **radar**, road borders can be detected, but not lane markings [PAFL04]. **Cameras** are probably best suited (and least expensive) for a complete lane description. Extensive research has been on vision-based camera [CAC02], and infrared camera [FW04], either in monovision or stereovision configuration [BLA$^+$08, SPFF10, DN11]. Vision-based perception of the subject lane is already available on market as part of Lane Departure Warning System (LDWS) and Lane Keeping Assist System (LKAS) [Mob12]. Research now extends perception of right and left lanes [IVGA05, LDLC06, PGT$^+$11, PRGG12].

The lane perception on LIVIC, HAVEit and ABV demonstrators will be presented in Chapter 4. It is mostly based on cameras. Lane attributes that cannot yet be obtained from state-of-the-art cameras (e.g. the end of a lane), are acquired from map.

Lane description

Table 2.4 presents the lane description needed in order to respect traffic rules, human rules and system rules. The variables are illustrated in Figures 2.22 and 2.23. The need for a **geometrical description** of the lanes, both ahead of and behind the subject, follows from traffic rules (Rules 5, 6, 7), human rules (Rule 11) and system rules (Rule 13). State-of-the-art perception usually models lanes as polynomials of second or third degree in XY. These polynomials respectively approximate circles or clothoids (i.e. a curve whose curvature changes linearly with curve length), which is usually accurate enough for highways, where curvature changes slowly. It is also a compact description, as only the coefficients of the polynomial, and X-range (i.e. perception zone) to which the polynomial applies, need to be communicated between system components. However, the real shape of the road generally does not follow a polynomial. Rather, it is designed as a line-clothoid-circle-clothoid-line sequence. In addition, polynomials cannot describe curves of 90° and more, which will appear when the application zone is enlarged to other environments. A more general description than a polynomial description exists of a list of points $p^L_x[i]$ and $p^L_y[i]$ in XY, which describe the center of the lane and the corresponding lane widths $w^L_[i]$, as in

Table 2.4. Vectors $p_x^L[i]$, $p_y^L[i]$ and $w_[^L i]$ have a fixed number of elements. The fixed number of elements is not explicitly communicated in the lane description, but is known by other system components. In a trade-off between description accuracy and data size, a list of 50 points is practical for describing the perception zone on highway environments, e.g. $50\,m$ behind and $150\,m$ ahead of the subject, with $4\,m$ spacing between lane center points. Vectors $p_x^L[i]$, $p_y^L[i]$ and $w_[^L i]$ define the **size of the perception zone**, i.e. the zone where lanes and objects can accurately be described. It is explicitly referred to in Rules 3 and 13. In general, vision is used for lane perception, which means that the size of the perception zone changes with day/night and weather conditions, e.g. fog [GCHA11].

In addition to a complete description of lane geometry with $p_x^L[i]$, $p_y^L[i]$ and $w_[^L i]$, a reduced lane geometry description on the next **curve** is given. The variable p_u^L in Table 2.4 indicates the beginning of the first clothoid of the line-clothoid-circle-clothoid-line model of the next curve. The subscript u indicates a curvilinear distance along the center of the subject lane. (This corresponds to the U coordinate of the lane coordinate system UW presented in Chapter 3.) If the subject is already in a curve, p_u^L takes the value -1.0. The variable ρ^L takes the maximum curvature of the curve, i.e. the curvature of the circle segment. The estimation of distance to the next curve and its curvature is subject to uncertainty. According to Rule 13, this uncertainty must be bounded. The variables p_u^L and ρ^L are taken as worst-case values according to this bounded uncertainty; p_u^L takes the minimum value and ρ^L the maximum value. The estimation of p_u^L and ρ^L far ahead of strong curves is still beyond reach of state-of-the-art perception algorithms. For the highways, curves generally vary slowly. The perception of the local curvature (i.e. $p_u^L = -1.0$) can be delivered by state-of-the-art camera and generally sufficient for keeping a safe vehicle speed at all times.

The algorithms for vision-based lane geometry description can also be used for detecting the **type of right and left lane markings**, for Rule 6. The variables p_{uR}^M and p_{uL}^M indicate the position where the right and left lane marking become *continuous*. If the lane marking is *dashed* in the complete perception zone, these variables take the value -1.0.

Rule 3 demands the adaptation to **speed limits**, which implies the detection of the corresponding traffic signs. Speed limit sign detection is commercially available as part of Intelligent Speed Adaptation (ISA) systems [Mob12]. As table 2.4 indicates, not only the value of a new speed limit v_u^S, but also the distance to it, p_u^S, must be known. The position of the traffic sign can be given in x and y coordinate. Alternatively, it is described with a single value; the curvilinear distance p_u^S, illustrated in Figure 2.22. Information on traffic signs is given for each lane, as some traffic signs do not apply to all lanes, e.g. speed limits that only apply to exit ramps [PNB11]. The recognition of other types of traffic signs is now being investigated [BZR+05, BFT+10, GYPT+11]. For example, the detection of signs that **prohibit overtaking** is needed for Rule 6. This traffic sign information is integrated in the variable p_{uL}^M. If overtaking is prohibited, a continuous lane marking p_{uL}^M is reported.

The lane perception also detects **when a lane ends**, at a curvilinear distance p_u^Q, illustrated in Figure 2.23. In this work, the end of a lane is called a **stop** and is treated as a still standing object, as the figure suggests. If another lane is available, a lane change is made, e.g. from entrance to highway. If all lanes end, the subject comes to a standstill, unless the human driver takes over. Detecting the end of a lane requires the recognition of traffic lights for lane closures, e.g. at the entrance of tunnels. Rule 12 demands the detection of the **end of the application zone**. This requires the detection of the traffic sign that indicate the end of the highway, and beginning of construction sites and toll sites. The end of the application zone is modeled as the end of the three lanes A, B and C, at a same curvilinear distance p_u^Q.

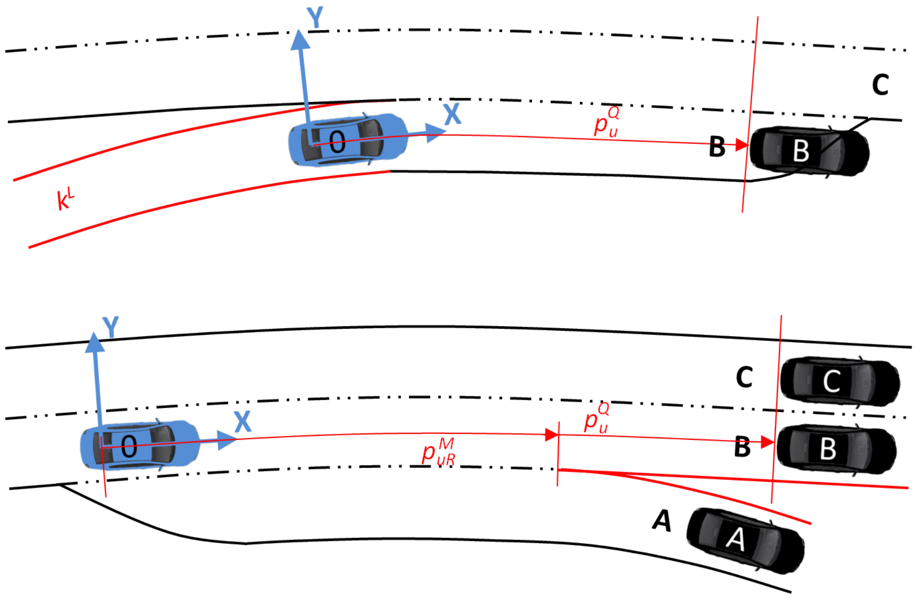


Figure 2.23: Lane perception (description in Table 2.4). Begin of highway (e.g. entrance ramp) and end of highway (e.g. exit ramp)

Traffic rules mention various **lane types**, which perception should distinguish, by the variable k^L in Table 2.4. Rule 7 differentiates between normal lanes, emergency lanes, entrance ramps and exit ramps. The end of the entrance ramp, is indicated with p_u^Q, as the end of a normal lane. A reduction of the number of lanes, whether indicated with arrows in the lane, traffic signs, or not, must be treated in the same way as entrance ramps.

Rule 3 demands adapting vehicle speed to **road friction**, variable μ^L. ESC sensors or other proprioceptive sensors could give a quite accurate road friction estimation [RPLG06, CC10], but could not predict a drop of road friction ahead of the vehicle, e.g. oil on the road, ice, snow and aquaplaning. Like the human driver, the system could estimate friction in front with the lane perception camera [Hol06b] or thermometer. As all perception information, the uncertainty on the road friction values must be bounded by Rule 13. In this case, μ^L takes the value of the lower bound.

Fully automated driving implies that the system detects when lighting is needed, for respecting Rule 8 and for facilitating lane perception. Intelligent **lighting** systems, which adapt lighting intensity and direction (e.g. to match lane curvature) are already on market. **Rain** detection for automatically activation of windshield wipers, is available on new vehicles. Rain drops on the windshield can also directly be detected by the lane perception cameras [CA11].

As mentioned above, Rule 13 stipulates that the **error on all variables** of the lane perception must be bounded. The accuracy of lane perception usually varies with road and weather conditions. The lane perception accuracy is represented in the lane description of Table 2.4. The error on the detection of lane markings is integrated in the **lane width** $w^L[i]$. With poor detection, the variables of the vector $w^L[i]$ decrease, in a way that, if the vehicle is kept within the *perceived lane*, it remains in the *real lane*. Rule 13 indicates that bounds on this error must be such that lane keeping remains possible, i.e. $w^L[i]$ must not be lower than the subject vehicle width. The better the lane marking positions can be estimated, the closer $w^L[i]$ comes to the real lane width, the more error exists for lateral control has and the better object lane assignment becomes. Concerning perception accuracy on other variables (e.g. p_u^L, ρ^L, p_u^Q, v_u^S), **worst-case values** are given, as was stated above.

Variable	Description	Sensor (example)
$p_x^L[i]$	Position vector in X	Camera
$p_y^L[i]$	Position vector in Y	Camera
$w^L[i]$	Width vector	Camera
p_u^L	Position of beginning of next curve	Camera
ρ^L	Maximum curvature of next curve	Camera
p_u^Q	Position of a stop, e.g. end of lane or application zone (-1.0 if not applicable)	Camera
p_u^S	Position of new speed limit (-1.0 if not applicable)	Camera
v_u^S	Value of new speed limit	Camera
p_{uR}^M	Position of begin of *continuous* right lane marking (-1.0 if not applicable)	Camera
p_{uL}^M	Position of begin of *continuous* left lane marking (-1.0 if not applicable)	Camera
k^L	Type: normal lane, emergency lane, entrance ramp or exit ramp	Camera
μ^L	Estimation of road friction	ESC, camera

Table 2.4: Lane description (illustration in Figures 2.22 and 2.23)

According to legal safety, perception should rely on **exteroceptive sensors** only. For lane perception, **cameras** seem most appropriate. Additionally, information from map or communication can be taken into account, if available.

A complete and robust lane perception is one of the challenges for the legal safety system. Many requirements presented in this section, cannot yet be met with the state-of-the-art technology. However, research on these topic is intensifying. Reliability and accuracy increase under the impulse of the commercialization of first lane detection systems for ADAS, e.g. LDWS and LKAS. The estimation is that a complete description of subject, right and left lane according to Table 2.4 can be achievable in **medium term**.

2.6.3 Object perception

Perception zone

Object perception is the third element of perception, after subject and lane perception. It needs to deliver all information needed to predict legal and non-legal object behavior according to Rules 2, 3, 4, 6, 7 and 9. The rules refer to **objects in the subject lane, right lane and left lane**, both ahead of and behind the subject vehicle. According to Rule 16, as illustrated in Figure 2.16, the objects in these lanes are clustered to a maximum of eight. **Objects on the second lane to the right of the subject and on the second lane to the left** that indicate a lane change towards the left and the right respectively, are in conflict with subject lane changes. When such object is detected, it can be modeled as an object on the side of the subject (i.e. object *4* or *5*). The presence of such object avoids a subject lane change to that side.

Object perception only gives **2D descriptions** of objects with which the subject can collide, i.e. objects between the road surface and the height of the subject vehicle plus a safety margin. Internally, object perception works with 3D descriptions of objects in order to be able to differentiate between vehicles and bridges that cross the highway.

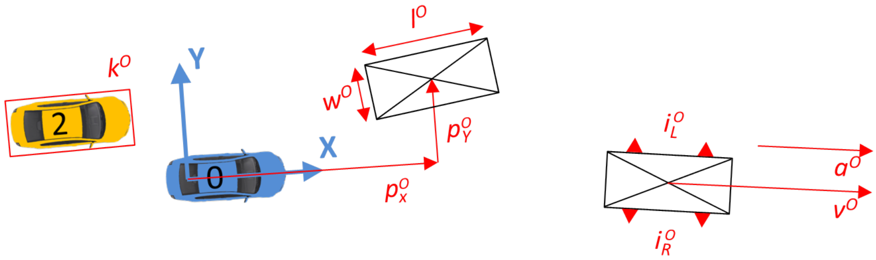


Figure 2.24: Object perception (description in Table 2.5)

Sensors

For object perception, a variety of sensors can be used. As for lane perception, the driving system can perform object perception by imitating human vision. The perception of *distance* is possible with a single **camera** that is moving with respect to the object [FJW09] or with stereovision [PF10, GZS11]. Various methods are inspired on human vision for estimating the object *speed*; e.g. detecting changes in object shape, optical flow and 3D-warping [CMA$^+$00, EBF11, KKFG11, MSF11]. The driving system has access to ranges in the electromagnetic spectrum, which are out of reach of the human driver, e.g. far-infrared (**FIR**) camera [SSRK11]. Another imitation of the human senses is the detection of the presence of objects with **acoustic** sensors [ABY$^+$11].

Sensors that are based on vision or audition are **passive sensors**. They detect naturally reflected or radiated signals. The main drawback of passive sensors is that they are easily influenced by ambient phenomena; e.g. illumination, weather and background noise. **Active sensors** emit electromagnetic energy and detect objects from the energy they reflect. This gives driving systems a sense that human beings do not have. Active sensors for object perception in automotive include **LIDAR** [MON09, MS11], Time-Of-Flight (**TOF**) camera [KKFG11], **sonar** [KOK$^+$05], near-infrared (**NIR**) camera [LRH10] and **radar** [GSDB07]. The advantage of active sensors is measurements do not depend on day/night or weather conditions. Some of the important variables, such as distance and speed, follow directly from the active measurement. This leads to higher accuracy and less computations compared to vision. The drawback of active sensors is the lack of identification of object attributes, e.g. the indicator status, which is essential for Rule 6.

Apart from information from exteroceptive sensors described above, the legal safety system integrates information from Vehicle-to-Vehicle (**V2V**) and Vehicle-to-Infrastructure (**V2I**) communication in the object description. However, as discussed in Section 2.2, safety does not depend on the availability of V2V or V2I communication.

Object perception based on radar, camera and LIDAR on LIVIC, HAVEit and ABV demonstrators will be presented in Chapter 4.

Object description

Table 2.5 lists the object variables required for applying traffic rules, human rules and system rules. **Radar** for *longitudinal variables* and **camera** for *lateral variables*, could form a winning combination for object perception in the future [ABC07, RSW08, SLSD09, She11]. They are relatively inexpensive and are continuously improving in performance and robustness. Some vehicles already integrate radar and camera, as a part of ACC and LKAS. For measurements in the **longitudinal direction** such as object position p_x^O, speed v^O and acceleration a^O, for Rules 3 and 4, radar outperforms vision [MJS11]. The human driver, who is considered to have strong vision, can estimate object positions and speeds quite well, but has a poor estimate of object **acceleration or deceleration**. The human driver bases detection of object deceleration mainly on object brake signals (which are compulsory on all vehicles by Rule 4). Brake signals do however not allow an accurate estimation. State-of-the-art radar delivers accurate object position, speed and acceleration, and also detects vehicles that do not have appropriate lighting, despite Rule 8. The variable v^O is the absolute value of the object velocity vector, in the longitudinal direction of the object. The variable a^O is the derivative of v^O, i.e. the acceleration in the longitudinal direction of the object. The lateral object acceleration is not strictly needed for decision component calculations.

Camera has difficulties to detect variables in the longitudinal direction, but performs better than radar for variables in the lateral direction [MJS11]. The object **position in the lane** is essential for the application of traffic rules. It defines the *relation* between object and subject, according to Rules 3, 6, 7 and 13. The object position in the lane is also used for defensive driving, e.g. the decision component predicts a non-legal lane change, when an object approaches the lane marking without activating indicators. Vehicle sensors have different measurement errors and are usually not synchronous, i.e. their measurements do not correspond to the same moment, as was mentioned in Section 2.5. Variables that depend on the combination of measurements are most accurately estimated when these measurements are performed with a single sensor. This is the case for the estimation of object position in the lane, which depends on the object description (p_y^O in Table 2.5) and lane description ($p_y^O[i]$ in Table 2.4). Accuracy of object lane assignment is considerably higher with a camera which obtains lane and object positions from a same image, than with the combination of camera for lane perception and radar for object perception.

The variables length l^O and width w^O give the objects **dimensions**. They also integrate the uncertainty on object position. In a worst case, when uncertainty on object lateral position is very poor, the width of an object covers the three lanes A, B and C. This excludes overtaking the object. The values of l^O and w^O are not necessarily *both* required for each object. For objects ahead of and behind (i.e. objects *1*, *2*, *3*, *6*, *7* and *8* in Figure 2.16) only the width is relevant. For objects on the side (i.e. objects *4*, *5* in Figure 2.16), only the length is relevant. This is explained in Chapter 3. For all eight objects, the value that is required (i.e. either l^O or w^O) is the value that is most *visible* from the subject perspective. Note that an estimation of the object **orientation** is not strictly needed. The orientation of the object is believed to be defined by the lane structure, both when the object keeps lanes or changes lanes. An accurate orientation measurement could improve defensive driving in some cases of non-legal object behavior, e.g. it helps predicting when an object plans to change lanes without activating indicators.

Unlike radars, cameras allow the detection of object **indicator** status i_R^O and i_L^O [FSF10]. This is crucial for the prediction of object trajectories and for the priority management between subject and object, according to Rule 6. As a minimum requirement, the indicator status must be available for objects in the subject lane. The knowledge of indicator status of objects to the right and left is not strictly needed, but helps defensive driving.

With radar, a rough object type **classification** is possible through analysis of the energy reflection. For example, this can help differentiating between static objects and bridges [DKS+11]. With camera, a more precise object type classification k^O can be obtained [CEV11]. This is especially needed for Rules 9 and 10, which require the detection of (a) priority vehicles and (b) vehicles of officials. In presence of these two types of authorized vehicles, different traffic rules apply. Their presence is treated as an end of the application zone.

As for the lane description, the object description in Table 2.5 integrates perception uncertainty. By Rule 13, this **uncertainty must be bounded** in order to allow fully automated driving. Similarly to human drivers, the driving system must not be able to *exactly* describe object variables, but must be able to deliver minimum and maximum bounds. Errors on the object position and size are integrated in l^O and w^O. For the other variables, worst-case values are given. For example, values of v^O and a^O correspond to minimum values for objects ahead of the subject and maximum values for objects behind. When the status of right and left indicators i_R^O or i_L^O cannot be determined, it is indicated as activated, which rules out overtaking the object.

Variable	Description	Sensor (example)
p_x^O	Position in X	Radar
p_y^O	Position in Y	Camera
l^O	Length	Radar
w^O	Width	Camera
v^O	Speed	Radar
a^O	Acceleration (based on v)	Radar
i_R^O	State of right indicators: activated or deactivated	Camera
i_L^O	State of left indicators: activated or deactivated	Camera
k^O	Type: normal vehicle, priority vehicle, official vehicle	Camera

Table 2.5: Object description (illustration in Figure 2.24)

As with lane perception, an object perception on highways according to legal safety, Table 2.5, is not yet available with state-of-the-art technology. Research on object perception is accelerating under impulse of first ADAS on market. If research efforts are directed towards highly and fully automated driving, safety perception could be expected in **medium term**.

The object perception accuracy in Rule 13 must not necessarily meet same standards in each of the **eight object zones** in Figure 2.16. For example, the knowledge of position, speed and acceleration of objects **on the side and behind** the subject is not as crucial as for objects in **front of the subject**. The mere detection of the presence (without information on position, speed and acceleration) of objects on the side and behind would already allows fully automated driving. When the presence of an object on the side or behind is detected, the system can deactivate lane changes, even when lane changes would be possible, if object position and speed were known, e.g. when the object is at sufficient distance. This type of system rules reduces the solution space of subject trajectories, but allows legal safety with simpler, less expensive equipment. However, in this work, the perception accuracy in the eight object zones will be considered identical.

2.6.4 Complete environment perception

Each of the perception subcomponents generally needs multiple sensors. **Complementary sensors** describe different parts of the perception zone in Rule 13, e.g. ahead of and behind the subject. **Cooperative and competitive sensors** share a part of the perception zone. The combination of data of different sensors, i.e. **sensor data fusion**, provides additional and/or more accurate information [HL01, TSL$^+$10, APKB11]. Requirements on subject, lane and object perception are presented separately in this work. This separation does not necessarily reflect the typical architecture of a perception component. Subject perception, lane perception and object perception can **collaborate** and benefit from each other's outputs. For example, lane perception helps focussing object perception on objects on the road and exclude objects off the road. Object perception can help reduce the zone of interest of lane perception algorithms.

The perception of subject s, lanes $l[j]$ and objects $o[j]$ are combined in complete description of the environment, as in Figure 2.16. Table 2.6 describes the **environment interactor** with subject, lane and object descriptions, sent from perception to decision component. The environment interactor is indicated on the system architecture in Figure 2.12. The variable t indicates the timestamp of the subject coordinate system XY, which was discussed in Section 2.5. According to Rule 16, the number of elements in the table of lanes and objects is fixed. As discussed above, the number of elements is 3 and 8 respectively. The variables n_l and n_o indicate how many elements in these tables are valid. For example, if two objects are detected, $n_o = 2$. In this case, $o[0]$ and $o[1]$ contain object information, other elements in the table $o[j]$ are not to take into account. For the subject, during normal functioning n_s is equal to 1. When no perception is possible, e.g. due to a sensor failure, the number of elements is -1. If this situation occurs, the system performs a Minimum Risk Maneuver (MRM), based on the last valid environment description.

Variable	Description
t	Timestamp
s	Subject description, Table 2.3 (Figure 2.21)
n_s	Number of valid elements in subject description: -1 or 1
$l[j]$	Lane description table, Table 2.4 (Figures 2.22 and 2.23)
n_l	Number of valid elements in lane description table: between -1 and 3
$o[j]$	Object description table, Table 2.5 (Figure 2.24)
n_o	Number of valid elements in object description table: between -1 and 8

Table 2.6: Environment interactor description. The interactor is indicated in the system architecture, Figure 2.12

The perception also sends an **estimation interactor** to control, described in Table 2.7. The estimation interactor is indicated with dotted lines in the system architecture in Figure 2.12. It contains the subject description s and a timestamp t. As described in Section 2.5, the control component compares timestamp t of the estimation interactor with timestamp t of the environment interactor, in order to estimate actual subject position in subject coordinate system XY.

Variable	Description
t	Timestamp
s	Subject description, Table 2.3 (Figure 2.21)
n_s	Number of valid subject descriptions: -1 or 1

Table 2.7: Estimation interactor description. The interactor is indicated in the system architecture, Figure 2.12

2.7 Control requirements by legal safety

This section specifies requirements on the control component, from a legal safety point of view (traffic rules, human rules, system rules). Some examples of technological implementations are referred to in order to give an estimation on how far legal safety control requirements are from state-of-the-art vehicle control.

According to Rule 1, a driver is always in control of the vehicle. In the application zone, the *driver* is either the human driver, driving system or a combination of both. In the application zone, the control component must be able to keep the vehicle on the **trajectory** delivered by decision component, with a bounded control error. For a natural feeling and for confidence, Rules 11 and 12 require that the human driver can always perform additional braking and change the vehicle trajectory by **overpowering** actions of the control component on the steering wheel. The control component must be able to handle these disturbances by the human driver.

Vehicle control is probably the area in driver assistance on which research is most advanced. The basic **control functionality in existing ADAS** can be extended for new driving system functionalities; e.g. speed and distance control for ACC forms a basis for longitudinal control of a legal safety system. Trajectories by the decision component generally keep well below limits on vehicle dynamics, in order to respect the integrity of control and perception, according to Rules 14. With state-of-the-art technology, limits of the perception component are usually reached earlier than limits of control, e.g. only slow lane changes are possible. In this case, vehicle dynamics can be assumed linear, which facilitates the task of control.

As indicated in the system architecture in Figure 2.12, the control component receives two interactors. The decision component provides the **trajectory interactor**, which is described in Table 2.9. The elements $r[j]$ in trajectory interactor contain the description of trajectories, which will be presented in this section. Similarly to the environment interactor (Table 2.6), the trajectory interactor contains a timestamp t and number of elements n_r, which indicates the elements in the trajectory table that should be taken into account. According to Rule 16, the decision component calculates four trajectories; one trajectory for each of three lanes and an MRM trajectory. Two trajectories are communicated to control: (a) a trajectory for normal system functioning, i.e. one of the three lane trajectories and (b) the MRM trajectory for system failure functioning. The control takes into account the automation mode, m. For example, it applies soft haptic feedback for driver assisted (DA) and semi-automated (SA) and harder actions on the steering wheel for highly automated (HA) and fully automated (FA). Perception delivers a second interactor to control, the **estimation interactor**, in Table 2.7. The use of the estimation interactor is explained in Section 2.5. It is needed for an Minimum Risk Maneuver (MRM) during system failure functioning, and also for normal system functioning if system calculation time is large.

Control components imitate the human driver, by separating control in a **longitudinal part and a lateral part**.

2.7.1 Longitudinal control

Rule 3 requires longitudinal control for **speed keeping**, **distance keeping** and, in the extreme case, **emergency braking**. Longitudinal control for Cruise Control (CC) and Adaptive Cruise Control (ACC) applications is based on a variety of control strategies, e.g. PID control [HGCV11], sliding mode control [NM07] and Lyapunov functions based control [EMGL09].

Table 2.8 presents the trajectory description. For longitudinal control, the **speed profile** specifies speed $v[i]$ in function of time $t[i]$. A speed profile is illustrated in Figure 2.25. The growth vector $g[i]$ specifies the longitudinal control error (in m/s) that is allowed on the speed profile, in correspondence to Rule 15. According to legal safety, highly and fully automated driving is only possible with **bounded control errors** (like bounded perception errors discussed in Section 2.6). Amongst others, this means that a minimum deceleration and acceleration capacity (considering road friction) must be guaranteed. More precise control algorithms allow using *thinner* speed profiles, i.e. smaller growth values. This increases the solution space of subject trajectories, which increases the optimality of trajectories found by the decision component.

In respect of Rule 16, the **number of elements** that describe the speed profile is limited. The speed profile description must be precise enough and time range of the speed profile must provide sufficient look-ahead information for control. The time range must be sufficient to describe a deceleration till standstill for the MRM trajectory. For highways, 50 elements and a description of 10 s are generally practical values.

A speed profile that is feasible for control necessarily starts at the **current subject speed**. It evolves to a **target speed**, with a certain **acceleration**, calculated by the decision component. The speed profile of the trajectory continuously adapts to the current subject speed. When no new trajectory is delivered, the control component estimates its position on the speed profile based on the estimation interactor, as was described in Section 2.5.

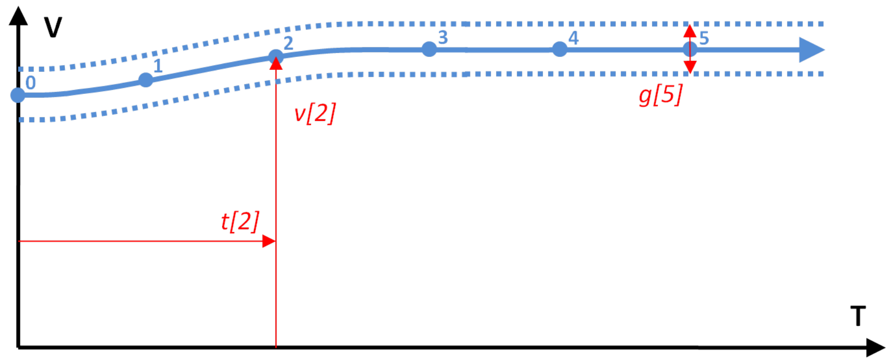


Figure 2.25: Trajectory description for longitudinal control (description in Table 2.8)

2.7.2 Lateral control

Rules 5, 6 and 7 require lateral control capable of **lane keeping** and **lane changing**. Currently, control development has mainly been focussing on lane keeping, e.g. for Lane Keeping Assist Systems (LKAS). Lane changing is not fundamentally different; a lane changing trajectory can be seen as a virtual lane that needs to be kept. Various types of lateral control are described in literature, e.g. PID-control [CNM04], fuzzy control [Van05, NGGdP08], H-infinity [RDM04, HLV+11] and backstepping [CNM+05, HGCV11].

Table 2.8 and Figure 2.26 give the **trajectory** description for lateral control. The trajectory is defined in the subject coordinate system XY, with position vectors $p_x[i]$ and $p_y[i]$. The requirement of control feasibility (Rule 14) implies that the trajectory starts on the **current subject position**; i.e. the origin of XY. The width vector $w[i]$ indicates the lateral control error that is allowed on the trajectory. The width vector $w[i]$ for lateral control has a similar role as the growth vector $g[i]$ for longitudinal control. Lateral **control error must be bounded** in order to allow highly or fully automated driving according to legal safety. Like the human driver, the driving system must not be able to keep the vehicle *exactly* on the subject trajectory, but must be able to keep it on a *limited* distance from the subject trajectory. A more precise lateral control allows using smaller width values $w[i]$. This leads to more optimal subject trajectories.

Most control algorithms analyze the difference between a current value and target value. For longitudinal control, the distance to target speed at each point of the speed profile is not explicitly given. It can be deduced from the speed profile as the distance from a point of the speed profile to a horizontal line through the last point of the speed profile. For lateral control, the target position cannot directly be deduced from vectors $p_x[i]$ and $p_y[i]$. It must be given explicitly. The target position of a trajectory is defined by the center of the target lane. As no lane information is communicated from perception to control, **target lane positions** $p_y^L[i]$ are integrated in the trajectory description, as is indicated in Table 2.8 and Figure 2.26.

Table 2.1 shows that no automation level is offered where the driving system offers **lateral control without longitudinal control**. This has been decided after human-system interaction studies but has also a technological reason. Lateral control stability is dependent of vehicle speed. Lateral control is usually designed to perform from zero speed until a certain maximum speed. When the human has longitudinal control, this speed can be exceeded. This is not the case if speed is controlled by the driving system. In contrast, the stability of longitudinal control is quite independent from lateral actions. During semi-automated driving, longitudinal control offered by the driving system is less influenced by lateral actions of the human driver.

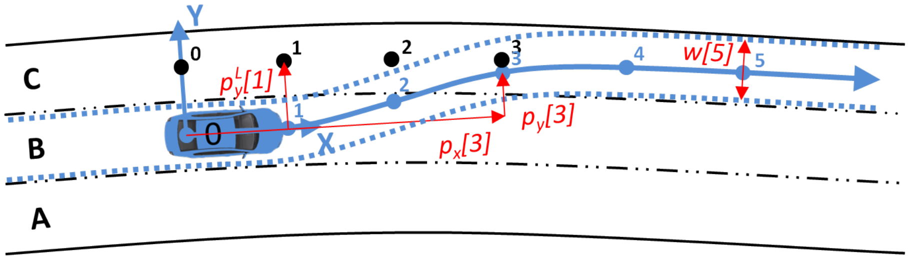


Figure 2.26: Trajectory description for lateral control (description in Table 2.8)

Variable	Description	Actuator (example)
$p_x[i]$	Position vector in X	Steering wheel
$p_y[i]$	Position vector in Y	Steering wheel
$w[i]$	Width vector, the maximum control error on $p_y[i]$	Steering wheel
$p_y^L[i]$	Position vector in Y, of the target lane	Steering wheel
$t[i]$	Time vector	Pedals
$v[i]$	Speed vector	Pedals
$g[i]$	Growth vector, the maximum control error on $v[i]$	Pedals

Table 2.8: Trajectory description (illustration in Figures 2.25 and 2.26)

2.8 HMI requirements by legal safety

System requirements for human-system interaction have been specified in human rules in Section 2.3. In this section, human rules are translated in HMI component **requirements**. The HMI interfaces decision component and human driver, as illustrated in the system architecture in

Variable	Description
t	Timestamp
$r[j]$	Trajectory description table, Table 2.8 (Figures 2.25 and 2.26)
n_r	Number of valid elements in trajectory description table: between -1 and 2
m^I	Automation mode accepted by system

Table 2.9: Trajectory interactor description. The interactor is indicated in the system architecture, Figure 2.12

Figure 2.12. This work gives a general description of the communication between decision component and human driver, and focusses on consequences for the decision component (Chapter 3). For an extensive discussion on actual HMI **design** and validation studies with human drivers, reference is made to the HAVEit project [FNG+10, FSS+11, HAV11f, HAV11g, HAV11h, HAV11k].

The human-machine interaction design of an everyday object, like the vehicle, should be simple and precise. Good design allows an **clear understanding and intuitive communication** between human driver and driving system [Nor88, Ina08, Nor09]. The driving system informs the human driver on *possible* actions, including automation modes, optimal speed and optimal lane. The human expresses *wished* actions, e.g. automation mode, target speed, target lane and style. And the system communicates back on the *actual* actions performed.

The understanding of new systems, such as a driving system, is facilitated by imitating known systems with similar functionality. As an example, the horse-rider metaphor (H-metaphor) used in the HAVEit project has been presented in Section 2.3 [FAC+03, GSFW06]. The H-metaphor allows a **natural interaction** and transfers a substantial part of communication from the saturated vision channel to non-saturated channels, e.g. with haptic and acoustic feedback [FH10]. Haptic feedback allows the human driver to keep control over the vehicle, but at the same time offers a natural feeling of system intentions. Resistance on the acceleration pedal when speed limit is reached or resistance on the steering wheel when a lane change is judged dangerous are examples of such haptic feedback.

2.8.1 Communication from human to system

Table 2.10 presents the interactor for communication from human to system. Rule 11 stipulates that the human driver can choose a target speed v^H (in all automation modes) and a target lane l^H (in all automation modes, except fully automated driving). Several research works propose complex models for predicting the human driver intentions based on a variety of indirect intention measurements, e.g. steering input, head position, subject position in the lane and presence of objects [BKLF05, MDT11]. However, complicated indirect measurements only give a guess on human intentions. This guess is likely in best cases, but still uncertain. The confusion that results from wrong human intention interpretations can be avoided with simple, direct intention measurements [HAV11k]. For example, target speed v^H and target lane l^H can be set with cruise control **lever** and lever for indicators, respectively. For the target lane l^H, the **navigation system** could also be taken into account, e.g. for exiting the highway.

The driving style k^H could be set with a button (e.g. the configuration button that adapts vehicle seats to different drivers) or read from the human driver's smartphone. According to Rule 12, the driver state (i.e. monitoring or not monitoring the situation) must be known (except in fully automated driving). The most straightforward way to measure the driver state is probably with a Driver State Assessment (DSA) camera [RKK+09, RKK+10]. The automation mode requested by the human driver, m^H, can explicitly be communicated by the human driver with a button. Alternatively, m^H is communicated implicitly. For example, when the driver releases pedals or loosens grip on steering wheel, the HMI requests a higher automation mode, for longitudinal and lateral control respectively. When the driver gives a clear action on pedals or steering wheel, the HMI requests a lower automation mode, in correspondence to Rule 12. The way of obtaining the human-to-system interactor variables is the choice of the HMI designer.

Variable	Description	Interface (example)
v_x^H	Target speed by human	Lever
l^H	Target lane by human	Lever
k^H	Driving style requested by human: normal, sportive, comfort	Button
f^H	State of human: monitoring or not monitoring	DSA
m^H	Automation mode requested by human	Button, haptic

Table 2.10: Human-to-system interactor description. The interactor is indicated in the system architecture, Figure 2.12

2.8.2 Communication from system to human

Table 2.11 presents the communication from system to human. In Table 2.11 similar variables can be found as in Table 2.10. According to Rule 11, the HMI communicates an optimal speed v_x^I, and explains if it is different from the target speed chosen by the human, with i_v^I. It also suggests an optimal lane l^I and explains when the target lane requested by the human cannot be reached, with i_l^I. The legal safety HMI outputs a **single advice on speed and lane**, which is consistent with all aspects of driving on highways. For i_v^I and i_l^I, a single icon can be used, which reflects the most relevant constraint on speed control and lane changing. This reduces the risk on information overload, compared to a set of ADAS subsystems which would compete for human driver attention [Hol06a]. The active automation mode m^I and available automation modes $n^I[i]$ indicate active and available automation modes, depending on the human state (f^H), system state (f^I) and environment.

Like the communication from human to system, the communication from system to human exists in different channels; e.g. visual, haptic or acoustic communication. **Visual** communication can be facilitated by head-up display, which allows the human driver to keep his attention on the road. When possible, communication is transferred to the less saturated haptic and acoustic channels. **Haptic** feedback consists of forces, vibrations and clicks on the pedals and steering wheel [FH10], or vibrations in seat or seat belt. **Acoustic** feedback can be directional, as haptic feedback, e.g. an object in the blind spot of the driver can be indicated by a sound coming from that direction. With haptic and acoustic feedback that is slightly different for each different message, an intuitive implicit interaction between human and system is created, which resembles that of rider and horse (H-metaphor) [FAC$^+$03, FH10].

2.9 Contribution

This chapter has introduced system requirements for highly (and fully) automated driving on highways according to legal safety. These requirements have been described in three sets of rules. A driving system that integrates **traffic rules** allows fully automated driving in mixed

Variable	Description	Interface (example)
v_x^I	Optimal speed by system	Haptic, visual
l^I	Optimal lane by system	Haptic, visual
i_v^I	Information on target speed by human: vehicle ahead, curve ahead, speed limit, maximum speed system	Haptic, visual
i_l^I	Information on target lane by human: no lane available, continuous lane markings, collision	Haptic, visual
f^I	State of system: normal system functioning, system failure functioning	Visual, Acoustic
m^I	Automation mode accepted by system	Button, haptic
$n^I[i]$	Automation mode availability table	Visual

Table 2.11: System-to-human interactor description. The interactor is indicated in the system architecture, Figure 2.12

traffic with human drivers and other driving systems. Traffic rules of the 1968 United Nations Vienna Convention on Road Traffic are used, without modifications. This work analyzes the use of traffic rules by human drivers and motivates the use of traffic rules by driving systems. **Human rules** allow the cooperation between driving system and human driver in the subject vehicle, in automation modes from driver assisted to fully automated driving. Human rules take over human-system interaction principles of HAVEit and ABV projects. This work studies the consequences of human rules on the driving system, rather than their influence on the human driver. **System rules** specify requirements that are needed in order to assure the integrity of all system components. System rules have been developed in this work, based on the many discussions with colleagues and project partners during the development of LIVIC, HAVEit and ABV demonstrators, presented in Chapter 4.

After the specification of traffic rules, human rules and system rules, the work proposes a **system architecture** with perception, decision, control and HMI components. It presents the specification of input and output signals (i.e. **interactors**) of perception, control and HMI components based on the three rule sets. This also specifies input and output signals of the decision component, as this component is situated between perception, control and HMI components in the system architecture. The **subject coordinate system** has been proposed as reference frame for the description of all interactors. A strategy for improving control precision by estimating the actual subject position in the subject coordinate system has been presented. This allows the system to bring the vehicle to a safe standstill with a Minimum Risk Maneuver (MRM), even in the case of hardware failure of perception and/or decision components.

For the perception, control and HMI components, this work stays on a specification level, it does not contribute to the actual design of those components. Chapter 2 does however discuss specifications with respect to state-of-the-art technology of the components. The chapter shows that the integration of traffic rules, system rules and human rules for *all possible environments* is still far beyond reach of state-of-the-art technology. From the discussion follows that, for highways, legal safety control and HMI are almost possible with state-of-the-art technology, while legal safety perception can be available in **medium term**. Chapter 3 will present the design of a legal safety decision component for highways.

Chapter 3

Decision component design based on legal safety

Contents

The decision component is the central component of the legal safety concept, which implements traffic rules, human rules and system rules. This is indicated on the system architecture in Figure 2.12. The inputs of the decision component are the environment interactor (Table 2.6) and human-to-system interactor (Table 2.10). The decision component computes **one optimal trajectory towards each lane** (right lane, subject lane and left lane). For each of the three optimal trajectories traffic rules, human rules and system rules are integrated. The intersection of traffic rules, human rules and system rules generally leaves a wide range of valid subject trajectories. Optimality in this work is defined as the correspondence of a trajectory to the driving style wished by the human driver or vehicle manufacturer. The consistence with all rules is guaranteed for at least one trajectory; the trajectory in the subject lane. In certain situations, trajectories to right and left lanes are indicated as not available, e.g. due to the presence of an object on these target lanes. The decision component also calculates **a Minimum Risk Maneuver (MRM) trajectory**, for cases of system failure or human failure (i.e. driver distraction or drowsiness). One optimal lane trajectory (i.e. either right, subject or left) and the MRM trajectory are communicated from decision component to control component in the trajectory interactor (Table 2.9). Information on the three optimal lane trajectories is integrated in the system-to-human interactor (Table 2.11), which is communicated to HMI.

This chapter starts with a discussion on state-of-the-art trajectory planning with respect to the requirements of legal safety, in Section 3.1. Section 3.2 presents a *lane coordinate system*, which facilitates trajectory calculations in a lane-structured environment, and a *zone model* for subject and object trajectories. Section 3.3 discusses the **prediction of object trajectories** according to legal safety. The **calculation of subject trajectories** is presented in Sections 3.4 and 3.5. Section 3.6 explains how the system **selects one optimal subject trajectory and chooses the active automation mode**. Section 3.7 concludes with a discussion on the main contributions of this chapter.

3.1 State of the art

A vast literature exists on trajectory planning algorithms, for a wide range of applications. An extensive, general overview of planning algorithms is given in [Lat91] and [LaV06]. This section discusses most relevant algorithms, **with respect to requirements by legal safety**, for highly (and fully) automated driving on highways. Table 3.1 gives an indication of the performance of these algorithms on the integration of the traffic rules, human rules and system rules presented in Chapter 2. The performance indicator ranges from $---$ (very difficult or impossible) to $+++$ (straightforward).

Requirements by **traffic rules** (Rules 1 to 10) include (a) the adaptation to a lane-structured environment, including lane geometry and additional lane information (e.g. on speed limits, road friction) and (b) the adaptation to dynamic objects without exact knowledge of their trajectories. The application of **human rules** (Rules 11 and 12) implies (a) the optimality of speed (i.e. with respect to the target speed set by the human driver), (b) the optimality of comfort (i.e. respecting the driving style set by the human driver), (c) the calculation of four trajectories; three optimal trajectories (i.e. one for each lane) and one MRM trajectory and (d) the possibility to share control with the human driver, along different automation modes (e.g. allowing disturbances on the steering wheel by the human driver). With respect to **system rules** (Rules 13 to 15), the algorithm's ability to (a) consider perception limitations (i.e. perception zone and perception errors), (b) consider control limitations (i.e. feasibility of trajectories and control errors) and (c) limit calculation time is required.

In planning literature, the set of all possible states that the subject can attain is called the **configuration space** [LP83]. The set of all trajectories that bring the subject from its current configuration to another configuration is referred to as **trajectory space**. The objective of trajectory planning in the application of this work is to find a trajectory in the trajectory space that respects the three rule sets of legal safety. In many cases, the solution can be obtained by a wide range of trajectories, think of human drivers with different personalities and capabilities. This defines the **solution space**. Trajectories in the solution space avoid accidents in cases of legal object behavior and reasonably foreseeable non-legal object behavior (LS and NLS situations). In some cases of non-legal object behavior, accidents cannot be avoided. These accidents are mitigated by trajectories in the solution space.

Figure 3.1 gives the general scheme followed by most trajectory planning algorithms. First, object trajectories are **predicted**. Then, subject trajectories are **generated and evaluated**. As indicated by the dashed line in the figure, the generation and evaluation of subject trajectories is sometimes done iteratively; i.e. complete trajectories or trajectory segments are generated and evaluated one after the other. The evaluation of subject trajectories is eventually used for selecting optimal trajectories for vehicle control and for communicating with the human driver.

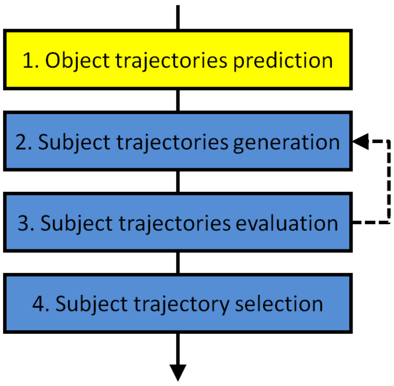


Figure 3.1: General scheme of trajectory planning

This section consecutively presents **combinatorial** trajectory planning (combinatorial roadmaps), **sampling-based** trajectory planning (sampling-based roadmaps, rapidly exploring random tree, environment-based trajectories) and **direct** trajectory planning (expert systems, potential fields, environment-based trajectories). Then it positions legal safety based trajectory planning as a

combination of direct and sampling-based trajectory planning.

3.1.1 Combinatorial roadmaps

A classic approach in trajectory planning consists of **transforming the continuous configuration space to a discrete configuration space** [LaV06]. The discrete problem can then be solved with dynamic programming, which searches a satisfactory combination of intermediate states to reach the target state, based on a cost function. Different strategies exist to decrease time to solution with dynamic programming, e.g. breadth first, depth first and best first algorithms, the Dijkstra algorithm [Dij59] or A* algorithm [Pea84]. The continuous-to-discrete transformation can be performed in two ways; combinatorial or sampling-based.

Combinatorial trajectory planning builds a discrete configuration space that exactly represents the original continuous configuration space. This guarantees *completeness*; the algorithm will either find a solution or will correctly report that no solution exists. Most combinatorial trajectory planning algorithms construct a **combinatorial roadmap** in the configuration space, which allows finding a solution according to different strategies, e.g. maximum-clearance (to objects) or shortest-path [Nil69, LaV06]. In order to construct the roadmap, **cell decomposition** can be used, which divides the configuration space in various shaped regions known as cells [SS83]. As an example, vertical cell decomposition is illustrated in Figure 3.2.

Combinatorial algorithms are universal; they can be applied to virtually any trajectory planning problem. However, their implementation is difficult and calculation times are high. Finding a **solution with static objects, without taking into account limits on subject vehicle dynamics** is already a challenge. Respecting traffic rules (e.g. without exact knowledge of the trajectories of objects), human rules (e.g. calculating four trajectories in a reasonable time) and system rules (e.g. taking into account perception and control errors and limits on vehicle dynamics), is considered out of reach of these algorithms, as is indicated in Table 3.1.

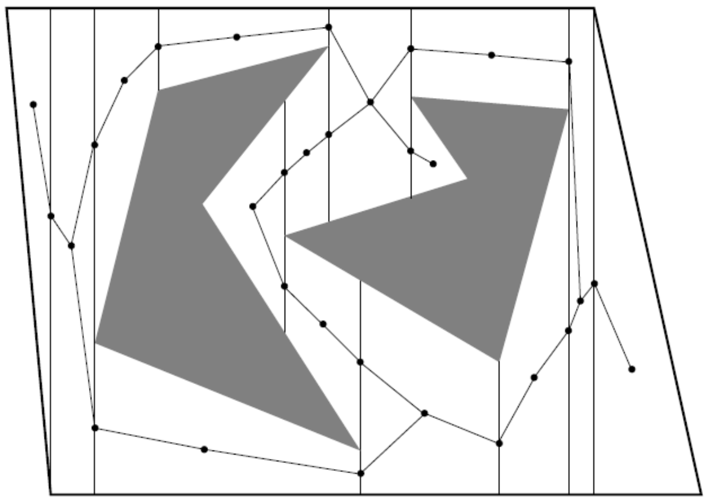


Figure 3.2: Combinatorial roadmap based on vertical cell decomposition. Source: [LaV06]

3.1.2 Sampling-based roadmaps

In contrast to combinatorial trajectory planning, sampling-based trajectory planning creates a discrete configuration space by **sampling the original configuration space**. This means that only a limited number of points in the original configuration space is considered as possible intermediate states to reach the target state. As combinatorial trajectory planning, sampling-based trajectory planning can use dynamic programming to connect begin and target states, via the intermediate states. Implementation is easier and calculation efficiency higher than with combinatorial trajectory planning. However, *completeness* is lost. If no solution exists, the algorithm could run forever. If a solution exists, the algorithm can find it by gradually increasing the sampling resolution, but the **time to solution** is not predefined. This means that within the predefined calculation time in the system rules (Rule 16) a solution is not guaranteed, even if it exists. The performance of sampling-based algorithms greatly depends on how the configuration space is sampled. Different **sampling techniques** exist, such as random sampling and grid sampling (low-dispersion sampling) [LaV06]. Some sampling schemes directly integrate environment information, e.g. the position of objects [Eid11].

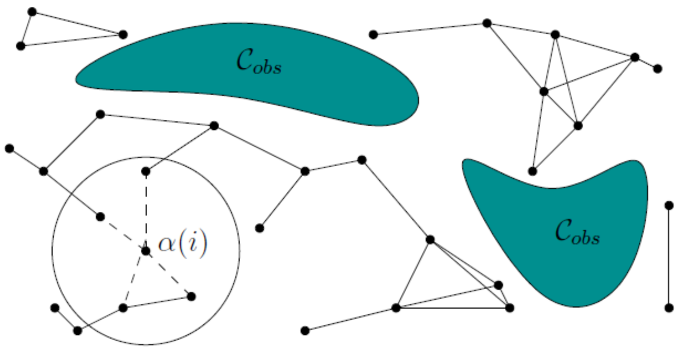


Figure 3.3: Sampling-based roadmap: incremental construction of trajectory by connecting samples to nearby vertices in the roadmap. Source: [LaV06]

Sampling-based roadmaps, also named Probabilistic RoadMaps (PRMs), are built from collision free samples in the configuration space [KSLO96]. For each sample, a connection with nearby vertices in the roadmap is constructed, as in Figure 3.3 [LaV06]. A local planning algorithm (e.g. A*) finds a trajectory from begin to end state, through the intermediate states on the roadmap. Taking into account **dynamic objects** is a challenge for these algorithms. A roadmap that is collision-free on the current configuration of the environment, is not necessarily collision-free in future environment configurations. This can be handled by augmenting the configuration space with one dimension; time. However, time cannot be treated like the other state variables, as can only increase, not decrease. In practice, it is easier to perform the spatial and temporal trajectory planning separately, through a path-velocity decomposition [KZ86]. In this case, the algorithm first plans a path to avoid collisions with static objects and then plans the velocity along the path to avoid collisions with dynamic objects. As calculation times are high, strategies have been developed for reusing parts of trajectories calculated previously, e.g. Dynamic (D*) or Anytime Dynamic (AD*) replanning algorithms [Ste94, LFG+05].

Table 3.1 gives an indication of the performance of sampling-based roadmaps with respect to legal safety. Implementation is easier than with combinatorial roadmaps, but **fundamental challenges remain**. Interaction with dynamic objects that have several possible trajectories (traffic rules), the optimality of speed and comfort (human rules) and consideration of vehicle dynamics and control errors (system rules) seem difficult to manage.

3.1.3 Rapidly exploring Random Tree (RRT)

In robotics, Rapidly exploring Random Tree (RRT) algorithms have become popular during last decade [LaV98, CSL01, BV02]. The main idea of these algorithms is to incrementally grow a search tree by connecting collision-free samples in the direction of the target state. The sampling resolution is gradually increased, as is illustrated in Figure 3.4 [LaV06]. In comparison with combinatorial and sampling-based roadmap algorithms, RRT is better in taking into account **kinematic (i.e. nonholonomic) and dynamic vehicle constraints** [US03, KKT+09] and partial or uncertain knowledge of dynamic environments [PL06, MS07]. However, with the original RRT algorithms, the time to calculate a solution is not bounded. Partial Motion Planning (PMP), which is derived from RRT, explicitly takes into account a **calculation time constraint** [PF05a, PF05b, Ben08]. It calculates as much trajectory segments as possible in the available time and guarantees that the vehicle can be brought to a collision-free standstill after the last trajectory segment. To this end, samples that correspond to a *Inevitable Collision State* are excluded. This allows taking into account some worst-case future object movements in a dynamic, uncertain environment. An extension of RRT and PMP algorithms allows calculating with a probabilistic instead of a deterministic representation of object movements [FTSL08]. In this case, objects are believed to move along typical, likely trajectories that have previously been observed, e.g. modeled with a Gaussian distribution. The RRT or PMP algorithm then finds the safest trajectory for uncertain object movements by rewarding samples with low object collision probability.

Both RRT and PMP algorithms will be referred to as RRT algorithms in this work. RRT algorithms are integrated on vehicle by HAVEit partner INRIA on the HAVEit Joint System Demonstrator [FNG+10, RN10, HAV11e, HAV11j] and by ABV partner IEF on the ABV Low Speed Demonstrator [ABV13b]. RRT algorithms were also integrated on vehicles in the DARPA challenge [UAB+08]. RRT algorithms provide **universal** trajectory planning for vehicle applications. They apply to most environments, whether lane-structured or not. And they are able to describe complex maneuvers, e.g. trajectories which include backward driving. However, they do not seem optimal for highly automated driving on highways, as Table 3.1 indicates. Finding **feasible trajectories** that avoid collisions with dynamic objects with known trajectories is already a challenge. Taking into account vehicle constraints and object movements usually involves post-deformation of the trajectory [DF08]. It is unclear how these algorithms can implement the complete set of traffic rules, including the smooth adaptation to lane structure, speed limits, road friction limits and unknown object behavior. **Optimizing trajectories** with respect to human rules concerning target speed and driving comfort also appears difficult. Today, the large amounts of computational memory and time needed are an issue. On powerful computers the calculation of *one* trajectory takes around $200\,ms$ to $500\,ms$ [HAV11j]. But human rules and system rules imply the **calculation of four trajectories**. Large calculation times are difficult to handle in a dynamic environment where the human driver can disturb the vehicle trajectory and object trajectories change continuously. Large calculation times also complicate vehicle control, as was explained in Chapter 2 in the discussion on the subject coordinate system and subject position estimation.

However, as a universal trajectory planning algorithm, RRT can be useful in **some applications at low speeds**. RRT can temporarily take over in situations where specialized trajectory planning algorithms bring the vehicle to a standstill. For example, RRT can find solutions in situations where lanes are partially obstructed by objects [MBB+08, ABV13b], or in non-structured environments such as rest areas.

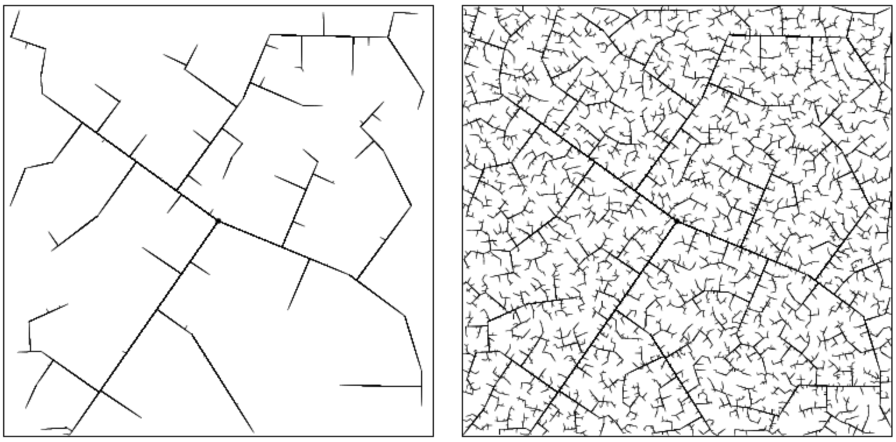


Figure 3.4: Rapidly exploring Random Tree: exploration of configuration space (left: after 45 iterations, right: after 2345 iterations). Source: [LaV06]

3.1.4 Sampling-based environment-based trajectories

Sampling-based roadmaps and RRT algorithms do not **take into account environment information** (i.e. description of subject, lanes and objects) in the subject trajectory generation step in Figure 3.1. These algorithms *blindly* propose new trajectory segments and only consider the environment in the subject trajectory evaluation step, for example for collision checking. This is a universal method that applies to all types of environments. However, on highways, trajectory planning is greatly facilitated by using the lane structure as a basis for the trajectory generation step. Optimal trajectories necessarily adapt to the lane structure.

The lane structure provides a natural **sampling scheme for the trajectory space**. For example, only trajectories towards the middle of the right, subject or left lane are considered. These are called **environment-based trajectories**. If the lateral target position is discretized (i.e. middle of right, subject and left lane), there remains a continuity of possible lateral speeds to reach the target position, e.g. slow or fast lane changes. There is also a continuity of longitudinal target speeds and longitudinal accelerations to reach these target speeds. The trajectory space can further be discretized by sampling the remaining continuities, i.e. lateral speed, longitudinal speed and longitudinal acceleration. As an example, the sampling-based algorithm can combine 2 possible values for average lateral speed, 10 possible longitudinal speeds and 4 average longitudinal accelerations. This gives 80 possible trajectories per lane, or 240 trajectories in total. When a trajectory is generated, it is evaluated according to multiple performance indicators that correspond to different aspects of legal safety. Performance indicators include safety (i.e. collisions with objects or road boundaries), traffic rules (e.g. crossing continuous lane markings, overtaking an object on its right), comfort (e.g. longitudinal and lateral jerk) and consumption (e.g. according to a simple consumption model that considers longitudinal speed and acceleration). The algorithm can be iterative. It can carry out a second trajectory generation with finer sampling around first generation trajectories that performed well. In the second generation, the algorithm neglects samples around first generation trajectories that performed poorly, e.g. trajectories towards lanes that are not meant for driving.

A sampling-based environment-based approach with two trajectory generations was followed in the **grid algorithm**, which was a first attempt to a legal safety decision component for this work [VGMG09, Van10a, VGGM10, GVM+10, GVMG11]. The first trajectory generation of the grid algorithm is illustrated in Figure 3.5 [VGMG09]. An experiment on simulator with the grid algorithm configured for different driving styles is shown on `http://youtu.be/IZeKlCsrU1E`. An experiment of the grid algorithm on vehicle can be found on `http://youtu.be/Wrca1mqShxA`.

A similar approach was used by the Stanford team that won the 2005 **DARPA** Grand Challenge and finished second in the 2007 DARPA Urban Challenge [TMD$^+$06, MBB$^+$08]. Their vehicle Stanley generates around 10 trajectory candidates, with different lateral offsets to the center of the road. Trajectory candidates are combined with 2 average lateral speeds: (a) a lateral speed that reaches the lateral offset slowly, and (b) a lateral speed that reaches the lateral offset quickly. The 20 trajectory candidates are evaluated on collisions with objects, lateral offset (lower lateral offset to the road center is encouraged) and lateral speed (low lateral speed is encouraged). In the 2007 DARPA Urban Challenge, the Stanford team combined the environment-based approach with a roadmap approach [MBB$^+$08]. The roadmap approach (with A* algorithms) was used when the environment-based approach could not offer a solution, e.g. when the normal passage on an intersection was blocked by other vehicles. Implementations of sampling-based environment-based trajectory calculations have recently been presented by other research teams [HWC$^+$11, LAB$^+$11]. A sampling-based trajectory planning algorithm is currently being integrated on the ABV Low Speed Demonstrator by project partner INDUCT [ABV13b]. **Dynamic window** algorithms evaluate a set of trajectories that combine a certain longitudinal velocity and certain yaw rate that can be reached from current vehicle state, i.e. circular trajectories with acceleration or deceleration [FBT97]. Environment-based trajectory planning could be seen as an evolution of the **dynamic window** approach, which considers both subject vehicle constraints (like dynamic windows) and environment structure (unlike dynamic windows).

Environment-based trajectory planning can be seen as environment-based RRT, where **complete trees (i.e. trajectories) are generated at once**, instead of single branches (i.e. trajectory segments). Calculation is ten to one hundred times faster in comparison with RRT, and trajectories naturally adapt to lane structure and kinematic and dynamic constraints of the subject vehicle. This leads to easier integration of traffic rules, human rules and system rules, as is indicated in Table 3.1.

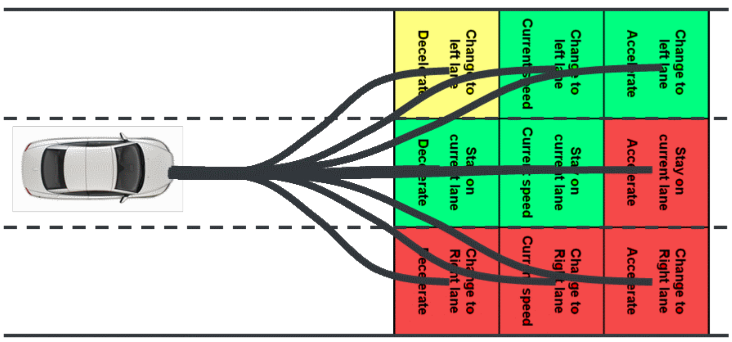


Figure 3.5: Exploring complete trajectories with maneuver grid algorithm: first attempt to a decision component for this work [VGMG09]

3.1.5 Expert systems

Trajectory planning algorithms in Sections 3.1.2, 3.1.3 and 3.1.4 are sampling-based. In the trajectory generation step, in Figure 3.1, these algorithms generate sample trajectories or segments of trajectories. Trajectory generation sometimes takes into account environment information partially (environment-based trajectories, Section 3.1.4), but does not intend to integrate all driving requirements. In the trajectory evaluation step, samples that do not meet driving requirements are discarded. As the trajectory generation step hardly incorporates driving intelligence (i.e. environment information), it is generally hard to find optimal solutions in a limited amount of time with sampling-based algorithms. Algorithms described in Sections 3.1.5, 3.1.6 and 3.1.7 attempt to **directly generate an optimal trajectory**. This allows leaving out the trajectory evaluation step.

Expert systems base trajectory planning on **if-then rules**. The decision component output directly follows from the application of rules on environment information input. An algorithm based on fuzzy logic has been implemented by HAVEit partner DLR on the HAVEit Joint System Demonstrator [LF09, HAV11e, HAV11j, HAV11m]. Recently, processing uncertain environment information with Bayesian networks has been demonstrated [SSW10, Sch11], see Figure 3.6 [SSW10]. Bayesian networks are seen as probabilistic extensions of expert systems.

Trajectory planning with expert systems is extremely fast. A rule-based algorithm seems a good basis for integrating the rule sets of legal safety. This is especially the case for **legal safety rules with a discrete character**, such as human rules (e.g. automation mode transitions, lane changes), as Table 3.1 indicates. Expert systems are intuitive to understand for human drivers (and straightforward to design for engineers) as they emulate human reasoning. However, the application of traffic rules and system rules requires the discretization of numerous environment variables (e.g. position, speed and acceleration of different objects) and demands a detailed description of the subject trajectory. This leads to a high **number of rules and tuning parameters**. A challenge is proofing the safety of algorithm decisions in all situations.

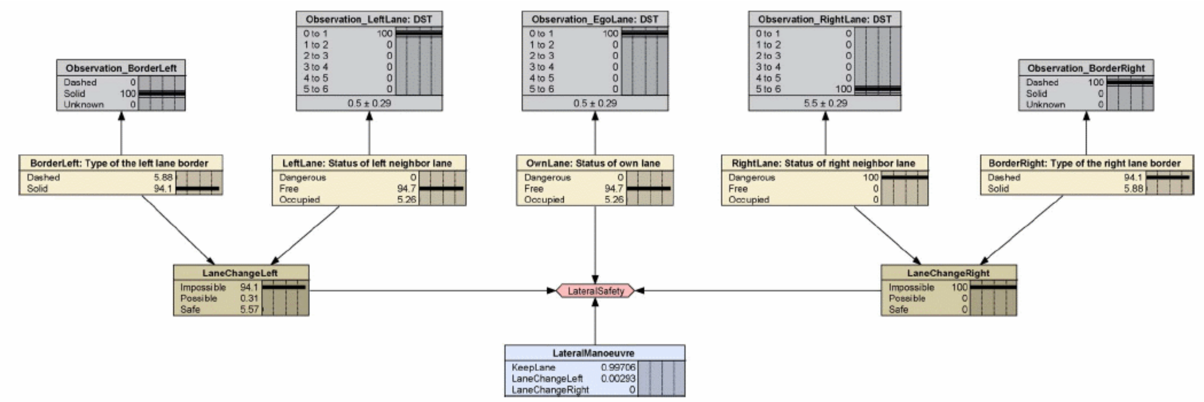


Figure 3.6: Expert systems: lane changing based on Bayesian networks. Source: [SSW10]

3.1.6 Potential fields

Like expert systems in Section 3.1.5, potential field algorithms directly generate an optimal subject trajectory, without the need for an trajectory evaluation step in Figure 3.1. Potential field algorithms are based on functional analysis, instead of logic with if-then rules on expert systems. **Potential fields** attribute repulsive forces to obstacles in the environment and attractive forces to a target position in front of the subject vehicle. The optimal trajectory is found along the steepest gradient of the resulting potential field [Kha85, BLL92]. **Elastic band algorithms** model the subject-environment interaction as a combination of point masses and spring forces

[QK93, SB08, TMS+08], as is illustrated in Figure 3.7 [TMS+08]. The principles of elastic bands and potential fields are similar; forces can be interpreted as derivatives of potential fields. **Vector field histograms** take over principles of force fields and focus on dealing with perception uncertainty [BK91]. **Optimal control** is another approach that bases on a continuous cost function (i.e. a potential) to find optimal subject trajectories [SS98, CBC04, BBDL05, BBDL07].

Trajectory planning based on potential fields and similar approaches have demonstrated robustness in automotive applications, especially in simple use cases such as lane keeping in a virtual half-pipe [TMS+08]. In more complex use cases, which include lane changing and dynamic objects, problems with **local minima**, which trap the subject vehicle, can arise. Recovery methods to solve the local minima problem have been presented, but it seems difficult assure solutions in all situations. In general, it seems difficult to integrate all traffic rules of legal safety with these algorithms, as indicated in Table 3.1. Additionally, potential field algorithms do not directly consider limitations on vehicle **kinematics and dynamics**, which is required by system rules. The use of force models in potential field algorithms allows a natural **interaction with the human driver**, but it seems uncertain that optimal speed and comfort can be provided in all situations, as is required by human rules.

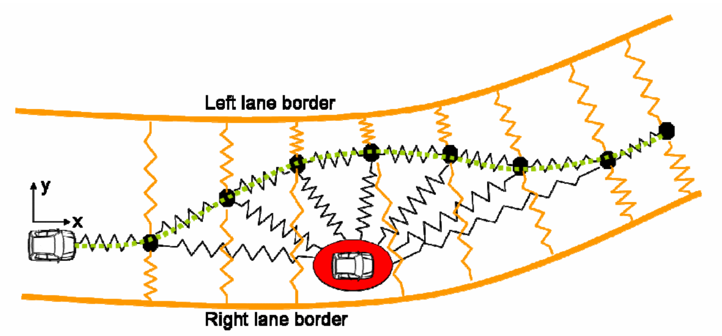


Figure 3.7: Elastic bands for lane keeping. Elastic bands and potential fields are similar approaches. Source: [TMS+08]

3.1.7 Direct environment-based trajectories

Environment-based trajectory planning described in Section 3.1.4 was sampling-based; its trajectory generation step considers certain elements in the environment, but a trajectory evaluation step is needed to take into account remaining elements. This section presents **environment-based trajectories** with a **direct** trajectory generation approach, without the need of trajectory evaluation.

A direct environment-based trajectory planning is offered by a wide range of **vehicle control** algorithms. Control theory uses a subject vehicle model to directly take into account kinematic and dynamic constraints. It uses feedback to cancel out model, perception and control errors. Constraints on vehicle dynamics, control errors and perception errors are difficult to handle with traditional trajectory planning algorithms (e.g. combinatorial roadmaps, sampling-based roadmaps and RRT), but come naturally with algorithms based on control. Current implementations of vehicle control usually focus on **one or few aspects of legal safety**, either in longitudinal direction, in lateral direction or in both directions. Examples include vehicle following (longitudinal direction) [EMGL09] and lane keeping (lateral direction) [EMNL10]. Vehicle trajectories are usually not calculated *explicitly* by vehicle control algorithms, but are considered *implicitly* in the control theory.

Another direct and powerful approach in a lane-structured environment is the **analytical** calculation of subject trajectories. Examples are collision avoidance [Hup97, BCS10] and lane changing [JKI00, KKL01, KK03, PT03, Sha04, MGVP11]. An analytical algorithm which integrates several longitudinal and lateral aspects has been integrated by HAVEit partner INRIA in the HAVEit Joint System Demonstrator [RN10, HAV11e, HAV11j, HAV11m] and ABV Low Speed Demonstrator [ABV13b].

Direct environment-based trajectories cover the **complete solution space**, in contrast to their sampling-based variant. This increases the smoothness and optimality of the trajectories. The interaction with the human driver (via human rules) benefits from this, as Table 3.1 illustrates. However, direct environment-based algorithms generally only focus on one driving aspect, or on a limited number of driving aspects. The challenge in their future development is to integrate the complete set of traffic rules and system rules.

Algorithm	Traffic rules	Human rules	System rules
Combinatorial roadmaps	− − −	− − −	− − −
Sampling-based roadmaps	−−	−−	−−
Rapidly exploring Random Tree (RRT)	−	−	−
Sampling-based environment-based trajectories	+	++	
Expert systems	+	++	+
Potential fields	−	+	−
Direct environment-based trajectories	++	++	++
Legal safety based trajectories	+ + +	+ + +	+ + +

Table 3.1: Overview of state-of-the-art planning algorithms with respect to the requirements of legal safety. With performance indicator from − − − (very difficult or impossible) to + + + (straightforward)

3.1.8 Legal safety based trajectories

The discussion in Sections 3.1.1 to 3.1.7 has distinguished two types of algorithms: sampling-based algorithms and direct algorithms. **Sampling-based algorithms** (sampling-based roadmaps, RRT, environment-based trajectories) allow a *universal* approach by generating random samples in the trajectory space and evaluating these samples. **Direct algorithms** (expert systems, potential fields, environment-based trajectories) offer an *application-specific* approach by generating trajectories that directly consider all driving aspects, without the need for evaluation. Direct algorithms find solutions that are more optimal and need less calculations than with sampling-based algorithms. Sampling-based algorithms can solve complex problems that direct algorithms cannot solve.

The decision component with legal safety based trajectory planning presented in Chapter 3 combines direct and sampling-based trajectory planning. **Direct** calculations are used in the **longitudinal** direction, to calculate subject speed profiles. Direct calculations are simple and precise for *continuous* variables, such as longitudinal speed from zero to maximum speed, longitudinal acceleration from extreme braking to strong acceleration. The **sampling-based approach** is used in the **lateral** direction, which has a discrete character by the lane structure. Only trajectories to the middle of a lane are generated and evaluated. The sampling-based approach in the lateral direction sometimes means a loss of optimality, as valid trajectories that do not target the middle of a lane are not considered. For example, if a still standing object only occupies a part of the lane, the legal safety system will either propose to stop behind the object, or to perform a complete lane change, instead of slightly adapting the subject position in the lane. The sampling-based approach might be related what psychologists call *satisficing* [Sim96]; *human beings do not necessarily attempt to find the absolutely optimal solution, but rather tend to minimize mental effort and take the first solution that seems satisfactory.* When still standing objects partially block the road, the legal safety brings the subject to a safe standstill until the situation changes. In this case, the human driver or a generic trajectory planning algorithm such as RRT can also temporarily take over control and slowly maneuver around the obstacles. As calculation times are low, additional trajectories that do not target the middle of the lane could easily be added in the sampling scheme of the legal safety trajectory planner. This would allow increasing optimality by unblocking situations in certain cases.

The strategy behind the legal safety based trajectory planner is that, (a) the direct approach is used for all calculations for which a direct approach is found, and (b) the sampling-based approach is used for remaining calculations. With respect to **RRT** algorithms (Section 3.1.3), the environment-based **grid** algorithm (Section 3.1.4 that was first developed in this work transforms a substantial part of sampling-based calculations into direct calculations. The grid algorithm directly takes into account lane structure in the trajectory generation. With respect to the grid algorithm, the **legal safety based trajectory** planner that was finally developed in this work further reduces sampling-based calculations in favor of direct calculations. Unlike the grid algorithm, it directly takes into account object information and additional lane information in the trajectory generation. This further decreases algorithm calculation time and leads to smoother and more optimal solutions. Direct calculations also allow separating calculations for each aspect of driving, as will be shown in this chapter. This facilitates proofing safety and tuning driving style, in comparison with the grid algorithm that mixes different driving aspects in a single trajectory cost. In future work, remaining sampling-based calculations of the legal safety based trajectory planner might further be converted to direct calculations. For example, a direct approach could be developed for the lateral direction. The sampling-based part of the algorithm could then be kept for calculations in that cannot (yet) be dealt with by direct calculations, e.g. in **more complex environments**.

The legal safety based trajectory planning is presented in Sections 3.3 (prediction of object trajectories), 3.4 (generation of subject trajectories), 3.5 (evaluation of subject trajectories) and 3.6 (selection of subject trajectory), respectively the four steps of the general scheme in Figure 3.1. Table 3.2 gives a short overview of the output of each step. The **prediction of object trajectories** is based on traffic rules and includes principles of defensive driving. The object trajectory description covers a range of foreseeable object trajectories (both trajectories that are congruent with traffic rules and trajectories that are not), as is illustrated for object *1* in Figure 3.8. For the subject, 7 trajectories are **generated**, which directly integrate most aspects of legal safety. The generation includes 1 optimal trajectory towards each lane for normal system functioning (*0A*, *0B*, *0C*), 1 Minimum Risk Maneuver (MRM) trajectory towards each lane for system failure functioning (*FA*, *FB*, *FC*) and 1 emergency trajectory in the subject lane (*JB*). The 7 samples are **evaluated** on legal safety aspects that were not included in the trajectory generation. 2 trajectories are **selected** for control; one optimal trajectory for normal system functioning and one MRM trajectory for system failure functioning. Information on the 3 optimal lane trajectories is communicated to the HMI.

Step	Output
Prediction of object trajectories (3.3)	1 trajectory per object: *1 - 8*
Generation and evaluation of subject trajectories (3.4 and 3.5)	7 subject trajectories: *0A*, *0B*, *0C*, *FA*, *FB*, *FC*, *JB*
Selection of subject trajectories (3.6)	2 subject trajectories for control: {*0A* or *0B* or *JB* or *0C*}, {*FA* or *FB* or *JB* or *FC*} 3 subject trajectories for HMI: *0A*, {*0B* or *JB*}, *0C*

Table 3.2: The three steps of the legal safety decision component (indication of corresponding section between parentheses)

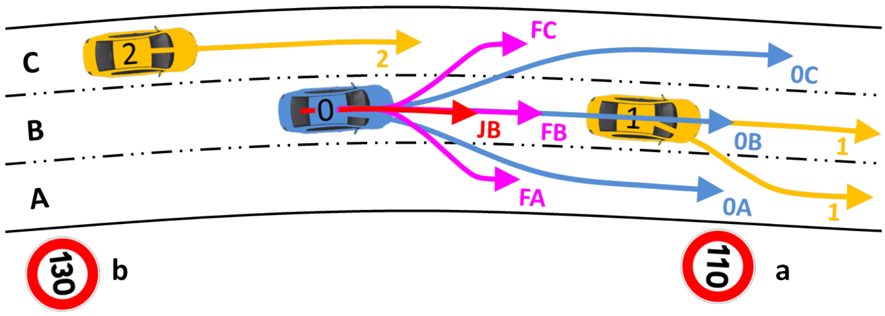


Figure 3.8: Legal safety based trajectory planning: combination of direct and sampling-based planning. Object trajectories (*1*, *2*) are **predicted** based on traffic rules. For the subject, 7 trajectories are **generated** based on traffic rules, human rules and system rules: 3 trajectories for normal system functioning (*0A*, *0B*, *0C*), 3 trajectories for system failure functioning (*FA*, *FB*, *FC*) and 1 emergency braking trajectory (*JB*). The 7 samples are **evaluated**. Finally, 1 trajectory is **selected** for control during normal system functioning and 1 trajectory for control during system failure functioning

3.2 Lane coordinate system and zone model for subject and object trajectories

This section presents some mathematical tools for legal safety trajectory calculations in Sections 3.3, 3.4, 3.5 and 3.6. First, it introduces a **lane coordinate system**, which greatly facilitates calculations with subject and object trajectories. Then, a **zone model** is presented for the mathematical description of subject and object trajectories. Notations are explained throughout the chapter and are summarized in the notation sheet in the beginning of the document.

3.2.1 Lane coordinate system UW

The curvilinear **lane coordinate system** UW, with the same origin as subject coordinate system XY, with the U-axis **parallel to the middle of each lane** and with the W-axis perpendicular on U, is a natural environment for calculations with subject and object trajectories. The lane coordinate system UW and subject coordinate system XY are indicated in Figure 3.9. Figure 3.10 shows that in the lane coordinate system UW, lanes are defined by W-coordinate lines, i.e. lines with constant W-coordinate. Subject and object trajectories that follow the middle of a lane can be represented by a transient section (with varying W-coordinate) and a permanent section (with constant W-coordinate). Calculations with constant W-coordinates are a lot easier and faster than calculations in the real lane geometry in XY, which is usually (but not necessarily) based on a combination of lines, clothoids and circles [Raj06]. A similar lane coordinate system is used by the Stanford team that won the DARPA Grand Challenge [TMD+06, MBB+08, LAB+11].

Name	Reference frame	Coordinate system	Use
Subject coordinate system XY	Position and orientation of subject at start perception cycle	Cartesian	System
Lane coordinate system UW	Position of subject, orientation of lane at start perception cycle	Curvilinear	Decision
Speed profile system TV	Time at start perception cycle	NA	System, decision

Table 3.3: Description of subject coordinate system XY, lane coordinate system UW and speed profile system TV

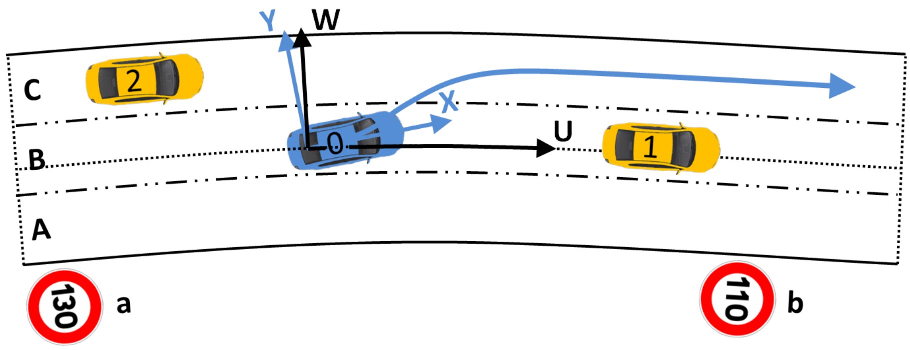


Figure 3.9: Highway environment with subject vehicle (*0*), lanes (*A*, *B*, *C*), traffic signs (*a*, *b*) and object vehicles (*1*, *2*). Indication of subject coordinate system XY and lane coordinate system UW

The first step of the decision algorithm consists of transforming the environment interactor (Table 2.6) and human-to-system interactor (Table 2.10) **from** XY **to** UW. All subject and object trajectory calculations are performed in UW. In a final step, the decision component applies an inverse transformation from UW **to** XY, to describe the trajectory interactor (Table 2.9) and system-to-human interactor (Table 2.11).

The application of **traffic rules** and **human rules** in UW is direct, as they refer to subject and object positions *relative to the lane*, rather than actual Cartesian positions in XY. For **system rules**, the actual curvature of the lane is considered additionally, e.g. to limit vehicle speed to avoid slipping in a curve.

The XY to UW transformation allows trajectory planning algorithms for straight lane environments to be extended to curved lane environments. Trajectory planning in UW could also be used on *virtual lanes* found by a trajectory planning algorithm for unstructured environments, such as a Rapidly exploring Random Tree (RRT) algorithm. In environments with curves, the XY to UW transformation is **non-orthogonal**; it does not keep distance. For highways, where curvature values are low (typically under $1/500\,m^{-1}$), errors introduced by non-orthogonality are assumed much lower than errors by state-of-the-art perception and control. Errors by non-

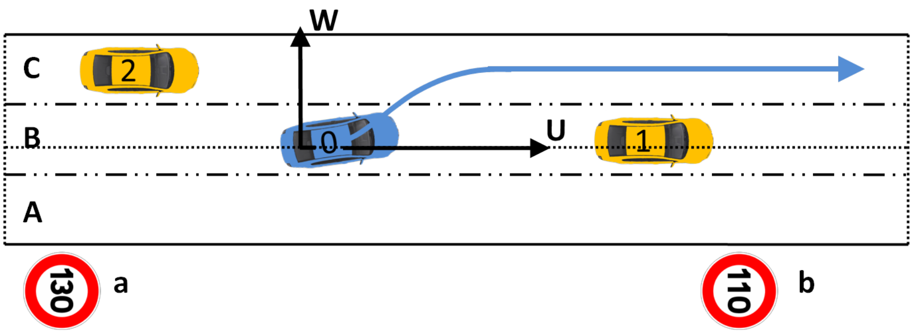


Figure 3.10: Highway environment with subject vehicle (*0*), lanes (*A*, *B*, *C*), traffic signs (*a*, *b*) and object vehicles (*1*, *2*) in the lane coordinate system UW

orthogonality are covered by existing safety margins in trajectory calculations. For environments with higher curvature, a deeper study on the effects of the non-orthogonality of UW should be conducted.

3.2.2 Zone model for subject trajectories

For the mathematical description of subject and object trajectories many alternatives exist, e.g. polynomials, circular arcs, splines and sinusoids [KK03]. In an attempt to assure that trajectory descriptions are precise, these alternatives are usually based on a vehicle model, such as bicycle, tricycle or Dubins car [Dub57]. However, no **single, exact trajectory** can realistically describe subject movement, due to perception and control errors (Rules 13 and 15). Object movement cannot be represented by an exact trajectory, due to perception errors and uncertainty on object behavior. According to legal safety, both subject and object trajectories are subject to uncertainty. However, assuming *unbounded* uncertainty on subject or object trajectories (e.g. with a Gaussian description) would not be realistic. In an application where the driving system controls the vehicle over longer periods (i.e. highly and fully automated driving), safety is not negotiable. In this case, an unbounded uncertainty on subject and object trajectories is difficult to defend; no threshold on the probability of collisions between subject and objects seems low enough. A level of trust (i.e. bounded uncertainty) between traffic participants is essential to allow sharing the infrastructure. This work proposes a **zone description** for subject and object trajectories, which represents a **bounded and uniform uncertainty**.

A bounded, uniform description is probably the simplest probabilistic description of subject and object movement. A *non-uniform* description of trajectories would not allow to increase safety or optimality, it would only make calculations more complex. The zone description is similar to *segment cones* proposed in [GLR+11]. In contrast to segment cones, the zone description **adapts to the lane structure**. This corresponds to an implicit implementation of traffic rules; the subject and objects stay within the lane, except during certain specific maneuvers, which are described by traffic rules.

The **zone description** for trajectories/speed profiles consists in a minimum and maximum (worst-case) trajectory/speed profile, between which subject and object position/speed is located. In the trajectory interactor that describes subject trajectories (Table 2.8), position vectors $p_x[i]$ and $p_y[i]$ correspond to the middle of minimum and maximum subject trajectories. The width vector $w[i]$ corresponds to the difference of maximum and minimum subject trajectories. Similarly, the speed vector $v[i]$ corresponds to the middle of minimum and maximum subject speed profiles. The growth vector $g[i]$ corresponds to the difference between maximum and minimum subject speed profiles.

First, the **mathematical model** for the zone description of subject trajectories and speed profiles in UW is presented. After this, the mathematical model of object trajectories and speed profiles will be presented.

Trajectories

The subject cannot *exactly* be kept on its optimal trajectory. It can only be kept on a trajectory within *bounded error*, which is function of **perception accuracy** (Rule 13) and **control accuracy** (Rule 15).

Figure 3.11 illustrates the mathematical model for subject trajectories, with a minimum (i.e. lower bound) and maximum trajectory (i.e. higher bound), in dashed lines. A zone model allows making abstraction of the actual subject trajectory (an example is given in continuous line in the figure), which is uncertain and could be difficult to describe with geometrical functions. For the minimum and maximum trajectory of the zone model, a simple geometrical description can be used; a combination **linear sections**. This facilitates and accelerates trajectory calculations. Equations 3.1 and 3.2 respectively describe the minimum trajectory (indicated with underscore) and maximum trajectory (indicated with overscore). The equations of Chapter 3 follow the notations used in Chapter 2; p indicates position, v velocity and a acceleration. A first subscript indicates the coordinate axis, i.e. U or W. In the second subscript, 0 refers to the start state, 1 the final state and 01 the average value between them. The first line in Equation 3.1 describes a section of the **minimum trajectory** in which the minimum lateral position stays constant at $\underline{p}_{w_0}$ over a reaction distance p_u^R. In the second line of the equation, a section with constant slope $\underline{s}_{w01}$ is described, followed with a constant target position $\underline{p}_{w_1}$ in the third line. The **maximum trajectory** in Equation 3.2 gives a similar description for the maximum lateral positions of the subject, but without reaction distance. This zone model corresponds to a worst-case lateral subject control that keeps the subject in the lane. Subject control is situated between instant action (maximum trajectory, without reaction distance) and delayed action (minimum trajectory, with reaction distance). The reaction distance p_u^R is related to a system reaction time t^R, which is bounded by Rule 16. Equations 3.1 and 3.2 describe trajectories towards *higher* lateral target positions. For trajectories towards *lower* target positions, the reaction position p_u^R comes on the maximum trajectory, instead of on the minimum trajectory. For trajectories towards a target position that is *equal* to the current lateral position (i.e. zero), the reaction position is omitted.

$$\begin{cases} \underline{p}_w(u) = \underline{p}_{w_0} & \text{if } u < p_u^R \\ \underline{p}_w(u) = \underline{p}_{w_0} + \underline{s}_{w01}\,(u - p_u^R) & \text{if } p_u^R \le u < \underline{p}_{u_1} \\ \underline{p}_w(u) = \underline{p}_{w_1} & \text{if } \underline{p}_{u_1} \le u \end{cases} \tag{3.1}$$

$$\begin{cases} \overline{p}_w(u) = \overline{p}_{w_0} + \overline{s}_{w01}\,u & \text{if } u < \overline{p}_{u_1} \\ \overline{p}_w(u) = \overline{p}_{w_1} & \text{if } \overline{p}_{u_1} \le u \end{cases} \tag{3.2}$$

Speed profiles

Figures 3.12 and 3.13 show two different zone models of **speed profiles** in TV, which describe subject speed in function of time. The first model, in Figure 3.12, corresponds to bringing the subject vehicle from its current speed to a certain target speed, with a certain average

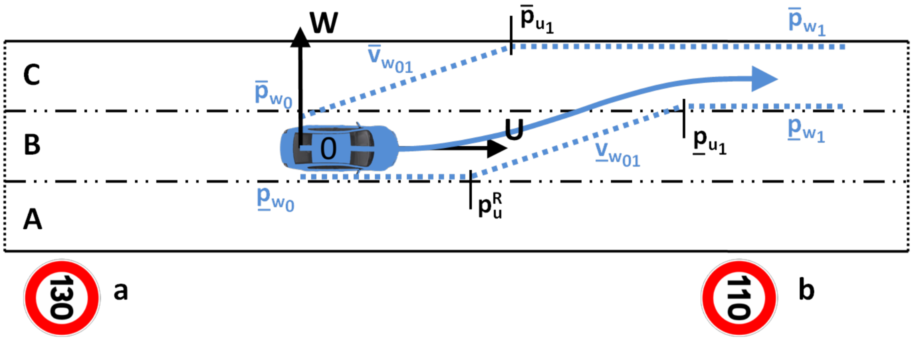


Figure 3.11: Zone model of trajectory of subject *0*: minimum and maximum trajectories (dashed lines) vs. an exemplary actual trajectory (continuous line)

acceleration. This is called **speed control** in this work. Its mathematical description is similar to the subject trajectory description, it is given in Equations 3.3 and 3.4. The minimum speed profile starts at current speed $\underline{v}_{u0}$. It consists of a linear section at constant acceleration $\underline{a}_{u01}$, followed by a constant section at target speed $\underline{v}_{u_1}$. The maximum speed profile follows a similar geometry, but integrates a **reaction time** t^R. The difference between $\underline{v}_{u_0}$ and $\overline{v}_{u0}$ corresponds to the error on the perception of subject speed, which is usually small and bounded by Rule 13. The difference between $\underline{v}_{u_t}$ and $\overline{v}_{u_t}$ allows an error on longitudinal speed control, in correspondence to Rule 15. This error corresponds to the **growth** in Table 2.8. *Growth* models speed control errors as if the subject *length* would increase in time. Equations 3.3 and 3.4 are given for speed profiles towards lower target speed, i.e. for deceleration. For speed profiles towards higher target speeds, the reaction time t^R is implemented on the minimum speed profile, instead of on the maximum speed profile. For speed profiles towards the current subject speed, no reaction time is needed.

$$\begin{cases} \underline{v}_u(t) = \underline{v}_{u0} + \underline{a}_{u01}\, t & \text{if } t < \underline{t}_1 \\ \underline{v}_u(t) = \underline{v}_{u_1} & \text{if } \underline{t}_1 \leq t \end{cases} \tag{3.3}$$

$$\begin{cases} \overline{v}_u(t) = \overline{v}_{u0} & \text{if } t < t^R \\ \overline{v}_u(t) = \overline{v}_{u0} + \overline{a}_{u01}\,(t - t^R) & \text{if } t^R \leq t < \overline{t}_1 \\ \overline{v}_u(t) = \overline{v}_{u_1} & \text{if } \overline{t}_1 \leq t \end{cases} \tag{3.4}$$

The zone model in Figure 3.12 and Equations 3.3 and 3.4 is not adequate for **distance control**, i.e. regulating distances to an object. As Figure 3.13 suggests, distance control usually involves reaching an intermediate speed, before reaching target speed. This requires a second zone model. The second zone model is inspired on algorithms in control theory [EMGL09], in Equation 3.5. Variables without superscript relate to the subject, variables with superscript O to the object being followed. This equation states that the subject acceleration is (a) offset with the object acceleration (i.e. when the object brakes, the subject brakes with the same deceleration) in the first term, (b) proportional with the difference in speeds between subject and object in the second term, and (c) proportional with the difference in distance between subject and object, with respect to a chosen target distance p_u^K in the third term. The target distance to the object p_u^K, is calculated from traffic rules, human rules and system rules, as will be explained in Section 3.4. The parameters k_p and k_v only depend on subject vehicle dynamics; they follow from stability analysis and tuning on vehicle.

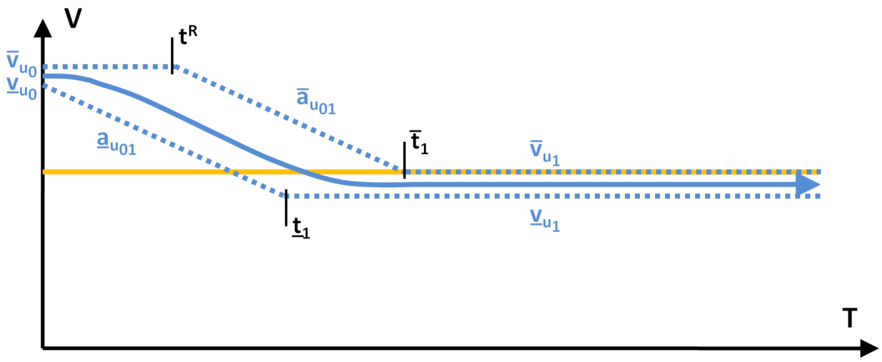


Figure 3.12: Zone model of speed profile for speed control of subject *0*: minimum and maximum speed profiles (dashed lines) vs. an exemplary actual speed profile (continuous line)

$$[a_u(t) - a_u^O(t)] + k_v\,[v_u(t) - v_u^O(t)] + k_p\,[p_u(t) - p_u^O(t) + p_u^K] = 0 \tag{3.5}$$

Equation 3.5 has the form $\ddot{x}(t) + k_v\,\dot{x}(t) + k_p\,x(t) = 0$, with $x(t) = p_u(t) - p_u^O(t) + p_u^K$, $\dot{x}(t) = v_u(t) - v_u^O(t)$ and $\ddot{x}(t) = a_u(t) - a_u^O(t)$. This is a second order homogeneous differential equation with constant coefficients, with simple analytical solution [Kha99]. If tuning parameters k_p and k_v are such that $4\,k_p - k_v^2 > 0$ (which is the case for all LIVIC, HAVEit and ABV simulators and vehicles) solving to $p_u(t)$ and differentiating to obtain the speed profiles gives Equations 3.6 and 3.7. Note that the only difference between the minimum speed profile $\underline{v}_u(t)$ and maximum speed profile $\overline{v}_u(t)$ is the sixth term with g_u^I, i.e. the **growth** of the speed profile. The first four terms correspond to regulating the distance to the object to p_u^K. The fifth term corresponds to following the minimum speed profile of the object. Note that in the equations, maximum values (overscored) are used for the subject and minimum values (underscored) for the object ahead. These values correspond to worst-case values, i.e. closest distance between subject and object. No reaction time t^R has been included in this model; t^R is integrated in the target distance p_u^K, as will be explained in Section 3.4.

Subject speed necessarily **stays positive** as driving in the opposite direction is prohibited on highways (Rule 10). The speed profiles are saturated to zero. This has not explicitly been indicated in Equations 3.3, 3.4, 3.6 and 3.7, in order not to overload the description unnecessarily.

$$\begin{aligned}\underline{v}_u(t) \;=\;& k_1\,k_3\,e^{k_1\,t}\,cos(k_2\,t) - k_2\,k_3\,e^{k_1\,t}\,sin(k_2\,t) + k_1\,k_4\,e^{k_1\,t}\,sin(k_2\,t) + k_2\,k_4\,e^{k_1\,t}\,cos(k_2\,t)\\ &+\underline{v}_u^O(t) - \tfrac{1}{2}\,g_u^I\end{aligned} \tag{3.6}$$

$$\begin{aligned}\overline{v}_u(t) \;=\;& k_1\,k_3\,e^{k_1\,t}\,cos(k_2\,t) - k_2\,k_3\,e^{k_1\,t}\,sin(k_2\,t) + k_1\,k_4\,e^{k_1\,t}\,sin(k_2\,t) + k_2\,k_4\,e^{k_1\,t}\,cos(k_2\,t)\\ &+\underline{v}_u^O(t) + \tfrac{1}{2}\,g_u^I\end{aligned} \tag{3.7}$$

with

$$\begin{cases} k_1 &= -\frac{1}{2}\,k_v\\ k_2 &= -\frac{1}{2}\,\sqrt{4\,k_p - k_v^2}\\ k_3 &= \underline{p}_{u0}^O + p_u^K\\ k_4 &= \frac{1}{k_2}\,(\overline{v}_{u0} - \underline{v}_{u0}^O - k_1\,k_3)\end{cases} \tag{3.8}$$

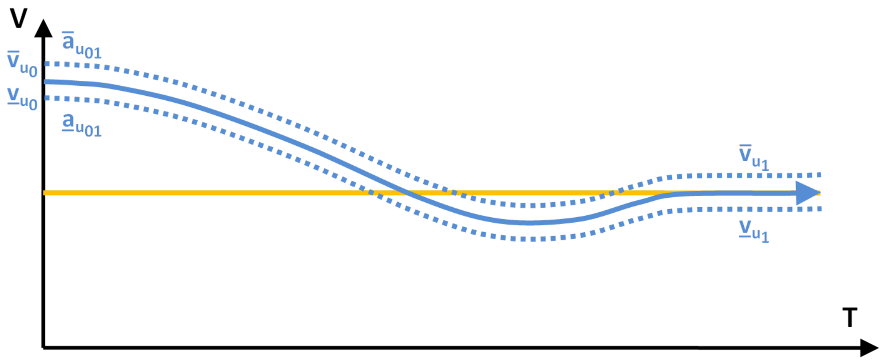


Figure 3.13: Zone model of speed profile for distance control of subject *0*: minimum and maximum speed profiles (dashed lines) vs. an exemplary actual speed profile (continuous line)

The zone model for subject trajectories and speed profiles shows that **decision performance** is closely related to **performance of perception and control**. State-of-the-art vehicle control can usually not cover the complete range of trajectories and speed profiles that is physically feasible on the vehicle. Control is often not adapted to decision, rather, decision is adapted to control; i.e. it only generates trajectories that are feasible with existing vehicle control. For the choice of the zone model for subject trajectories and speed profiles, test are performed on vehicle. The limitations of existing vehicle control are tested and then integrated in the zone model used by the decision component. Tests on vehicle control for different target positions p_{w_1} and slopes $s_{w_{01}}$ allow studying the zone model for subject trajectories. Similarly, tests with different target speeds v_{u_1} and accelerations $a_{u_{01}}$ specify the zone model for subject speed profiles. Smaller perception and control errors, and better knowledge of these errors by the decision component can lead to a narrower zone model in future system development. In order to decrease the difference between minimum and maximum trajectories and speed profiles, a more complex zone model would be needed. A narrower zone model allows increasing optimality of trajectories, i.e. enabling higher speeds, closer distances to objects and tighter lane changes, in certain situations.

3.2.3 Zone model for object trajectories

Similar to subject trajectories, an exact description of **object** trajectories is not realistic. An object trajectory cannot *exactly* be predicted by traffic rules, but only *within bounds* (e.g. Rule 6, Figure 2.6). The legal safety system uses a **zone description** for object trajectories, i.e. a minimum and maximum (worst-case) trajectory, between which the object is predicted to move. This section presents the **mathematical zone model** for object trajectories and speed profiles in UW.

Trajectories

Figure 3.14 and Equations 3.9 and 3.10 illustrate the zone model for **object trajectories**, indicated with superscript O. It is similar to the zone model for subject trajectories (Equations 3.1 and 3.2), except that the consideration of a reaction distance p_u^R is not needed. For objects a worst-case *zero* reaction distance is assumed. Traffic rules do not stipulate that objects should drive in the center of the lane, only that they keep sufficient lateral distance while overtaking other vehicles. The zone model of object trajectories covers the worst case, by (a) assuming that objects that are in the lane cover the complete lane width (b) assuming that objects which cross a lane markings will change lanes, whether activating indicators (i.e. conform traffic rules) or not (i.e. not conform traffic rules).

$$\begin{cases} \underline{p}_w^O(u) = \underline{p}_{w0}^O + \underline{s}_{w01}^O\, u & \text{if } u < \underline{p}_{u1} \\ \underline{p}_w^O(u) = \underline{p}_{w1}^O & \text{if } \underline{p}_{u1} \leq u \end{cases} \tag{3.9}$$

$$\begin{cases} \overline{p}_w^O(u) = \overline{p}_{w0}^O + \overline{s}_{w01}^O\, u & \text{if } u < \overline{p}_{u1} \\ \overline{p}_w^O(u) = \overline{p}_{w1}^O & \text{if } \overline{p}_{u1} \leq u \end{cases} \tag{3.10}$$

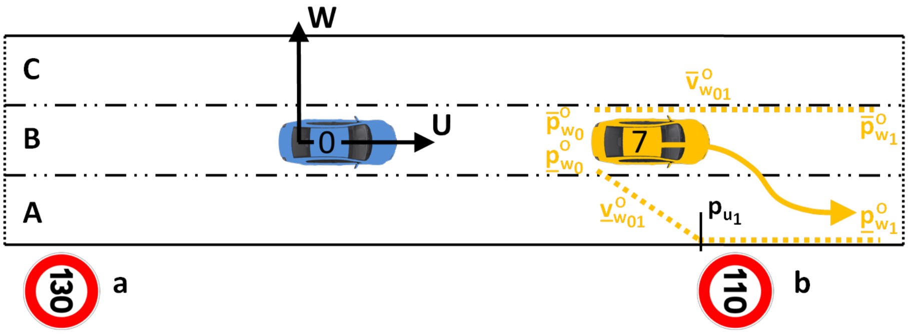


Figure 3.14: Zone model of trajectory of object *7*: minimum and maximum trajectories (dashed lines) vs. an exemplary actual trajectory (continuous line)

Speed profiles

Figure 3.15 and Equations 3.11 and 3.12 show the zone model of **object speed profiles**, which takes over the zone model of subject speed profiles for **speed control** (Equations 3.3 and 3.4), without reaction time t^R. For objects, no distance control model (Equations 3.6 and 3.7) is used. The speed control model accounts for worst-case object behavior. The zone model for object trajectories and speed profiles is also used for the description of stops (superscript Q) and phantoms (superscript P) in Section 3.3.

Like subject speed, object speed should be positive as driving in the opposite direction is prohibited on highways by Rule 10. In order to address the non-legal situation of a ghost object (i.e. an object moving in the opposite direction), the object speed is allowed to be negative, but is not allowed **to change signs**. This has not explicitly been indicated in Equations 3.9 and 3.10, in order not to unnecessarily complicate the speed profile descriptions.

$$\begin{cases} \underline{v}_u^O(t) = \underline{v}_{u0}^O + \underline{a}_{u01}^O\, t & \text{if } t < \underline{t}_1 \\ \underline{v}_u^O(t) = \underline{v}_{u1}^O & \text{if } \underline{t}_1 \leq t \end{cases} \tag{3.11}$$

$$\begin{cases} \overline{v}_u^O(t) = \overline{v}_{u0}^O + \overline{a}_{u01}^O\, t & \text{if } t < \overline{t}_1 \\ \overline{v}_u^O(t) = \overline{v}_{u1}^O & \text{if } \overline{t}_1 \leq t \end{cases} \tag{3.12}$$

Sections 3.3, 3.4, 3.5 and 3.6 describe the prediction of object trajectories and generation, evaluation and selection of subject trajectories, in correspondence to the general scheme of trajectory planning in Figure 3.1. These sections give the description of the **unknown variables**

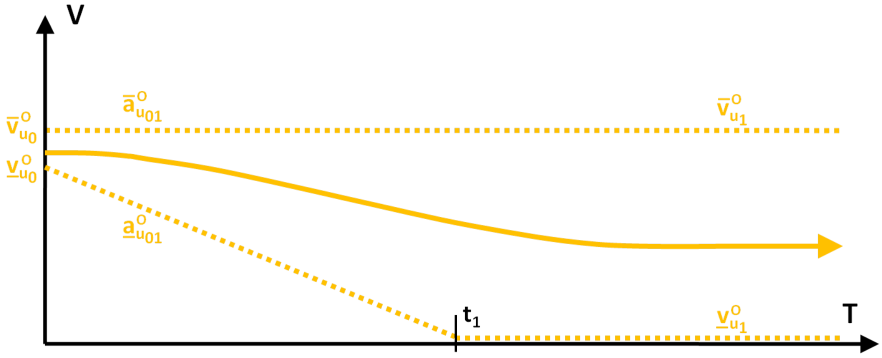


Figure 3.15: Zone model of speed profile of object *7*: minimum and maximum speed profiles (dashed lines) vs. an exemplary actual speed profile (continuous line)

in the Equations 3.1 - 3.12. For trajectories, unknown variables are start positions p_{w_0}, target positions p_{w_1} and average slopes $s_{w_{01}}$. For speed profiles, unknown variables are start speeds v_{u_0}, target speeds v_{u_1}, average accelerations $a_{w_{01}}$ and target distance p_u^K.

3.3 Prediction of object trajectories

The prediction of object trajectories is the first step of most trajectory planning algorithms (see Figure 3.1). A common approach is to assume that an object will **continue its current movement**, without taking into account environment structure. For example, a Kalman filter or one of its derivatives is used, together with one or several motion models such as Constant Turning Rate and Acceleration (CTRA) [BSL95, SRW08]. This supposes deterministic object behavior; one trajectory per object is computed.

Another approach is to calculate the **probability of all possible object movements**, e.g. with Gaussian distribution. Random object behavior can be analyzed with Monte Carlo sampling [EP08, LGSP08, WYY09, GVMG11, MJS11], abstracted as a Markov chain [AM11] or modeled with an IMM (Interacting Multiple Model) algorithm [GLR$^+$11]. The subject trajectory is then calculated as a tradeoff between subject speed and the number of collisions with the randomly moving objects. It is however not clear what is an acceptable threshold for this collision *risk*. It seems difficult to defend that reasonably foreseeable object behavior and unforeseeable object behavior are considered on an equal basis. This approach can however be defended for applications that do not intent continuous vehicle control for highly or fully automated driving. For example, probabilistic approaches are used in Collision Mitigation Avoidance Systems (CMAS) that estimate all possible (i.e. realistic and non-realistic) object trajectories in order to avoid system activation that is not indispensable.

Sometimes, the **relationship between object and environment structure** is taken into account in object trajectory prediction, e.g. analysis of *time to lane crossing* for the estimation of an object lane change [GVM$^+$10]. Some work takes into account object attributes other than dynamics, e.g. the state of object **indicators** [HWC$^+$11].

By not taking traffic rules into account, the approaches described above frequently **underestimate or overestimate** the danger that an object represents. For example, when an object is moving straight with its indicators activated, a lane change can be expected, but lane keeping is predicted according to a motion model. When an object moves towards the middle of its lane without activating indicators, lane keeping can be expected, but lane changing would be predicted with a motion model. Assuming random object behavior usually overestimates danger in safe situations, and underestimates danger in dangerous situations.

This section presents the use of **traffic rules** (listed in Section 2.2) as a natural basis for object trajectory prediction. The legal safety system does not only consider legal object behavior (Legal and Safe (LS) situations) but also reasonably foreseeable non-legal behavior, i.e. driving defensively (Not Legal, but Safe (NLS) situations). It should however not anticipate unforeseeable non-legal behavior, but only act when this behavior actually occurs. A minimum amount of confidence must exist between drivers (i.e. driving systems or human drivers) in order to allow sharing the road. Recently, other work has been presented that base object trajectory prediction on road structure and traffic rules, notably on the estimation of object intentions on intersections [LLIG11, LLIGB11].

The zone model for object trajectories and speed profiles was presented in Section 3.2. The zone model corresponds to a **uniform, bounded distribution object trajectories**, e.g. between lane keeping and lane changing. The use of the zone model is more conservative than deterministic approaches, which only analyze one object trajectory. It is less conservative than probabilistic approaches, which only place weak bounds on object trajectories, or no bounds at all.

3.3.1 Object trajectories and speed profiles

Trajectories

The maximum number of objects described by perception is eight. These objects correspond to closest objects ahead of and behind the subject in each of the three lanes, and objects on the side of the subject, as was illustrated in Figure 2.16. Objects that are two lanes to the right or two lanes to the left and which indicate to change lanes towards the subject are incorporated as objects to the sides, as was explained in Section 2.6. Figure 3.16 presents possible **trajectories for these eight potential objects** (*1-8*) around the subject vehicle (*0*), according to the traffic rules. The object trajectories are described with the **zone model** of Equations 3.9 and 3.10 presented in Section 3.2. For objects, the parameters of Equation 3.9 (minimum trajectories) correspond either to Equation 3.13 (lane keeping) or Equation 3.15 (lane changing), as will be described below. The parameters of Equation 3.10 (maximum trajectories) correspond either to Equation 3.14 (lane keeping) or Equation 3.16 (lane changing).

The default trajectory for objects corresponds to **lane keeping**. For lane keeping, the parameters of the minimum and maximum trajectories of the zone model are specified in Equations 3.13 and 3.14, respectively. The trajectory start positions ($\underline{p}^O_{w_0}$ and $\overline{p}^O_{w_0}$) corresponds with the position of the **corresponding lane marking** ($\underline{p}^L_w$ or $\overline{p}^L_w$). Objects are predicted to occupy the complete lane, as their exact future position in the lane is not known and neither specified by traffic rules. For lane keeping, the target positions ($\underline{p}^O_{w_1}$ and $\overline{p}^O_{w_1}$) are equal to start positions $\underline{p}^O_{w_0}$ and $\overline{p}^O_{w_0}$ and slopes ($\underline{s}^O_{w_{01}}$ and $\overline{s}^O_{w_{01}}$) are zero. Lane keeping trajectories are predicted for **all objects, except *2***, behind the subject, as Figure 3.16 illustrates. Object 2 is assumed to keep an appropriate distance from the subject in all circumstances (e.g. even if the subject performs emergency braking), according to Rule 3. Adapting to the lane keeping trajectory of object *2* goes beyond reasonably limits of defensive driving. Because of this, the lane keeping trajectory of object *2* is not calculated.

$$\begin{cases} \underline{p}^O_{w_0} &= \underline{p}^L_w \\ \underline{p}^O_{w_1} &= \underline{p}^L_w \\ \underline{s}^O_{w_{01}} &= 0 \end{cases} \tag{3.13}$$

$$\begin{cases} \overline{p}^O_{w_0} &= \overline{p}^L_w \\ \overline{p}^O_{w_1} &= \overline{p}^L_w \\ \overline{s}^O_{w_{01}} &= 0 \end{cases} \tag{3.14}$$

According to Rule 6, objects *2* and *7* have priority on the subject when **changing lanes** if their **indicators** (i^O_R or i^O_L in the object description in Table 2.5) are activated, and if the subject has not activated indicators before. In this case, a lane change is predicted for these objects. Other objects that change lanes must give priority to the subject. No objects should hinder the subject by changing lanes towards subject lane B, whether they activate indicators, or not. This means that, in principle, the lane changing trajectories of objects other than *2* and *7* should not be predicted. However, the system is more defensive than strictly needed by traffic rules by predicting, and adapting to, **non-legal object trajectories** towards lane B for objects *6* and *8*, as illustrated in Figure 3.16. For objects *1*, *3*, *4* and *5* behind and on the side of the subject, lane change trajectories to B are not predicted. Adapting to objects behind or on the side that move towards the subject lane goes beyond reasonable limits of defensive driving.

Legally (by Rule 6), the only possibility for objects to change lanes is by activating indicators. However, in order to promote defensive driving, the subject also predicts that objects *2*, *6*, *7* and *8* **change lanes non-legally** when they are **crossing a lane marking** without activating indicators, whether these lane markings are continuous or not. The lateral position of the object p^O_w to analyze whether it crosses the lane marking, or not, is given in the object description in Table 2.5. A reliable measurement of this variable is still a challenge for state-of-the-art perception, but will probably be available in medium term. The detection of non-legal object lane changes could be refined by analyzing variables that are even harder to measure, e.g. object lateral speed in the lane (e.g. time to lane crossing), object lateral acceleration or object heading angle [KWD+11]. For object *2*, on the subject lane, behind the subject vehicle, a lane change to the right (minimum trajectory) and lane change to the left (maximum trajectory) could be predicted if it approaches at high speed, which indicates that it will probably overtake the subject vehicle. An other application of defensive driving principles would be to monitor object behavior over time, e.g. an object that is swarming in the lane could be predicted to change lanes. Or, as human drivers probably do, the system could calculate **optimal object trajectories around obstacles seen from an object point of view, as if the subject were not there**. Recently work has been presented where object trajectories on intersections are predicted according to the presence of other objects, assuming that all object positions are known [LLIGB11]. The perception of objects ahead of objects *6*, *7* or *8* on highways is beyond reach of state-of-the-art perception, by become possible in medium term. With the prediction of trajectories from an object point of view, the driving system could implement some *courteousness* towards other drivers, e.g. by creating a gap for objects on the entrance ramp [MGVP11], or by giving objects in front the possibility to overtake slower objects. This is however not needed by traffic rules and is not described in this work. In its current development, the decision component only considers object position in the lane (i.e. crossing lane marking or not) and indicator status.

Object lane changing trajectories towards the right ($L-1$) and left ($L+1$) are defined by Equations 3.15 and 3.16. The start position of the trajectory ($\underline{p}^O_{w_0}$ or $\overline{p}^O_{w_0}$) corresponds to the **position of the corresponding lane marking** (indicated as $\underline{p}^L_w$ or $\overline{p}^L_w$). The target position

($\underline{p}^O_{w_1}$ or $\overline{p}^O_{w_1}$) corresponds to the position of the corresponding lane marking on the target lane. As the slope of the lane change ($\underline{s}^O_{w_{01}}$ or $\overline{s}^O_{w_{01}}$) cannot be known, a worst-case lane change with a high slope s^G_w, is assumed. The maximum slope of objects is set by limits on vehicle dynamics. In order to be on the safe side, values reached by sport cars could be used. If object perception manages to distinguish between different types of vehicles (i.e. variable k^O in Table 2.5), the value of maximum slope could be refined. For example, trucks cannot reach the same slope values as cars [RZ03]. Integrating lower trajectory slopes for trucks would allow a more realistic trajectory prediction and allow a more assertive subject behavior in certain situations.

$$\begin{cases} \underline{p}^O_{w_0} & = & \underline{p}^L_w \\ \underline{p}^O_{w_1} & = & \underline{p}^{L-1}_w \\ \underline{s}^O_{w_{01}} & = & -s^G_w \end{cases} \tag{3.15}$$

$$\begin{cases} \overline{p}^O_{w_0} & = & \overline{p}^L_w \\ \overline{p}^O_{w_1} & = & \overline{p}^{L+1}_w \\ \overline{s}^O_{w_{01}} & = & s^G_w \end{cases} \tag{3.16}$$

Note that for an object with a minimum/maximum trajectory for lane changing, the other trajectory corresponds with lane keeping, as if it were **expanding in the future**. This reflects the uncertainty whether the lane change will actually take place or not. When there is a reason to belief that the object could perform any possible maneuver (lane keeping, lane changing to the right or to the left), minimum and maximum trajectories correspond to lane changing to the right and to the left respectively. Note also that, as objects **fill the complete start and target lane**, the system does not attempt to find solutions that consist in sharing a part of a lane with an object, even in situations where such solution exists.

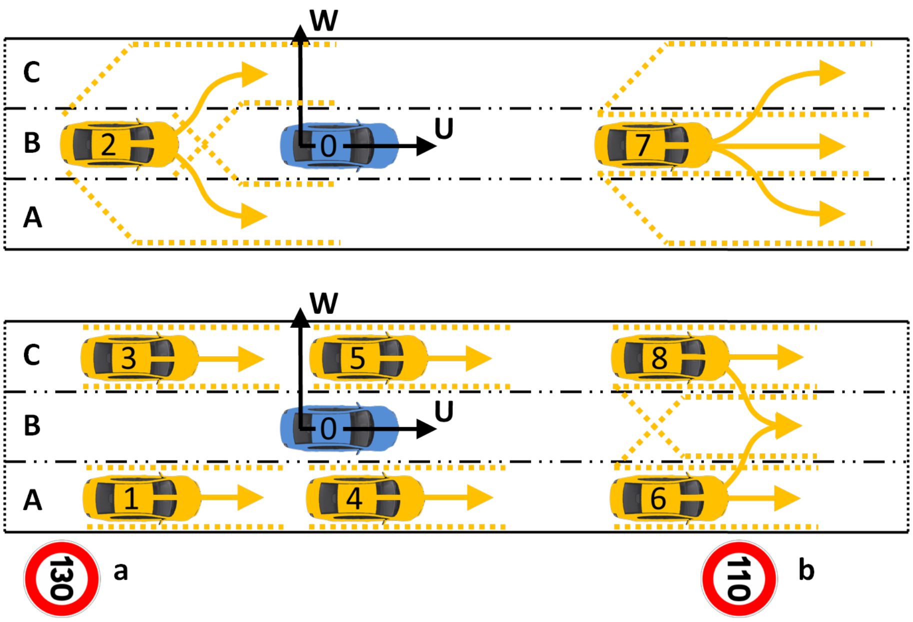


Figure 3.16: Prediction of trajectories of objects *1* to *8* in function of position with respect to subject *0*. Overview of possibilities according to traffic rules

Speed profiles

Figure 3.17 illustrates the prediction of **object speed profiles**. Equation 3.17 (for keeping speed) or 3.18 (for decelerating) defines the minimum speed profile according to the model in Equation 3.11, as will be explained below. Equation 3.19 (for keeping speed) or 3.20 (for acceleration) defines the maximum speed profile according Equation 3.12.

The objects are believed to expand between two **worst-case speed profiles** according to their position with respect to the subject, as illustrated in Figure 3.17. For objects **behind and on the side of the subject** (*1 - 5*), a minimum speed profile corresponds to keeping speeds, in Equation 3.17. If these objects are accelerating, their maximum speed profile corresponds to continuing accelerating till the maximum speed that can reasonably be reached in the environment (without taking into account speed limits; these might be neglected by the object) v_u^G, in Equation 3.20. If objects behind or on the side are keeping speed or are decelerating, both minimum and maximum speed profiles correspond to keeping speeds, Equation 3.19. The driving system is conservative by not relying on the fact that an object behind the subject that is decelerating, keeps decelerating. It takes into account the possibility that the object refrains from decelerating and holds its speed. This conservative prediction precluded subject lane changes in certain situations.

An opposite logic is followed for **objects on the side and ahead** (*4 - 8*). Minimum speed profiles for objects on the side and ahead, which are decelerating, continue decelerating till zero speed, in Equation 3.17. If these objects are keeping speed or accelerating, their minimum trajectories correspond to keeping speed, in Equation 3.17. In a similar conservative approach as for objects behind, maximum speed profiles for objects on the side an ahead always correspond to keeping speed, in Equation 3.19.

The legal safety system considers the possibility that object speed profiles offend traffic rules, which is a principle of defensive driving. For example, it allows predictions where objects overtake other objects (including the subject) on the right, despite Rule 6. Objects can also be predicted to exceed speed limits, despite Rule 3.

$$\begin{cases} \underline{v}_{u0}^O &= v_u^O \\ \underline{v}_{u1}^O &= v_u^O \\ \underline{a}_{u01}^O &= 0 \end{cases} \tag{3.17}$$

$$\begin{cases} \underline{v}_{u0}^O &= v_u^O \\ \underline{v}_{u1}^O &= 0 \\ \underline{a}_{u01}^O &= a_u^O \end{cases} \tag{3.18}$$

$$\begin{cases} \overline{v}_{u0}^O &= v_u^O \\ \overline{v}_{u1}^O &= v_u^O \\ \overline{a}_{u01}^O &= 0 \end{cases} \tag{3.19}$$

$$\begin{cases} \overline{v}_{u0}^O &= v_u^O \\ \overline{v}_{u1}^O &= v_u^G \\ \overline{a}_{u01}^O &= a_u^O \end{cases} \tag{3.20}$$

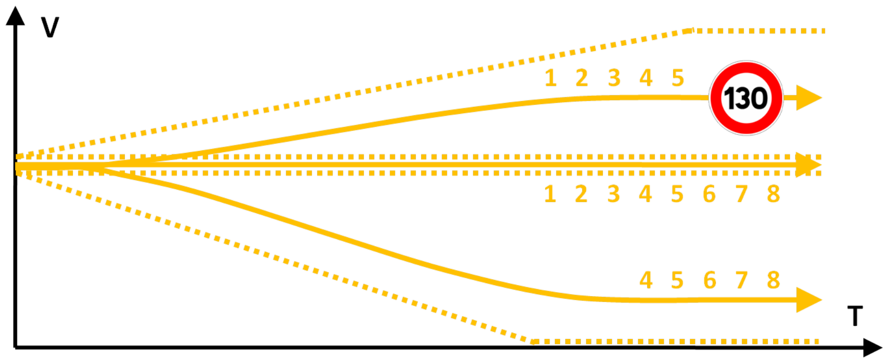


Figure 3.17: Prediction of speed profiles of objects *1* to *8* in function of position with respect to subject *0*. Overview of possibilities according to traffic rules

3.3.2 Stop trajectories and speed profiles

Section 2.6 has presented **stops**. Stops are still standing, virtual objects that model that the end of a lane, e.g. the end of an entrance ramp or the end of the application zone. Stops are denoted with a superscript Q. The description of stop trajectories according to the zone model takes over the description of object trajectories, but for stops lane changes are not considered. Equations 3.21 and 3.22 give the trivial trajectory description, and Figure 3.18 illustrates it.

$$\begin{cases} \underline{p}^Q_{w0} & = & \underline{p}^L_w \\ \underline{p}^Q_{w1} & = & \underline{p}^L_w \\ \underline{s}^Q_{w01} & = & 0 \end{cases} \tag{3.21}$$

$$\begin{cases} \overline{p}^Q_{w0} & = & \overline{p}^L_w \\ \overline{p}^Q_{w1} & = & \overline{p}^L_w \\ \overline{s}^Q_{w01} & = & 0 \end{cases} \tag{3.22}$$

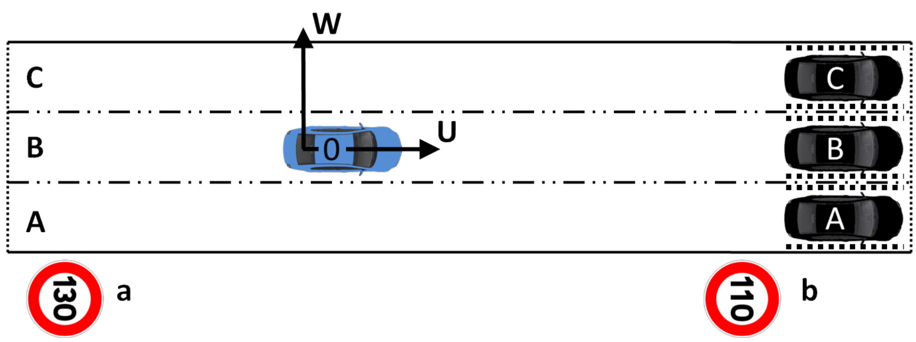


Figure 3.18: Prediction of trajectories of possible stops A, B and C ahead of subject *0*

Stop speed profiles, in Equations 3.23 and 3.24 and Figure 3.19, correspond to object speed profiles at zero speed.

$$\begin{cases} \underline{v}_{u_0}^{Q} & = & 0 \\ \underline{v}_{u_1}^{Q} & = & 0 \\ \underline{a}_{u_{01}}^{Q} & = & 0 \end{cases} \tag{3.23}$$

$$\begin{cases} \overline{v}_{u_0}^{Q} & = & 0 \\ \overline{v}_{u_1}^{Q} & = & 0 \\ \overline{a}_{u_{01}}^{Q} & = & 0 \end{cases} \tag{3.24}$$

Figure 3.19: Prediction of speed profiles of possible stops A, B and C ahead of subject *0*

3.3.3 Phantom trajectories and speed profiles

Rule 3 stipulates that the subject vehicle must be able of avoiding collisions with **potential objects outside the perception zone**. For this purpose, trajectories of phantoms, worst-case virtual objects and stops at the limits of the perception zone, are calculated. Figures 3.20 and 3.21 illustrate phantom trajectories and speed profiles. As driving in the opposite direction is prohibited on highways by Rule 7, worst-case phantoms ahead of the subject correspond to **still standing objects**, labeled *IV*, *V* and *VI*. This also covers worst-case **stops** out of the perception zone. By considering phantoms, the legal safety system limits its speed so that it is able to brake for traffic congestion (i.e. objects) or end of a lane (i.e. stops) that appears at the end of the perception horizon, as will be explained in Section 3.4.

Behind the subject, worst-case phantoms *I* and *III* correspond to vehicles traveling **at speed limit**. This prevents the subject from overtaking a slower vehicle when subject speed and/or perception horizon to the rear are low, as will be explained in Section 3.5. In order to drive more defensively, the subject could consider a phantom that travels faster than the speed limit, i.e. non-legally. In non-congested traffic, the phantom *I* on the right lane could be ignored, as no object is allowed to right overtake the subject by Rule 6. However, a phantom *I* that travels at speed limit is considered as a part of defensive driving. Phantom *II* is never considered as the subject vehicle has priority over vehicles that come from behind on the subject lane by Rule 3.

Equations 3.25 - 3.28 give the specification of phantom trajectories and speed profiles according to the zone model. As for stops, these are a simplified version of the object equations, without lane changes and without deceleration or acceleration.

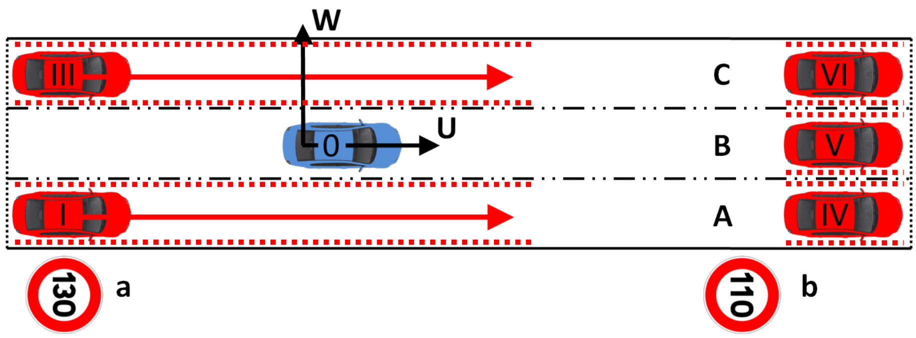


Figure 3.20: Prediction of trajectories of phantoms *I*, *III*, *IV*, *V* and *VI* in function of position with respect to subject *0*, according to traffic rules

Figure 3.21: Prediction of speed profiles of phantoms *I*, *III*, *IV*, *V* and *VI* in function of position with respect to subject *0*, according to traffic rules

$$\begin{cases} \underline{p}^P_{w0} & = & \underline{p}^L_w \\ \underline{p}^P_{w1} & = & \underline{p}^L_w \\ \underline{s}^P_{w01} & = & 0 \end{cases} \tag{3.25}$$

$$\begin{cases} \overline{p}^P_{w0} & = & \overline{p}^L_w \\ \overline{p}^P_{w1} & = & \overline{p}^L_w \\ \overline{s}^P_{w01} & = & 0 \end{cases} \tag{3.26}$$

$$\begin{cases} \underline{v}^P_{u0} & = & 0 \text{ or } v^S_u \\ \underline{v}^P_{u1} & = & 0 \text{ or } v^S_u \\ \underline{a}^P_{u01} & = & 0 \end{cases} \tag{3.27}$$

$$\begin{cases} \overline{v}^P_{u0} & = & 0 \text{ or } v^S_u \\ \overline{v}^P_{u1} & = & 0 \text{ or } v^S_u \\ \overline{a}^P_{u01} & = & 0 \end{cases} \tag{3.28}$$

3.4 Generation of subject trajectories

After predicting object trajectories, the decision component generates 7 candidate subject trajectories, as was indicated in Table 3.2. Figures 3.22 and 3.23 sketch the **7 speed profiles and**

trajectories. Three optimal trajectories, one per target lane, are calculated for normal system functioning; *0A*, *0B* and *0C*. Additionally, three Minimum Risk Maneuver (MRM) trajectories, one per target lane, have a terminal speed of zero and are to be used during system failure functioning and situations of driver distraction or drowsiness; *FA*, *FB* and *FC*. One trajectory for emergency braking in the subject lane, *JB*, is calculated to mitigate collisions if an accident cannot be avoided, in certain cases of non-legal object behavior.

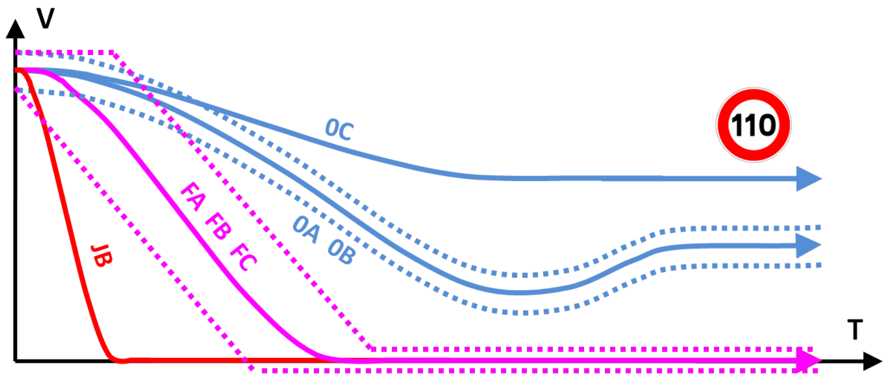


Figure 3.22: Generation of 7 speed profiles for subject: 3 for normal functioning (*0A*, *0B*, *0C*), 3 for failure functioning (*FA*, *FB*, *FC*) and 1 for emergency braking (*JB*). The zone model for speed profiles *0A*, *0B*, *FA*, *FB* and *FC* is indicated

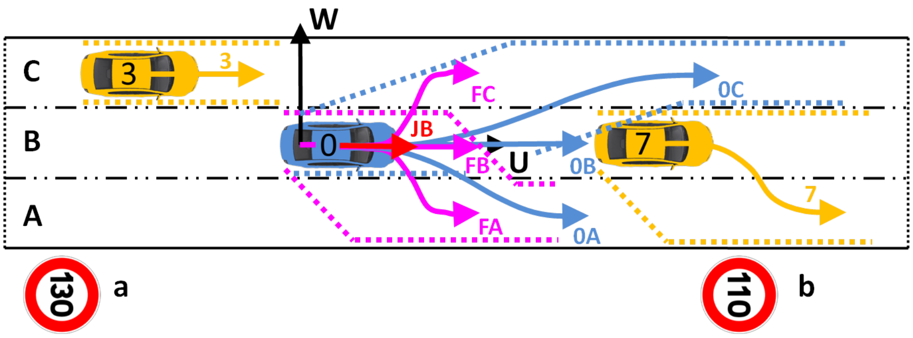


Figure 3.23: Generation of 7 trajectories for subject: 3 for normal functioning (*0A*, *0B*, *0C*), 3 for failure functioning (*FA*, *FB*, *FC*) and 1 for emergency braking (*JB*). The zone model for trajectories *FA* and *0C* is indicated

The decision component first calculates speed profiles, and then calculates trajectories. This approach is **opposite to the classic path-velocity decomposition approach** [KZ86], which first calculates trajectories and then adapts the speed profile to match environment dynamics, as mentioned in Section 3.1. This section first presents optimal subject speed profiles according to several individual aspects of legal safety, respectively in Sections 3.4.1, 3.4.2, 3.4.3, 3.4.4, 3.4.5 and 3.4.6. Such speed profiles are called *individual* speed profiles. After the calculation of individual speed profiles, the legal safety subject speed profile is calculated as the **minimum of these individual speed profiles**. This is illustrated for *0C* in Figure 3.24. It is related to what in control theory is called *override control* [LAB+11]. After the calculation of speed profiles, trajectories in *UW* are calculated. A legal safety subject trajectory is found as the

maximum (in absolute value) of individual trajectories presented in Sections 3.4.7, 3.4.8 and 3.4.9. This is illustrated for *0C* in Figure 3.25.

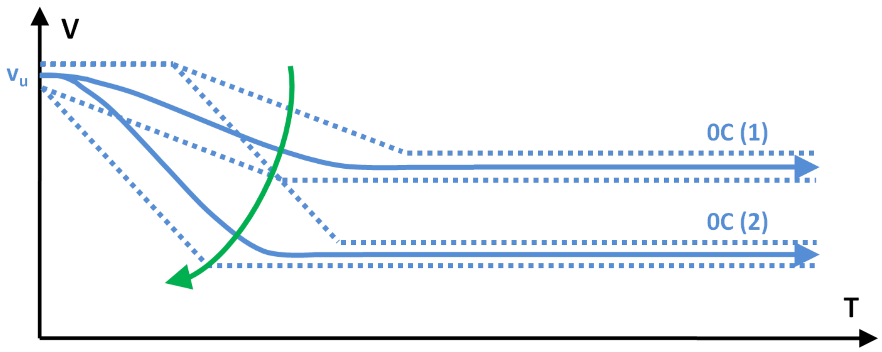


Figure 3.24: A subject speed profile is calculated as the minimum of individual speed profiles for each aspect of legal safety. Illustration with two individual speed profiles for *0C*

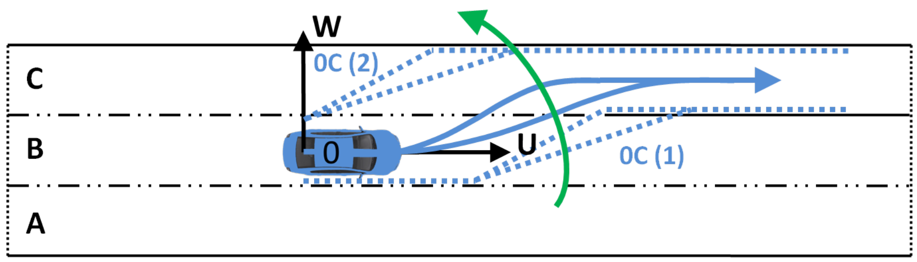


Figure 3.25: A subject trajectory is calculated as the maximum (in absolute value) of individual trajectories for each aspect of legal safety. Illustration with two individual trajectories for *0C*

According to the zone model presented in Section 3.2 (Equations 3.1 - 3.8), six parameters define the zone description of individual subject speed profiles; $\underline{v}_{u0}$, $\underline{v}_{u1}$, $\underline{a}_{u01}$, $\overline{v}_{u0}$, $\overline{v}_{u1}$, $\overline{a}_{u01}$. Six parameters define the zone description of individual subject trajectories; $\underline{p}_{w0}$, $\underline{p}_{w1}$, $\underline{s}_{w01}$, $\overline{p}_{w0}$, $\overline{p}_{w1}$, $\overline{s}_{w01}$. **Nine of these parameters do not need to be calculated**, as they directly follow from other parameters, as is indicated in Equations 3.29 and 3.30. In Equation 3.29, the minimum and maximum start speed of speed profiles $\underline{v}_{u_0}$ and $\overline{v}_{u_0}$, correspond to the minimum and maximum current subject speed according to perception measurements. The minimum target speed $\underline{v}_{u_1}$ is equal to the maximum target speed minus speed error, growth g_u^I. The minimum acceleration $\underline{a}_{u_{01}}$ is equal to the maximum acceleration. In Equation 3.30, the minimum and maximum start position of trajectories $\underline{p}_{w_0}$ and $\overline{p}_{w_0}$ follow from the size of the subject vehicle. The minimum and maximum target position take the borders of the target lane L. For trajectories towards higher lateral positions, $\overline{s}_{w_{01}}$ directly follows from $\underline{s}_{w_{01}}$, as in the equation. For clarity, the description in this work will only be given for trajectories towards higher lateral positions. Trajectories towards lower lateral positions, $\underline{s}_{w_{01}}$ changes roles with $\overline{s}_{w_{01}}$.

$$\begin{cases} \underline{v}_{u_0} & = & \underline{v}_u \\ \underline{v}_{u_1} & = & \overline{v}_{u_1} - g_u^I \\ \underline{a}_{u01} & = & \overline{a}_{u01} \\ \overline{v}_{u_0} & = & \overline{v}_u \\ \overline{v}_{u_1} & = & \text{to be calculated} \\ \overline{a}_{u01} & = & \text{to be calculated} \end{cases} \tag{3.29}$$

$$\begin{cases} \underline{p}_{w_0} & = & \underline{p}_w \\ \underline{p}_{w_1} & = & \underline{p}_w^L \\ \underline{s}_{w01} & = & \text{to be calculated} \\ \overline{p}_{w_0} & = & \overline{p}_w \\ \overline{p}_{w_1} & = & \overline{p}_w^L \\ \overline{s}_{w01} & = & \underline{s}_{w01} \end{cases} \tag{3.30}$$

The calculation of the **three remaining parameters**, $\overline{v}_{u_1}$, $\overline{a}_{u01}$ and $\underline{s}_{w01}$ for individual speed profiles and trajectories is presented in Sections 3.4.1 to 3.4.9. These calculations are done for each of the three target lanes (A, B and C), for normal functioning (0), failure functioning (F) and emergency braking (J). Throughout the description, the example situation in Figures 3.22 and 3.23 will be followed.

3.4.1 Subject speed profile for friction limits, human limits and system limits (longitudinal)

A first condition on the subject speed profile is that it respects friction limits (superscript G), human limits (superscript H) and system limits (superscript I). In Section 3.4.1, individual speed profiles according to **longitudinal limits** are discussed. Section 3.4.2 discusses individual speed profiles according to **lateral limits**.

The most extreme deceleration profile that is possible according to longitudinal friction limits, human limits and system limits corresponds to an **emergency deceleration** $-a_u^J$ till standstill. This speed profile is described in Equations 3.31 and 3.32 and is illustrated in Figure 3.26. The parameter k_u^G indicates which part of the ideal deceleration $-\mu^L g$ can be delivered by the subject tires, with μ^L the road friction estimated by perception. As was explained in Section 2.6, μ^L corresponds to a worst-case estimation of road friction. Uncertainty on the road friction measurement must be bounded (i.e. the worst-case estimation must not be zero), in order to allow highly or fully automated driving according to legal safety. The most extreme deceleration allowed by the human driver and driving system are $-a_u^H$ and $-a_u^I$, respectively. These parameters are to be set so that most extreme deceleration chosen by the decision component is acceptable for the human driver and respects limits of perception of control. All individual speed profiles (*0A*, *0B*, *0C*, *FA*, *FB*, *FC*, *JB*) will be described in Sections 3.4.2 to 3.4.6 are limited to the emergency deceleration profile in Equation 3.32.

$$\begin{cases} a_u^G & = & k_u^G \, \mu^L \, g \\ a_u^J & = & min(a_u^G, a_u^H, a_u^I) \end{cases} \tag{3.31}$$

$$\begin{cases} \underline{v}_{u_1} & = & 0 \\ \underline{a}_{u01} & = & -a_u^J \end{cases} \tag{3.32}$$

The maximum speed profile for *0A*, *0B* and *0C* corresponds to a **comfort deceleration/acceleration** $\pm a_u^K$ towards maximum speed v_u^K in Equation 3.34. Like a_u^J, the value a_u^K is bounded by longitudinal friction limits, system limits and human limits, in Equation 3.33. The human driver sets the comfort acceleration indirectly by specifying a driving style k^H in the human-to-system interactor (Table 2.10). The speed v_u^K is the maximum speed allowed by human driver (v_u^H, in the human-to-system interactor) and by driving system components (v_u^I, a system design limit). Note that values of a_u^G, a_u^H and a_u^I for the maximum speed profile (a_u^K) in Equation 3.33 are usually smaller than values for the emergency deceleration (a_u^J) in Equation 3.31.

$$\begin{cases} a_u^G &= k_u^G \, \mu^L \, g \\ a_u^K &= min(a_u^G, a_u^H, a_u^I) \\ v_u^K &= min(v_u^H, v_u^I) \end{cases} \tag{3.33}$$

$$\begin{cases} \overline{v}_{u_1} &= v_u^K \\ \overline{a}_{u_{01}} &= \pm \, a_u^K \end{cases} \tag{3.34}$$

The **Minimum Risk Maneuver (MRM)** speed profiles *FA*, *FB* and *FC* are found by replacing v_u^K in Equation 3.34 by zero and $-a_u^K$ by a deceleration value $-a_u^F$, which can be chosen between $-a_u^K$ and $-a_u^J$. This results in Equation 3.35. For the **emergency** speed profile *JB*, the extreme deceleration value $-a_u^J$ is chosen, corresponding to Equation 3.36. Speed profiles for MRM and emergency braking are illustrated in Figure 3.26.

$$\begin{cases} \overline{v}_{u_1} &= 0 \\ \overline{a}_{u_{01}} &= -a_u^F \end{cases} \tag{3.35}$$

$$\begin{cases} \overline{v}_{u_1} &= 0 \\ \overline{a}_{u_{01}} &= -a_u^J \end{cases} \tag{3.36}$$

The **speed-acceleration map** in Figure 3.27 illustrates that the acceleration range from $-a_u^J$ to $+a_u^K$ usually changes with the subject speed v_u. At lower speeds, larger accelerations a_u^K are usually possible, while decelerations $-a_u^K$ and $-a_u^J$ generally do not change over the speed range. The figure indicates that for a speed profile, the lowest acceleration value a_u^K for the corresponding speed range is taken. For example, when accelerating from current speed *0* to speed *1*, the value a_u^K at speed *1* is taken. When decelerating to speed *2*, the value a_u^K at speed *0* is used.

If the friction μ^L is equal for all lanes, the speed profiles *0A*, *0B* and *0C* are identical, as Figure 3.26 suggests. This is also the case for speed profiles *FA*, *FB* and *FC*.

Equations 3.34, 3.35 and 3.36 describe the individual speed profiles for *0A*, *0B*, *0C*, *FA*, *FB*, *FC* and *JB*, with respect to longitudinal friction limits, human limits and system limits. As was explained above, each subsequent aspect of legal safety, described in Sections 3.4.2 to 3.4.6, further limit (i.e. decrease) these speed profiles. Note that, as *JB* already corresponds with the most extreme deceleration, it does not change under further limitations.

3.4.2 Subject speed profile for friction limits, human limits and system limits (lateral)

A second set of individual speed profiles takes into account friction limits, human limits and system limits in the **lateral direction**. **Speed in a curved lane** generates a centrifugal,

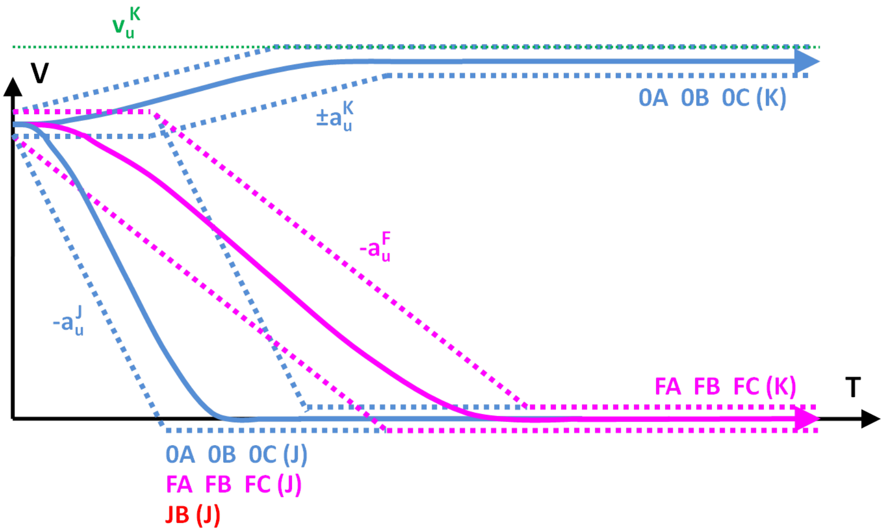


Figure 3.26: Generation of individual subject speed profiles *0A*, *0B*, *0C*, *FA*, *FB*, *FC* and *JB* with respect to longitudinal friction limits, human limits and system limits (superscripts J and K)

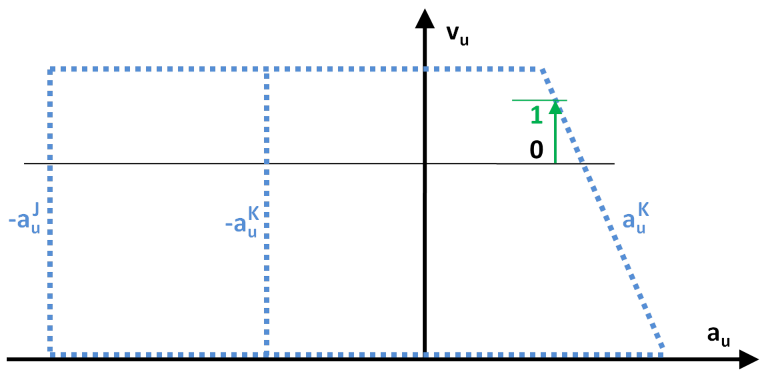


Figure 3.27: The speed-acceleration map for subject speed profiles

lateral acceleration. The maximum lateral acceleration a_w^K takes into account the maximum lateral acceleration by **friction limits** (a_w^G), **human limits** (a_w^H, which is indirectly set by the human driver via the driving style k^H) and **system limits** (a_w^I, which is required for the optimal functioning of perception and control components).

The maximum lateral acceleration without slipping a_w^G is calculated in Equation 3.37. The factor k_w^G depends on the vehicle tires, like k_u^G in Equations 3.31 and 3.33. Note that factor k_w^G in Equation 3.37 is dependent of the factor k_u^G in Equation 3.31, according to the **friction ellipse** that models the friction between the road surface and vehicle tires [Won01]. Increasing k_u^G means decreasing k_w^G, and vice versa. The values of k_u^G and k_w^G are chosen as a compromise between longitudinal emergency deceleration a_u^J (which allows higher speeds with respect to phantoms, as will be discussed later) and lateral comfort acceleration a_w^K (allowing higher speeds with respect to curves). Note that, for human driver comfort, the maximum lateral acceleration allowed by human limits (a_w^H) is usually much lower than acceleration allowed by friction limits (a_w^G). This means that even in curves, longitudinal emergency deceleration a_u^J remains high.

$$\begin{cases} a_w^G &= k_w^G \, \mu^L \, g \\ a_w^K &= min(a_w^G, a_w^H, a_w^I) \\ v_u^K &= \sqrt{\frac{a_w^K}{\rho^L}} \\ a_u^K &= min(a_u^G, a_u^H, a_u^I) \end{cases} \tag{3.37}$$

For a given lateral acceleration a_w^K, the **maximum subject speed in curves** v_u^K depends on the lane curvature ρ. On highways, lanes can usually be modeled as a sequence of straight lines (where ρ is zero), clothoids (where ρ increases linearly with U) and circles (where ρ has a constant value ρ^L). This is illustrated in Figure 3.28. If lane geometry does not correspond to this model, an equivalent, conservative **line-clothoid-circle model** is calculated. Variables p_u^L and ρ^L of the line-clothoid-circle model are given by perception (Table 2.4). These variables correspond to worst-case values estimated by perception, i.e. minimum value of p_u^L and maximum value ρ^L. This implies that, in order to allow highly and fully automated driving, perception uncertainty on these variables must be bounded.

The speed v_u^K is set by the maximum curvature ρ^L, according to Equation 3.37. In **straight lanes**, ρ^L tends to zero and v_u^K in Equation 3.37 to infinity, which means that this individual speed profile will not represent a limitation on the legal safety speed profile. **When approaching a new curve**, the subject speed v_u is reduced to v_u^K before the beginning of the curve (which corresponds to the distance p_u^L). The deceleration required for this is given by Equation 3.38. The equation takes into account the distance traveled during system reaction time t^R, as is illustrated in Figure 3.29. **In the curve**, the decision component keeps the subject speed on v_u^K with a longitudinal comfort acceleration a_u^K, as is expressed in Equation 3.39.

$$\begin{cases} \overline{v}_{u_1} &= v_u^K \\ \overline{a}_{u01} &= -\frac{1}{2} \frac{(v_u)^2-(v_u^K)^2}{p_u^L - v_u \, t^R} \end{cases} \tag{3.38}$$

$$\begin{cases} \overline{v}_{u_1} &= v_u^K \\ \overline{a}_{u01} &= \pm \, a_u^K \end{cases} \tag{3.39}$$

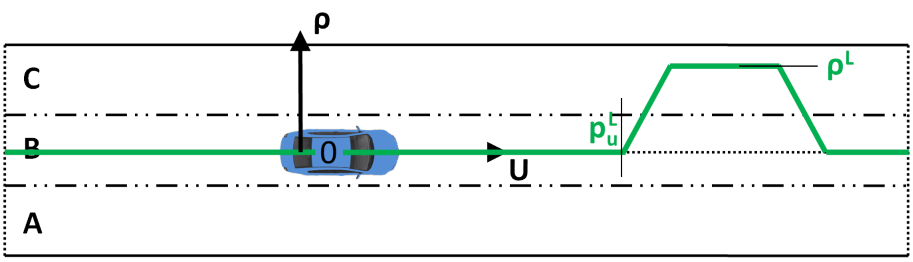


Figure 3.28: Lane model as a combination of straight lines, clothoids and circles

If the difference of friction μ^L and curvature ρ^L of the different lanes can be neglected, individual speed profiles for lateral limits are equal for *0A*, *0B* and *0C*, and also for *FA*, *FB* and *FC*, as is suggested in Figure 3.29.

Sections 3.4.1 and 3.4.2 describe two sets of individual speed profiles (in longitudinal direction and in lateral direction), according to friction limits, human limits and system limits. These

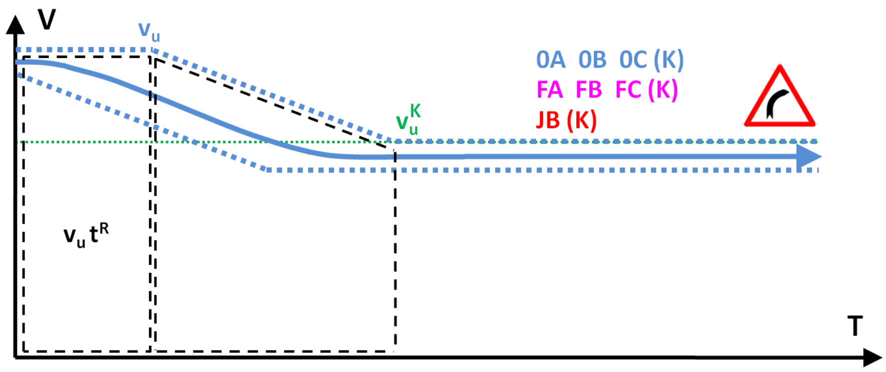


Figure 3.29: Generation of individual subject speed profiles *0A*, *0B*, *0C*, *FA*, *FB*, *FC* and *JB* with respect to lateral friction limits, human limits and system limits (superscript K)

individual speed profiles cover all **human rules and system rules**. Individual speed profile presented in Sections 3.4.3 to 3.4.6 are related to traffic rules.

3.4.3 Subject speed profile for speed limits

A next aspect of legal safety is the adaptation of subject speed to the speed limit (superscript S), according to Rule 3. The individual speed profiles with respect to speed limits are **similar to individual speed profiles with respect to curves**. The curve speed v_u^K and the distance to the start of the curve p_u^L in Equations 3.38 and 3.39 are replaced by the speed limit v_u^S and the distance to the speed limit p_u^S. This gives Equations 3.40 and 3.41. The values of v_u^S and p_u^S are given in the lane description by perception (Table 2.4). The individual speed profiles with respect to speed limits are illustrated in Figure 3.30.

$$\begin{cases} \overline{v}_{u_1} &= v_u^S \\ \overline{a}_{u_{01}} &= -\frac{1}{2}\,\frac{(v_u)^2-(v_u^S)^2}{p_u^S-v_u\,t^R} \end{cases} \tag{3.40}$$

$$\begin{cases} \overline{v}_{u_1} &= v_u^S \\ \overline{a}_{u_{01}} &= \pm\, a_u^K \end{cases} \tag{3.41}$$

Like individual speed profiles for friction limits, human limits and system limits, individual speed profiles for speed limits are **usually identical** for the three lanes A, B and C, as in Figure 3.30.

3.4.4 Subject speed profile for phantoms ahead

Rule 3 stipulates that subject speed should be such that a collision with phantoms, i.e. worst-case foreseeable objects and stops outside the perception zone, can be avoided. On highways **phantoms ahead** are standing still at the end of the perception zone, at a position p_u^P, as was explained in Section 3.3. The deceleration $-a_u^P$ that is needed to avoid the accident when the phantom proves to be a real object or stop, is a parameter to choose between $-a_u^K$ and $-a_u^J$. A more extreme deceleration, i.e. higher value of a_u^P, allows higher subject speeds v_u^P.

Figure 3.31 illustrates the **calculation** of the target speed of the individual speed profile related to phantoms ahead; v_u^P. The speed v_u^P must allow decelerating with $-a_u^P$ from a distance

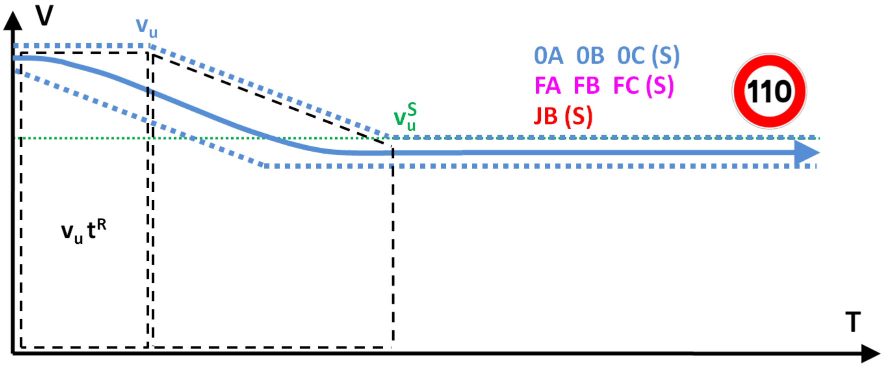


Figure 3.30: Generation of individual subject speed profiles *0A*, *0B*, *0C*, *FA*, *FB*, *FC* and *JB* with respect to speed limit (superscript S)

p_u^P from the phantom till standstill at a minimum distance d_u^J from the phantom. The calculation takes into account the system reaction time t^R. Solving $v_u^P\, t^R + \frac{(v_u^P)^2}{2\, a_u^P} = p_u^P - d_u^J$ to v_u^P gives Equation 3.42. As an example, a deceleration $-a_u^P = -6\, m/s^2$, system reaction time $t^R = 1\, s$, perception horizon $p_u^P = 150\, m$ and minimum distance $d_u^J = 5\, m$, allows a subject speed $v_u^P = 36.1\, m/s = 130.1\, km/h$.

Equation 3.43 indicates that the comfort deceleration/acceleration $\pm\, a_u^K$ (defined in 3.33) is used to adapt to v_u^P. The end of the perception zone p_u^P is assumed to **change slowly**, e.g. due to changing weather conditions. If this is not the case, a deceleration that corresponds to the variation in v_u^P is applied, instead of $-a_u^K$.

$$v_u^P \quad = \quad a_u^P\, (-t^R + \sqrt{(t^R)^2 + 2\, \frac{p_u^P - d_u^J}{a_u^P}}) \tag{3.42}$$

$$\begin{cases} \overline{v}_{u_1} & = \quad v_u^P \\ \overline{a}_{u_{01}} & = \quad \pm\, a_u^K \end{cases} \tag{3.43}$$

As Figure 3.31 indicates, individual speed profile with respect to phantoms ahead are identical for the three target lanes A, B and C.

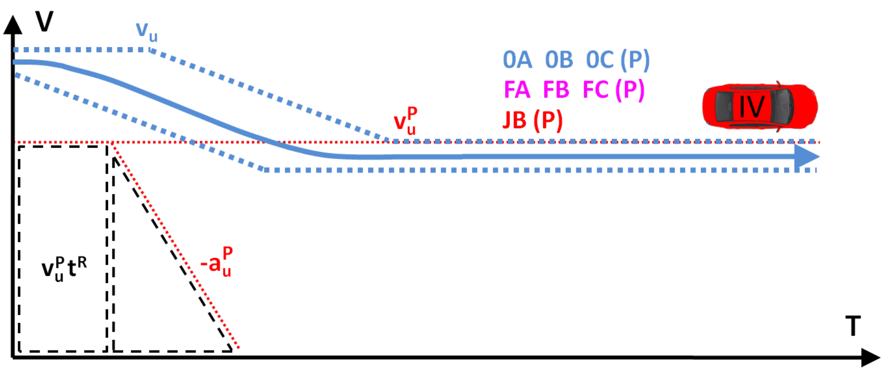


Figure 3.31: Generation of individual subject speed profiles *0A*, *0B*, *0C*, *FA*, *FB*, *FC* and *JB* with respect to phantoms (superscript P)

Phantoms behind the subject vehicle (introduced in Section 3.3) are not taken into account in the generation of individual speed profiles. Phantoms behind are only considered in the evaluation step, presented in Section 3.5.

In this work, phantoms are only introduced for *objects*, not for *curves and speed limits*. However, the subject speed should also be limited so that it allows decelerating in time for worst-case curves and speed limits; i.e. **phantom curves** and **phantom speed limits**. This work assumes that the perception horizon p_u^P and deceleration $-a_u^P$ for phantom curves and phantom speed limits is the same as for phantom objects. In this case, **phantom objects** constitute a bigger constraint on subject speed than phantom curves and phantom speed limits. Additionally, on highways, curvature and speed limits usually change slowly. This means that the deceleration needed to adopt to curves and speed limits does not reach $-a_u^P$. In application zones with strong variations in curvature and speed limits, phantom curves and phantom speed limits are useful. Calculations with phantom curves and phantom speed limits can easily be introduced; they are similar to calculations with phantom objects.

3.4.5 Subject speed profile for object following

Target objects

This section describes the individual speed profiles that adapt to **objects ahead of the subject**. Rules 3 and 6 refer to the **safety distance** to be kept from objects with the **same target lane** as the subject. This includes objects that are already in the subject lane and objects that are predicted to change lanes towards the subject lane. The safety distance should be such that **a collision can be avoided in the case that the object performs an emergency brake till standstill**, according to Rule 3.

Rule 6 specifies that right overtaking should be avoided, except in congested traffic. In congested traffic, the object can be overtaken on the right side, but with a limited speed difference. This is treated as an additional speed limit. As the adaptation to speed limits has been described above, the case of congested traffic is not considered here. In non-congested traffic, the driving system keeps a distance to objects with a **target lane left** to the target lane of the subject. The subject keeps the same distance to objects to the left and objects in the subject lane, so that no additional braking is required if the object changes lanes from the left lane to the subject lane. The objects referred to in the equations (superscript O), are understood to be the objects with a trajectory towards the **same target lane as the subject, or the lanes left to it**. If more than one object applies, individual speed profiles are calculated for each object and the minimum is taken.

The situation in Figure 3.23, where *7* indicates to change lanes to the right, is used in Figures 3.32 and 3.33. For speed profiles *0A* and *FA*, object *7* applies twice, once for its lane changing trajectory and once for its lane keeping trajectory. If an additional object *6* ahead of the subject were present on lane A, a third individual speed profile would apply for keeping a safety distance to *6*. For speed profiles *0B*, *FB*, *JB*, distance should be kept to object *7*. Speed profiles *0C* and *FC* do not apply as no object ahead of the subject is present on lane C, and as *7* is not predicted to change lanes to the left. Objects **on the side of and behind** the subject are not considered in the generation step. These objects are only considered in the evaluation step, which is presented in Section 3.5.

Distance control to comfort distance p_u^K

For object following, the individual speed profile **can correspond to either of the two types** presented in Section 3.2; distance control or speed control. In certain situations, distance control (targeting a comfort distance p_u^K) does not provide sufficient deceleration to avoid a collision in the case that the object performs an emergency brake. In these situations, speed control is chosen, as will be explained later in this section.

The **distance control model** (Equations 3.3 - 3.4) is entirely specified by the parameter **p_u^K; the comfort distance**. The calculation of this parameter is presented in Equation 3.44. The comfort distance p_u^K takes into account the distance p_u^H wished by the **human driver** and a minimum distance p_u^I required by the system. Target distance p_u^H can be specified directly with a lever (like target speed v_u^H), or indirectly through driving style k^H. Choosing a sportive driving style allows smaller distances to the object, but leads to harder decelerations in the case that the object brakes. The human driver distance p_u^H has generally a minimum value d_u^H and a term that varies proportionally with speed, via a time headway t^H. The minimum distance p_u^I that is required by the driving system, takes the same structure as p_u^H. It has a minimum value d_u^I and is proportional with speed, via a time headway t^I and the system reaction time t^R. This conforms to the *X-second rule* for safe following distances, which is often recommended by local traffic rules, but which does not appear in the Vienna Convention. The convention only stipulates that the subject should be able to avoid an accident when the object performs an emergency brake. A forth term $\frac{(v_u^O)^2}{2\,a_u^J} - \frac{(v_u^O)^2}{2\,\mu^L\,g}$ applies if subject and object speed and/or their deceleration capacity are different. As an example, if the maximum braking capacity of the subject is only $-a_u^J = -6\,m/s^2$ and subject and object speeds are equal $v_u^O = v_u^O = 36.1\,m/s = 130\,km/h$ and road friction $\mu^L = 1$, then an additional distance of $42\,m$ is needed in order to assure safety in the case of object emergency brake till standstill. This calculation of p_u^I will follow from the discussion on speed control. The minimum distance p_u^I required by the driving system mainly corresponds to the system reaction time t^R, when making abstraction of the first two terms (the safety margin when subject and object come to a standstill after an emergency brake) and forth term (which only applies when subject and object have different braking capacity). System reaction time t^R is usually below $1\,s$, which is comparable to the reaction time of a typical human driver. This means that the legal safety system does not keep larger inter-distances to objects than human drivers, even with the requirements that it avoids accidents when the object performs an emergency brake. As system reaction time decreases, safety distance to objects can be decreased.

Equation 3.45 indicates that the **target speed** $\overline{v}_{u_1}$ of the distance control model corresponds to the target speed $\underline{v}_{u_1}^O$ of the minimum speed profile of the object. The subject **acceleration** $\overline{a}_{u01}^O$ is proportional with distance error, speed error and object acceleration. The individual speed profiles for distance control to an object with constant speed are illustrated in Figure 3.32.

$$\begin{cases} p_u^H &= d_u^H + v_u\,t^H \\ p_u^I &= d_u^I + v_u\,t^I + v_u\,t^R + \frac{(v_u)^2}{2\,a_u^J} - \frac{(v_u^O)^2}{2\,\mu^L\,g} \\ p_u^K &= max(p_u^H, p_u^I) \\ p_u^J &= d_u^J + v_u\,t^J + v_u\,t^R + \frac{(v_u)^2}{2\,a_u^J} - \frac{(v_u^O)^2}{2\,\mu^L\,g} \end{cases} \tag{3.44}$$

$$\begin{cases} \overline{v}_{u_1} &= \underline{v}_{u_1}^O \\ \overline{a}_{u_{01}} &= k_p\,(p_u^O - p_u^K) + k_v\,(v_u^O - v_u) + a_u^O \end{cases} \tag{3.45}$$

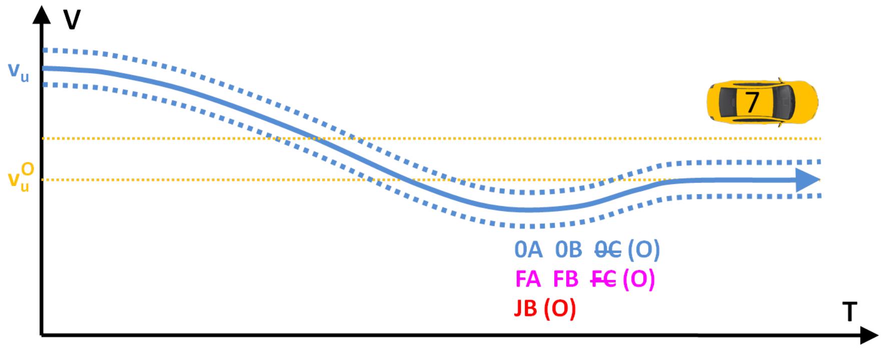


Figure 3.32: Generation of individual subject speed profiles *0A*, *0B*, *0C*, *FA*, *FB*, *FC* and *JB* with respect to object following (superscript O). In the example of Figure 3.23, *0C* and *FC* do not apply

Speed control to safety distance p_u^J

The distance control law $k_p\,(p_u^O - p_u^K) + k_v\,(v_u^O - v_u) + a_u^O$ in Equation 3.45 always converges to object target position p_u^K, speed v_u^O and acceleration a_u^O. But, if only distance control is used, the object position p_u^O can **temporarily go below the minimum distance** p_u^J (Equation 3.44) that is needed to avoid an accident when the object performs an emergency brake. This is avoided by switching to speed control instead of distance control, when p_u^O approaches p_u^J.

Figure 3.33 presents the situation where the **object is performing an emergency brake** with extreme deceleration $-\mu^L\,g$. This situation explains the calculation of p_u^J. The triangle on the left and on the right illustrate the distance traveled during emergency braking by the object and subject respectively. Equation 3.44 expresses that the subject should keep a distance p_u^J from the object, so that a small distance $d_u^J + v_u\,t^J$ is left when both subject and object come to a standstill after emergency braking. Small values are usually chosen for parameters d_u^J and t^J. Equation 3.44 indicates that the safety distance p_u^J can be reduced, by decreasing system reaction time t^R and increasing deceleration value a_u^J. For a **platooning** application, system reaction time t^R should be small and deceleration values a_u^J should be gradually increased from the first vehicle of the platoon to the last one.

Figure 3.34 illustrates how the deceleration according to **distance control** (full line) is hardened towards emergency braking $-a_u^J$ with **speed control** (dashed line) if the distance to the object p_u^O approaches minimum distance p_u^J. Between points 1 and 2, distance control is applied. When p_u^O approaches p_u^J, between points 2 and 3, speed control is applied with a value that is a linear interpolation between $-a_u^J$ and the comfort acceleration $k_p\,(p_u^O - p_u^K) + k_v\,(v_u^O - v_u) + a_u^O$. When p_u^O comes below p_u^J, between points 3 and 4, an extreme deceleration $-a_u^J$ is applied. The speed control model is specified by Equation 3.46, with the interpolation factor $0 < k < 1$.

The **distance** p_u^I in Equation 3.44 is the minimum distance p_u^K that is allowed by the driving system. In the calculation of p_u^I and p_u^J only the first two terms differ. The parameters d_u^I and t^I are chosen sufficiently higher than d_u^J and t^J, so that the activation of speed control (points 2 till 4 in Figure 3.34) is only needed in extreme situations.

$$\begin{cases} \overline{v}_{u_1} &= \underline{v}_{u_1}^O \\ \overline{a}_{u_{01}} &= k\,[-a_u^J] + (1-k)\,[k_p\,(p_u^O - p_u^K) + k_v\,(v_u^O - v_u) + a_u^O] \end{cases} \tag{3.46}$$

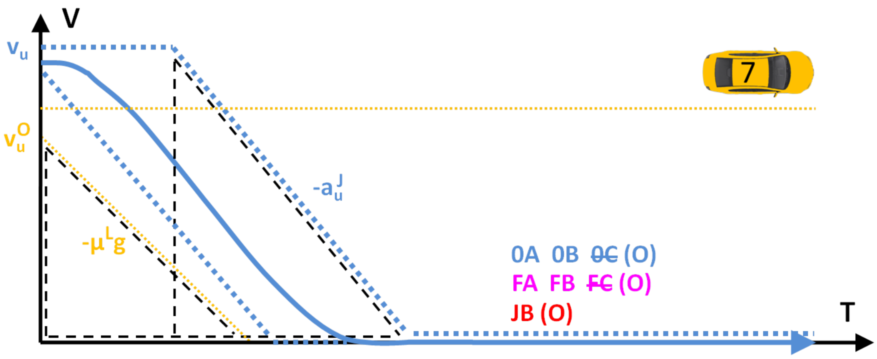


Figure 3.33: Generation of individual subject speed profiles *0A*, *0B*, *0C*, *FA*, *FB*, *FC* and *JB* with respect to object following (superscript O) if object is performing an emergency brake. In the example of Figure 3.23, *0C* and *FC* do not apply

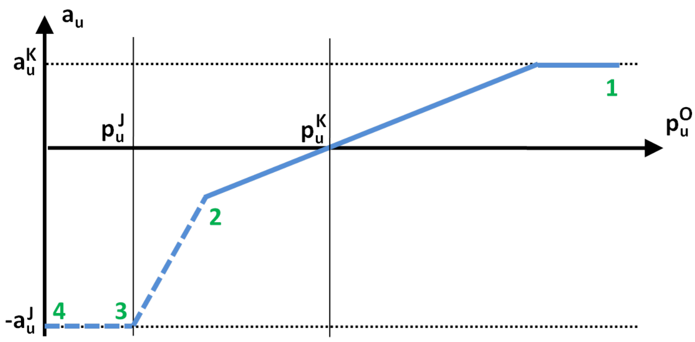


Figure 3.34: The combination of distance control (point 1 and 2) and speed control (point 3 and 4), with a linear interpolation between both (dashed line)

Safety zone: NLS vs. NLNS situations

Figure 3.35 visualizes the **safety zone** around the subject vehicle; the combination of object positions p_u^O, speeds v_u^O and (negative) accelerations a_u^O for which the subject can avoid a collision with an **emergency brake** $-a_u^J$. This relates to what is called *region of inevitable collision* in trajectory planning literature [LaV06]. The figure indicates the limits of the safety zone for several object decelerations till standstill with deceleration value a_u^O. The safety zone is described by Equation 3.47, which follows from Equation 3.44, by replacing p_u^J by p_u^O, replacing the minimum distance $d_u^J + v_u\, t^J$ by zero and replacing object deceleration $-\mu^L\, g$ by a_u^O. If the object has a deceleration which equals the subject extreme deceleration $-a_u^J$, an accident can still be avoided if the object has a same speed v_u as the subject, at a minimum distance of $v_u\, t^R$ (point 1 in the figure). A collision with a still standing object can be avoided if it is detected at a distance $v_u\, t^R + \frac{(v_u)^2}{2\, a_u^J}$ (point 2). In this equation, the calculation of the maximum subject speed with respect to phantoms ahead can be recognized. If the object has less extreme decelerations, a collision can be avoided for lower object speeds (point 3). If the object adopts an **emergency deceleration** $\mu^L\, g$ (e.g. point 4), a collision can only be avoided at $v_u\, t^R + \frac{(v_u)^2}{2\, a_u^J} - \frac{(v_u^O)^2}{-\mu^L\, g}$, which corresponds to the calculation of p_u^J in Equation 3.44, except for the additional term $d_u^J + v_u\, t^J$.

The safety zone separates Legal and Safe (LS) and Not Legal, but Safe (NLS) from Not Legal and Not Safe (**NLNS**) situations when an object cuts in on the subject lane. For example, for object positions and speeds below the object acceleration curve, the driving system cannot avoid a collision by braking, if the object performs a (non-legal) sudden lane change towards the subject lane. The accident might be avoided by a lane change instead of braking, or a combination of both, but this is not always possible, e.g. due to objects on target lanes A and C.

$$p_u^O = v_u\, t^R + \frac{(v_u)^2}{2\, a_u^J} - \frac{(v_u^O)^2}{-2\, a_u^O} \tag{3.47}$$

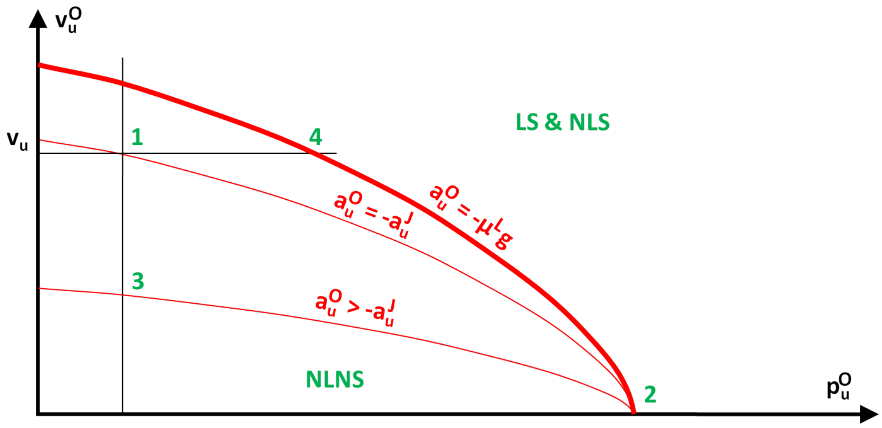


Figure 3.35: Safety zone around the subject in the case of decelerating object

3.4.6 Subject speed profile for stop

Individual speed profiles for a stop are found in the same way as individual speed profiles for an object with zero speed. Equations 3.44, 3.45 and 3.46 translate in Equations 3.48, 3.49 and 3.50. Figure 3.36 illustrates the individual speed profiles in the case of a stop.

$$\begin{cases} p_u^H &= d_u^H \\ p_u^I &= d_u^J \\ p_u^K &= max(p_u^H, p_u^I) \\ p_u^J &= d_u^J \end{cases} \tag{3.48}$$

$$\begin{cases} \overline{v}_{u_1} &= 0 \\ \overline{a}_{u01} &= k_p\,(p_u^Q - p_u^K) - k_v\, v_u \end{cases} \tag{3.49}$$

$$\begin{cases} \overline{v}_{u_1} &= 0 \\ \overline{a}_{u01} &= k\,[-a_u^J] + (1-k)\,[k_p\,(p_u^Q - p_u^K) - k_v\, v_u] \end{cases} \tag{3.50}$$

3.4.7 Subject trajectory for friction limits, human limits and system limits

According to Equation 3.30, only one parameter needs to be calculated for the zone model of subject trajectories; the **trajectory slope** $\underline{s}_{w01}$.

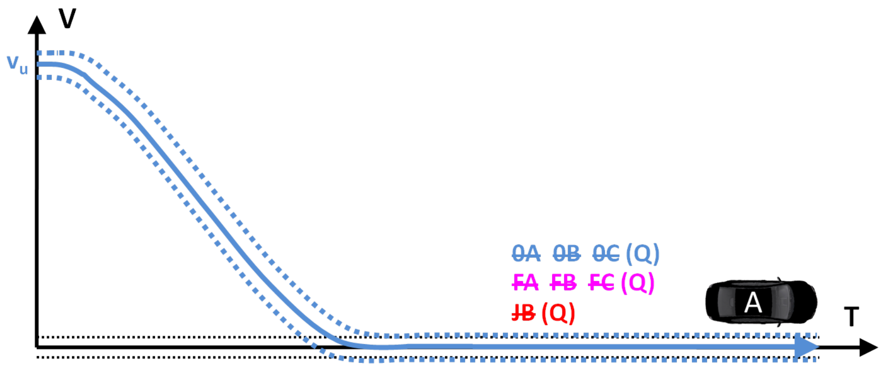


Figure 3.36: Generation of individual subject speed profiles *0A*, *0B*, *0C*, *FA*, *FB*, *FC* and *JB* with respect to stops (superscript Q). In the example of Figure 3.23, neither of these individual speed profiles applies

Like subject speed profiles (presented previously), subject trajectories must respect limits of road friction, limits imposed by the human driver and limits imposed by the driving system. Equations 3.51 and 3.52 present the corresponding individual trajectories with a **minimum trajectory slope** s_w^K, wished by the **human driver and driving system**. If the presence of continuous lane markings or objects ahead does not put additional constraints on a subject trajectory, the subject trajectory slope equals s_w^K.

$$s_w^K = max(s_w^H, s_w^I) \tag{3.51}$$

$$\underline{s}_{w01} = \pm s_w^K \tag{3.52}$$

Due to continuous lane markings and the presence of objects, higher trajectory slopes are sometimes required, as will be explained in following Sections 3.4.8 and 3.4.9. Equations 3.53 and 3.54 describe subject **trajectories with maximum slope** s_w^J. Like s_w^K, s_w^J integrates human limits s_w^H and system limits s_w^I. Values s_w^H and s_w^I for the extreme trajectory slope s_w^J in Equation 3.53 are higher than values for comfort trajectory slopes s_w^K in Equation 3.53. The maximum slope also integrates the **friction limit** s_w^G, which represents the lateral friction forces that are left after the longitudinal and lateral friction forces used by the subject speed profiles.

$$s_w^J = min(s_w^G, s_w^H, s_w^I) \tag{3.53}$$

$$\underline{s}_{w01} = \pm s_w^J \tag{3.54}$$

The **speed-slope map** in Figure 3.38 shows that higher trajectory slopes s_w^J are usually possible at lower speeds. For the speed range covered by the subject speed profiles, the lowest absolute slope value is used. For example, when accelerating from current speed *0* to speed *1*, the maximum slope at speed *1* is used. When decelerating from speed *0* to speed *2*, the maximum slope at speed *0* applies.

3.4.8 Subject trajectory for lane markings

Figure 3.39 and Equations 3.55 and 3.56 describe the minimum trajectory slope s_w^M to avoid crossing **continuous lane markings** according to Rule 6. The calculation takes into account

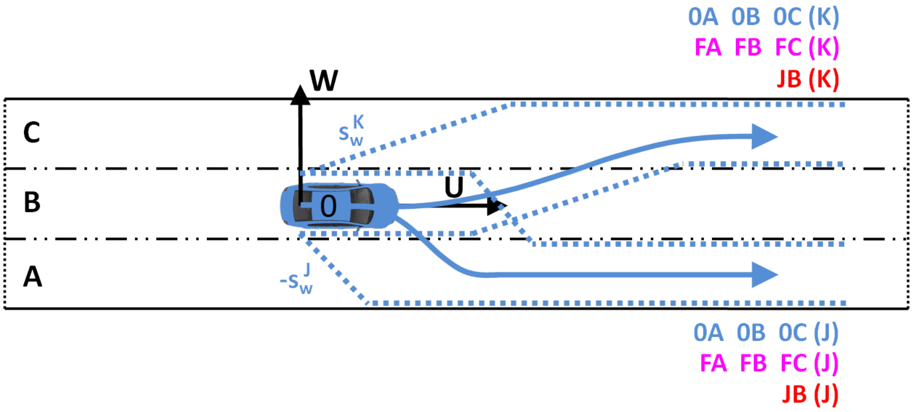


Figure 3.37: Generation of individual subject trajectories *0A*, *0B*, *0C*, *FA*, *FB*, *FC* and *JB* with respect to friction limits, human limits and system limits (superscripts J and K). Illustration for *0A*(J), *FA*(J), *0C*(K) and *FC*(K)

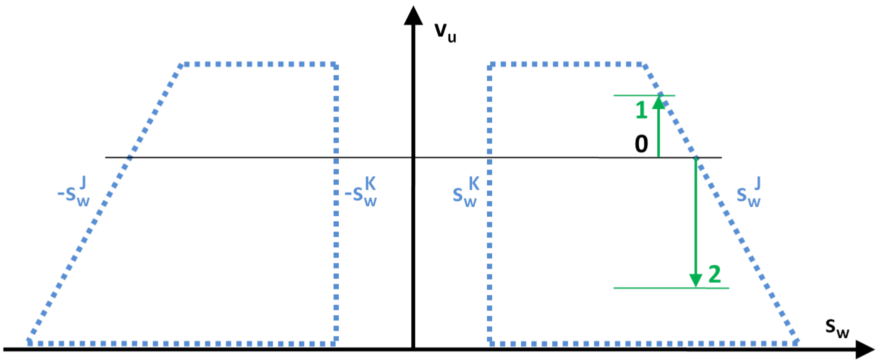


Figure 3.38: The speed-slope map for subject trajectories

the distance to the beginning of the continuous lane marking p_u^M and the system reaction distance p_u^R. For a lane change to the left, the lateral distance to the lane p_w^L in Equation 3.55 corresponds to the distance between the right side of the subject vehicle and the right lane marking of the target lane. The slope s_w^M is limited to extreme slope s_w^J, which means that crossing continuous lane markings cannot be avoided in all situations, even if $p_u^M > p_u^R$. The trajectory evaluation step verifies that continuous lane markings are not crossed, as will be described in Section 3.5.

If **no continuous lane markings** are detected, p_u^M corresponds to the end of the perception zone. Integrating these *phantom* lane markings avoids crossing of potential continuous lane markings outside the perception zone.

$$s_w^M = \frac{p_w^L}{p_u^M - p_u^R} \tag{3.55}$$

$$\underline{s}_{w01} = \pm\, s_w^M \tag{3.56}$$

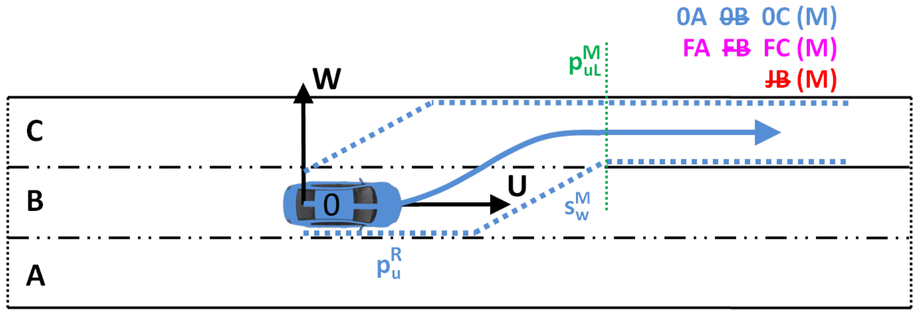


Figure 3.39: Generation of individual subject trajectories *0A*, *0C*, *FA* and *FC* with respect to continuous lane markings (superscript M). Illustration for *0C* and *FC*. This never applies to *0B*, *FB* and *JB*

3.4.9 Subject speed profile and trajectory for object overtaking

Aspects of legal safety presented in Sections 3.4.1 to 3.4.8 either involve the generation of subject speed profiles, or the generation of subject trajectories. Overtaking an object involves adapting **both subject speed profiles and trajectories**. Research work on object overtaking sometimes assumes that subject and/or object speeds are constant during the maneuver [JKI00, KKL01, Sha04]. In this work, both subject and object speed can change during overtaking. As for object following, subject speed during object overtaking must be such that an accident can be avoided, **if the object performs an emergency brake** during the maneuver, according to Rule 3.

Figures 3.40 and 3.41 illustrate the overtaking trajectory and speed profile for *0C* and *FC*. A subject trajectory with **slope** s_w^L **(to be calculated)** performs a lane change over a distance p_u^L. Until the target lane is reached, the subject speed v_u is increased by an **acceleration** a_u^L **(positive or negative, to be calculated)**, resulting in a target speed v_u^L. Equation 3.57 describes the conditions on s_w^L and a_u^L, so that during the lane change, a safety distance p_u^J is kept from the object at all times. The first line gives the relation between p_u^L and s_w^L. The variable p_w^L is the distance between the right edge of the subject and right lane marking of the target lane, in the case of a lane change to the left. The second and third line write p_u^L and v_u^L in function of the acceleration a_u^L and the time needed to reach the target lane t^L. The forth and the fifth line describe the object position p_u^{OL} and speed v_u^{OL} at t^L, in function of the predicted object acceleration a_u^O. The sixth line states that until the lane change is completed, the distance $p_u^{OL} - p_u^L$ between object and subject must be greater than the **safety distance** p_u^J from Equation 3.44. The safety distance p_u^J allows avoiding an accident in the case that the object performs an emergency brake and in the case that the subject cannot complete the lane change. If the subject accelerates to overtake the object, the left side of the sixth line decreases monotonously (the distance between object and subject decreases), while the right side increases monotonously (the subject speed decreases). Due to this, the condition at t^L covers the condition for the complete time range from 0 and t^L.

$$\begin{cases} p_u^L & = p_u^R + \frac{p_w^L}{s_w^L} \\ p_u^L & = p_u^R + v_u\,(t^L - t^R) + \frac{a_u^L\,(t^L - t^R)^2}{2} \\ v_u^L & = v_u + a_u^L\,(t^L - t^R) \\ p_u^{OL} & = v_u^O\,t^L + \frac{a_u^O\,(t^L)^2}{2} \\ v_u^{OL} & = v_u^O + a_u^O\,t^L \\ p_u^{OL} - p_u^L & > d_u^J + v_u\,t^J + v_u\,t^R + \frac{(v_u^L)^2}{2\,a_u^J} - \frac{(v_u^{OL})^2}{2\,\mu^L\,g} \end{cases} \tag{3.57}$$

Equation 3.57 cannot easily be solved analytically to s_w^L and a_u^L. It can be solved very quickly numerically, by **sampling s_w^L and** a_u^L, and verifying the condition on $p_u^{OL} - p_u^L$. The sampling procedure can be explained by rewriting Equation 3.57 in a compact form in Equation 3.58. In the first two lines, p_u^L and t^L are obtained from the s_w^L and a_u^L samples. From t^L, the variables v_u^L, p_u^{OL} and v_u^{OL} are calculated and the condition in the sixth line is checked. For example, 10 values of s_w^L between s_w^K and s_w^J and 100 values a_u^L between $-a_u^J$ and a_u^K are taken, giving 1000 samples. For example, for an acceleration range between $-10\,m/s^2$ and $4\,m/s^2$, the sampling resolution is $0.14\,m/s^2$. **Incrementally increasing sampling density** in the border zone between successful and unsuccessful samples would allow reaching even higher resolutions.

$$\begin{cases} p_u^L & = f_0(s_w^L) \\ t^L & = f_1(a_u^L, s_w^L) \\ v_u^L & = f_2(a_u^L, t^L) \\ p_u^{OL} & = f_3(t^L) \\ v_u^{OL} & = f_4(t^L) \\ p_u^{OL} - p_u^L & > f_5(v_u^L, v_u^{OL}) \end{cases} \tag{3.58}$$

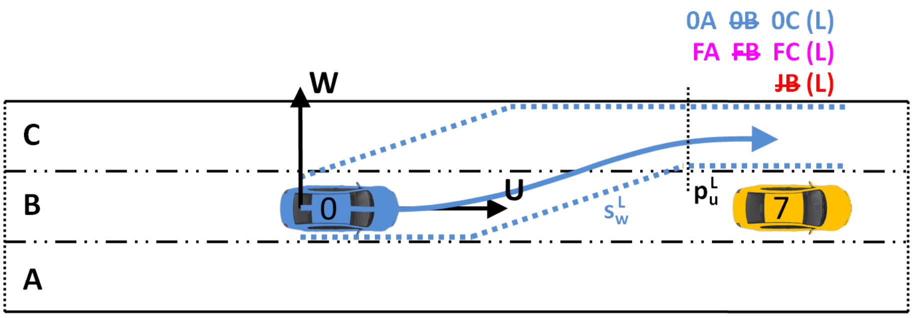


Figure 3.40: Generation of individual subject trajectories *0A*, *0B*, *0C*, *FA*, *FB*, *FC* and *JB* with respect to object overtaking (superscript *L*). Illustration for *0C* and *FC*. In the example of Figure 3.23, *0B*, *FB* and *JB* do not apply

Figure 3.42 indicates the constraints on the trajectory slope by the different aspects of legal safety. The minimum slope according to comfort slope s_w^K and lane marking slope s_w^M is speed-independent. The maximum slope according to extreme slope s_w^J is speed-independent for speeds below the subject speed, indicated by 0 and decreases for higher speeds. The **slope constraints by object overtaking** is function of both slope s_w^L and acceleration a_u^L. The figure indicates the valid combinations of s_w^L and a_u^L (i.e. that respect Equation 3.58) on the speed-slope map,

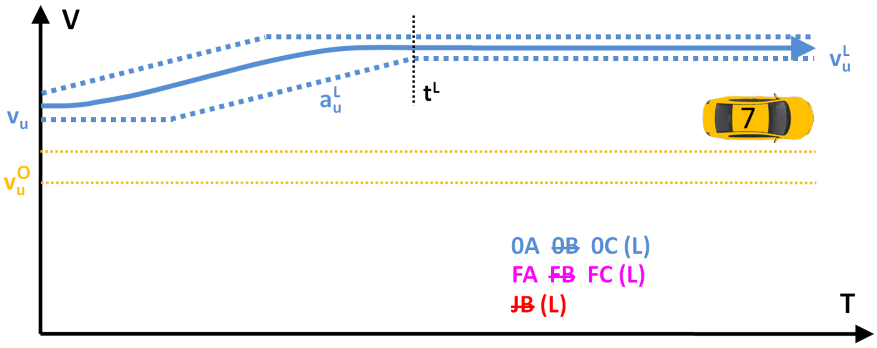


Figure 3.41: Generation of individual subject speed profiles *0A*, *0B*, *0C*, *FA*, *FB*, *FC* and *JB* with respect to object overtaking (superscript *L*). In the example of Figure 3.23, *0B*, *FB* and *JB* do not apply

replacing a_u^L with the corresponding speed v_u^L. As the figure suggests, higher accelerations a_u^L, i.e. higher speeds v_u^L, require higher slopes s_w^L, but the relationship is not necessarily linear as in Figure 3.42. The zone of speeds v_u^L and slopes s_w^L that meet all constraints is indicated by the zone *S*. The algorithm chooses the couple v_u^L and s_w^L on segments *I*, *II* or *III*, which have decreasing optimality with respect to speed and comfort. If possible, accelerating on a minimum trajectory slope s_w^K (segment *I*) is chosen. If not, a constant speed with higher slope (segment *II*) or deceleration with even higher slope (segment *III*) is used. Note that the existence of the zone *S* is not guaranteed. In the case that the constraints overlap, object overtaking is not possible and the corresponding trajectory will be excluded in the trajectory evaluation step.

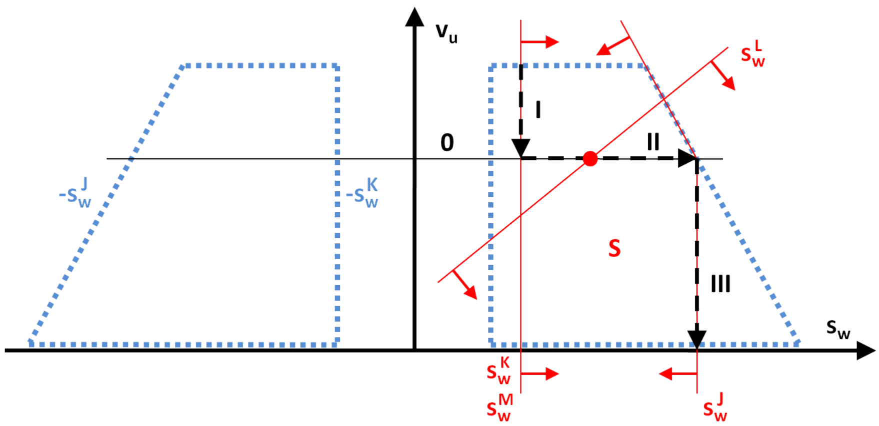


Figure 3.42: The speed-slope map for subject trajectories, with indication of constraints by lane markings and object overtaking

Equations 3.59 and 3.60 specify the zone model for individual subject speed profiles and trajectories for the calculated v_u^L, a_u^L and s_w^L.

$$\begin{cases} \overline{v}_{u_1} &= v_u^L \\ \overline{a}_{u_{01}} &= a_u^L \end{cases} \tag{3.59}$$

$$\underline{s}_{w_{01}} = \pm\, s_w^L \tag{3.60}$$

3.5 Evaluation of subject trajectories

The decision component integrates **most aspects of legal safety directly in the generation** of subject speed profiles and trajectories. In the order of presentation in Section 3.4, *individual speed profiles* are generated with respect to friction limits, human limits, system limits, speed limits, phantoms ahead, objects ahead and stops. *Individual trajectories* are generated with respect to friction limits, human limits, system limits, continuous lane markings and objects ahead. *Legal safety speed profiles* are obtained by taking the minimum values of the individual speed profiles for every abscissa of T. *Legal safety trajectories* are found by taking the maximum value of the slopes required by individual trajectories. This gives 7 subject speed profiles and trajectories: *0A*, *0B* and *0C* for normal functioning of the system, *FA*, *FB* and *FC* for failure functioning and *JB* for collision mitigation.

In the trajectory evaluation step, the 7 trajectories are **evaluated on the legal safety aspects** that were yet not considered in the trajectory generation step. Examples are the presence of phantoms and objects behind the subject and on the side of the subject. For each of the remaining aspects of legal safety, trajectories are attributed a **performance cost**. The performance cost is binary; for each aspect it is either 0 or 1. A trajectory can only be selected for control if respects all legal safety aspects (i.e. all its performance cost are 0), as will be explained in Section 3.6. An exception is the performance cost on object collisions, which is proportional with collision impact speed. This allows choosing the trajectory with minimum collision impact in situations where an accident cannot be avoided. At the end of Section 3.5, it is shown that in all cases of legal object behavior and in most cases of non-legal object behavior, the trajectory in the subject lane *0B* has zero performance cost. In some cases of non-legal object behavior, accidents cannot be avoided, only mitigated with emergency trajectory *JB*.

3.5.1 Subject speed profile with respect to phantoms behind

In the trajectory generation step, phantoms ahead of the subject have been considered, but not phantoms behind the subject. Figure 3.43 illustrates the evaluation of **lane changing** trajectories *0A*, *0C*, *FA* and *FC*. The subject speed profile values must be high enough, so that a **phantom can brake till subject speed with a reasonable deceleration** $-a_u^P$, within the distance $p_u^P - p_u^J$. The variable p_u^P is the initial distance between subject and phantom, i.e. the distance to the perception horizon behind the subject. The final distance, when phantom and subject speeds are equal, must correspond with the safety distance p_u^J. The safety distance p_u^J is calculated with Equation 3.44, from a phantom perspective. The numerical integration of the difference of phantom and subject speed profiles can be used to verify this condition. When the condition is not met, the trajectory is marked with a binary performance cost c, presented in Equation 3.61.

$$\begin{cases} c = 0 & \text{if no collision with phantom behind} \\ c = 1 & \text{if collision with phantom behind} \end{cases} \tag{3.61}$$

The evaluation does not apply to **lane keeping** trajectories *0B*, *FB* and *JB*. According to traffic rules, the subject does not need to consider phantoms coming from behind.

3.5.2 Subject speed profile with respect to objects behind and on the side

As for phantoms, the generation of subject trajectories and speed profiles only considers objects ahead, not objects behind and on the side. Rule 6 states that during **changing lanes**, the

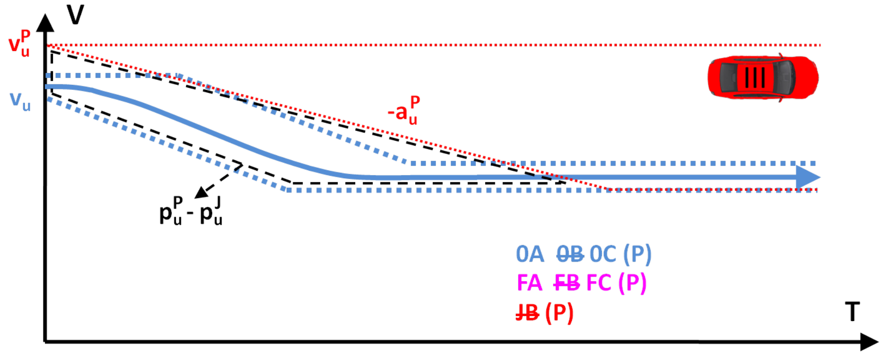


Figure 3.43: Evaluation of subject speed profiles *0A*, *0C*, *FA* and *FC* with respect to phantoms behind (superscript P). This never applies to *0B*, *FB* and *JB*

subject should not hinder objects behind and on the side. Figure 3.44 illustrates the evaluation of trajectories *0A*, *0C*, *FA* and *FC*. The subject speed profile should be such that the **initial distance between object and subject is reduced** from p_u^O to a minimum distance p_u^J, which is calculated with Equation 3.44, from an object perspective. In contrast to phantoms, objects from behind are not assumed to decelerate for the subject. A subject lane change only receives zero performance cost if objects from behind can keep their speed and if safety distances are respected at all times. The presence of an object on the side automatically leads to the exclusion of the subject trajectory towards the corresponding target lane. As the subject and objects on the side are assumed to cover the complete lane width, a lane change by the subject always leads to a collision. With respect to objects behind and on the side, a binary performance cost c is attributed, as in Equation 3.62.

$$\begin{cases} c &= 0 \quad \text{if no collision with object behind or on the side} \\ c &= 1 \quad \text{if collision with object behind or on the side} \end{cases} \tag{3.62}$$

Lane keeping trajectories *0B*, *FB* and *JB* are not evaluated. During lane keeping, the subject does not need to consider objects behind and on the side.

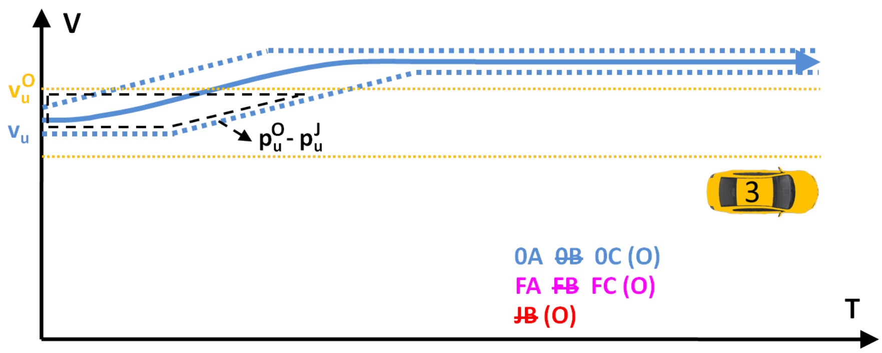


Figure 3.44: Evaluation of subject speed profiles *0A*, *0C*, *FA* and *FC* with respect to objects behind and on the side (superscript O). Illustration for *0C* and *FC*. This never applies to *0B*, *FB* and *JB*

3.5.3 Subject trajectory with respect to object collisions

The generation and evaluation of subject trajectories described above, cover all aspects of legal safety with respect to objects and phantoms. However, trajectories are additionally verified with a **collision analysis**. In cases of non-legal object behavior where collisions cannot be avoided, collision analysis allows to find the less worse trajectory between *0A*, *0B* and *0C*, e.g. the trajectory with smallest collision impact, or to select the emergency brake trajectory *JB*.

Collision analysis is performed over a period $t^O = t^R + \frac{v_u}{a_u^J}$, which is long enough to come from highway speed to a standstill with emergency trajectory *JB*, if needed. The minimum and maximum positions of the subject and object are found by **integrating their minimum and maximum speed profile** on a time vector from $t = 0\,s$ till $t = t^O$ and combining it with the **minimum and maximum trajectory descriptions**. Figure 3.45 illustrates the collision checking algorithm for two consecutive time steps on the time vector (′-labeled and ″-labeled). A collision between subject and object means that at least one line in Equation 3.63 and one line in Equation 3.64 are true. The four lines, *1* and *2* for Equation 3.63 and *3* and *4* for Equation 3.64, are illustrated in the figure. For the situation in the figure, all lines *1* till *4* are true; a collision is detected. The difference of subject and object speed at the moment of the collision can be used as metric for the performance cost, as is suggested by Equation 3.65. In the case of a collision with more than one object, the sum of the respective terms in Equation 3.65 is made.

$$\begin{cases} (\underline{p}_u^{O'} - \overline{p}_u{}') \cdot (\underline{p}_u^{O''} - \overline{p}_u{}'') < 0 \\ (\overline{p}_u^{O'} - \underline{p}_u{}') \cdot (\overline{p}_u^{O''} - \underline{p}_u{}'') < 0 \end{cases} \tag{3.63}$$

$$\begin{cases} (\underline{p}_w^{O'} - \overline{p}_w{}') \cdot (\overline{p}_w^{O'} - \underline{p}_w{}') < 0 \\ (\underline{p}_w^{O''} - \overline{p}_w{}'') \cdot (\overline{p}_w^{O''} - \underline{p}_w{}'') < 0 \end{cases} \tag{3.64}$$

$$\begin{cases} c = 0 & \text{if no collision with object} \\ c = c_v\,(\underline{v}_u^O - \overline{v}_u)^2 & \text{if collision with object} \end{cases} \tag{3.65}$$

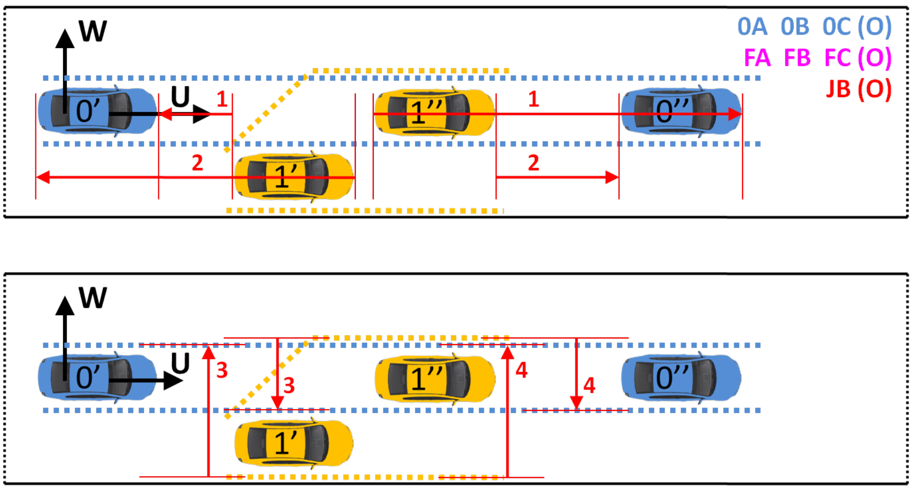


Figure 3.45: Evaluation of subject speed profiles *0A*, *0C*, *FA* and *FC* with respect to object collisions (superscript *O*)

Note that the approach for collision analysis presented in this section **avoids the tunneling effect**. The tunneling effect appears when subject and object cross each other on their continuous trajectories, but have well-separated positions when sampled with a large interval. Collision analysis that would only check if subject and object sample positions overlap, would wrongly report that there is no collision. The collision analysis in Equations 3.63 and 3.64 combines information on two subject and object position samples in every collision check. This allows taking quite large sampling intervals, while avoiding the tunneling effect. A typical time step between two samples used in implementation is $0.25\,s$. At highway speed of $36\,m/s$ ($130\,km/h$) samples are separated with $9\,m$. This is distance at which tunneling effect would appear, if only individual sampled positions were considered.

3.5.4 Subject trajectory with respect to lane markings and lane type

A last evaluation on subject trajectories concerns the **type of target lane**, which is described by perception under the variable k^L. Rule 7 stipulates that trajectories for normal functioning *0A*, *0B*, *0C* and *JB* must target *normal lanes* only. Trajectories for failure functioning *FA*, *FB* and *FC* preferably end on the *emergency lane*. As in previous evaluation steps, only lane changing trajectories *0A*, *0C*, *FA*, *FC* are to be considered. The subject lane type for *0B* and *FB* is necessarily appropriate, as a lane change towards the current subject lane has been validated before. Lane change trajectories towards non-appropriate target lanes have not been excluded a priori (i.e. before the trajectory generation step) as these trajectories might help avoid accidents in **non-legal situations**. For example, a lane change towards an emergency lane during normal system functioning is given a performance cost, but is preferred to a collision with an object on the subject lane.

The evaluation step also gives a performance cost to lane changing trajectories when they **cross continuous lane markings**. Additionally, the evaluation step penalizes lane changes in congested traffic as these are not allowed by traffic rule 6. Finally, trajectories towards zero speed that do not allow to **reach the target lane** before the speed reaches zero receive a performance cost. Performance costs with respect to target lane and lane markings are either 0 or 1, as in Equation 3.66.

$$\begin{cases} c = 0 & \text{if no offence on lane markings or lane type} \\ c = 1 & \text{if offence on lane markings or lane type} \end{cases} \tag{3.66}$$

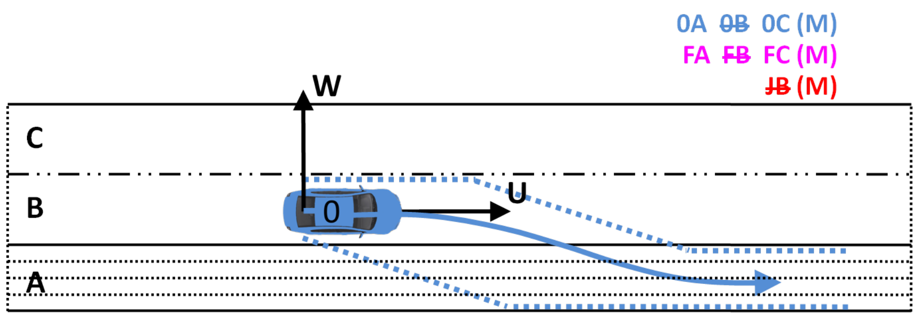


Figure 3.46: Evaluation of subject speed profiles *0A*, *0C*, *FA* and *FC* with respect to lane markings and lane type (superscript M). This never applies to *0B*, *FB* and *JB*

3.5.5 The existence of at least one subject trajectory

A legal safety trajectory must respect all **traffic rules, human rules and system rules**. The application of each rule further reduces the trajectory solution space. For example, traffic rules may exclude the possibility of lane changing, human rules limit the subject speed and system rules limit subject deceleration and acceleration. However, Rule 14 requires that at least one subject trajectory exists for control. This implies that the solution space at the intersection between the three rule sets is not empty and that the decision component is able to find a trajectory in this solution space.

This is the case with the legal safety decision component. In the case of **legal object behavior**, at least for the **subject lane** a legal safety trajectory is found, as is indicated in Figure 3.47. This is the case both for optimal trajectory *0B* for normal system functioning and for Minimum Risk Maneuver (MRM) trajectory *FB* for system failure functioning. The subject lane trajectory consists in keeping the lane and keeping a distance from objects ahead. The distance to the object ahead in the subject lane is such that even if the object performs an emergency brake an accident can be avoided, as was explained in Section 3.4. The subject lane trajectory also avoids accidents with objects ahead in the right and left lanes. When these objects touch the lane markings of the subject lane or activate indicators, they are predicted to change lanes towards the subject lane. In this case, the subject lane trajectory anticipates and keeps a safe distance from the object. When these objects do not cross the lane markings and do not activate indicators, a collision is avoided as both object and subject stay entirely within their lane, according to the zone model. The subject lane trajectory does not adapt to *objects behind and on the side* of the subject, but has priority on them. In most cases of **non-legal object behavior** a collision-free **subject, right or left lane trajectory** can be found. In some cases of non-legal object behavior an accident cannot be avoided. In this case, the trajectory with lowest collision impact is chosen, both for normal system functioning (i.e. *0A*, *0B*, *0C* or *JB*) and system failure functioning (i.e. *FA*, *FB* or *FC*.

Note that decreasing constraints by human rules and system rules increases the trajectory solution space. This allows increasing safety in non-legal situations, i.e. **converting Not Legal and Not Safe situations (NLNS) in Not Legal, but Safe situations (NLS)**. For example, if more extreme decelerations and high trajectory slopes are allowed by system rules, and if automatic lane changes (i.e. fully automated driving) are allowed by human rules, some accidents that cannot be avoided by braking in the subject lane can be avoided by a **fast lane change**.

3.6 Selection of subject trajectory and automation mode

Sections 3.4 and 3.5 have presented the generation and evaluation of subject trajectories. Section 3.6 discusses the selection of the **optimal** trajectory to communicate to the human driver through HMI, and the selection of the trajectory **performed** by control. The last step in the decision component is the selection of the **automation mode**.

3.6.1 Selection of subject trajectory

The evaluation of subject trajectories (presented in Section 3.5) allows selecting the **optimal subject trajectory** *0A*, *0B*, *0C* or *JB*. The **left lane trajectory** *0C* is suggested as optimal trajectory if it has zero performance cost and allows increasing target speed, in comparison with the subject lane trajectory *0B*. The **right lane trajectory** *0A* is selected if it has zero

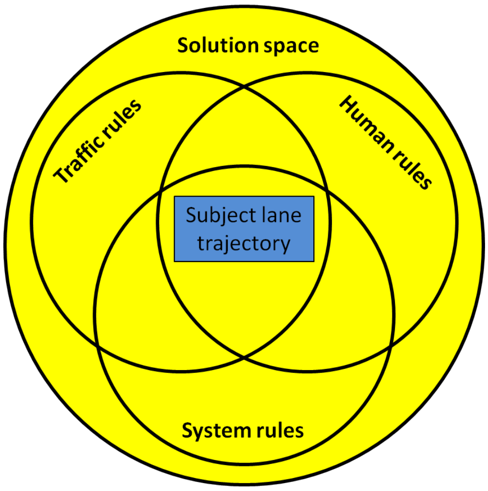


Figure 3.47: At the intersection of traffic rules, human rules and system rules, a legal safety trajectory in the subject lane can always be found

performance cost and has a target speed that is not lower than the target speed of subject lane trajectory *0B*. In other cases, the **subject lane trajectory** *0B* is selected. This selection scheme allows maximizing vehicle speed and encourages driving in the right-most lane (Rule 5). In the top part of Figure 3.48, the left lane trajectory *0C* is optimal as the maximum speed set by the human driver is high enough to overtake the object ahead without hindering the object behind. The bottom part of the figure shows the case where the target speed set by the human driver is not high enough to allow overtaking. In this case, the right lane trajectory *0A* is indicated as optimal.

In cases of non-legal object behavior where the subject lane trajectory *0B* is not collision-free, the right or left lane trajectory *0A* or *0C* can be selected, even if it has a non-zero performance cost. This allows the driving system to violate traffic rules for safety reasons. For example, if an object suddenly cuts in on the subject lane, a lane change trajectory which crosses continuous lane markings without collisions is preferred to lane keeping with collisions. If none of the trajectories *0A*, *0B*, *0C* or *JB* is collision-free, the trajectory with lowest collision impact is selected for collision mitigation. The target lane l^I and target speed v^I of the optimal trajectory is communicated to the human driver through the **system-to-human interactor** (Table 2.11).

One **subject trajectory to be performed** during normal functioning (*0A*, *0B*, *0C* or *JB*) and one to be performed during failure functioning (*FA*, *FB*, *FC* or *JB*) is selected and communicated to the control component via the trajectory interactor (Table 2.9). In the case of fully automated (FA) driving, the performed subject trajectory for **normal functioning** corresponds to the **optimal subject trajectory**, i.e. optimal lane changes are performed automatically. In automation modes driver assisted (DA), semi-automated (SA) and highly automated (HA), the performed subject trajectory corresponds with target lane l^H specified by the human driver in the human-to-system interactor (Table 2.10), if this trajectory has a zero performance cost. If the trajectory towards the target lane wished by the human driver has a non-zero performance cost, the subject lane trajectory *0B* is selected as performed trajectory. Information on why the target lane specified by the human driver cannot be met (e.g. object in the target lane, continuous lane markings) is written in the variable i_l^I in the system-to-human interactor (Table 2.11). Information on the biggest constraint on the subject speed (e.g. speed limit, object ahead) written in the variable i_v^I in the system-to-human interactor.

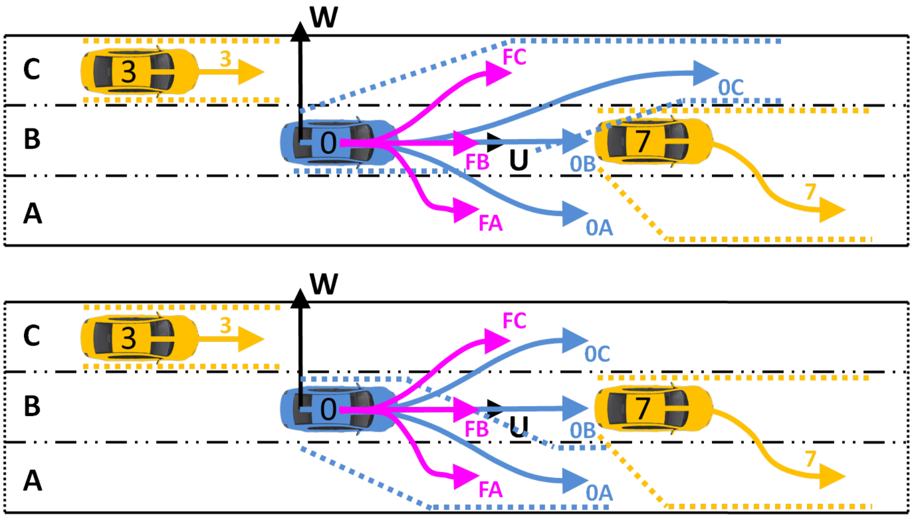


Figure 3.48: Selection of a trajectory for normal functioning (*0A*, *0B*, *0C* or *JB*) and a trajectory for failure functioning (*FA*, *FB*, *FC* or *JB*). Situation where target speed by human driver allows overtaking object (top) and situation where target speed by human driver does not allow overtaking object (bottom)

The performed MRM trajectory for **failure functioning** (*FA*, *FB*, *FC* or *JB*) is the trajectory that targets the emergency lane, if available and if this trajectory has zero performance cost. If not, the right lane trajectory *FA* is selected. During MRM, the subject performs subsequent lane changes to the right till the emergency lane is met. A similar strategy has recently been presented by other research teams [APKB11]. Note that the performed trajectory for MRM is communicated to control, even in non-MRM situations. Thanks to this, a trajectory is always available to the control component, even in the case of failure of the decision component hardware or failure of the communication channel between decision and control components.

Both performed subject trajectories (one for normal functioning and one for failure functioning) are converted from the lane coordinate system UW to the **subject coordinate system** XY and written in the trajectory interactor (Table 2.9).

3.6.2 Selection of automation mode

The management of automation modes, i.e. the selection of the active and available automation levels according to Rule 12, could be carried out by a dedicated component. For example, in the HAVEit project, this is performed by a Mode Selection and arbitration Unit (MSU) [HAV11j, HAV11k]. In the legal safety system described in this work, the automation modes are **managed by the decision component**.

The selection of the automation mode is a negotiation between human driver and driving system. The human driver specifies the **requested automation mode** m^H in the human-to-system interactor (Table 2.10). The driving system indicates the **available automation modes** $n^I[i]$ in the system-to-human interactor (Table 2.11). The **automation mode accepted** by the driving system is communicated as m^I in the system-to-human interactor (Table 2.11) and trajectory interactor (Table 2.9). At the end of the application zone or in presence of a priority vehicle, the driving system **gives over control to the human driver**; the available automation modes are reduced to *driver assisted*. If the human driver fails to take over control, an *MRM* (as a special case of fully automated driving) is selected. The MRM is also activated if the state f^H of the human driver is drowsy or distracted, or if state f^I of the driving system indicates a system failure. The driving system **takes over control** if the deceleration on the performed trajectory approaches the extreme value $-a_u^J$ and if other trajectories are not collision-free. In this case, an accident can only be avoided by hard braking and the system automatically switches from driver assisted (DA) to semi-automated (SA) driving. State-of-the-art Brake Assist Systems (BAS) have can avoid accidents at low speeds, with a limited perception of the environment [KSD09, Eid11]. As the driving system integrates a complete environment model and traffic rules (e.g. considering lane description and the presence of objects on right and left lanes), it could take over control earlier than state-of-the-art BAS and avoid a higher number of accidents. The deceleration that is needed directly follows from the subject trajectory calculations. Additionally, steering wheel actions to keep the vehicle on the subject lane or to perform a lane change for object avoidance can be calculated from the subject trajectory, and is consistent with this deceleration. This could open the way to Collision Mitigation Avoidance System (CMAS) that switch to highly automated (HA) driving (i.e. combining longitudinal and lateral actions) in order to avoid a wider range of accidents on highways.

3.7 Contribution

Chapter 3 has presented a novel design for a legal safety decision component for highways, which predicts object trajectories and calculates optimal subject trajectories. The decision component uses traffic rules as a powerful basis for the **prediction of object trajectories**, both in the case of legal and non-legal object behavior. It also predicts phantoms, i.e. foreseeable objects outside the perception zone, based on traffic rules. The **calculation of subject trajectories** that respect traffic rules, human rules and system rules, combines a direct, analytical approach (trajectory generation step) and sampling-based approach (trajectory evaluation step). The decision component calculates 7 trajectories, 3 trajectories on the three lanes for normal system functioning, 3 trajectories on the three lanes for system failure functioning and 1 emergency trajectory on the subject lane. In the subject lane, a legal safety trajectory can always be found, both for normal system functioning and system failure functioning. Trajectories towards right and left lanes are not always available.

The work proposes a curvilinear **lane coordinate system** as a natural environment for efficient trajectory calculations. In the lane coordinate system, subject and object trajectories are specified by a **zone model**, rather than by an exact description. A simple, *wide* zone model with piecewise linear borders has been developed. As state-of-the-art perception and control performance improve, *narrower* zone models could be developed. This would further increasing trajectory optimality (e.g. higher speeds, tighter lane changes).

Chapter 3 presents a legal safety decision algorithm that is straightforward and fast for the application zone of this work, the **lane-structured highway environment** that was defined in Chapter 2. Calculation times on standard PC are below $1\,ms$ and on automotive ECU below $25\,ms$, as will be shown in Chapter 4. Respecting traffic rules, human rules and system rules in *all possible* environments is out of reach of the presented decision algorithm. The algorithm assumes that the road topology can be represented by maximum three lanes (right lane, subject lane and left lane), which host all objects that appear in traffic rules. This is the case for highway environments. In **other road topologies** (e.g. with intersections) new topics arise, such as giving priority to objects while traveling on the subject lane. However, in other road topologies, the lane-structure of the environment (whether these lanes are separated by lane markings, or not) also plays a dominant role in the implementation of traffic rules. Future study is required on the possibility to extend the proposed decision algorithm for different road topologies and geometries, and to create a lane coordinate system for such environments.

The decision algorithm developed in this work exploits the information on a maximum of eight objects on three lanes (three objects ahead, three objects behind and two objects on the sides), which is believed to be available by perception technology in medium term, as discussed in Chapter 2. Chapter 3 shows that this information is sufficient for **respecting traffic rules** in the application zone under study. At least, it allows avoiding accidents in the case that all objects respect traffic rules. The information also allows integrating several basic principles of **defensive driving**, which avoids accidents in many cases of non-legal object behavior. Further study is required on the acceptability of this level of defensive driving. On the one hand, increased information from perception might be needed to increase the level of defensive driving. For example, the trajectory prediction of objects ahead of the subject can be refined based on perception information of objects ahead of those objects. In this case, optimal trajectories could be calculated from an object point of view, which also allows increasing **courteousness** by the subject towards objects ahead, as was mentioned in this chapter. On the other hand, the level of defensive driving might be decreased on certain aspects, in order to better match the level of **assertiveness** that is generally accepted by human drivers.

Chapter 4 will discuss the implementation of the legal safety decision component on LIVIC, HAVEit and ABV demonstrators. Validation scenarios cover the application of all traffic rules, human rules and system rules. At the intersection of the three rule sets, a variety of subject trajectories exists, corresponding with different **driving styles**. Chapter 4 will demonstrate the adaptation of parameters in the decision component for sportive and green (comfortable) driving styles, and will compare with the driving style of an average human driver.

Chapter 4

System implementation and validation on LIVIC, HAVEit and ABV demonstrators

Contents

Chapter 1 has presented the goal of legal safety, Chapter 2 system requirements and Chapter 3 decision component design. Chapter 4 continues the V-cycle description (Figure 1.8) with the **legal safety system implementation and validation** on LIVIC, HAVEit and ABV demonstrators. First, Section 4.1 presents legal safety validation scenarios. The scenarios are common to all demonstrators. Section 4.2 briefly discusses the modular approach, which allows using same component C-files on different demonstrators.

An overview of the LIVIC, HAVEit and ABV demonstrators has been given in Figure 1.9 and Table 1.2. Section 4.3 presents the **LIVIC Legal Safety Demonstrator (LSD)**, which implements all legal safety components (i.e. perception, decision, control and HMI) on simulator and vehicle, on PC and ECU. Perception is designed by LIVIC colleagues. Decision, control and HMI are designed in this work. The LIVIC LSD focusses on the interaction between driving system and environment (traffic rules and system rules), in cases where human drivers and other driving systems in the environment respect traffic rules, and in cases where they do not. The LIVIC LSD compares system driving styles, e.g. sportive and green (comfortable) driving. The consequences of a non-legal driving style (e.g. driving too close from the object ahead) will be presented.

The integration of legal safety decision and control on HAVEit and ABV project simulators and vehicles is discussed in Sections 4.4, 4.5 and 4.6. Project demonstrators are complementary. Each demonstrator focuses on a different aspect that is important for legal safety. The **HAVEit Joint System Demonstrator (JSD)** focuses on the interaction between driving system and human driver (human rules), during driver assisted, semi-automated and highly automated driving. The **HAVEit Architecture Migration Demonstrator (AMD)** demonstrates driving system implementation on automotive ECU. The **ABV Low Speed Demonstrator (LSD)** shows fully automated driving in congested traffic. HAVEit and ABV demonstrators are discussed with respect to legal safety concepts. For a detailed presentation of other aspects of these demonstrators, reference will be made to project deliverables.

4.1 Validation scenarios for all demonstrators

Table 4.1 presents **legal safety scenarios** for the validation of LIVIC, HAVEit and ABV demonstrators. The table indicates how all traffic rules, human rules and system rules are covered. The legal safety scenarios cover **HAVEit and ABV scenarios** [HAV11f] and **ISO standard test procedures** for ADAS on highways [ISO07, ISO08, ISO09a, ISO09b, ISO10]. A legal safety system considers *all* aspects of legal safety simultaneously, but at all times only *one* aspect represents the biggest constraint on target speed and target lane. This explains why each validation scenario focusses on only **one aspect of legal safety**.

The scenario **Following a human target speed** consists in lane keeping and reaching the target speed set by the human driver. **Approaching a curve** corresponds to lane keeping and adapting vehicle speed to curves. Both scenarios cover HAVEit use cases *Normal driving in a lane without obstacles* and *Normal driving in a lane, lane departure*. In the scenario **Approaching a speed limit** the driving system adapts to speed limits, which corresponds to HAVEit use case *Driving and speed limit change*. **Approaching a phantom** involves adjusting vehicle speed to worst-case objects out of the perception zone (phantoms) and avoiding an accident in the case that such object is present. This scenario is not directly targeted by HAVEit and ABV demonstrators. **Following an object** means keeping a safe distance from an object in the subject lane and avoiding an accident in the case that the object performs an emergency brake. A same distance is kept from objects in the left lane, except in situations where right overtaking is allowed. This scenario includes HAVEit use cases *Normal driving in a lane with obstacles*, *Driving and right overtaking*, *Driving and detected obstacle* and ISO test procedures *Automatic stop*, *Follow target in curves*. **Overtaking an object** involves changing lanes in order to overtake a slower object. **Changing to human target lane** corresponds to reaching the target lane chosen by the human driver, while considering the intentions of other objects, type of lane markings and type of target lane. These scenarios comprehend HAVEit use case *Driving and lane change* and ISO test procedure *Subject vehicle overtaking target vehicle*. The scenario **Approaching a stop** consists in stopping before the end of a lane or application zone, as in HAVEit use case *Driving and deactivation necessary*. The scenarios **Decreasing or increasing automation mode to driver assisted (DA), semi-automated (SA), highly automated (HA), fully automated (FA) and Minimum Risk Maneuver (MRM)** cover automation mode transitions on command of the human driver, due to changes in the environment (e.g. end of application zone, presence of priority vehicle or officials) or due to system failure. Automation mode transitions were extensively studied in HAVEit, in use cases *Normal driving in a lane without obstacles*, *Driving and activation not possible*, *Driving and deactivation necessary*, *Misuse situations*, *Driving and driver drowsy*, *Driving and driver distracted*, *Driving, driver unresponsive and transition to Minimum Risk Maneuver*, *Driving and technical failure*, *Driving and priority vehicle coming*.

Scenario	LIVIC LSD	HAVEit JSD	HAVEit AMD	ABV LSD	Rules
Following a human target speed	×	×	×	×	1 - 4, 13 - 16
Approaching a curve	×		×	×	2 - 4, 13 - 16
Approaching a speed limit	×	×		×	2 - 4, 13 - 16
Approaching a phantom	×				2 - 4, 13 - 16
Following an object	×	×	×	×	2 - 8, 13 - 16
Overtaking an object	×	×		×	2 - 8, 13 - 16
Changing to human target lane	×	×		×	2 - 8, 13 - 16
Approaching a stop	×	×		×	1 - 4, 13 - 16
Decreasing automation mode to DA	×	×	×	×	1, 9 - 12
Decreasing automation mode to SA	×	×	×	×	1, 11, 12
Decreasing automation mode to HA	×			×	1, 11, 12
Increasing automation mode to SA	×	×	×	×	1, 11, 12
Increasing automation mode to HA	×	×	×	×	1, 11, 12
Increasing automation mode to FA	×			×	1, 11, 12
Increasing automation mode to MRM	×	×	×	×	1, 11, 12

Table 4.1: Validation scenarios on each demonstrator with indication of the related traffic rules (1 - 10), human rules (11 - 12) and system rules (13 - 16)

4.2 Modularity of legal safety components

Each legal safety component is coded on a **single C-file**, but integrated in different demonstrators. Figure 4.1 illustrates how small interface functions are used to translate between legal safety data structures (interactors in Tables 2.3 - 2.11) and demonstrator-specific data structures. This is far less labor intensive and less error-prone than reprogramming functionality for each **demonstrator**. An interface function translates demonstrator-specific *inputs* to legal safety inputs and legal safety *outputs* to demonstrator-specific outputs. Between different demonstrators, only component *parameters* differ. These parameters can be changed via demonstrator-specific tools and translated to legal safety data structures through a third interface function.

Interface functions allow making abstraction of communication channels between components, e.g. CAN communication if a component is implemented on **automotive ECU** or inter-process communication if it is implemented on **PC**. In a similar way, interface functions allow making abstraction of whether a **vehicle or simulator** is used. Same system components are present on vehicle and simulator, but interface functions that translate system inputs (e.g. from sensors to perception) and system outputs (e.g. from control to actuators) are different.

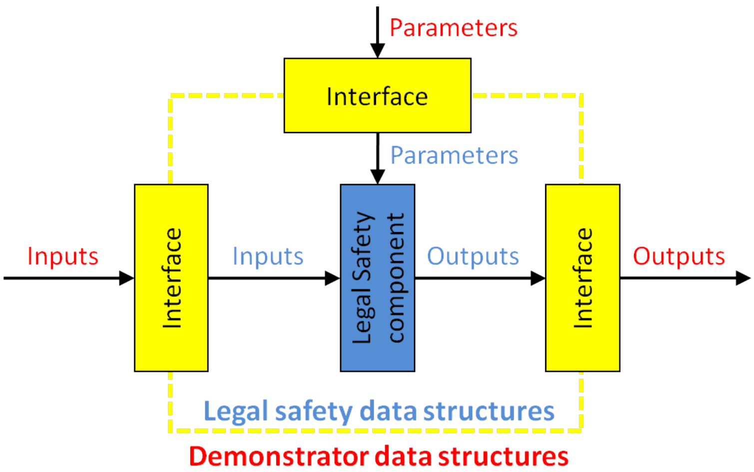


Figure 4.1: Modularity of legal safety components: interfacing of between legal safety data structures and demonstrator data structures

4.3 LIVIC Legal Safety Demonstrator

4.3.1 Description

Figure 4.2 presents the system architecture of the LIVIC Legal Safety Demonstrator. All components are **designed at LIVIC**. Lane detection and object detection for the perception component are developed by LIVIC **colleagues** [IVGA05, PRGG12]. The fusion of lane, object, map and driver information in the perception component is developed in **this work**. For the control component, low-level (actuator) control is designed by LIVIC colleagues, while high-level (trajectory) control is designed in this work. Decision and HMI components are developed in this work.

Classic Proportional-Integral-Derivative (PID) controllers have been developed in this work for high-level longitudinal and lateral control. High-level longitudinal control outputs an acceleration based on the slope of the subject speed profile ($v[i]$ in Table 2.8). Low-level longitudinal control translates this acceleration in commands on motor and brakes. High-level lateral control outputs a curvature that is proportional with lateral offset, heading and curvature of the target lane. Parameters of lateral control vary with both longitudinal speed and lateral offset, i.e. four parameter sets are used. Low-level lateral control translates this curvature in a steering wheel angle. The zone model of subject trajectories and speed profiles in the decision component (described in Chapter 3) is specified after tests with this longitudinal and lateral control. In this way, the decision component only proposes trajectories and speed profiles that can be handled by control. A basic HMI that shows automation mode, optimal speed and optimal lane has been developed. Some images of HMI will be shown 4.3.6.

The decision component has completely been described in Chapter 3. A detailed description of parts of the perception, control and HMI components developed in this work is not given in this document.

First, components were implemented on **standard PC**. This will be discussed in Section 4.3.4. Later, legal safety decision and control components were implemented on **automotive ECU** delivered by HAVEit partner Continental [HAV11b]. The integration on ECU is presented in Section 4.3.5. In future work, perception will also be transferred to ECU. This will bring the complete perception-decision-control automation loop on close-to-market hardware. HMI is less safety-critical and more demonstrator-specific; it will be kept on PC.

As explained in Chapter 1, the V-cycle methodology (see Figure 1.8) consists in first testing the system on simulator. The **LIVIC Legal Safety Simulator** is presented in Section 4.3.2. Functionality that is validated on simulator is tested on the **LIVIC Legal Safety Vehicle**, which will be presented in Section 4.3.3.

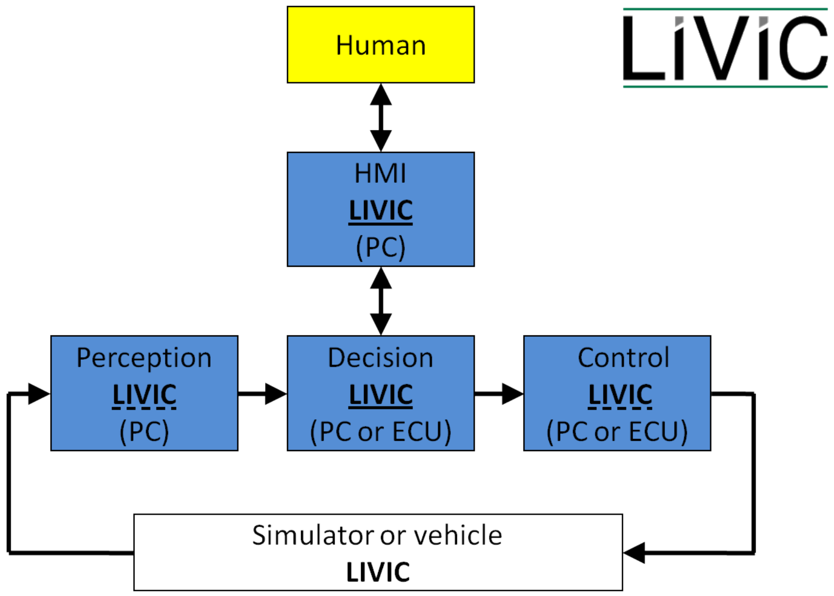


Figure 4.2: System architecture of the LIVIC Legal Safety Demonstrator. All components are developed at LIVIC. Components developed in this work are underlined with a solid line. Components partially developed in this work, partially developed by LIVIC colleagues are underlined with a dashed line

4.3.2 LIVIC Legal Safety Simulator

The legal safety system is developed and demonstrated on simulator **SiVIC**, which was developed at LIVIC and has now been commercialized [CIV12]. SiVIC simulates subject vehicle and a road environment with lanes and objects. Figure 4.3 gives an image of the SiVIC environment, during a platooning experiment. In this experiment, 9 BMW Mini Coopers were simulated, each equipped with the legal safety system. The test track in the image corresponds to the Satory test track in Versailles (see Figure 4.7), which is also used for tests on the LIVIC Legal Safety

Vehicle.

One of the features of SiVIC is that it is able to simulate sensor data. Raw sensor data from camera, radar and LIDAR attached to the subject vehicle could be simulated and delivered to the legal safety perception. This sensor simulation is however not used. In the LIVIC Legal Safety Simulator, the legal safety perception component is replaced by an **ideal perception** component. This ideal perception component translates the exact subject, lane and object description in simulator world coordinates into an environment interactor in subject coordinates XY. The availability of an exact environment interactor (Table 2.6) in simulator is essential for **decision component** development. It allows testing the decision component independently of the perception component development. It also allows demonstrating the use of information that cannot yet be delivered by state-of-the-art perception, e.g. object indicator status or distance to a curve ahead. The model of vehicle dynamics in the simulator respects the main characteristics of the real demonstrator vehicle in Figure 4.4. Testing the legal safety **control** component in simulator allows verifying the fundamental behavior of the control algorithm.

Figure 4.3: Simulation software SiVIC used for LIVIC Legal Safety Simulator and ABV Low Speed Simulator

A simulator is a **convenient and safe** environment for tests in a wide range of scenarios. This includes scenarios that are expensive to set up on real test track, e.g. the platooning experience in Figure 4.3. During system development, a big number of issues can be dealt with easier on simulator than on vehicle. However, a simulator can never represent all aspects of driving on a real vehicle and on a real track. After tests with the LIVIC Legal Safety Simulator (i.e. first development loop on the V-cycle), development continues on the LIVIC Legal Safety Vehicle (i.e. second development loop on the V-cycle), which is presented in Section 4.3.3.

4.3.3 LIVIC Legal Safety Vehicle

Figure 4.4 shows the LIVIC Legal Safety Vehicle, a Peugeot 307 SW, developed by LIVIC colleagues. It is equipped with a **camera** for lane perception [IVGA05, PRGG12] and **LIDAR** for object perception. A **radar** will be installed in order to extend the perception horizon and provide a more accurate estimation of object deceleration/acceleration. This will allow higher subject speeds with respect to phantoms and smaller safety distance to objects, in comparison to object perception with LIDAR. The additional use of camera for object perception could improve the precision of object-to-lane assignment. The perception of **multiple lanes** (i.e. right, subject and left lane) is currently under development. At this moment, only subject lane perception can be demonstrated. Also, the perception of **objects behind and on the side of the subject**, which is essential for lane changing scenarios, is under development. In Section 4.3.6, validation scenarios that keep the subject vehicle in the lane are shown on the LIVIC Legal Safety Vehicle. Scenarios that involve lane changing are shown on the LIVIC Legal Safety Simulator.

According to legal safety, the environment description must only be based on **exteroceptive sensors** such as camera and LIDAR. This is not yet possible with state-of-the-art perception. For example speed limits (p_u^S, v_u^S), object indicator status (i_R^O, i_L^O), curves ahead (p_u^L, ρ^L) and end of the application zone (p_u^Q) are variables in the environment interactor (Table 2.6) that cannot yet be delivered with exteroceptive sensors on the LIVIC Legal Safety Vehicle. These variables are currently delivered by **map, Vehicle-To-Infrastructure (V2I) and Vehicle-To-Vehicle (V2V) communication**, based on positioning by GPS with normal precision. In this way, all information that is required by the legal safety decision component is available on the LIVIC Legal Safety Vehicle. Map matching, V2I communication and V2V communication are developed by LIVIC colleagues. The increased GPS precision based on RTK is only used as reference for validation.

For control, the vehicle has been equipped with **actuators** on steering column, brakes and motor valve, developed by LIVIC colleagues. The actuator configuration corresponds to specifications by legal safety, except for the fact that it **does not yet allow sharing control** between driving system and human driver through haptic feedback. If pedals or steering wheel are touched, longitudinal or lateral control is completely given over to the human driver. Haptic feedback, which allows continuous cooperation between human driver and driving system, is currently under development.

Vehicle development with LIVIC colleagues is organized as a *Federator project* with three-monthly integration weeks.

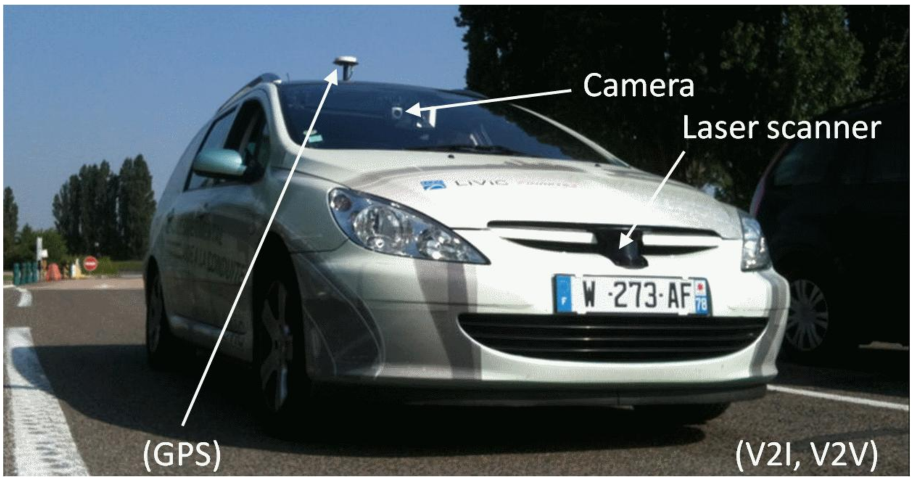


Figure 4.4: LIVIC Legal Safety Vehicle with camera (CNB 36X) for lane perception and LIDAR (SICK LMS 400) for object perception. A GPS (Thales Sagitta 02), V2I and V2V communication (NETGEAR WG121) are used for variables that cannot yet be detected by camera or LIDAR

4.3.4 Implementation on PC

The implementation of legal safety components on PC is done with RTMaps software [Int12]. Figure 4.5 shows an RTMaps diagram for the **LIVIC Legal Safety Simulator**. The C-files of perception, decision, control and HMI **components** are encapsulated in RTMaps modules via Microsoft Visual Studio. Other modules on the diagram are **interfaces** towards the simulator SiVIC. Note that for the experiment with 9 vehicles in Figure 4.3, the modules in this diagram were copied 9 times; once for each legal safety system. RTMaps has been a valuable tool for system development as it manages the communication between components and gives a direct access to component parameters.

The RTMaps diagram for the **LIVIC Legal Safety Vehicle** is similar. Only interfaces and parameters change, in correspondence to the modularity scheme presented in Section 4.2.

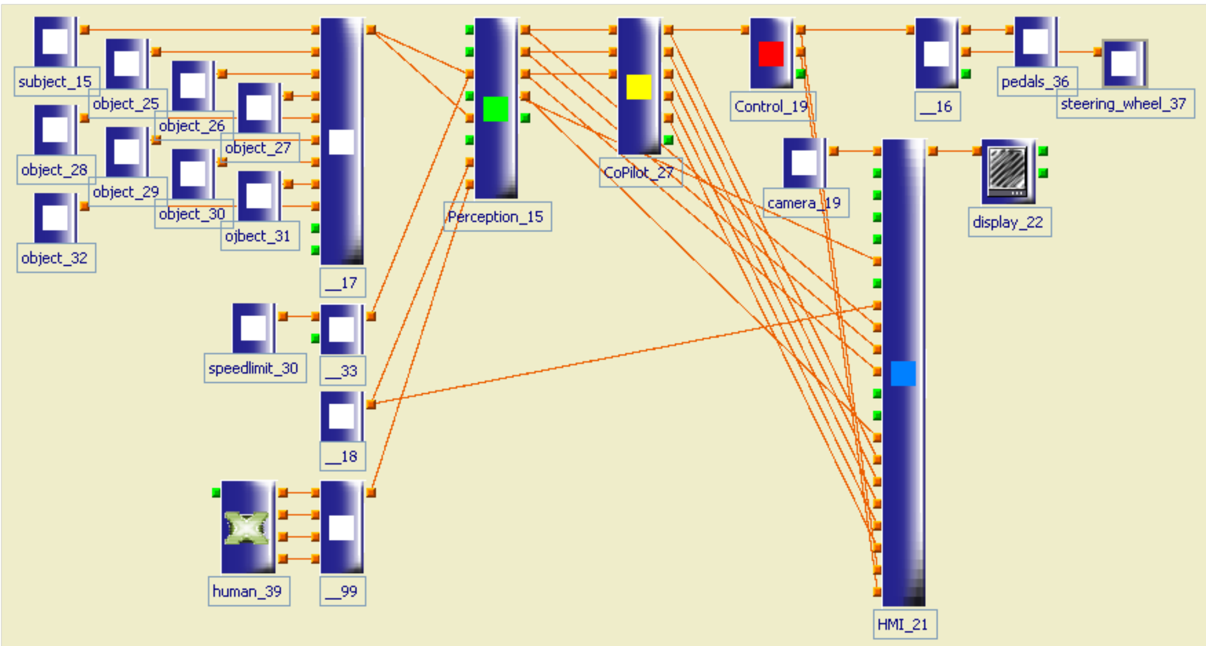


Figure 4.5: RTMaps diagram for LIVIC Legal Safety Demonstrator. Perception, decision, control and HMI modules can be recognized in the middle of the diagram. Other modules are interfaces towards sensors (left side) and actuators (right side) of LIVIC Legal Safety Simulator. A similar RTMaps diagram is used for LIVIC Legal Safety Vehicle, ABV Low Speed Simulator and ABV Low Speed Vehicle

The **calculation time** of legal safety perception and HMI on PC is around 40 ms, which corresponds to the cycle time of vehicle sensors. Calculation times of decision and control are below 1 ms. These component calculation times are bounded by system design as the number of elements in each interactor, and the maximum number of calculations in each component are bounded. For example, the maximum number of objects and lanes to be considered by the decision component are 8 and 3 respectively. The analytical and sampling-based calculation of 4 trajectories by the decision component is reached within a maximum number of steps.

4.3.5 Implementation on ECU

The legal safety decision and control components are integrated on automotive ECUs, in order to demonstrate their compatibility with series production platforms with limited memory and calculation power. Figure 4.6 shows the ECU set-up in a suit case. (The suit case was also used to travel for integration work on the HAVEit Architecture Migrator Demonstrator, which will be presented in Section 4.5). In the lower part of the figure, three **ECUs** developed by HAVEit partner Continental can be recognized. At Continental, these ECUs are known as Chassis and Safety Controller (CSC). Decision and control components are each implemented on one ECU. The third ECU is unused for the moment, but might later host perception. The ECUs have a SPACE 2FB30-M microcontroller with clock frequency of $120\,MHz$, $3\,MB$ Flash memory, $100\,kB$ RAM memory. They are based on the AUTomotive Open System ARchitecture (**AUTOSAR**) standard, version 2.1.0. On ECU, AUTOSAR fulfills a similar function as RTMaps on PC (see Section 4.3.4). It encapsulates the algorithms and makes abstraction of the physical connection to simulator or vehicle. For example, the communication between ECUs is done via CAN and a special transfer protocol is implemented in order to assure the coherence of large data structures. But, this is not visible on application level. On an AUTOSAR-based ECU, decision and control components access input and output variables in the same way as on PC. Details on the ECUs, AUTOSAR and component implementation are documented in HAVEit deliverables [HAV11b, HAV11c, HAV11n, HAV11o].

Vector CANcaseXL interfaces [Vec12] (lower part of the suit case, not visible in Figure 4.6) make the **connection between CAN and the PC** that holds perception and HMI components. Perception and HMI are integrated in an RTMaps diagram on PC, as in Figure 4.5. Decision and control modules in the diagram in Figure 4.5 are replaced by modules that interface between CAN messages and legal safety data structures. One interface module translates the environment interactor given by the perception component on PC to CAN messages for the decision component on ECU. Another interface module translates CAN messages from the decision component on ECU to a system-to-human interactor for HMI on PC. A third interface translates CAN messages from control on ECU to longitudinal and lateral commands on the actuators of the simulator on PC or of the vehicle.

A Lauterbach Power Trace II debugger with Nexus interface [Lau12] (upper part of the suit case in Figure 4.6) and Vector CANape software on the PC are used for **debugging and tuning** decision and control components on ECU.

As most of today's automotive ECUs, the ECUs do not allow dynamic programming in C++. They require static data structures, with a size that is defined at compilation, not during operation. Legal safety components are compatible with static data structures, as they **bound the number of data elements** by design. For example, perception limits the number of objects to a maximum of 8 that cover worst-case actions of all objects in the environment. The decision component calculates a maximum of 7 trajectories and outputs a maximum of 4, as was explained in Chapters 2 and 3. This allows using C instead of C++, both on PC and ECU.

The **calculation time** needed by legal safety components is bounded, as required by Rule 16. For example, the decision component always calculates the 7 subject trajectories in a maximum number of steps and guarantees the existence of at least the trajectory in the subject lane, as was explained in Chapter 3. On ECU, the calculation time of decision and control components is below $25\,ms$.

In the beginning of the development, when ECU hardware and architecture were defined, a safe choice of one ECU per component was made. Current algorithm performance would allow hosting decision and control components on a **single ECU**. This would facilitate the

Figure 4.6: The LIVIC Legal Safety Demonstrator suit case: Continental CSC ECUs (lower half), Lauterbach Power Trace II with Nexus interface for code flashing and debugging (upper half) and connection to vehicle CAN and PC for code flashing and debugging (left side)

communication between both components (as no CAN communication would be required) and further reduce total system calculation time (no delay would be caused by CAN communication). Many state-of-the-art sensors perform a substantial part of perception calculations directly on sensor ECU. For example, instead of raw data, they directly provide a lane or object description. In this case, remaining perception calculations (e.g. the fusion of lane and object descriptions of different sensors) could be integrated on ECU with decision and control, which further facilitates the communication between components and reduces system calculation time.

4.3.6 Results on validation scenarios

This section discusses the results of the LIVIC Legal Safety Demonstrator on the validation scenarios in Table 4.1. **Legal safety functionality** is validated on either LIVIC Legal Safety Vehicle (for scenarios that do not involve lane changing) or LIVIC Legal Safety Simulator (for scenarios that involve lane changing). Unless specified differently, tests are performed in highly automated driving. Maximum speed and target lane are specified by the human driver and longitudinal and lateral control is performed by the driving system.

Legal safety allows a large variety of **driving styles**. Parameters in the **decision component** (Chapter 3) can be set to allow stronger longitudinal and lateral accelerations (i.e. a_u^H, a_w^H, a_u^P), smaller distances to an object (i.e. p_u^H) and higher trajectory slopes (i.e. s_w^H), while keeping safety and respecting traffic rules, human rules and system rules. These parameters also influence the maximum vehicle speed that can safely be reached with the system. As was mentioned in Chapter 1, perception and control components are objective by nature. These components do not change for different driving styles.

Experiments with *sportive* and *green (comfortable)* driving styles in the LIVIC Legal Safety Simulator will be presented. Note that *sportive* and *green (comfortable)* are mere names for two exemplary driving styles; they do not intent to show the most sportive or greenest (most comfortable) driving style that can be reached with the system. The goal is provide a **first estimate** whether system driving style could be matched to the style of the human driver, or not. A comparison with non-legal driving and with one human driver (myself) is made. Obviously, a single test per scenario with a single human driver does not allow a general comparison between driving systems and human drivers. The test rather is meant as an invitation to more extensive tests with a diverse group of human drivers in future HMI research.

Figure 4.7 shows the Satory test track in Versailles, which is used for testing LIVIC Legal Safety Simulator and LIVIC Legal Safety Vehicle. Testing is limited to situations with **flat, dry asphalt** in clear weather conditions. ISO test procedures require testing with motorcycles as objects (i.e. the smallest objects on highway), but in the tests only **passenger cars** are used. These *friendly* test conditions allow demonstrating the general principles of the legal safety system, with a focus on the validation of the decision component that is designed in this work. Extensive tests on perception and control in worse conditions and with smaller objects should be carried out in future work. As this work focusses on the specification of requirements on perception and control, but not on their actual design, such tests are not in the scope of this work.

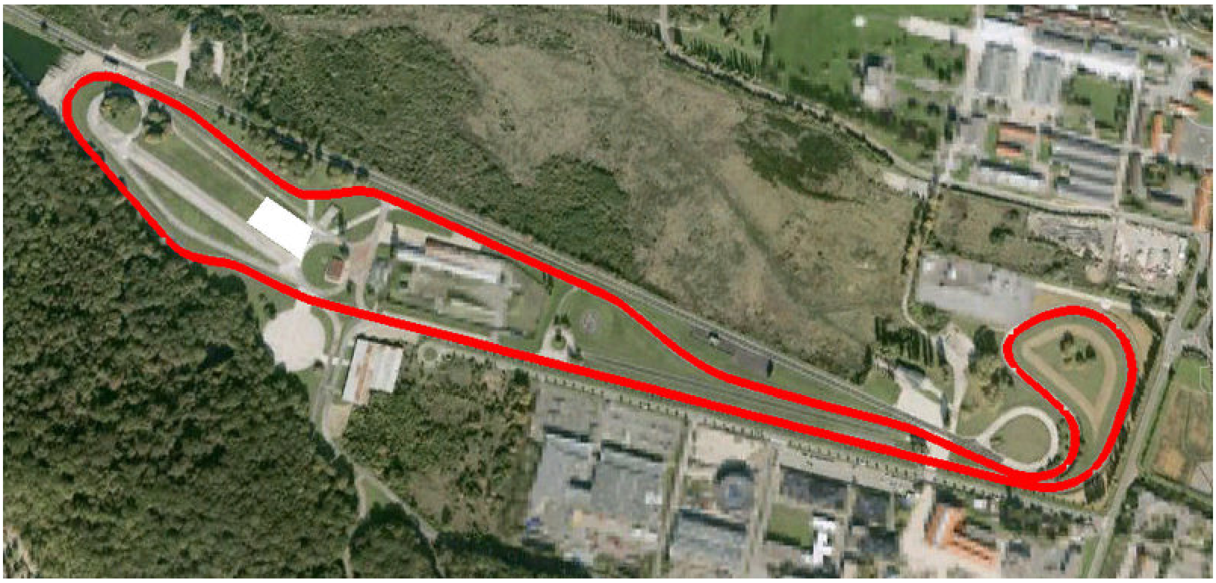


Figure 4.7: Test track in Versailles, France used for validation of LIVIC Legal Safety Demonstrator and ABV Low Speed Demonstrator

A video of the LIVIC Legal Safety Simulator that combines several validation scenarios can be found on `http://youtu.be/dMaifGaqngo`. A video of the LIVIC Legal Safety Vehicle is available on `http://youtu.be/9-2lRFm7BYw`. In next sections, reference will be made to several videos of the actual validation tests.

Following a human target speed,
Approaching a speed limit,
Approaching a curve

This section presents results on three related scenarios; *Following a human target speed*, *Approaching a speed limit* and *Approaching a curve*.

Figure 4.8 shows a snapshot of HMI during a test that combines *Following a human target speed* and *Approaching a speed limit* on the LIVIC Legal Safety Vehicle. System-to-human information is projected on the image of the vehicle camera. (Similarly, this information could be shown by head-up display.) The HMI shows the **automation mode**; highly automated. The **vehicle speed** is $50\,km/h$. This corresponds to the target speed set by the driver, which is indicated with numbers on the speed panel, in a different color. The speed panel ranges from zero to the actual speed limit; $90\,km/h$. A new speed limit of $30\,km/h$ is detected. This is indicated by a **warning message** and by the **target speed** recommended by the decision component. The actual speed limit sign is not visible in Figure 4.8. On the LIVIC Legal Safety Vehicle the speed limit is not detected by camera, it is obtained by V2I communication. The proposed **target lane** is the subject lane, as is indicated with the arrow in the lower part of the image. This HMI is kept very rudimentary, as actual HMI design is not the focus of this work. Several simple modifications could be done to make the HMI easier to understand, e.g. using standard icons for automation mode and warning messages.

Figure 4.9 shows the evolution of the vehicle speed (circle label) in function of the actual speed limit (square label). The target speed for the speed profile $0B$ in the subject lane is labeled with a triangle. The **human target speed** is $50\,km/h$ ($13.9\,m/s$) during the complete test. The vehicle accelerates and keeps the human target speed, with an error of $3\,km/h$ ($0.8\,m/s$), at $t = 19\,s$ (point 1 on the figure). At $t = 20\,s$ (point 2), a **speed limit** of $30\,km/h$ ($8.3\,m/s$) is detected at a distance of $60\,m$ (the distance is not visible in the figure). The target speed of the system (triangle label) is adapted to the speed limit. The speed profile is such that system reaches the limit with minimal braking, i.e. just in time, at $t = 25\,s$ (point 3). A speed control error of $1.5\,km/h$ ($0.4\,m/s$) remains. The **zone model** for the speed profile at $t = 20\,s$ is sketched with dashed lines. The control of the vehicle speed corresponds quite well to the zone model, except for a slight positive speed offset of $1.5\,km/h$ ($0.4\,m/s$). This offset should be easy to correct in the control component.

Figure 4.10 shows the results of a test with different driving styles in the scenario *Approaching a speed limit* with the LIVIC Legal Safety Simulator. The subject speed is plotted against the curvilinear distance (with respect to subject position at the start of the test), and compared with the actual **speed limit**. The parametrization for sportive driving and green (comfortable) driving differs by the maximum deceleration and acceleration that is used for adapting to speed limits (a_u^H in Chapter 3). The **sportive driving system** sprints with maximum acceleration ($2.25\,m/s^2$) till the first speed limit of $120\,km/h$ ($33.3\,m/s$). At the detection of the second speed limit (point 1 on the figure), the system brakes strongly ($-4.5\,m/s^2$) in order to adapt vehicle speed to $50\,km/h$ ($13.9\,km/h$) at the begin of that speed limit (point 2). Compared to the sportive driving system, **human driver** applies a slightly lower acceleration until the first speed limit and starts braking a little earlier for the second speed limit. After a slight undershoot and overshoot, the human driver stabilizes speed at $50\,km/h$ ($13.9\,km/h$). The **green (comfortable) driving system** adopts a softer acceleration to the first speed limit and softer deceleration to the second speed limit. Note that the green driving system limits its speed to $83\,km/h$ ($23\,m/s$), which is far below the first speed limit of $120\,km/h$ ($33.3\,m/s$). This illustrates the *phantom speed limit* concept that was mentioned in Chapter 3. Phantom speed limits have a similar function as phantom objects; they limit subject speed, so that the system can adapt to worst-case speed limits with a limited deceleration a_u^H. This allows the green driving system to reach the second speed limit with a softer deceleration than the sportive driving system. Phantom speed limits are not required for highways (they were not explicitly described in Chapter 3), but are useful for roads with high variations in speed limits, as on the Satory test track. A video of this test is available on `http://youtu.be/s-Z71lw_L6k`.

Figure 4.11 compares the sportive driving system, green driving system and human driver in the scenario *Approaching a curve* on the LIVIC Legal Safety Simulator. The test starts on the straight section of the test track. A section with **left-right curves with different curvatures** follows after $900\,m$. The curves on the Satory test track are much stronger than on highways. Curvature values of almost $0.040\,1/m$ $(1/25\,1/m)$ are reached, while on highways curvature is usually below $0.002\,1/m$ $(1/500\,1/m)$. The figure demonstrates the concept *phantom curves*, which is similar to phantom speed limits and phantom objects. It limits subject speed, so that the system can decelerate in time for a worst-case curve that appears at the end of the perception zone. Like phantom speed limits, phantom curves were only briefly mentioned in Chapter 3. They are implemented in the legal safety decision component, in order to deal with environments with stronger curves than highways, such as the Satory track. The phantom curve explains why both the **sportive driving system** and **green driving system** limit vehicle speed in the straight section of the track, although no explicit speed limit is given in this test. The sportive driving system reaches higher speeds than the green driving system, at the expense of a stronger deceleration between the detection of a curve and the beginning of that curve, from point 1 to point 2 on the figure. Note that the system matches target speed to the maximum curvature of the curve, and reaches this target speed before the curve begins, both during sportive driving and green driving. Note also that the green driving system, could be greener (but less comfortable) by allowing higher speeds in the curves. To this end, the maximum lateral acceleration parameter could be increased, and the maximum longitudinal acceleration parameter kept unchanged. This would flatten out the speed profile and reduce accelerations. The **human driver** reacts around the same moment as the driving system, but ends the deceleration after the beginning of the curve. In the curved section, the speed profile of the human driver is situated between that of both driving systems. Note that the three tests were done over a same duration, in which the green (comfortable) driving system comes less far than the sportive driving system and human driver. The video of the test is available on `http://youtu.be/6XXhbhbr_Es`.

The **system design** presented in Chapters 2 and 3 delivers satisfactory behavior for the scenarios *Following a human target speed*, *Approaching a speed limit* and *Approaching a curve*. Additionally, it seems possible to **match the style** of the driving system with that of a human driver, e.g. by interpolating between sportive and green driving styles. The **perception** of speed limits and curves, according to the principles of legal safety, is currently only available on the LIVIC Legal Safety Simulator. As can be seen in Figures 4.10 and 4.11, a perception horizon of around $200\,m$ is sufficient for adapting to strong variations of speed limits and curvature on the Satory test track. On the LIVIC Legal Safety Vehicle, speed limits and curves cannot yet be detected by camera as is required by legal safety. They are currently given by communication and map. Detection of speed limits and curves at $200\,m$ is probably out of reach of state-of-the-art perception. As in highway environments speed limits and curvature vary less quickly, the perception horizon can be shorter.

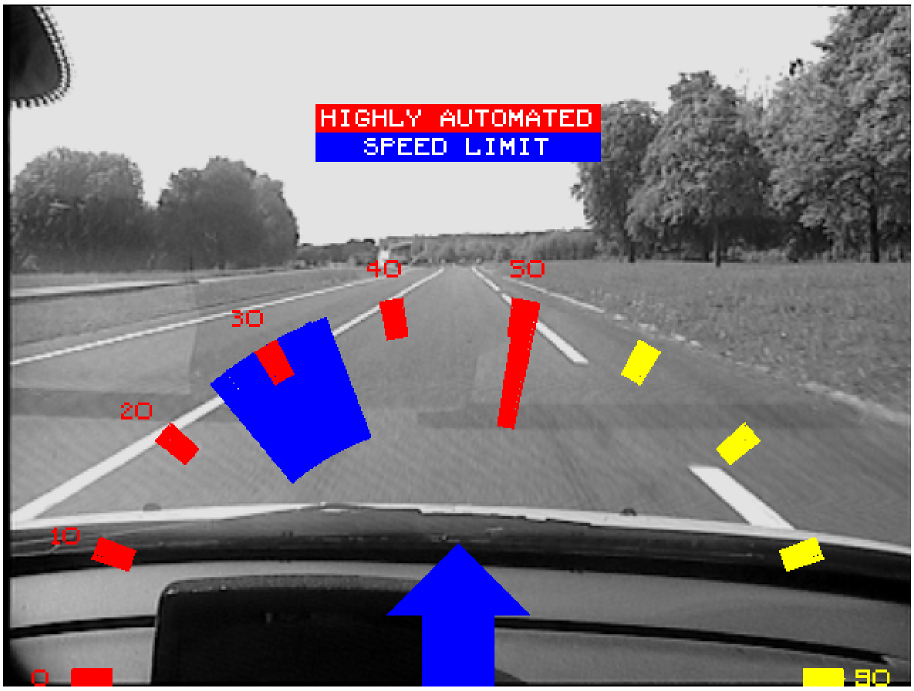


Figure 4.8: Scenarios *Following a human target speed* and *Approaching a speed limit* on LIVIC Legal Safety Vehicle: HMI at $t = 21\,s$. Subject speed is $50\,km/h$, matching human target speed. Current speed limit is $90\,km/h$. A future speed limit of $30\,km/h$ has been detected

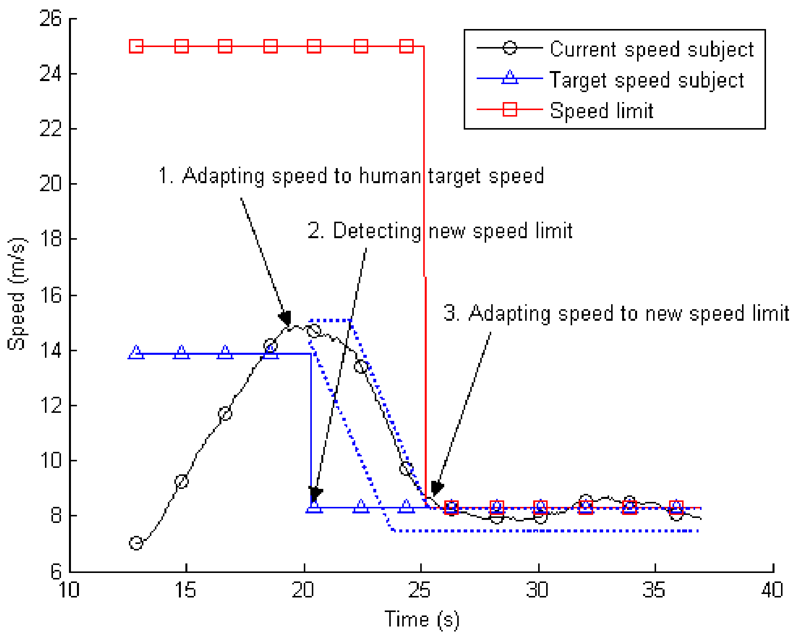


Figure 4.9: Scenarios *Following a human target speed* and *Approaching a speed limit* on LIVIC Legal Safety Vehicle: subject speed in function of time. The zone model of the speed profile at $t = 20\,s$ is illustrated with dashed lines

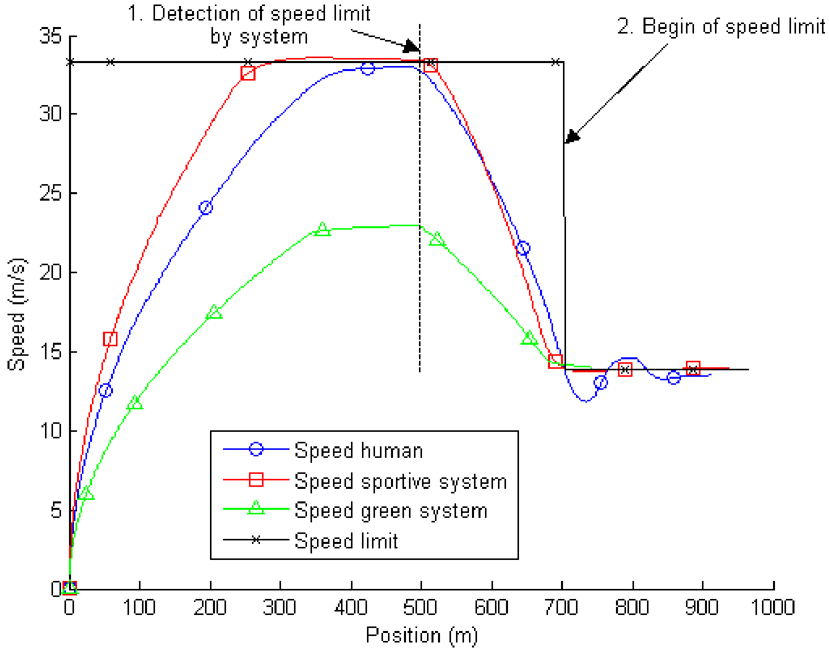


Figure 4.10: Scenario *Approaching a speed limit* on LIVIC Legal Safety Simulator: subject speed in function of curvilinear distance. Comparison between human driver, sportive driving system and green driving system

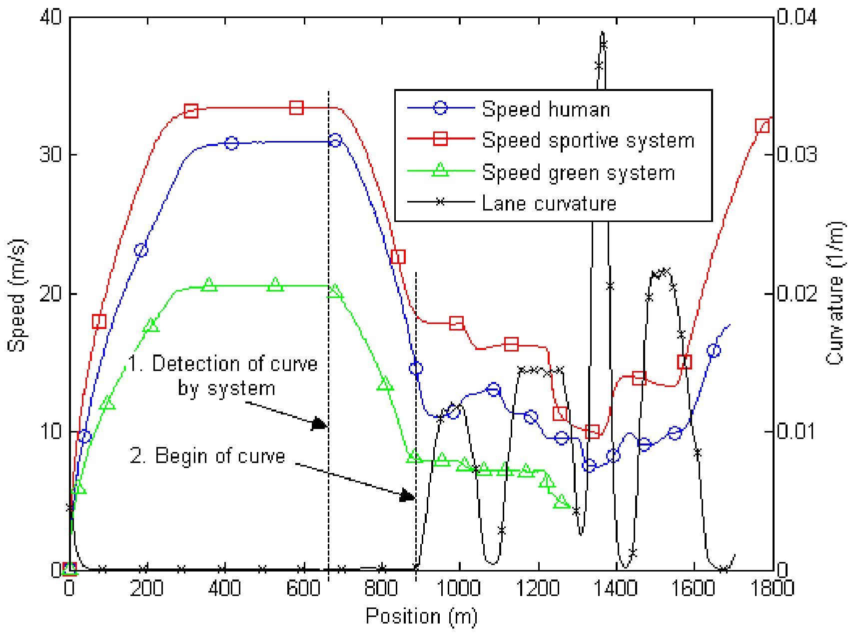


Figure 4.11: Scenario *Approaching a curve* on LIVIC Legal Safety Simulator: subject speed in function of curvilinear distance. Comparison between human driver, sportive driving system and green driving system

Approaching a phantom,
Approaching a stop

The scenario *Approaching a phantom* shows how the LIVIC Legal Safety Demonstrator limits vehicle speed, in order to be able to stop for a **still standing object** outside the perception zone. Decelerating for a still standing object also illustrates the scenario *Approaching a stop.*

Figure 4.12 shows the HMI on the LIVIC Legal Safety Vehicle. Speed limit and human target speed are $90\,km/h$. The system does however not reach these target speeds. It limits subject speed to $78\,km/h$ in order to be able to stop if a still standing object would appear at $70\,m$; the **perception horizon** with LIDAR. The HMI snapshot was taken just before the actual detection of such object.

Figure 4.13 shows subject speed in function of time. In the beginning of the test, no object is detected. Subject speed is kept on the **maximum speed** allowed by phantoms; $78\,km/h$ ($21.7\,m/s$) (point 1 on the figure). At $t = 38\,s$ an **object** at the end of the perception zone is detected (point 2). Its position is square-labeled. The target speed (triangle label) is adapted to the zero object speed. The figure reveals some error on the estimation of object speed during hard braking. The measured object speed varies between $0\,km/h$ and $18\,km/h$ ($5\,m/s$), but the actual object speed is zero at all times. This measurement error has however little influence on the overall maneuver. The system applies a deceleration of around $-5\,m/s^2$ (i.e. close to the maximum deceleration allowed by the system) and comes to a standstill at $13\,m$ from the object (point 3), i.e. with an acceptable error of $3\,m$ on the target distance of $10\,m$. Note two moments of false object detections at $t = 40\,s$ and $t = 42\,s$. On these moments, the vehicle pitch increases due to hard braking and the LIDAR points to the road, rather than to the object. Such ground readings could be avoided with multi-layer LIDAR, which allows distinguishing horizontal objects (e.g. the road) and vertical objects (e.g. actual objects). Additionally, object tracking could exclude sudden jumps in object position. The subject speed profile corresponds quite well to the **zone model**, from the detection of the object at $t = 38\,s$ till standstill at $t = 48\,s$. In the beginning, from $t = 38\,s$ to $t = 42\,s$, the deceleration is a bit too strong. From $t = 42\,s$ to $t = 48\,s$ the deceleration becomes softer.

Figure 4.14 compares different driving styles with respect to the scenarios *Approaching a phantom* and *Approaching a stop* on LIVIC Legal Safety Simulator. In the test, a still standing object is present at a $830\,m$ from the start point. The figure compares the approach of the object by a sportive driving system, a non-legal driving system (that does not take into account phantom objects) and a human driver. The **sportive driving system** takes off with maximum acceleration till a speed around $131\,km/h$ ($36.5\,m/s$). The perception zone of the system is $200\,m$; the still standing object (point 2) is detected at curvilinear position $630\,m$ (point 1 on the figure). At a speed of $131\,km/h$, the sportive driving system is still able to come to a standstill behind the object with hard braking ($-4.5m/s^2$, the most extreme deceleration allowed with the vehicle model in the simulator). The **non-legal driving system** has the same parameters as the sportive system, but it does not consider phantoms. It accelerates till $150\,km/h$ ($41.6\,m/s$), the maximum speed allowed by the human driver. As a consequence, an emergency brake at $-4.5m/s^2$ is not sufficient to bring the vehicle to a standstill before the still standing object. A crash occurs at $830\,m$. (No crash model is integrated in the simulator. The driving system continues driving after the collision.) Compared to both driving systems, the **human driver** keeps a lower speed, of around $100\,km/h$ ($27\,m/s$). The human driver has a perception horizon of around $300\,m$ (braking is started at $530\,m$), which is larger than that of the driving systems. The lower speed and bigger perception horizon allow a moderate (yet slightly uneven) deceleration till standstill. A video of this test can be found on `http://youtu.be/MM_w2c1aje8`.

The tests show the safety benefits of limiting vehicle speed with respect to the perception horizon, via the phantom concept. The test in Figure 4.13 shows that a perception horizon of $70\,m$ with the LIDAR on the LIVIC Legal Safety Vehicle is not sufficient to reach highway speeds. A maximum speed of $78\,km/h$ is reached. The simulation in Figure 4.14 shows that a **perception horizon of** $200\,m$ is needed to reach a highway speed of around $130\,km/h$, if the deceleration is limited to $-4.5\,m/s^2$. This motivates the integration of radar on the LIVIC Legal Safety Vehicle in future development. If higher deceleration values are allowed by human driver or if system reaction times decrease, a smaller perception horizon allows reaching highway speed. For example a perception horizon of $120\,m$, deceleration of $-8\,m/s^2$ and reaction time of $1\,s$ allows reaching $130\,km/h$. On the LIVIC Legal Safety Simulator, the test presented in this section covers both approaching a **stop (i.e. end of the lane, end of the application zone)** and approaching a still standing object. Stops and objects are detected with the same ease on simulator. On the LIVIC Legal Safety Vehicle, a still standing object can be already detected by perception, but reliability and precision are still an issue. As stops (e.g. end of application zone) cannot yet be detected with exteroceptive sensors, they are described by map.

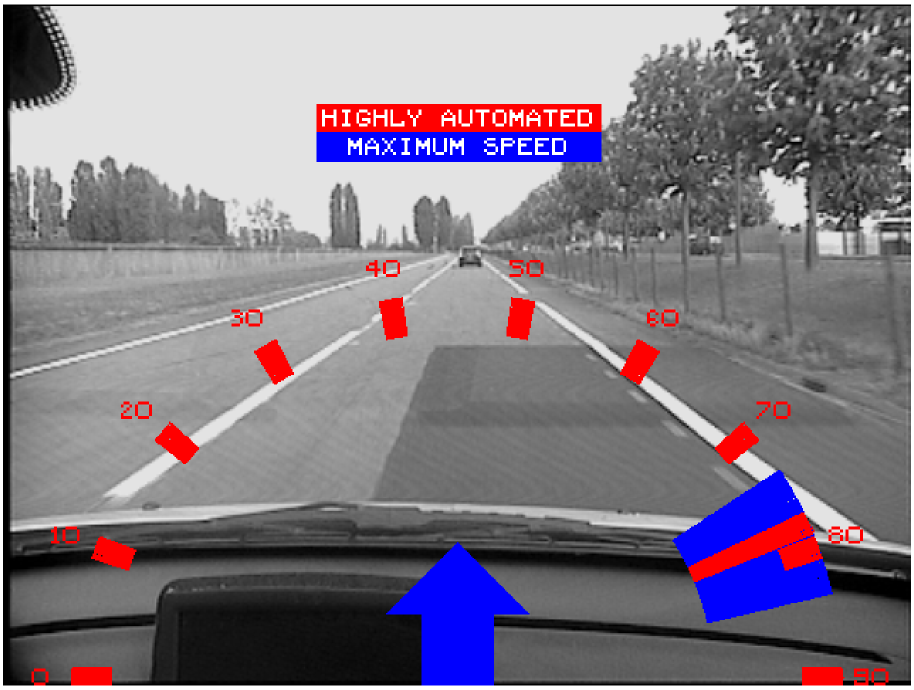


Figure 4.12: Scenarios *Approaching a phantom* and *Approaching a stop* on LIVIC Legal Safety Vehicle: HMI at $t = 36\,s$. Object is not yet detected. Subject speed is $78\,km/h$, matching the maximum speed allowed by phantoms at $70\,m$, which is the end of the perception zone. Human target speed and speed limit are $90\,km/h$

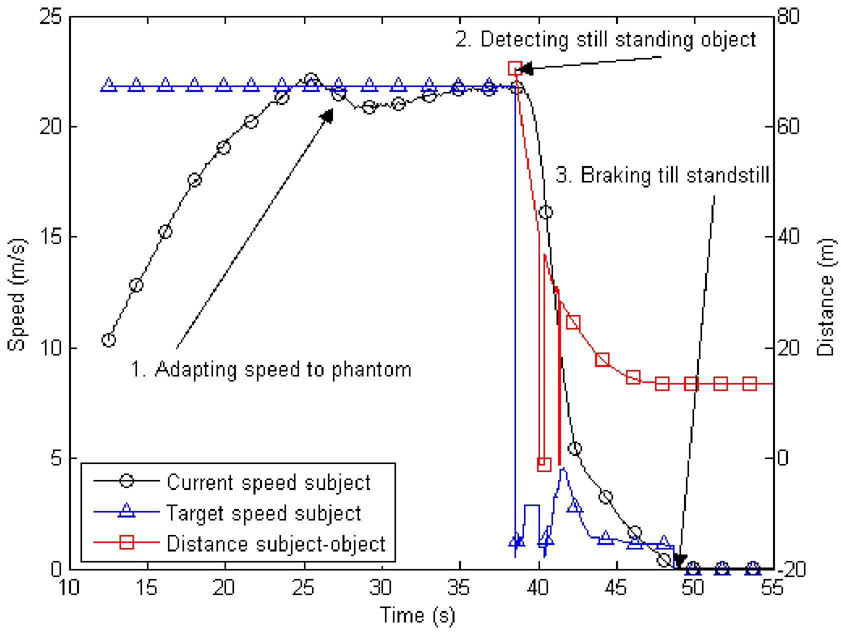


Figure 4.13: Scenarios *Approaching a phantom* and *Approaching a stop* on LIVIC Legal Safety Vehicle: subject speed and distance to object in function of time

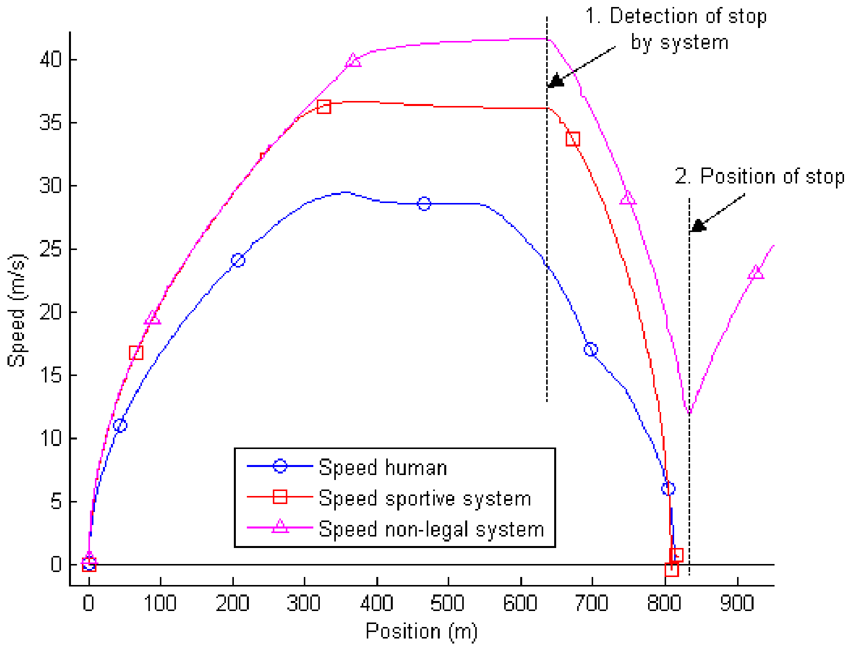


Figure 4.14: Scenario *Approaching a phantom* and *Approaching a stop* on LIVIC Legal Safety Simulator: subject speed in function of curvilinear distance. Comparison between human driver, sportive driving system and non-legal driving system

Following an object

Figure 4.15 shows the HMI during the scenario *Following an object* on the LIVIC Legal Safety Vehicle. The system controls distance to an **object** that varies its speed and that changes lanes between subject and left lane. In the image, the object is on the left lane but crosses the lane marking towards the subject lane. The system predicts that the object will change lanes and announces it as *vehicle ahead*.

Figure 4.16 shows how the system adapts subject speed (circle label) to object speed (i.e. subject target speed, triangle label) and object position (square label). During the test, the object continuously **changes lanes** between subject and left lanes. This does not influence the distance control by the system. A same distance of $2\,s$ is kept from objects on subject and left lanes. After a period of constant speed (point 1 on the figure), the object starts continuously **changing its speed** (point 2). The distance between subject and object varies between $20\,m$ and $30\,m$. Note that during the test, the variation of subject speed is around $20\,\%$ higher than the variation of object speed. It would be interesting to perform tests with a **platoon** of vehicles equipped with the system. If these tests would show that the variation of vehicle speed increases with each additional vehicle in the platoon, the last vehicles would regularly come to a complete standstill. This would correspond to the phenomenon of traffic waves that can be seen in traffic with human drivers. A study could then follow on a distance control law (see Chapter 3) for decreasing (instead of increasing) speed variations, in order to avoid or flatten out traffic waves. At $t = 85\,s$ the object is lost for $3\,s$. It is wrongly assigned outside of the lanes. This perception problem could be tackled with more robust object tracking, and with the use of camera instead of LIDAR to determine the object-to-lane assignment. As the subject accelerates, distance to the object decreases and the object is again detected at $t = 88\,s$. The object is braking with a deceleration of around $-1.5\,m/s^2$ **until standstill**. The subject decelerates at around $-2.0\,m/s^2$ till standstill at $10\,m$ of the object (point 3), which is close to the minimum distance allowed by the decision component.

Figure 4.17 compares different driving styles for following an object on the LIVIC Legal Safety Simulator. A **sportive driving system, non-legal driving system and human driver** start at zero speed at reference position $0\,m$. In the beginning of the test, when no object is present on subject or left lanes, the sportive driving system, non-legal driving system and human driver increase speed. (The vehicle speed is not indicated on the figure.) An object starts on the right lane and accelerates to $80\,km/h$ ($22.2\,m/s$). The object performs a (non-legal) lane change to the subject lane, just in front of the driving systems (the human driver is following further behind, at around $100\,m$ from the driving systems) (point 1 on the figure). Both sportive and non-legal driving system avoid the collision with the object by hard braking. After this, the **sportive driving system** keeps a distance at $1.3\,s$ from the object. This corresponds with the system reaction time t^R. It is the minimum distance required to be able to avoid a collision in the case that the object performs an emergency brake (see Equation 3.44 for calculation of minimum safety distance p_u^J). The **non-legal driving system** follows at $0.5\,s$ from the object, which is not enough to avoid collisions in emergency situations. Both driving systems keep the distance of $1.3\,s$ and $0.5\,s$ respectively, as the object varies speed from $80\,km/h$ ($22.2\,m/s$) to $60\,km/h$ ($16.6\,m/s$) to $110\,km/h$ ($30.6\,m/s$). The **human driver** keeps a distance that is close to distance kept by the non-legal driving system. The human driver is however a little less reactive than the driving systems. His distance to the object shows bigger variations. When the object performs an **emergency brake** at a position $2700\,m$, the driving systems and human driver try to avoid a collision by braking. Only the sportive driving system succeeds; it stops at around $10\,m$ from the object (point 2). As the non-legal driving system and human driver followed at a distance from the object that is smaller than their respective reaction times, an accident occurs (point 3). The video of this test can be watched on `http://youtu.be/GCmAieHw4Kc`.

This section shows how the LIVIC Legal Safety Demonstrator keeps a distance from objects on subject and left lanes. The description of object position, speed and acceleration is available with **state-of-the-art perception**. When the object performs an **emergency brake**, a collision can only be avoided by braking if the distance from the object is larger than a certain **safety distance**, which is function of reaction time and deceleration capacity. As driving systems have quite small reaction times and can estimate sudden object decelerations quite precisely, a legal safety distance of $1\,s$ can typically be reached. This safety distance could be acceptable for the average human driver, and can further be decreased as perception and control become more precise. In certain situations of object emergency braking, a collision can be avoided by lane changing. This might explain why some human drivers feel safe at small distances from the object. Further investigation on the ability of human drivers to avoid accidents with braking objects, as is required by traffic rules, could be interesting.

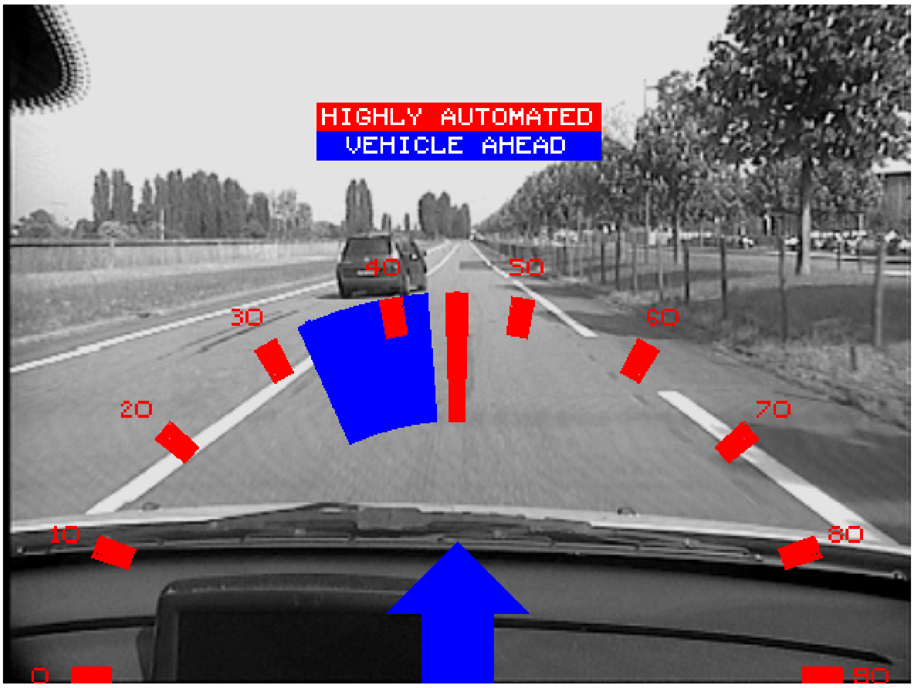


Figure 4.15: Scenario *Following an object* on LIVIC Legal Safety Vehicle: HMI at $t = 60\,s$. Subject speed is $45\,km/h$, target speed human driver and speed limit are $90\,km/h$. Object speed $38\,km/h$. Object is crossing lane markings and predicted as *Vehicle Ahead*

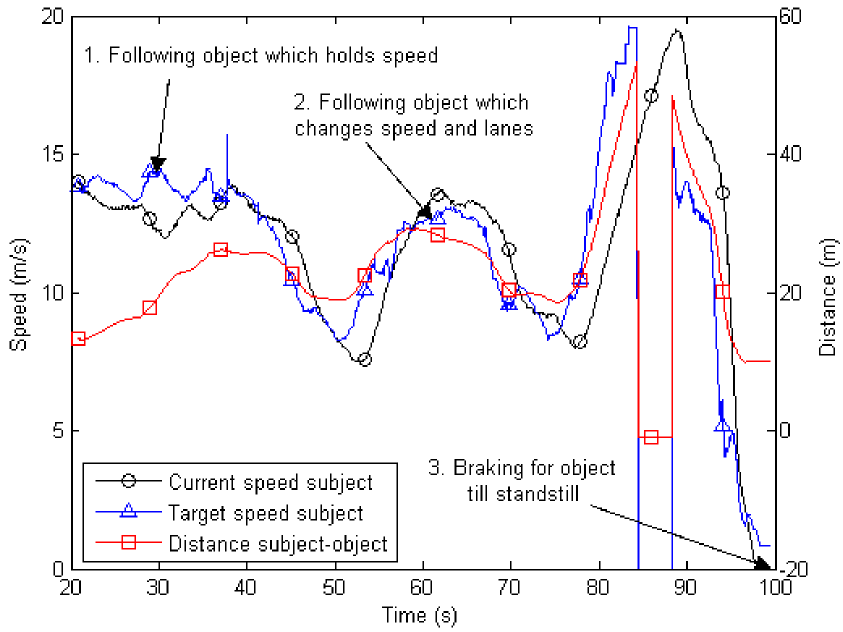


Figure 4.16: Scenario *Following an object* on LIVIC Legal Safety Vehicle: subject speed and distance to object in function of time

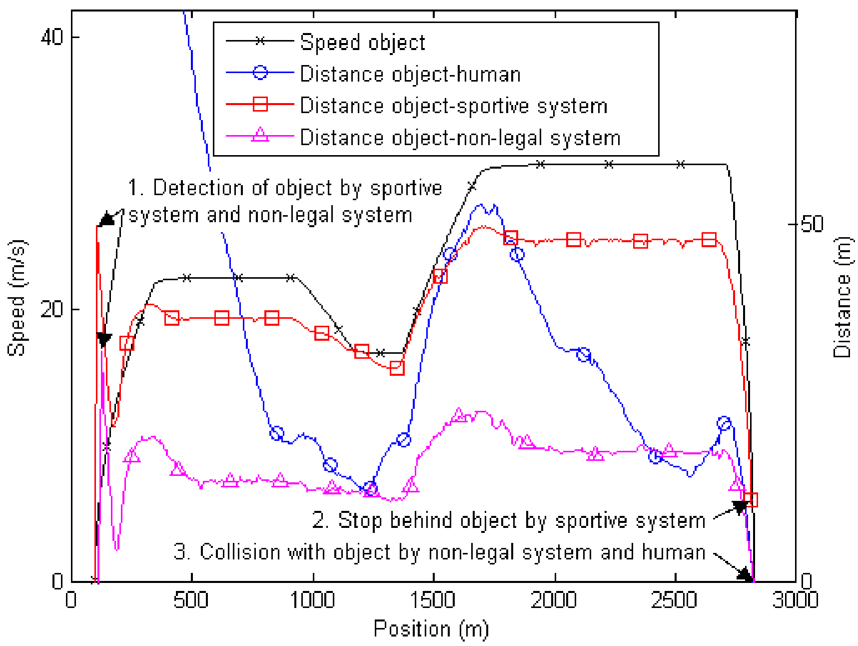


Figure 4.17: Scenario *Following an object* on LIVIC Legal Safety Simulator: subject speed in function of curvilinear distance. Comparison between human driver, sportive driving system and non-legal driving system

Overtaking an object,
Changing to human target lane

Figure 4.18 shows the HMI on scenarios *Overtaking an object* and *Changing to human target lane*. As was mentioned in Section 4.3.3, perception on the LIVIC Legal Safety Vehicle currently only describes the subject lane, the perception of right and left lanes is under development. Scenarios that involve lane changing are shown on the **LIVIC Legal Safety Simulator**.

Figure 4.19 shows the lateral offset of the subject (i.e. of the origin of the subject coordinate system XY) with respect to the right border of the road. It also shows the **predicted lateral offset of the object**. In the beginning of the test, the object has its left indicators activated (point 1 on the figure). It is predicted to either keep its lane (which is not indicated in the figure) or change lanes to the left (as is indicated in the figure). Consequently, the driving system does not propose a lane change to the left for overtaking the object. (If it were requested by the human driver, the driving system would perform a lane change, but would not overtake the object. It would stay at a safety distance behind the object.) At $p = 230\,m$, the object deactivates indicators and driving system proposes a lane change. The human driver acknowledges at $p = 250\,m$ and the driving system performs the lane change (point 2). The zone model of the trajectory at $p = 250\,m$ is indicated with dashed lines in the figure. The **lateral offset of the subject** (with respect to right road border) corresponds quite well to this zone model. The subject accelerates during the lane change, but keeps minimally a safety distance from the object (i.e. the minimum distance required to avoid a collision by braking only, if the object suddenly performs an emergency maneuver), until the end of the lane change at $p = 330\,m$. After passing the object, the driving system proposes a lane change to the original lane. This lane changed is acknowledged by the human driver and performed by the driving system from $p = 390\,m$ to $p = 460\,m$ (point 3).

Figure 4.20 compares different driving styles for the scenario *Changing to human target lane*. In this test, **two objects** follow each other. Both objects are equipped with the legal safety system. The distance between the objects is indicated in the figure. In the beginning of the test, the subject (with the legal safety system that is under study) is situated between both objects. At $p = 450\,m$, the human driver in the subject vehicle requests a **lane change to the object-free lane on the right** (point 1 on the figure). In the development of control, the trajectory slopes of the sportive driving system and green (comfortable) driving system are identical, as can be seen in the figure. In future development, the slope could be adapted to the driving style. The sportive driving system could perform faster lane changes than the green (comfortable) driving system. (Currently, trajectory slopes only change with subject speed. Slower speeds allow higher slopes, but this is not visible in the figure.) As the subject is not any longer between both objects, the second object comes closer to the first object, at a distance of $65\,m$. At $p = 1300\,m$, the human driver requests a lane change to the left to **reinsert between both objects**, according to the scenario *Changing to human target lane*. The human driver himself performs this insertion immediately (point 2). He forces the second object to slow down slightly. In comparison, the sportive and green driving system only change lanes if this does not require the second object to slow down. The driver systems perform the insertion when the distance between the objects is twice the safety distance. The green (comfortable) driving system keeps a bigger safety distance than sportive driving system and waits for larger object inter-distances before performing the insertion. The video of this test is available on `http://youtu.be/onOIRjRwGNY`.

This section has presented tests on simulator for highly automated lane changes for overtaking an object or inserting between objects. In order to perform these maneuvers on vehicle, additional **perception development** is required. For example, the detection of object indicators and the description of right and left lanes are needed. The **control component** is able to perform lane changes according to the zone model, but could be adapted to driving style in future development, e.g. with faster lane changes for sportive driving. A first experiment with different driving styles shows that the human driver is more assertive than the driving system for an insertion between objects. The human driver inserts between objects, even if temporarily, the distance between subject and objects becomes smaller than the safety distance. In contrast, the driving system only inserts between objects if the safety distance between subject and objects is kept at all times. For example, with a safety distance of $1\,s$, the distance between objects must be $2\,s$ before insertion. Allowing temporary non-legal behavior by the driving system (distance is smaller than safety distance) might be considered in certain situations. This might be reasonable when there is a temporal constraint for the insertion, e.g. when changing lanes towards the right lane before exiting the highway. Alternatively, system reaction time, perception precision and control precision are improved, in order to decrease safety distances.

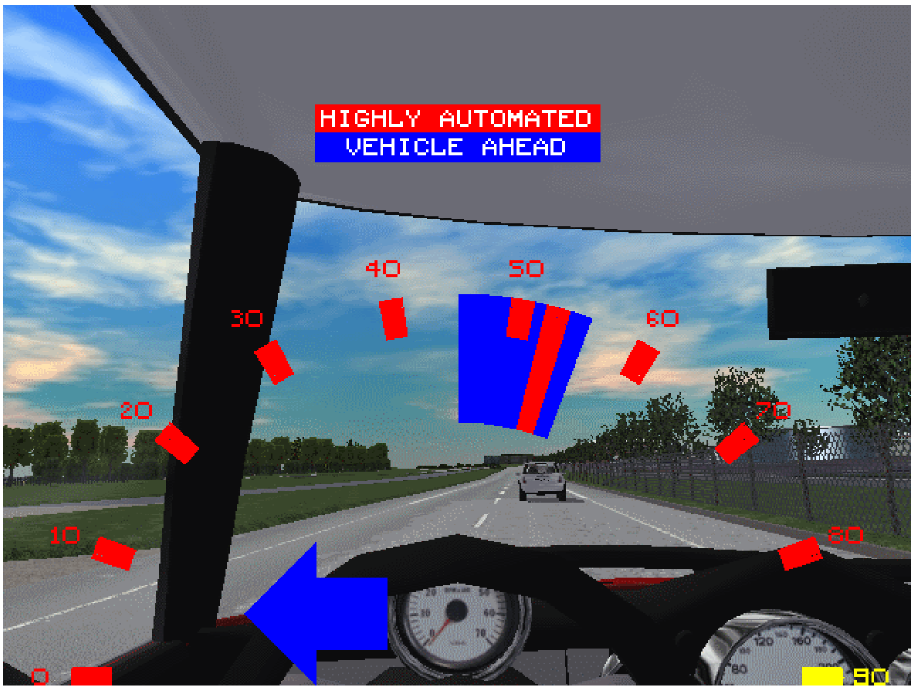


Figure 4.18: Scenarios *Overtaking an object* and *Changing to human target lane* on LIVIC Legal Safety Simulator: HMI at $p = 260\,m$. Subject speed is $52\,km/h$, object speed $50\,km/h$, human target speed $80\,km/h$ and speed limit $90\,km/h$. The overtaking maneuver has started

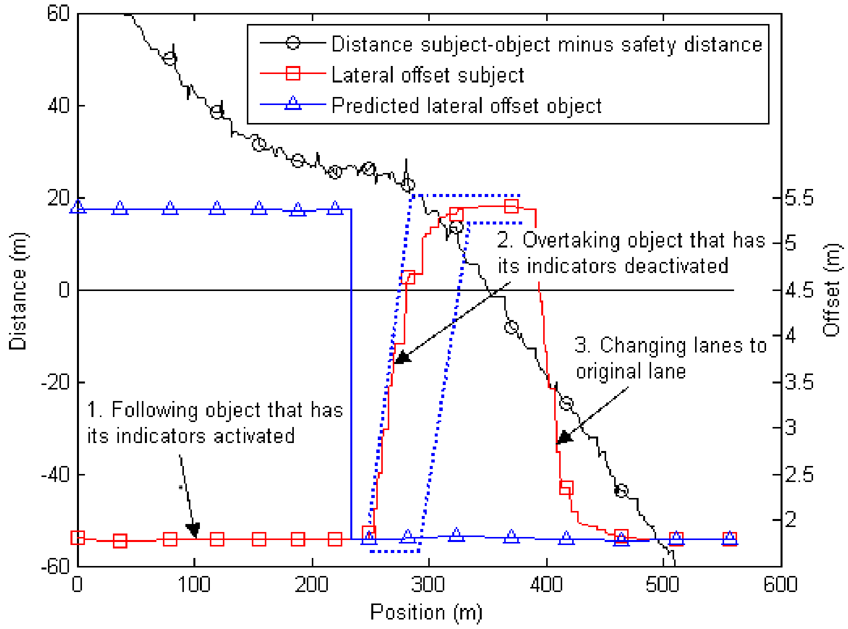


Figure 4.19: Scenarios *Overtaking an object* and *Changing to human target lane* on LIVIC Legal Safety Simulator: subject speed and distance to object in function of time. The zone model of the trajectory at $p = 250\,m$ is illustrated with dashed lines

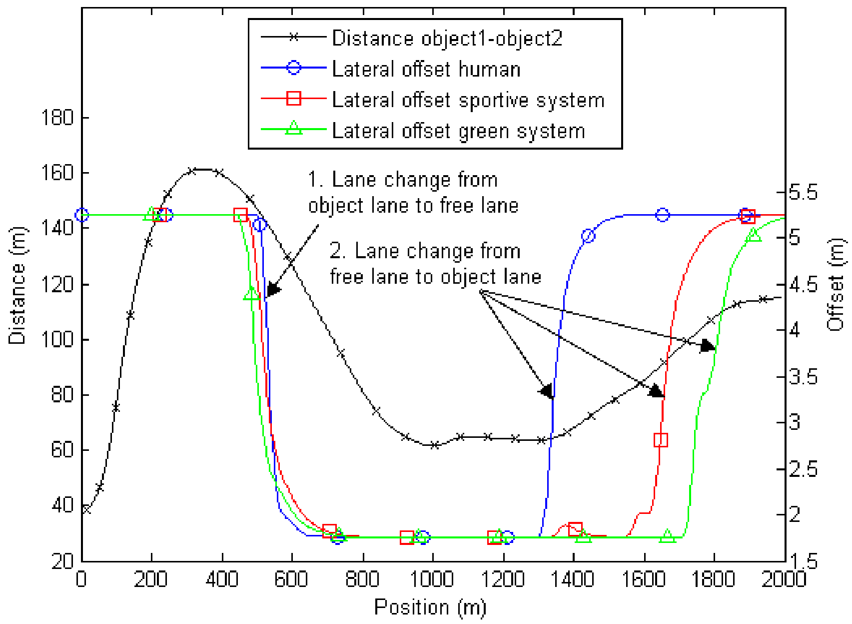


Figure 4.20: Scenario *Changing to human target lane* on LIVIC Legal Safety Simulator: lateral offset in lane in function of curvilinear distance. Comparison between human driver, sportive driving system and green driving system

Decreasing automation mode to DA,
Decreasing automation mode to SA,
Decreasing automation mode to HA,
Increasing automation mode to SA,
Increasing automation mode to HA,
Increasing automation mode to FA,
Increasing automation mode to MRM

A last test on the LIVIC Legal Safety Demonstrator combines several automation mode transitions, which are triggered by **driving system** or **human driver**. It covers validation scenarios *Decreasing or increasing automation mode to DA, SA, HA, FA and MRM* in Table 4.1. Figure 4.21 shows the HMI at the start of an MRM. The driving system has started a multiple lane change to bring the vehicle to a standstill on the emergency lane.

Figure 4.22 shows subject speed (upper part), automation mode (upper part), distance to object (lower part) and lateral offset to road border (lower part) during the test. At the start of the test, point 1 on the figure, the human driver performs longitudinal and lateral control; **driver assisted (DA)**. A slower object is present on the subject lane. The human driver fails to see the object and continues accelerating. When the **deceleration needed to keep a minimum distance** from the object (i.e. p_u^J in Chapter 3) comes below a certain threshold, the driving system takes over longitudinal control; **semi-automated (SA)**, at point 2. As a result, subject speed decreases and the distance to object stabilizes. When the deceleration with respect to object distance becomes moderate again, longitudinal control is given back to the human driver; DA, at point 3. At point 4, the human driver manually switches to SA. Longitudinal control is performed by the driving system, lateral control by the human driver. The human driver is asked to steer the subject outside the subject lane without activating indicators. From point 5 to 6, the driver system temporarily takes over lateral control in **highly automated (HA)**, in order to **avoid a lane departure**. Note that human rules of legal safety prescribe that lateral control is performed through haptic feedback. Haptic feedback that already exists in SA for communication with the human driver, becomes stronger in HA in order to be able to control the vehicle. However, the human driver can counter actions of the driving system with a reasonable couple on the steering wheel. When the vehicle is brought back in the lane, the driving system switches back to SA, at point 6. At point 7, the human driver manually switches on HA. In this case, the driving system delivers longitudinal and lateral control to follow the object in the subject lane, which is the target lane specified by the human driver. At point 8, the object performs an emergency brake. Thanks to the safety distance kept from the object, the driving system is able to avoid a collision with emergency braking. However in this test, the driving system is allowed to automatically switch to **fully automated (FA)**, in order to **avoid the object with a lane change** with smaller deceleration, without lane change acknowledgement by the human driver. At point 9, the driving system reaches the target lane (lane to the left of the original lane) and switches back to highly automated (HA) to keep that lane. At point 10, the human driver manually triggers an **MRM**. The driving system reduces vehicle speed and performs two lane changes, in order to bring the vehicle to a standstill on the emergency lane. The video of the test is available on `http://youtu.be/7FS7TDcfCJ0`.

This section has presented basic automation mode transitions according to human rules. Additional automation mode transitions triggered by human driver or driving system, i.e. additional human rules, could be studied. In the test, several **functionalities of existing ADAS** can be recognized, e.g. Adaptive Cruise Control (ACC), Brake Assist System (BAS) and Lane Keeping Assist System (LKAS). In comparison to existing ADAS, legal safety systems integrate the **complete environment description** (i.e. subject, lanes and objects), instead of a partial environment description (e.g. only lanes or only the object in front). Many functionalities benefit from a complete environment model. For example, lane departure avoidance can be triggered earlier if an object is detected on the target lane. And automatic lane changes (in FA) can be activated if no object is coming from behind. Note that this test only shows MRM without system failure (i.e. only MRM due to human failure; human distraction or drowsiness). **MRM with system failure**, e.g. sensor failure that requires that control estimates subject position during several seconds, is subject for future development.

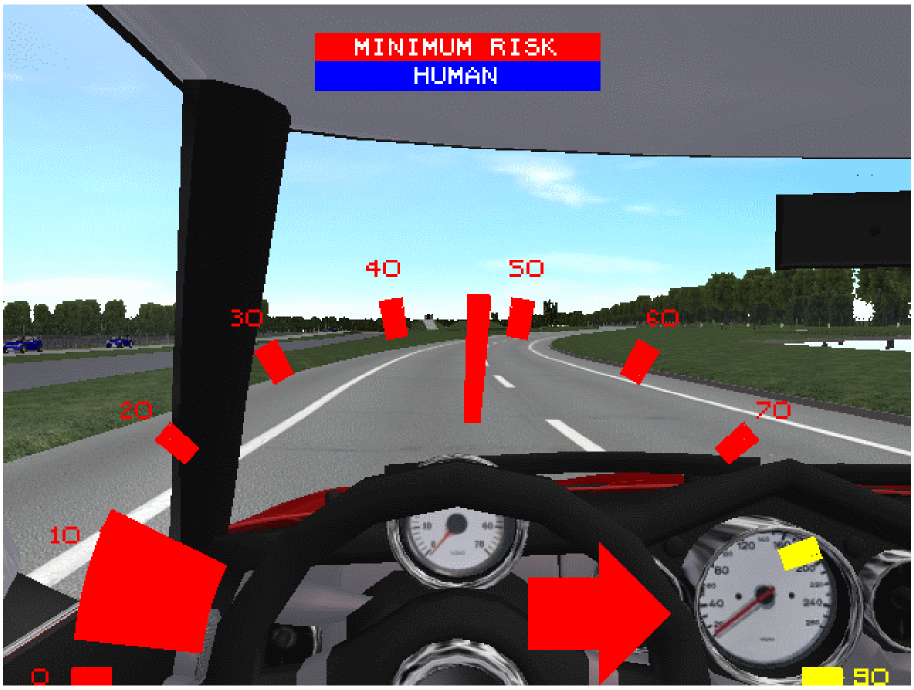


Figure 4.21: Scenarios *Decreasing or increasing automation mode to DA, SA, HA, FA and MRM* on LIVIC Legal Safety Simulator. Subject speed is 47 km/h, human target speed 70 km/h and speed limit 90 km/h. The subject has started an MRM, it decelerates and performs multiple lane changes towards the emergency lane

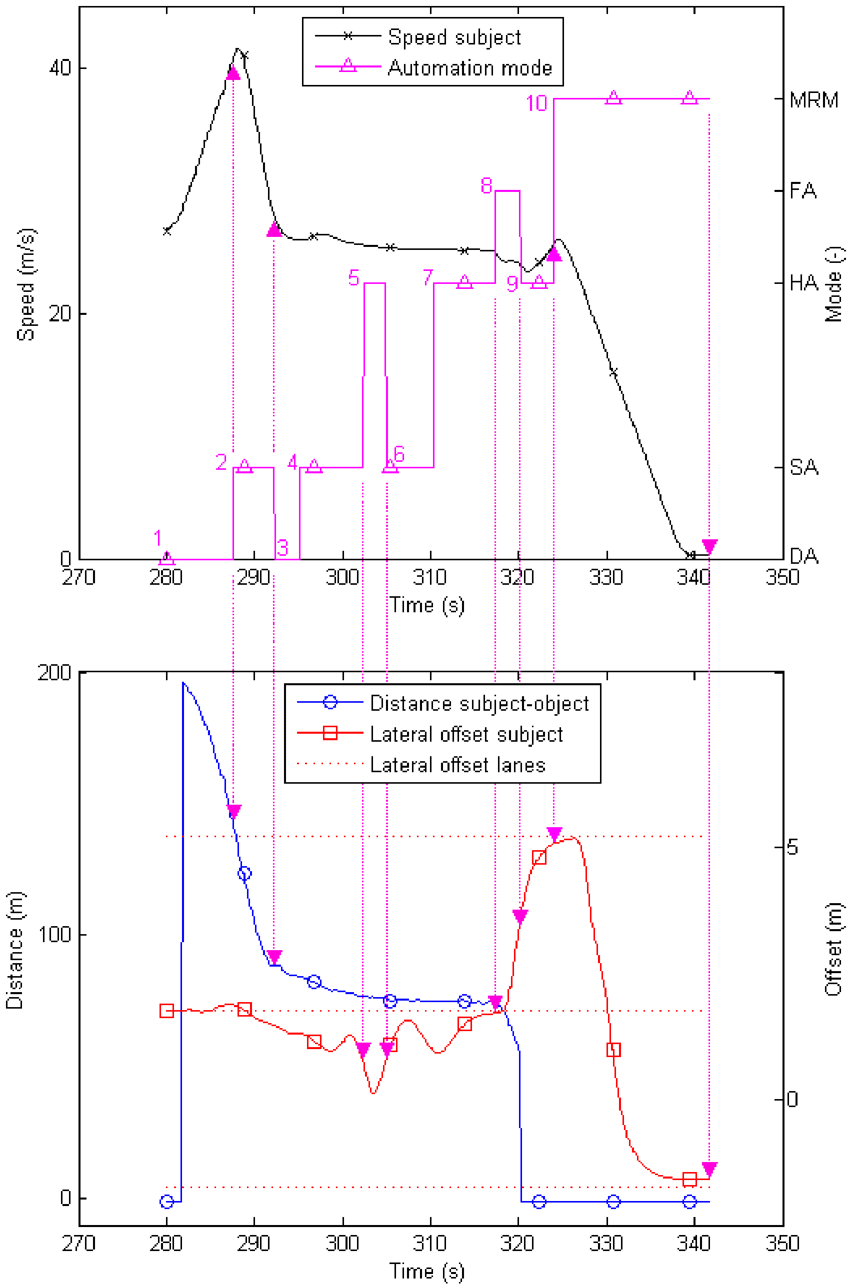


Figure 4.22: Scenarios *Decreasing or increasing automation mode to DA, SA, HA, FA and MRM* on LIVIC Legal Safety Simulator: subject speed (upper part), automation mode (upper part), distance to object (lower part) and lateral offset to road border (lower part) in function of time

4.4 HAVEit Joint System Demonstrator

4.4.1 Description

The HAVEit Joint System Demonstrator focuses on the study of **human-system interaction** during driver assisted, semi-automated and highly automated driving. The HAVEit Joint System Demonstrator is developed by an interdisciplinary team of several European research institutes and companies. It was built up during weekly teleconferences and 13 integration weeks at DLR in Braunschweig (Germany), over three project years. Figure 4.23 sketches the contribution of every partner. The implementation of components developed in this work is underlined with a solid line under the LIVIC institute name IFSTTAR. Components that are partially developed in this work and partially by LIVIC colleagues are underlined with a dashed line.

The perception component is developed by partners SICK (detection of objects by LIDAR) and ICCS (tracking and data fusion of lanes and objects). In the decision component, three algorithms for trajectory planning run in parallel. DLR developed a fuzzy logic based **maneuver tree algorithm** [LF09] that gives a quality indicator (valential) on three maneuvers for normal functioning: (a) lane keeping, (b) lane changing to the right, (c) lane changing to the left. For failure situations it also gives a valential on (d) MRM and (e) emergency braking. The legal safety decision component described in this work is integrated as **maneuver grid algorithm**; it gives a valential on the same five maneuvers (a)-(e). The subject lane trajectory (*0B*), right lane trajectory (*0A*), left lane trajectory (*0C*), MRM trajectory (*FA*, *FB* or *FC*) and emergency trajectory (*JB*) calculated in the legal safety decision component (see Chapter 3) correspond exactly to maneuvers (a)-(e). The valential of the maneuvers follows directly from the performance cost calculated in the trajectory evaluation step of the decision component. For each of the maneuvers (a)-(e), a **polynomial trajectory planner** delivered by INRIA [RN10] calculates the actual trajectory that is communicated to control. Lane changing (maneuvers (b) and (c)) is only performed if the three algorithms (i.e. maneuver tree algorithm, maneuver grid algorithm and polynomial trajectory planner) agree on a high valential. (Lane changing in highly automated driving, implies a forth acknowledgement by the human driver.) Lane keeping (either maneuver (a) or (e)) and MRM (maneuver (d)) are always possible. The **control component** for following the subject trajectory and speed profile is partially developed in this work, partially by LIVIC colleagues and DLR partners. Several control algorithms based on H-infinity [HLV+11], sliding mode and PID for calculating required longitudinal and lateral actions have been studied. For the HAVEit Joint System Demonstrator, the PID algorithm was withheld for both longitudinal and lateral control. Limits of control were tested and integrated in the zone model of subject trajectories and speed profiles in the decision component. Actuator control developed by DLR is used for executing the actions calculated by PID and for giving additional haptic feedback to the human driver. HAVEit demonstrators have a dedicated component for automation mode transitions; the Mode Selection and arbitration Unit (**MSU**). (In contrast, in the legal safety system automation mode transitions are managed by the decision component.) The MSU is developed by DLR [FH10]. The **HMI**, also developed by DLR, integrates a variety of visual, acoustic and haptic feedback elements for system-to-human and human-to-system communication [FSS+11]. A Driver State Assessment (**DSA**) component is developed by WIVW [RKK+10], for detecting human driver distraction or drowsiness. A detailed description of all algorithms is given in HAVEit deliverables [HAV11d, HAV11e, HAV11i, HAV11j].

The implementation of components of the HAVEit Joint System Demonstrator on **PC** will be described in Section 4.4.4. MSU and DSA are also available on ECU. The demonstrator consists of the **HAVEit Joint System Simulator** and **HAVEit Joint System Vehicle**, which are

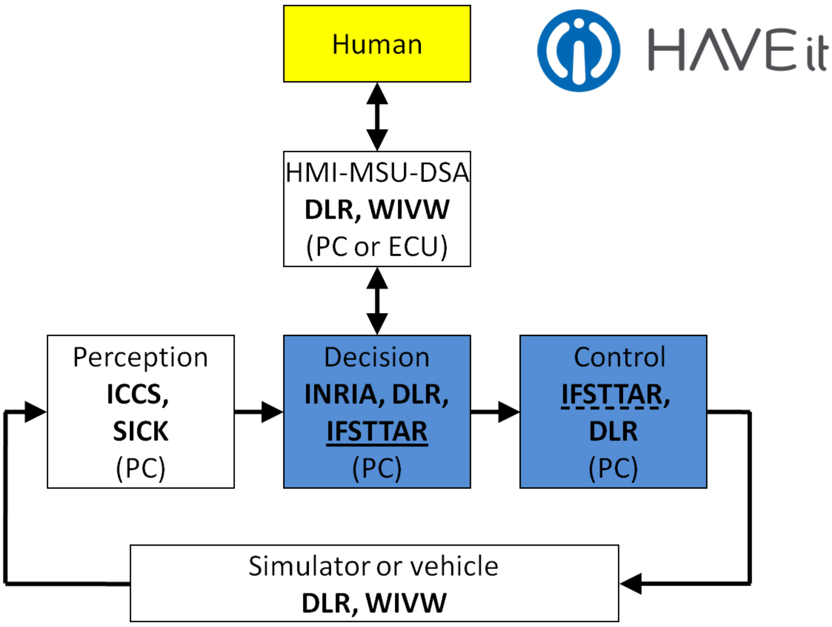


Figure 4.23: Simplified system architecture of the HAVEit Joint System Demonstrator and partner contributions. Components developed at LIVIC are indicated with institute name IFSTTAR. Components developed in this work are underlined with a solid line. Components partially developed in this work, partially developed by LIVIC colleagues are underlined with a dashed line

presented in Sections 4.4.2 and 4.4.3 respectively. Section 4.4.5 shortly presents results on the validation scenarios.

4.4.2 HAVEit Joint System Simulator

Figure 4.24 shows the HAVEit Joint System Simulator, which is based on simulation software SILAB of HAVEit partner WIVW. Like for the LIVIC Legal Safety Simulator (presented in Section 4.3.2), the perception component is replaced by an **ideal perception component** that gives a complete, exact environment description. This allows decoupling the development of all components and demonstrating scenarios that are not yet possible with state-of-the-art perception. Other system components are equal on HAVEit Joint System Simulator and HAVEit Joint System Vehicle. On the HAVEit Joint System Simulator, a replica of the steering wheel on the HAVEit Joint System Vehicle was used, with same inertia, same button configuration and similar **haptic feedback elements**. Other HMI elements include an **acoustic interface** and **visual interface** with new icons for highly automated driving. The HMI on the HAVEit Joint System Demonstrator is more advanced than the HMI of the LIVIC Legal Safety Demonstrator. The HAVEit Joint System Simulator is a powerful basis for the development and demonstration of legal safety decision, with relation to human rules. It has allowed testing with unexperienced drivers and continuously refining the component.

A detailed description on the implementation of the HAVEit Joint System Simulator can be found in HAVEit deliverables [HAV11l, HAV11m].

Figure 4.24: HAVEit Joint System Simulator with simulation software SILAB

4.4.3 HAVEit Joint System Vehicle

Figure 4.25 presents the HAVEit Joint System Vehicle, a VW Passat, developed by DLR. It is equipped with similar **exteroceptive sensors** as the LIVIC Legal Safety Vehicle (presented in Section 4.3.3). A camera is used for lane perception and LIDAR for object perception. Extensive development on vehicle has lead to quite robust tracking and data fusion of lanes and objects, both during lane keeping and lane changing [TSL+10].

Like on the LIVIC Legal Safety Vehicle, perception on the HAVEit Joint System Vehicle does not yet reach all requirements of legal safety. For instance, object indicator status is not known and no description of objects behind or on the side of the subject is available. As on the LIVIC Legal Safety Vehicle, **map, GPS, Vehicle-To-Vehicle (V2V) communication and Vehicle-To-Infrastructure (V2I) communication** are used for the description of variables that cannot yet be described by exteroceptive sensors. For example, map is used to detect the end of the application zone, V2I communication is used for the perception of speed limits and V2V is used for the detection of a priority vehicle. The object indicator status and presence of objects behind the subject was assumed known, depending on the scenario.

The HAVEit Joint System Vehicle integrates the same **control, decision and HMI** components as the HAVEit Joint System Simulator. The implementation of hardware and software on vehicle is documented in HAVEit deliverables [HAV11a, HAV11l, HAV11m].

4.4.4 Implementation on PC

For the implementation of partner components, a HAVEit Joint System Framework was built up in Microsoft Visual Studio. The framework respects the **modularity** scheme presented in Section 4.2. It encapsulates original partner C-files and uses interfaces for translating inputs, outputs and parameters. The HAVEit Joint System Framework has been described in HAVEit deliverables [HAV11a, HAV11j, HAV11l, HAV11m].

4.4.5 Results on validation scenarios

Table 4.1 indicates that the HAVEit Joint System Demonstrator integrates many aspects of legal safety. In a development where components come from different partners, **system rules**, which

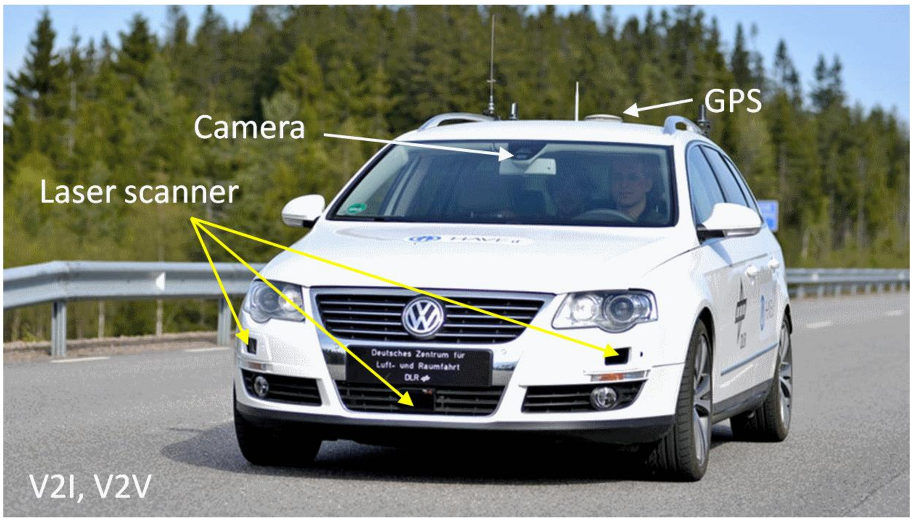


Figure 4.25: HAVEit Joint System Vehicle with camera for lane perception and LIDAR for object perception. The GPS, V2I and V2V communication are used for the detection of stops, speed limits and priority vehicles

manage consistency between components, play an important role. For example, lane changes performed by the control component of one partner must be smooth enough to allow lane marking tracking by the perception component of another partner. Additionally, the advanced HMI (with haptic, acoustic and visual elements) and MSU (with automation mode management), makes the HAVEit Joint System Demonstrator powerful for the study of human-machine interaction; i.e. **human rules**. Legal safety scenarios *Decreasing automation mode to DA*, *Decreasing automation mode to SA*, *Increasing automation mode to SA*, *Increasing automation mode to HA* and *Increasing automation mode to MRM* have extensively been studied in HAVEit (see Section 4.1 for the corresponding HAVEit use case terminology).

Figure 4.26 shows the straight section on the Volvo test track in Hällered, Sweden where the **HAVEit Joint System Vehicle** was presented during the HAVEit final event in June 2011. The **HAVEit Joint System Simulator** was presented on the main exhibition zone in the middle of the oval track. Results of the HAVEit Joint System Demonstrator have been described in a team publication [FNG$^+$10] and deliverables [HAV11a, HAV11f, HAV11g, HAV11k, HAV11l, HAV11m]. A short video on the HAVEit Joint System Vehicle during the scenario *Overtaking an object* is available on `http://youtu.be/jnXCxPeXLb8`. Official video material of the final event can be found on the HAVEit website [HAV11q]. Generally, reactions by users are positive. Users find that the **highly automated driving** system makes driving more comfortable and is easy to understand. If system limits are known, transitions to lower automation modes due to system limits (e.g. the end of the application zone), can be done easily and quickly. In the case of unexpected system limits however, take over by the human driver is slower. These situations must be avoided. A critic of users is that highly automated driving is more sleep-inducing than manual driving. During highly automated driving, most driving tasks are performed by the system, but users must keep attention on the road. (If they do not, the system switches to an MRM). Some users would like either be more involved in the driving task (i.e. **semi-automated driving**), or less involved (i.e. **fully automated driving**). User studies that include fully automated driving, i.e. the scenario *Increasing automation mode to FA*, seems an interesting topic for future research.

Figure 4.26: Volvo test track in Hällered, Sweden used for validation of HAVEit Joint System Demonstrator (straight track) and HAVEit Architecture Migration Demonstrator (oval track)

4.5 HAVEit Architecture Migration Demonstrator

4.5.1 Description

If the HAVEit Joint System Demonstrator focusses on highly automated driving *functionality*, the HAVEit Architecture Migration Demonstrator focusses on system integration on platforms used in *series production*. The HAVEit Architecture Migration Demonstrator shows that a highly automated driving system can be implemented on **state-of-the-art automotive ECUs**. The demonstrator was developed during 10 integration weeks with all involved project partners, mainly at Continental in Regensburg and Frankfurt, and at IFSTTAR in Paris.

Figure 4.27 shows partner contributions. The **perception component** on ECU is developed by Continental [She11]. The **decision** developed in this work is used. The **control** component is partially developed in this work, by LIVIC colleagues and by Continental. The HAVEit Architecture Migration Demonstrator illustrates lane keeping functionality only, it does not perform lane changes. In this configuration, the decision component only communicates one trajectory to control. This trajectory is the optimal subject lane trajectory *0B* or *JB* during normal functioning, or MRM subject lane trajectory *FB* during failure functioning. Actuator control was developed by Continental. **HMI, MSU and DSA** on ECU are delivered by Continental, DLR and WIVW [FH10, RKK^{+}10, FSS^{+}11].

Details on the architecture and algorithms on the HAVEit Architecture Migration Demonstrator can be found in HAVEit deliverables [HAV11d, HAV11e, HAV11i, HAV11j, HAV11n, HAV11o]. The HAVEit Architecture Migration Demonstrator was directly implemented on **vehicle**, without first testing on a simulator. Implementation on this demonstrator was in a second

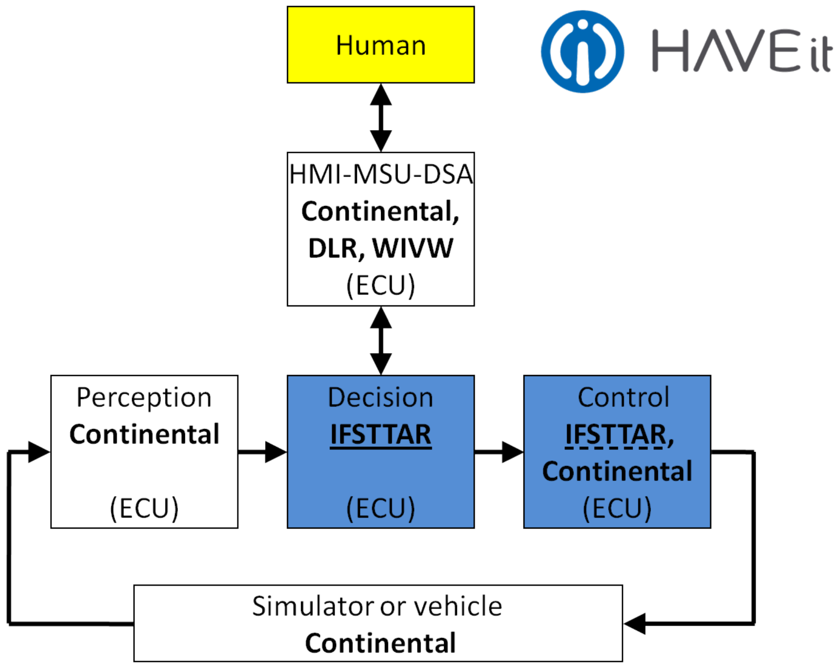


Figure 4.27: Simplified system architecture of the HAVEit Architecture Migration Demonstrator and partner contributions. Components developed at LIVIC are indicated with institute name IFSTTAR. Components developed in this work are underlined with a solid line. Components partially developed in this work, partially developed by LIVIC colleagues are underlined with a dashed line

phase of the project. It built on the experience on simulators and vehicles of the LIVIC Legal Safety Demonstrator and HAVEit Joint System Demonstrator.

4.5.2 HAVEit Architecture Migration Vehicle

Figure 4.28 shows the HAVEit Architecture Migration Vehicle developed by Continental. Its perception is based on **exteroceptive sensors only**, a camera and radar developed by Continental. Object perception combines radar measurements for variables in the longitudinal direction (e.g. object speed and acceleration) and camera measurements for variables in the lateral direction (e.g. object lateral position in the lane) [She11]. This is a powerful combination with respect to legal safety requirements. The long range of radar in comparison to LIDAR (which is used LIVIC Legal Safety Demonstrator and HAVEit Joint System Demonstrator) allows **higher subject speed** with respect to phantoms. Measuring lateral object position and lateral lane positions on the same camera image allows a precise **object lane assignment**, which is essential for the object trajectory prediction, as was discussed in Chapter 3. For example, the driving system reacts earlier to objects that cut-in on the subject lane, if it can discriminate objects that cross a lane marking from objects that do not. Note that, as no lane changing functionality is demonstrated, perception of objects behind and on the side of the subject is not needed. Scenarios that cannot yet be shown with state-of-the-art exteroceptive sensors (e.g. requiring the detection of the end of the lane) are not shown on this demonstrator. Vehicle control is performed through **haptic feedback control** on the steering wheel, which allows a continuous cooperation between human driver and driving system, conform the human-system interaction principles of HAVEit and human rules of legal safety.

Details on the implementation of system components on vehicle have been documented in HAVEit deliverables [HAV11n, HAV11o].

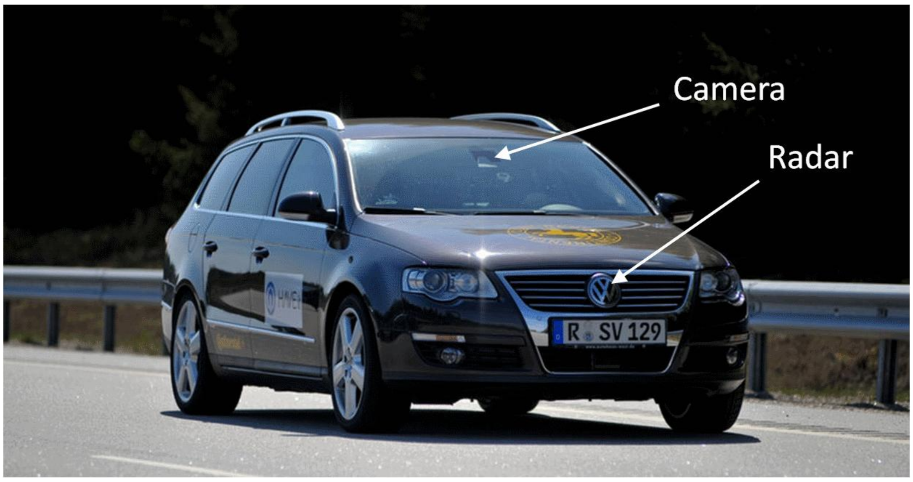


Figure 4.28: HAVEit Architecture Migration Vehicle with camera for lane perception and radar for object perception

4.5.3 Implementation on ECU

Automotive ECUs with a clock frequency of $120\,MHz$, $3\,MB$ Flash memory, $100\,kB$ RAM memory, based on the AUTomotive Open System ARchitecture (**AUTOSAR**) standard were developed by Continental [HAV11b, HAV11c]. The integration of legal safety decision and control components on these ECUs was discussed at the presentation of the LIVIC Legal Safety Demonstrator in Section 4.3.5. The legal safety components on the HAVEit Architecture Migration Demonstrator, HAVEit Joint System Demonstrator and LIVIC Legal Safety Demonstrator are identical, except for input and output interfaces and demonstrator-specific parameters. Many calculations for perception are directly performed on sensor ECU. Remaining calculations for sensor data fusion fit on an AUTOSAR-based HAVEit ECU. HAVEit deliverables give details on the implementation work [HAV11n, HAV11o].

In the beginning of the development, when the CAN interfaces were defined, a prudent choice of **one ECU per component** (i.e. perception, decision, control, HMI, MSU and DSA) was made. A **transfer protocol** is set up by Continental to assure the coherence of communication of large data structures on CAN, e.g. environment description from perception to decision components and trajectory description from decision to control components [HAV11b, HAV11c]. Vehicle control design was adapted in order to deal with extra delays caused by to CAN communication between components. By the end of the development, component efficiency had increased, e.g. decision calculation time is below $25\,ms$ and control calculation time below $10\,ms$. All components could now fit on a **single ECU**. This would avoid the need for a transfer protocol and significantly reduce system calculation times.

4.5.4 Results on validation scenarios

The HAVEit Architecture Migration Demonstrator was presented on the HAVEit final event on the oval track of the Volvo test ground in Hällered, Sweden, see Figure 4.26. Table 4.1 shows that for this demonstrator, only a some of the scenarios that involve **traffic rules** and **system rules** are presented, as the focus is on showing the migration of HAVEit architecture on series hardware. For example, lane changing functionality was not studied. However, the legal safety decision and control components running on the HAVEit Architecture Migration Demonstrator cover all legal safety scenarios. HMI, MSU and DSA algorithms on ECU implemented most of the human-system interaction scheme (**Human rules**). The demonstrator shows that a highly automated driving system **can be implemented on state-of-the-art automotive ECUs**. A video of the HAVEit Architecture Migration Vehicle during a lap on the Volvo test track is available on `http://youtu.be/Xn0vsVQ36Tc`. Additional video material and a detailed discussion on results are available on the HAVEit website and in deliverables [HAV11q, HAV11n, HAV11o].

4.6 ABV Low Speed Demonstrator

4.6.1 Description

The ABV Low Speed Demonstrator for driver assisted, semi-automated, highly automated and **fully automated driving in congested traffic** on highways is presented in April 2013. The development of the ABV Low Speed Demonstrator is lead by former HAVEit partners IFSTTAR (LIVIC) and INRIA. It is based on the principles and experience of LIVIC and HAVEit demonstrators described in Sections 4.3, 4.4 and 4.5. Three-monthly integration weeks with all involved partners are organized at LIVIC in Paris.

Figure 4.29 shows partner contributions. **Perception** components are developed by LIVIC, INRIA and LEPSIS. Four **decision** components are available for trajectory planning, (a) the legal safety decision component of this work (indicated as LIVIC), (b) a polynomial trajectory planner developed by INRIA, (c) a Rapidly exploring Random Tree (RRT) algorithm of IEF and (d) a sampling-based algorithm of INDUCT. IEF and INDUCT decision components are activated in situations with still standing objects that partially block the lane, where it is not possible to continue on lane-based trajectories by LIVIC and INRIA decision components. This allows unblocking such situations at footpace, without intervention of the human driver. Longitudinal and lateral **control** of the subject is developed by LIVIC, INRIA and IBISC. **HMI, MSU and DSA** are developed by LAMIH. The legal safety concept is used as a basis for system design [ABV13a], e.g. interactors of ABV can directly be translated to interactors of LIVIC and HAVEit demonstrators. All system components are implemented on **PC**, as will briefly be described in Section 4.6.4. A detailed description of this implementation work will be given in project deliverables [ABV12].

The ABV Low Speed Demonstrator consists of a **simulator** of LAMIH, a **vehicle** equipped by LIVIC and a **vehicle** equipped by INRIA, which are shortly presented in Sections 4.6.2 and 4.6.3.

4.6.2 ABV Low Speed Simulator

Similarly as for the LIVIC and HAVEit demonstrators, the development of the ABV demonstrator starts on simulator, the ABV Low Speed Simulator. The simulation software **SiVIC** [CIV12], which is also used for the LIVIC Legal Safety Simulator, is used for **first tests** with the system. For a presentation of SiVIC, reference is made to Section 4.3.2.

The **final presentation** of the ABV Low Speed Simulator will be done on simulation software **SHERPA** of LAMIH [LAM12], which is shown in Figure 4.30. The HMI of the LIVIC

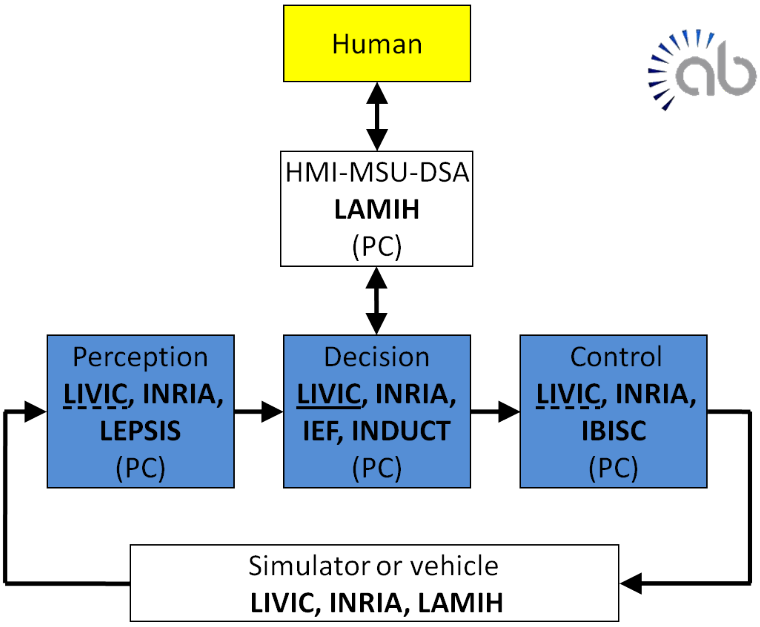


Figure 4.29: Simplified system architecture of the ABV Low Speed Demonstrator and partner contributions. Components developed at LIVIC are indicated. Components developed in this work are underlined with a solid line. Components partially developed in this work, partially developed by LIVIC colleagues are underlined with a dashed line

Legal Safety Demonstrator (Section 4.3) serves as development HMI for project parters, while the project HMI is being developed at LAMIH. The figure shows the optimal speed and optimal lane according to the legal safety decision component, during the scenario *Overtaking an object*.

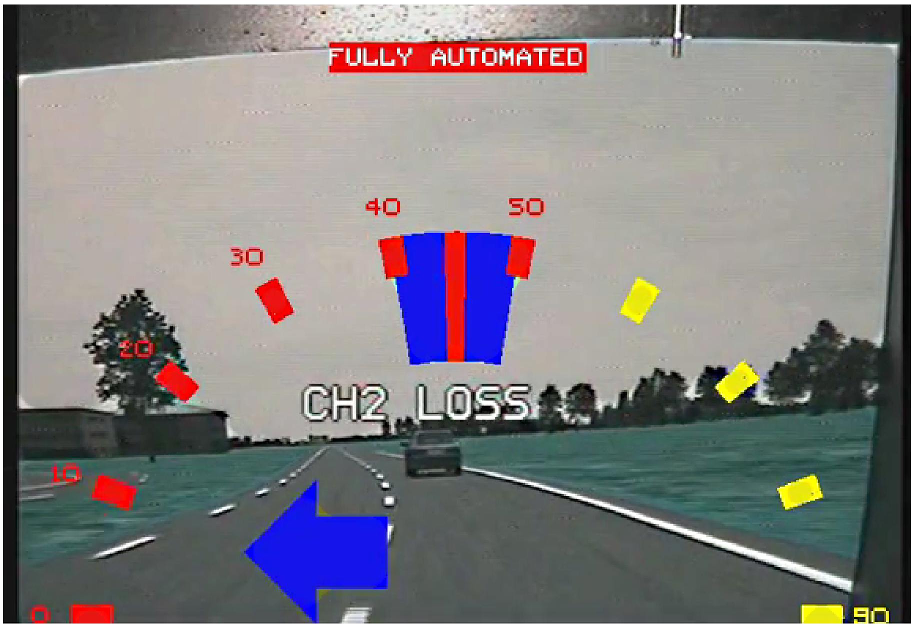


Figure 4.30: ABV Low Speed Simulator with simulation software SHERPA

4.6.3 ABV Low Speed Vehicle

Figure 4.31 presents the ABV Low Speed Vehicle equipped by LIVIC, a **SECMA F16**. Currently, only proprioceptive sensors and actuators have been installed. Exteroceptive sensors for lane and object perception are being added. Meanwhile, system functionality for the ABV Low Speed Vehicle is first developed on the **Peugeot 307 SW**, which is also used as LIVIC Legal Safety Vehicle. For a presentation of the Peugeot 307 SW reference is made to Section 4.3.3.

The equipment of SECMA F16 will be close to the Peugeot 307 SW on the **perception** side. For **control and HMI** however, it offers additional possibilities, e.g. differentiated braking on the 4 wheels. A **Citroën C1** (not in Figure 4.31) is being equipped by INRIA.

Legal safety perception, decision and control are integrated on the ABV Low Speed Vehicle equipped by LIVIC (SECMA F16/ Peugeot 307 SW). INRIA integrates own components for perception, decision and control on its ABV Low Speed Vehicle (Citroën C1). Other partner contributions are divided over both vehicles.

Figure 4.31: ABV Low Speed Vehicle: proprioceptive sensors and actuators have been installed. Exteroceptive sensors are now being added

4.6.4 Implementation on PC

The **RTMaps software** is used for the implementation of system components on ABV vehicles and simulator [Int12]. The implementation of components of the ABV Low Speed Demonstrator follows the same logic as the implementation of components of the LIVIC Legal Safety Demonstrator on RTMaps, which was presented in Section 4.3.4. RTMaps encapsulates C-files by partners, which are interfaced to the project structures for input variables, output variables and parameters, according to the modularity scheme presented in Section 4.2.

4.6.5 Results on validation scenarios

Requirements for the ABV Low Speed Demonstrator have now been specified and are in line with the principles of the legal safety concept and HAVEit project. In the remaining months of the project, components are **integrated** and validated on the ABV Low Speed Simulator and ABV Low Speed Vehicles. Some videos with intermediate results of the legal safety decision component on the first ABV Low Speed Simulator SiVIC are available on `http://youtu.be/AdFLDjuuZrg`, `http://youtu.be/RgdIcmRjAjU` and `http://youtu.be/USMOQt3wK7E`. Videos of the implementation of the legal safety decision component on the second ABV Low Speed Simulator SHERPA are available on `http://youtu.be/eB2VBnwu6to`, `http://youtu.be/Lly0v3UOOXk` and `http://youtu.be/gF8YG1GKaZs`. The ABV Low Speed Demonstrator will be presented at the project final event in April 2013 on the Satory test track in Versailles, France.

Chapter 5

Conclusion

Contents

Section 5.1 discusses the contribution of this research work. Section 5.2 draws a perspective on future development.

5.1 Contribution

5.1.1 Highly automated driving on highways based on legal safety

This work proposes legal safety as a natural concept to allow **driving systems and human drivers to share the road**, without necessarily changing equipment on other vehicles or infrastructure. Legal safety lets driving systems interact with the environment in the same way as human drivers react with the environment, through traffic rules. This allows **fully automated driving** in traffic with human drivers. It also facilitates the cooperation between driving system and human driver in the subject vehicle during **highly automated driving**. Highly automated driving is an important use case, as fully automated driving is still not possible with state-of-the-art technology and not (yet) permitted by international law. This work presents legal safety-based system design for a limited application zone: **highways**.

5.1.2 System design

Requirements for system design based on legal safety are expressed in three sets of rules: (a) traffic rules for the interaction between driving system and environment, (b) human rules for the interaction between driving system and human driver and (c) system rules for the interaction between system components. **Traffic rules** are a powerful basis for predicting object trajectories and calculating subject trajectories, both in cases of legal object behavior or non-legal object behavior. System design based on traffic rules promotes defensive driving; the driving system foresees worst-case legal object behavior (phantoms) and recognizes non-legal object behavior early. Using traffic rules seems reasonable in the sense that it does neither assume worst-case non-legal object behavior at all times (which overestimates danger in safe situations), nor perfectly legal object behavior (which underestimates danger in dangerous situations). **Human rules** follow the human-system interaction scheme proposed in HAVEit and ABV projects. Vehicle control is shared between driving system and human driver according to different automation levels; driver assisted (DA), semi-automated (SA), highly automated (HA) and fully automated (FA). Automation levels build on known interaction schemes on existing ADAS, and extend them by following known interaction schemes in nature; e.g. through the horse-rider metaphor. The automation mode can be adapted by the human driver, but also by the driving system. For example, the driving system can take over control if this is the only way to avoid an accident. This work discusses the consequences of human rules on driving system design. Trajectories calculated by the decision component take into account precision of perception and control components, via **system rules**. Legal safety implies that perception and control errors can be subject to variation (i.e. uncertainty), but that this variation must be bounded. Only in this case, the decision component can assure a safety level that is comparable with that of a human driver, in order to allow fully automated driving.

Requirements of traffic rules, human rules and system rules on each system component (perception, decision, control and HMI) are presented and compared to state-of-the-art technology. The main challenge of legal safety is on **perception**. The environment description required by legal safety cannot yet be delivered with state-of-the-art perception. According to legal safety, perception only depends on proprioceptive and exteroceptive sensors. Radar and camera seem to be fundamental components of future legal safety perception. Additionally, information from non-exteroceptive sensors such as Vehicle-To-Vehicle (V2V) communication, Vehicle-To-Infrastructure (V2I) communication and map might be considered. A precise lane perception and precise estimation of object position in the lane are essential for legal safety. Legal safety perception is estimated to become available in medium term. Legal safety **control** and **HMI** based on haptic feedback are within reach of state-of-the-art technology. However, research is on-going on how technology can be used to make human-machine interaction more intuitive. Especially the design space for mode transitions from and to fully automated (FA) driving is quite unexplored.

The discussion on perception, control and HMI stays on the requirement level. A complete component design is presented for the legal safety **decision component**. The decision component is the central component of legal safety. It calculates subject trajectories that respect traffic rules, human rules and system rules. A curvilinear **lane coordinate system** is proposed as natural environment for calculations with trajectories. A simple and quite wide **zone model** for trajectory descriptions is presented, which covers errors of state-of-the-art perception and control. Subject trajectories are calculated in a combined **analytical and sampling-based** approach. Calculations are performed analytically, if possible. If not, calculations are sampling-based, which is simple and universal but less optimal. This might be a generic approach, which can also be used in other environments than highways. While perception and control deliver objective functionalities (i.e. environment perception and trajectory control can be compared with respect to a single truth), decision is subjective by nature. Different *correct* subject trajectories exist, depending on driving style. Legal safety decision guarantees the existence of **at least one subject trajectory**, which follows an object in the subject lane. The legal safety decision component for highways presented in this work (a) avoids all accidents when objects respect traffic rules, (b) avoids most accidents when objects do not respect traffic rules, i.e. it integrates several important principles of defensive driving, (c) mitigates accidents that cannot be avoided.

5.1.3 System implementation and validation

The legal safety decision component has been integrated in **LIVIC, HAVEit and ABV demonstrators**. Perception, control and HMI on demonstrators are in line with legal safety, to smaller or greater extent. HAVEit and ABV demonstrators mainly focus on human rules, but also implement a part of traffic rules and system rules. The **HAVEit Joint System Demonstrator** and **HAVEit Architecture Migration Demonstrator** focus on highly automated driving. HAVEit studies show that highly automated driving can be implemented on automotive ECU, is allowed by international law and is generally received positively by test users. One critic of users is that monitoring during highly automated driving is quite monotonous. This is the reason why legal safety targets fully automated driving in a restricted application zone as the long-term solution. Fully automated driving on highways with congested traffic at speeds below $50\,km/h$ is presented on the **ABV Low Speed Demonstrator**.

The main focus of the **LIVIC Legal Safety Demonstrator** is illustrating traffic rules and system rules. The demonstrator implements basic human rules. In principle, the legal safety system respects all traffic rules. In some critical situations however, a subject trajectory that violates traffic rules is chosen. The extent to which non-legal subject trajectories are allowed is an interesting topic for discussion. One obvious case is, if in the case of non-legal object behavior, a non-legal subject trajectory is the only solution to avoid an accident. For example, right overtaking of an object that cuts in is preferred to a crash with that object. In some cases, a non-legal subject trajectory might be preferred for comfort reasons. For example, crossing continuous lane markings (i.e. non-legal) to avoid a still standing object is better accepted by a human driver than hard braking behind the object (i.e. legal). This work briefly compares a human driver and driving systems with different driving styles (sportive or green/comfortable). The tests shows that in most cases, system driving style is in line with human driving style. For example, the distance kept from objects is similar for driving systems and human drivers. A case where human driver and driving system differ, is that the human driver inserts between objects even if temporarily, safety distances are not longer respected. Allowing a similar behavior in driving system design might be considered, e.g. in order to reach an exit ramp in time.

5.2 Perspective

Starting with state-of-the-art technology, two strategies could be followed for the deployment of legal safety systems. One strategy is to offer highly automated driving, without fully automated driving, in a larger application zone. A second strategy is to concentrate on fully automated driving in a smaller application zone. Both strategies might be combined, **providing highly automated driving in a larger application zone and fully automated driving in a reduced application zone**.

5.2.1 Highly automated driving in larger application zone

A first strategy exists in focussing on highly automated driving, in which the human driver monitors the driving system and **acknowledges certain maneuvers**. The legal safety system performs most driving tasks, but leaves some decisions to the human driver. For example, if the driving system does not dispose of a perception of objects behind, it asks the human driver to acknowledge lane changes. The cooperation between human driver and driving system is facilitated by the common understanding of traffic rules and by corresponding driving styles. Commercializing the system would require the integration of local variations on the Vienna Convention on Road Traffic for every country.

With the first strategy, highly automated driving could **gradually be extended to other environments**. After this, the role of automation could be increased. This might eventually result in autonomous driving, i.e. fully automated driving in all environments.

5.2.2 Fully automated driving in smaller application zone

A second strategy is to offer **fully automated driving** immediately. State-of-the-art technology would require reducing the application zone, e.g. to lane keeping in congested traffic, in good weather conditions. After this, fully automated driving could be extended to higher speeds, more assertive maneuvers and other environments. Eventually, autonomous driving might be reached.

Driving systems might become safer than human drivers, as driving systems are not subject to distraction, drowsiness or emotion. In this case, allowing fully automated driving would be rational. However, fully automated driving can probably not entirely exclude accidents, e.g. in certain situations of non-legal object behavior. The **ethical question** whether this is acceptable or not, is to be debated in society. The gradual introduction of driver assistance allows gradually evolving the debate and adapting legal structures, if needed. If autonomous driving is an ultimate target, intermediate steps with natural interaction between driving systems and human drivers already considerably increase safety, efficiency and comfort.

Appendix A

United Nations 1968 Vienna Convention on Road Traffic

This appendix gives the original description of articles in the United Nations 1968 Vienna Convention on Road Traffic [Uni68]. The original article index and title are indicated between parentheses. Parts of the convention, which do not apply on the **application zone** (e.g. on cross roads, on pedestrians) or which do not apply on the **driving system** (e.g. on driver intoxication, medical equipment, spare tire equipment) are excluded. The omission of parts of articles that do not apply is indicated with ellipsis points (. . .).

Article 1 (8. Drivers) *1. Every moving vehicle or combination of vehicles shall have a driver. 2. It is recommended that domestic legislation should provide that pack, draught or saddle animals, and, except in such special areas as may be marked at the entry, cattle, singly or in herds, or flocks, shall have a driver. 3. Every driver shall possess the necessary physical and mental ability and be in a fit physical and mental condition to drive. 4. Every driver of a power-driven vehicle shall possess the knowledge and skill necessary for driving the vehicle; however, this requirement shall not be a bar to driving practice by learner-drivers in conformity with domestic legislation. 5. Every driver shall at all times be able to control his vehicle or to guide his animals.*

Article 2 (7. General rules) *1. Road-users shall avoid any behavior likely to endanger or obstruct traffic, to endanger persons, or to cause damage to public or private property. 2.-5. . . .*

Article 3 (5. Status of signs and signals, 13. Speed and distance between vehicles) *(Article 5) 1. Road-users shall comply with the instructions conveyed by road signs, traffic light signals and road markings even if the said instructions appear to contradict other traffic regulations. 2. Instructions conveyed by traffic light signals shall take precedence over those conveyed by road signs regulating priority. (Article 13) 1. Every driver of a vehicle shall in all circumstances have his vehicle under control so as to be able to exercise due and proper care and to be at all times in a position to perform all manoeuvres required of him. He shall, when adjusting the speed of his vehicle, pay constant regard to the circumstances, in particular the lie of the land, the state of the road, the condition and load of his vehicle, the weather conditions and the density of traffic, so as to be able to stop his vehicle within his range of forward vision and short of any foreseeable obstruction. He shall slow down and if necessary stop whenever circumstances so require, and particularly when visibility is not good. 2. Domestic legislation shall establish* *maximum speed limits for all roads. Domestic legislation shall also determine special speed limits applicable to certain categories of vehicles presenting a special danger, in particular by reason of their mass or their load. They may establish similar provisions for certain categories of drivers, in particular for new drivers. 3. . . . 4. No driver shall impede the normal progress of other vehicles by traveling abnormally slowly without proper cause. 5. The driver of a vehicle moving behind another vehicle shall keep at a sufficient distance from that other vehicle to avoid collision if the vehicle in front should suddenly slow down or stop. 6. . . .*

Article 4 (17. Slowing down) *1. No driver of a vehicle shall brake abruptly unless it is necessary to do so for safety reasons. 2. Every driver intending to slow down to an appreciable extent shall, except where his slowing down is in response to an imminent danger, first make sure that he can do so without danger or undue inconvenience to other drivers. He shall also, unless he has made sure that there is no vehicle following him or that any following vehicle is a long way behind, give clear and timely warning of his intention by making an appropriate signal with his arm. However, this provision shall not apply if warning of slowing down in given by the vehicle's stop lights, referred to in Annex 5, paragraph 31, of this Convention.*

Article 5 (10. Position on the carriageway) *1.-2. . . . 3. Without prejudice to the provisions to the contrary of Article 7, paragraph 1, Article 11, paragraph 6, and to other provisions of this Convention to the contrary, every driver of a vehicle shall, to the extent permitted by circumstances, keep his vehicle near the edge of the carriageway appropriate to the direction of traffic. However, Contracting Parties or subdivisions thereof may lay down more precise rules concerning the position of goods vehicles on the carriageway. 4.-5. . . . 6. Without prejudice to the provisions of Article 11 and when an additional lane is indicated by a sign, drivers of vehicles moving slowly shall use that lane.*

Article 6 (11. Overtaking, 14. Manoeuvres) *(Article 11) 1. (a) Drivers overtaking shall do so on the side opposite to that appropriate to the direction of traffic. (b) However drivers shall overtake on the side appropriate to the direction of traffic if the driver to be overtaken has signalled his intention to turn to the side of the carriageway opposite to that appropriate to the direction of traffic and has moved his vehicle or animals over towards that side in order to turn to that side for the purpose of taking another road, to enter a property bordering on the road, or to stop on that side. 2. Before overtaking, every driver shall, without prejudice to the provisions of Article 7, paragraph 1, or to those of Article 14, of this Convention, make sure: (a) That no driver who is following him has begun to overtake him; (b) That the driver ahead of him in the same lane has not given warning of his intention to overtake another; (c) That he can do it without endangering or interfering with the oncoming traffic making sure in particular that the lane which he will enter is free over a sufficient distance and that the relative speed of the two vehicles allows overtaking within a sufficiently short time; and (d) . . . 3. . . . 4. When overtaking, a driver shall give the road-user or road-users overtaken a sufficiently wide berth. 5. (a) On carriageways with at least two lanes reserved for traffic moving in the direction in which he is proceeding, a driver who should be obliged, immediately or shortly after moving back to the position prescribed by Article 10, paragraph 3, of this Convention, to overtake again may, in order to perform that manoeuvre, and provided he makes sure he can do so without undue inconvenience to the drivers of faster vehicles approaching from behind, remain in the lane he has occupied for the first overtaking manoeuvre. (b) However, Contracting Parties or subdivisions thereof shall be free not to apply the provisions of this paragraph to the drivers of cycles, mopeds, motor cycles and vehicles which are not motor vehicles within the meaning of this Convention,* *or to the drivers of motor vehicles whose permissible maximum mass exceeds 3500 kg or whose maximum speed, by design, cannot exceed 40 km (25 miles) per hour. 6. Where the provisions of subparagraph 5 (a) of this Article are applicable and the density of traffic is such that vehicles not only occupy the entire width of the carriageway reserved for traffic taking the direction in which they are moving but also are moving only at a speed which is governed by that of the vehicle preceding them in the line: (a) Without prejudice to the provisions of paragraph 9 of this Article, the movement of the vehicles in one line at a higher speed than that of those in another shall not be deemed to constitute overtaking within the meaning of this Article; (b) A driver not in the lane nearest to the edge of the carriageway appropriate to the direction of traffic may change lanes only in order to prepare to turn right or left or to park; however, this requirement shall not apply to changes of lane effected by drivers in accordance with domestic legislation resulting from the application of the provisions of paragraph 5 (b) of this Article. 7. When moving in lines as described in paragraphs 5 and 6 of this Article, drivers are forbidden, if the lanes are indicated on the carriageway by longitudinal markings, to straddle these markings. 8.-9. . . . 10. A driver who perceives that a driver following him wishes to overtake him shall, except in the case provided for in Article 16, paragraph 1 (b) of this Convention, keep close to the edge of the carriageway appropriate to the direction of traffic and refrain from accelerating. If, owing to the narrowness, profile or condition of the carriageway, taken in conjunction with the density of oncoming traffic, a vehicle which is slow or bulky or is required to observe a speed limit cannot be easily and safely overtaken, the driver of such vehicle shall slow down and if necessary pull in to the side as soon as possible in order to allow vehicles following him to overtake. 11. (a) Contracting Parties or subdivisions thereof may, on one-way carriageways and on two-way carriageways where at least two lanes in built-up areas and three lanes outside built-up areas are reserved for traffic in the same direction and are indicated by longitudinal markings: (i) Allow vehicles in one lane to overtake on the side appropriate to the direction of traffic vehicles in another lane; and (ii) Make inapplicable the provisions of Article 10, paragraph 3, of this Convention; provided that there are adequate restrictions on the possibility of changing lanes; (b) In the case referred to in subparagraph (a) of this paragraph, without prejudice to the provisions of paragraph 9 of this Article, the manner of driving provided for shall not be deemed to constitute overtaking within the meaning of this Convention. (Article 14) 1. Any driver wishing to perform a manoeuvre such as pulling out of or into a line of parked vehicles, moving over to the right or to the left on the carriageway, or turning left or right into another road or into a property bordering on the road, shall first make sure that he can do so without risk of endangering other road-users traveling behind or ahead of him or about to pass him, having regard to their position, direction and speed. 2. . . . 3. Before turning or before a manoeuvre which involves moving laterally, the driver shall give clear and sufficient warning of his intention by means of the direction-indicator or direction-indicators on his vehicle, or, failing this, by giving if possible an appropriate signal with his arm. The warning given by the direction-indicator or direction-indicators shall continue to be given throughout the manoeuvre and shall cease as soon as the manoeuvre is completed.*

Article 7 (25. Motorways and similar roads) *1. On motorways and, if so provided in domestic legislation, on special approach roads to and exit roads from motorways: (a) The use of the road shall be prohibited to pedestrians, animals, cycles, mopeds unless they are treated as motor cycles, and all vehicles other than motor vehicles and their trailers, and to motor vehicles or motor-vehicle trailers which are incapable, by virtue of their design, of attaining on a flat road a speed specified by domestic legislation; (b) Drivers shall be forbidden: (i) To have their vehicles standing or parked elsewhere than at marked parking sites; if a vehicle is compelled to stop, its driver shall endeavor to move it off the carriageway and also off the flush verge and, if* *he is unable to do so, immediately signal the presence of the vehicle at a distance so as to warn approaching drivers in time; (ii) To make U-turns, to travel in reverse, and to drive on to the central dividing strip, including the crossovers linking the two carriageways. 2. Drivers emerging on to a motorway shall give way to vehicles traveling on it. If there is an acceleration lane, they shall use it. 3. A driver leaving a motorway shall move into the traffic lane appropriate to the motorway exit in good time and enter the deceleration lane, if there is one, as soon as he can. 4. For the purpose of the application of paragraphs 1, 2 and 3 of this Article, other roads reserved for motor vehicle traffic, duly signposted as such and not affording access to or from properties alongside, shall be treated as motorways.*

Article 8 (25bis. Tunnels, 32. Lamps) *(Article 25bis) In tunnels indicated by the special road signs, the following rules shall apply: 1. All drivers are forbidden: (a) to reverse; (b) to make a U-turn; (c) to stop or to park a vehicle except at the places indicated for that purpose. 2. Even if the tunnel is lit, all drivers must switch on the driving or passing lamps. 3. . . . (Article 32) 1. Between nightfall and dawn and in any other circumstances when visibility is inadequate on account, for example, of fog, snowfall or heavy rain, the following lamps shall be lit on a moving vehicle: (a) On power-driven vehicles and mopeds the driving lamp(s) or passing lamp(s) and the rear position lamp(s), according to the equipment prescribed by the present Convention for the vehicle of each category; (b) On trailers, front position lamps, if such lamps are required according to Annex 5, paragraph 30, of this Convention, and not less than two rear position lamps. 2. Driving lamps shall be switched off and replaced by passing lamps: (a) In built-up areas where the road is adequately lighted and outside built-up areas where the carriageway is continuously lighted and the lighting is sufficient to enable the driver to see clearly for an adequate distance and to enable other road-users to see the vehicle far enough away; (b) When a driver is about to pass another vehicle, so as to prevent dazzle far enough away to enable the driver of the other vehicle to proceed easily and without danger; (c) In any other circumstances in which it is necessary to avoid dazzling other road-users or the users of a waterway or railway running alongside the road. 3. . . . 4. Fog lamps may be lit only in thick fog, falling snow, heavy rain or similar conditions and, as regards front fog maps, as a substitute for passing lamps. Domestic legislation may authorize the simultaneous use of front fog lamps and passing lamps and the use of front fog lamps on narrow, winding roads. 5. On vehicles equipped with front position lamps, such lamps shall be used together with the driving lamps, the passing lamps or the front fog lamps. 6. During the day, a motor cycle moving on the road shall display at least one passing lamp to the front and a red lamp to the rear. Domestic legislation may permit the use of daytime running lamps instead of passing lamps. 7. Domestic legislation may make it compulsory for drivers of motor vehicles to use during the day either passing lamps or daytime running lamps. Rear position lamps shall in this case be used together with the front lamps. 8.-15. . . .*

Article 9 (34. Exemptions) *1. When warned of the approach of a priority vehicle by its special luminous and audible warning devices every road-user shall leave room clear for it to pass on the carriageway and shall, if necessary, stop. 2. Domestic legislation may provide that drivers of priority vehicles shall not be bound, when warning of their movement is given by the vehicle's special warning devices, and provided that they do not endanger other road-users, to comply with all or any of the provisions of this Chapter II other than those of Article 6, paragraph 2. 3. Domestic legislation may determine to what extent persons working on the construction, repair or maintenance of the road, including the drivers of equipment used for such work, shall not be bound, provided they take the necessary precautions, to observe the provisions of this Chapter*

II during their work. 4. For the purpose of overtaking or passing the equipment referred to in paragraph 3 of this Article while it is engaged in work on the road, the drivers of other vehicles may, to the extent necessary and on conditions that they take all due precautions, disregard the requirements of Articles 11 and 12 of this Convention.

Article 10 (6. Instructions by officials) *1. When they are directing traffic, authorized officials shall be easily identifiable at a distance, at night as well as by day. 2. Road-users shall promptly obey all instructions given by authorized officials directing traffic. 3. It is recommended that domestic legislation should provide that directions given by authorized officials directing traffic shall include the following: (a) Arm raised upright: this gesture shall mean "attention, stop" for all road-users except drivers who are no longer able to stop with sufficient safety; further, if made at an intersection, this gesture shall not require drivers already on the intersection to stop; (b) Arm or arms outstretched horizontally; this gesture shall constitute a stop signal for all road-users approaching from any direction which would cut across that indicated by the outstretched arm or arms; after making this gesture, the authorized official directing traffic may lower his arm or arms; this gesture shall likewise constitute a stop signal for drivers in front of or behind the official; (c) Swinging red light: this gesture shall constitute a stop signal for road-users towards whom the light is directed. 4. The instructions given by authorized officials directing traffic shall take precedence over those conveyed by road signs, traffic light signals and road markings, and over traffic regulations.*

Appendix B

Publications

This appendix gives a list of publications that follow from this research work. The list is organized chronologically, per type of publication. A **short description** has been added on the role of each publication in the development of the work.

B.1 Scientific journal articles

[VGL+12] **B. Vanholme**, D. Gruyer, B. Lusetti, S. Glaser, and S. Mammar. Highly automated driving on highways based on legal safety. *IEEE Transactions on Intelligent Transportation Systems*, 2012. Accepted for publication.
Presentation of legal safety concept, as preparation for this work. Description of legal safety system with focus on decision component. Discussion of results on LIVIC Legal Safety Simulator and Vehicle.

[HVG+12] S. Hima, **B. Vanholme**, S. Glaser, A. Chaibet, S. Mammar, and B. Lusetti. Robust trajectory tracking for highly automated passenger vehicles. *IEEE Transactions on Vehicular Technology*, 2012. Submitted for publication.
Description of vehicle control on trajectories of legal safety decision component. Discussion of results on LIVIC Legal Safety Demonstrator.

[GVM+10] S. Glaser, **B. Vanholme**, S. Mammar, D. Gruyer, and L. Nouvelière. Maneuver-based trajectory planning for highly autonomous vehicles on real road with traffic and driver interaction. *IEEE Transactions on Intelligent Transportation Systems*, 11(3):589–606, September 2010.
Description of decision component with sampling-based trajectory algorithm in combination with a risk-based maneuver algorithm. Integration of first aspects of legal safety on prediction of object and phantom trajectories. Discussion of results on LIVIC Legal Safety Simulator.

B.2 Conference articles

[VLG+11] **B. Vanholme**, B. Lusetti, D. Gruyer, S. Glaser, and S. Mammar. Highly automated driving on highways: system implementation on PC and automotive ECUs. In *Proceedings of IEEE Intelligent Transportation Systems Conference (ITSC)*, October 2011.
Integration of legal safety system with decision and control components on ECU. Discussion of results on LIVIC Legal Safety Simulator and Vehicle.

[HGCV11] S. Hima, S. Glaser, A. Chaibet, and **B. Vanholme**. Controller design for trajectory tracking of autonomous passenger vehicles. In *Proceedings of IEEE Intelligent Transportation Systems Conference (ITSC)*, October 2011.
Description of vehicle control on trajectories of legal safety decision component. Discussion of results on HAVEit Joint System Simulator.

[GVMG11] S. Glaser, **B. Vanholme**, S. Mammar, and D. Gruyer. Probability and risk based maneuver planning for collision avoidance. In *Proceedings of SAE Conference on Future Active Safety Technology (FAST-zero)*, September 2011. (Nominated for best paper award)
Application of maneuver grid representation of legal safety trajectories

[VGGM11] **B. Vanholme**, D. Gruyer, S. Glaser, and S. Mammar. A legal safety concept for highly automated driving on highways. In *Proceedings of IEEE Intelligent Vehicles Symposium (IV)*, June 2011.
Presentation of legal safety concept. Description of legal safety system with focus on decision component. Discussion of results on LIVIC Legal Safety Simulator.

[VGGM10] **B. Vanholme**, D. Gruyer, S. Glaser, and S. Mammar. Fast prototyping of a highly autonomous cooperative driving system for public roads. In *Proceedings of IEEE Intelligent Vehicles Symposium (IV)*, pages 135–142, June 2010.
Description of system with sampling-based decision component. Integration of first aspects of legal safety on prediction of object and phantom trajectories. Discussion of results on LIVIC Legal Safety Simulator in an application with V2I and V2V communication.

[FNG+10] F. Flemisch, F. Nashashibi, S. Glaser, N. Rauch, G. Temme, P. Resende, **B. Vanholme**, A. Schieben, C. Löper, G. Thomaidis, H. Mosebach, J. Schömerus, and A. Kaussner. Towards highly automated driving: Intermediate report on the HAVEit Joint System. In *Proceedings of European Transport Research Arena Conference (TRA)*, pages 7–10, June 2010.
Integration of decision and control components in HAVEit demonstrators. Discussion of intermediate results on HAVEit Joint System Simulator and Vehicle.

[GGVM09] D. Gruyer, S. Glaser, **B. Vanholme**, and B. Monnier. Simulation of automatic vehicle speed control by transponder-equipped infrastructure. In *Proceedings of Intelligent Transport Systems Telecommunications (ITST)*, pages 628–633, October 2009.
Integration of system on LIVIC Legal Safety Simulator.

[VGMG09] **B. Vanholme**, S. Glaser, S. Mammar, and D. Gruyer. Manoeuvre based trajectory planning for highly autonomous vehicles on real road with traffic. In *Proceedings of European Control Conference (ECC)*, volume 9, pages 23–26, August 2009.
Description of system with sampling-based decision component, without legal safety concept. Discussion of results on LIVIC Legal Safety Simulator.

B.3 Congress articles

[HLV+11] S. Hima, B. Lusetti, **B. Vanholme**, S. Glaser, and S. Mammar. Trajectory tracking for highly automated passenger vehicles. In *Proceedings of IFAC World Congress*, August 2011.
Description of vehicle control on legal safety trajectories. Discussion of results on LIVIC Legal Safety Vehicle.

[PVG11] E. Pollard, **B. Vanholme**, and D. Gruyer. Détection de marquages pour l'assistance à la conduite. In *Proceedings of ACFAS Congress*, May 2011.
Short description of legal safety system with multi-lane perception and legal safety decision component. Video presentation of LIVIC Legal Safety Simulator.

[GGV+10] D. Gruyer, S. Glaser, **B. Vanholme**, N. Hiblot, and B. Monnier. SiVIC, a virtual platform for ADAS and PADAS prototyping, test and evaluation. In *Proceedings of International FISITA Congress*, May 2010.
Integration of system on LIVIC Legal Safety Simulator.

[GBVG10] D. Gruyer, J.-S. Barreiro, **B. Vanholme**, and S. Glaser. SiVIC: Un outil de simulation pour l'aide au prototypage et à la validation des ADAS. In *Proceedings of GTAA Congress*, January 2010.
Short description of integration of system on LIVIC Legal Safety Simulator.

B.4 Project deliverables

[ABVa] **ABV Consortium**. Deliverable L2200: règles et usages du code de la route. [Online]. Available: http://www.projet-abv.fr/en. Submitted for publication.
Integration of legal safety concept in ABV demonstrators.

[ABVb] **ABV Consortium**. Deliverable L2500: planification géométrique rapide de trajectoire. [Online]. Available: http://www.projet-abv.fr/en. Submitted for publication.
Integration of decision and control components in ABV demonstrators. Discussion of results in ABV Low Speed Simulator.

[HAV11a] **HAVEit Consortium**. Deliverable D13.1: optimized and validated demonstration vehicles. [Online]. Available: http://www.haveit-eu.org, June 2011.
Discussion and validation of decision and control components on HAVEit Joint System Vehicle.

[HAV11b] **HAVEit Consortium**. Deliverable D31.1: co-driver command vector available (1st version). [Online]. Available: http://www.haveit-eu.org, June 2011.
Integration of decision and control components in HAVEit demonstrators, 1st version.

[HAV11c] **HAVEit Consortium**. Deliverable D31.2: co-driver command vector available (2nd version). [Online]. Available: http://www.haveit-eu.org, June 2011.
Integration of decision and control components in HAVEit demonstrators, 2nd version.

[HAV11d] **HAVEit Consortium**. Deliverable D33.4: algorithm (C-code, 1st version) available for partners. [Online]. Available: http://www.haveit-eu.org, June 2011.
Discussion of results of decision and control components on HAVEit Joint System Simulator, first version.

[HAV11e] **HAVEit Consortium**. Deliverable D33.5: algorithm (C-code, 2nd version) available for partners. [Online]. Available: http://www.haveit-eu.org, June 2011.
Discussion of results of decision and control components on HAVEit Joint System Simulator, second version.

[HAV11f] **HAVEit Consortium**. Deliverable D41.1: concept and algorithm (1st version) validated in vehicle. [Online]. Available: http://www.haveit-eu.org, June 2011.
Discussion of results of decision and control components on HAVEit Joint System Vehicle, first version.

[HAV11g] **HAVEit Consortium**. Deliverable D41.3: joint system validation in vehicle (2nd version). [Online]. Available: http://www.haveit-eu.org, June 2011.
Discussion of results of decision and control components on HAVEit Joint System Vehicle, second version.

[HAV11h] **HAVEit Consortium**. Deliverable D43.1: transfer of HAVEit architecture to embedded platforms completed. [Online]. Available: http://www.haveit-eu.org, June 2011.
Discussion of results of decision and control components on HAVEit Architecture Migration Vehicle, first version.

[HAV11i] **HAVEit Consortium**. Deliverable D43.2: architecture migration validation. [Online]. Available: http://www.haveit-eu.org, June 2011.
Discussion of results of decision and control components on HAVEit Architecture Migration Vehicle, second version.

B.5 Non-peer reviewed work

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