Highly Automated Driving on Highways Based on Legal Safety

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***Abstract*—This paper discusses driving system design based on traffic rules. This allows fully automated driving in an environment with human drivers, without necessarily changing equipment on other vehicles or infrastructure. It also facilitates cooperation between the driving system and the host driver during highly automated driving. The concept, referred to as legal safety, is illustrated for highly automated driving on highways with distance keeping, intelligent speed adaptation, and lane-changing functionalities. Requirements by legal safety on perception and control components are discussed. This paper presents the actual design of a legal safety decision component, which predicts object trajectories and calculates optimal subject trajectories. System implementation on automotive electronic control units and results on vehicle and simulator are discussed.**

***Index Terms*—Decision making, driver assistance, driving automation, electronic control circuit, intelligent vehicles, legal safety, perception, vehicle safety.**

I. Introduction

VEHICLE automation is proposed as one of the solutions that will make transport safer, more comfortable, and more environmentally friendly [1]. Autonomous driving can currently be demonstrated, with highly equipped vehicles under human supervision. The VaMoRs experience [2], ARGO experience [3], Defense Advanced Research Projects Agency (DARPA) Grand Challenges [4], CyberCar [5], CityMobil [6], and CityNetMobil [7] demonstrations presented autonomous vehicles on dedicated infrastructure, with limited interaction with other vehicles. Recently, promising results on automated driving on public roads have been shown by the VisLab and Google teams [8], [9].

For economical, technical, legal, and psychological reasons, vehicle automation is not directly brought to market. It is incrementally introduced through advanced driver-assistance systems (ADASs) such as adaptive cruise control (ACC), intelligent speed adaptation (ISA), lane-keeping assist systems (LKAS), and lane-change decision aid systems [10]–[12]. These systems rely on a limited number of simple and safe hardware components that allow partially automated driving on the public road, in cooperation with the human driver in the subject vehicle (host driver).

Because ADASs trend toward higher levels of automation, the question on how driving systems should optimally interact with other drivers in the environment arises. Currently, traffic with human drivers with different personalities and capabilities is managed by traffic rules. Could traffic rules also safely and efficiently manage mixed traffic of human drivers and driving systems? The thesis of this paper, referred to as legal safety, responds to this question. Legal safety system design allows *fully* automated (FA) driving in mixed traffic. The second question is how the driving system can optimally interact with the host driver. The European Union Seventh Framework Programme (EU FP7) project Highly Automated Vehicles for Intelligent Transport (HAVEit) [13], [14] and the French National Research Agency (ANR) project Low-Speed Automation (ABV) [15] propose human–system interaction along several automation modes. Legal safety system design conforms to this interaction scheme to allow *highly* automated driving with continuous interaction with the host driver.

This paper is organized as follows. Section II presents the legal safety concept and its application to highway environments, based on traffic rules of the Vienna Convention on Road Traffic. Section III discusses the system architecture and presents the perception and control requirements. Sections IV and V explain how the decision component predicts object trajectories and calculates optimal subject trajectories. Section VI presents the system implementation on automotive electronic control units (ECUs) and results on a simulator (SiVIC) and a vehicle (CARLLA) along scenarios that combine ISO, HAVEit, and ABV test cases. Section VII discusses the contribution of this paper and gives a perspective on future work.

II. Legal Safety on Highways

A. Legal Safety Concept

The word *traffic* comes from the Arabic *taraffaqa*, which means "slowly walking along together." Currently, this is certainly not the most common type of road traffic. Traffic is complex because of the diversity of its participants (e.g., driver

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personality and vehicle type) and infrastructure (e.g., multiple lanes, junctions, and intersections). Traffic rules have been developed to promote traffic safety and efficiency.

If future driving systems are to begin driving autonomously, they will likely need to share the infrastructure with human drivers. A distant future where all vehicles would autonomously be driven would be preceded by a transient period where automated and nonautomated vehicles coexist. One alternative to sharing the infrastructure would be to exclusively assign a part of existing infrastructure to autonomous driving, e.g., dedicated lanes. 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 and environments with pedestrians and cyclists), and could prove difficult to implement [16]. A solution where driving systems and human drivers share the road seems preferable. This paper discusses the possibility of such a solution.

A legal safety system ensures safety when traffic rules are respected by all traffic participants. In everyday traffic, however, traffic rules are not always respected. A legal safety system uses traffic rules to detect and anticipate the nonlegal behavior of other traffic participants (objects). Several basic defensive driving principles will be discussed. In the case of nonlegal object behavior, a legal safety system prevents an accident if possible and mitigates the accident if not. By definition, a legal safety system allows FA driving. However, FA driving is not allowed by current legislation and raises the ethical question concerning the acceptability of an accident between a legal safety system and a human driver who does not respect traffic rules.

Legal safety system design does not depend on the equipment of other vehicles or infrastructure. A legal safety system *can* not only cooperate with vehicles that are equipped with compatible vehicle-to-vehicle (V2V) communication and with infrastructure equipped with vehicle-to-infrastructure (V2I) communication but can also share the road with human drivers in a nonequipped environment. The cooperative approach (i.e., with explicit communication) can be seen as a specific case of the independent approach (i.e., without explicit communication), where uncertainty is reduced. For example, V2V can decrease the uncertainty on future object trajectories.

B. Traffic Rules of the Vienna Convention for Highways

Basic traffic rules are defined by an international treaty under the authority of the United Nations, i.e., the 1968 Vienna Convention on Road Traffic [17]. It has not been signed by all countries, and local variations in practice can be found among signatories. Many of the local specificities do not directly apply to the driving task (e.g., driving under intoxication, day lighting, seat belt use, and tire equipment), but some of them do. However, these local variations are not discussed in this paper.

This paper focuses on the application of the Vienna Convention on highways, as suggested in Fig. 1. The highway might be the first environment where highly (and fully) automated driving will become possible, because its simple lane structure and unidirectional flow of large objects facilitate perception, decision, and control algorithms. The description in this paper assumes that driving is on the right side of the road and translation for left-side driving is straightforward. The environment and conditions (day/night conditions, lane keeping/changing, speed range, right/left-side driving) for which the system is designed are referred to as the *application zone*.

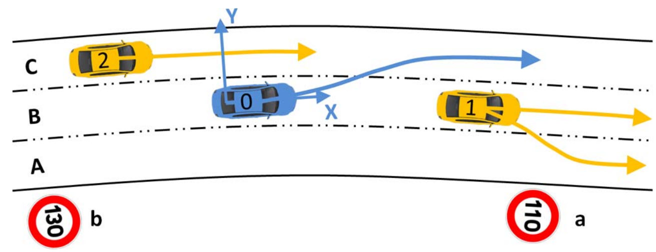

Fig. 1. Highway environment with subject vehicle (0), lanes (A, B, C), traffic signs (a, b) and object vehicles (1, 2). Possible object trajectories are predicted. An optimal subject trajectory is calculated.

A concise description of Vienna Convention articles that apply to highways is given as follows. The formulation of the rules is simplified for understandability but intends to reflect the exact article content. The original index of the article in the text of the convention is indicated between parentheses.

Rule 1 (7). Road users should avoid damage to road infrastructure or to other road users.

Rule 2 (8). The (human) driver should be in good physical and mental condition and should always be able to control the vehicle.

Rule 3 (10). Driving should be on the rightmost lane if possible, except for overtaking.

Rule 4 (11, 14). A vehicle shall only be overtaken on its left side, except in congested traffic, where right overtaking is also allowed. An overtaking maneuver can only be started if the vehicles in the front and back of the subject vehicle 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 shall not be performed if prohibited by a traffic sign, and continuous lane markings should not be crossed. The corresponding indicator must be activated during the entire overtaking maneuver.

Rule 5 (13). Speed must be adapted to road and weather conditions (e.g., visibility and road friction), speed limit signs, and the presence of other vehicles. The distance between vehicles must be such that a collision can be avoided if a vehicle performs an emergency brake. Drivers also must be able to avoid collisions with any foreseeable vehicle outside their perception zone.

Rule 6 (17). Braking should only be performed for safety reasons and must be indicated with braking lights.

Rule 7 (25). 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. If the vehicle needs to be stopped for a technical reason, this must be done on the emergency lane, if possible.

Rule 8 (32). The lighting of the vehicle should be adapted to visibility conditions.

Rule 9 (34). Priority vehicles are exempt from traffic rules, except from Rule 1 (7).

C. Human Rules

A human driver must always be ready to take over control according to the Vienna Convention (Rule 2). This allows *highly* automated driving, where the driving system controls the vehicle, and the human driver monitors the situation. The legal consequences of FA driving, where the human driver does not need to continuously monitor the situation, are currently investigated by research institutes and vehicle manufacturers [18]–[20]. For FA driving, adaptations to the Vienna Convention are needed. In anticipation of such adaptations, this paper assumes that the term *driver* in Rule 2 is extended to a *human driver*, a *driving system*, or a *combination of both* in the application zone. This means that, during FA driving, the driving system must monitor its condition (Rule 2) and be able to come to a safe standstill on the emergency lane if, in cases of system failure, the human driver cannot take over control (Rule 7).

Driver-only (DO), driver-assisted (DA), semiautomated (SA), and highly automated (HA) driving have extensively been studied in the HAVEit and ABV projects [14], [15]. During these automation levels, interaction between the human driver and the driving system is designed according to the horse-rider metaphor (H-metaphor) [21], [22]. Automation-level definition and automation-mode selection according to the projects are summarized in Rules 10 and 11.

Rule 10. In automation-level DO, the system is not active. In automation-level DA, the human driver performs longitudinal and lateral control, and the driving system gives feedback on the optimal speed and optimal lane. In SA, the driving system takes over longitudinal control. In HA, the driving system performs longitudinal and lateral control, whereas the human driver monitors the situation and specifies the target speed and target lane. In FA, the human driver no longer needs to monitor the situation, and lane changes are automatically performed. Optionally, the human can choose the driving style, e.g., normal, sportive, or comfortable.

Rule 11. Outside the application zone, only DO is possible. In the application zone, the system switches from DO to DA. The automation mode can be changed by either the human driver or the driving system. The human driver can switch between consecutive automation levels DA, SA, HA, and FA. If the human performs a decisive action on pedals or the steering wheel, the automation level directly switches to DA. The system automatically switches from DA to SA to avoid a collision by braking. The system switches to HA to avoid lane departure. In the case of a system failure or at the end of the application zone, the system automatically brings the vehicle to a standstill on the emergency lane, unless the human driver takes over control in DA.

Sections III–V discuss the legal safety system design according to the aforementioned traffic and human rules.

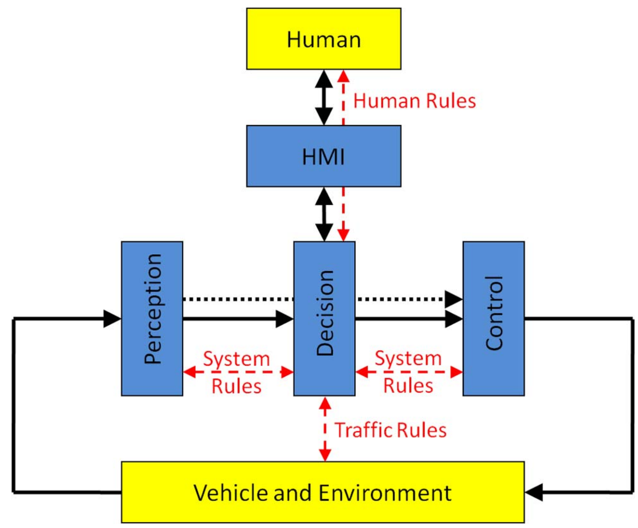

Fig. 2. System architecture with perception, decision, control, and HMI components. Continuous and dotted lines indicate communication between components. Dashed lines indicate interaction with traffic, human, and system rules.

III. Perception and Control Requirements

A. System Architecture

The functional architecture of a legal safety system is shown in Fig. 2. As most driving systems, it imitates human driving functions with perception, decision, and control components. The perception component gives an environment description (lanes, traffic signs, and objects) based on sensors such as cameras and radar. The decision component predicts object trajectories and calculates an optimal subject trajectory according to traffic rules (Section II-B), human rules (Section II-C), and system rules (Section III-B). In this paper, *optimality* refers to the trajectory with the highest speed that respects the three sets of rules, in the trajectory space that is considered by the decision algorithm. The control component keeps the vehicle on the subject trajectory and gives haptic feedback to the host driver. Human–machine interface (HMI) manages communication between the driving system and the host driver.

All information that is exchanged between the perception, decision, control, and HMI components (continuous and dotted lines in Fig. 2) is described in a subject coordinate system XY, with origin at the center of the subject rear wheel axle, X to the front and Y to the left, as shown in Fig. 1.

B. System Rules

Apart from traffic rules and human rules, *system rules* are imposed on each system component to ensure the integrity of calculations of other components. System rules are shortly described as follows.

Rule 12. Within the perception zone, the error on subject, lane, and object descriptions by perception must be within bounds.

Rule 13. Subject trajectories calculated by the decision component must be feasible for control.

Rule 14. The control keeps the subject on a trajectory with a bounded error. The accuracy of control is such that lane

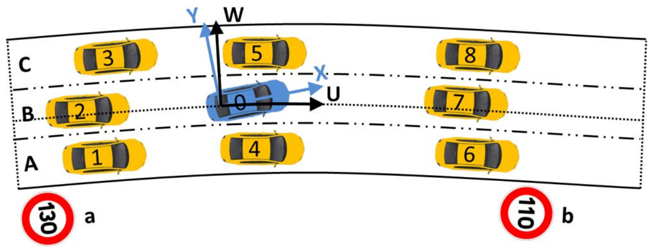

Fig. 3. Highway environment with subject vehicle (0), lanes (A, B, C), traffic signs (a, b), and objects (1–8). Indication of subject coordinate system XY and lane coordinate system UW.

changes are performed within a certain distance and that the vehicle can be kept within the target lane.

Rule 15. All information communicated between components has a bounded number of elements. Perception describes a maximum of the following three lanes: left, subject, and right lanes. Perception describes a maximum of eight objects, as shown in Fig. 3. Nearest objects ahead of and behind the subject in each of the three lanes and objects on either side of the subject are described. The decision component describes a maximum of four trajectories: one optimal trajectory in each lane and one trajectory that brings the vehicle to a standstill during failure functioning. In addition, the calculation time of perception, decision, and control meets predefined bounds.

The remainder of Section III discusses legal safety requirements (i.e., traffic, human, and system rules) with respect to the perception component (see Section III-C) and the control component (see Section III-D). This paper keeps the description of the perception and control components on a *requirement* level and compares with state-of-the-art technology. It does not aim at contributing to the actual *design* of these components.

C. Perception Requirements

The organization of the environment in lanes forms the basis for the interaction between traffic participants. Traffic rules (Rules 1, 3, 4, and 7), human rules (Rule 10), and system rules (Rule 12) make reference to the right, subject, and left lanes. These three lanes must be described by perception. In this paper, the lanes are labeled A, B, and C, respectively, as shown in Fig. 3. Lane indices A, B, and C change when the origin of XY crosses a lane marking. Lane description must be available ahead of and behind the subject.

In recent years, extensive research on lane perception based on different types of sensors has been presented. The camera is probably least expensive and best suited for a complete lane description. Vision-based perception of the subject lane is already available on the market as part of LKAS. Research currently investigates the perception of right and left lanes [23]. Perception must distinguish continuous from discontinuous lane markings for Rule 4 and must differentiate normal lanes, emergency lanes, entrance ramps, and exit ramps for Rule 7.

Rule 5 requires the perception of traffic signs, i.e., speed limits, overtaking prohibitions, and lane closures. Both the content and distance of traffic signs are required. Traffic sign recognition by vision has been studied during the last years [24] and currently has first commercial applications such as ISA. Rule 5 also demands adapting the vehicle speed to the road friction. Electronic stability control (ESC) sensors or other proprioceptive sensors could give quite accurate road friction estimation [25] but could not predict a drop of road friction ahead, e.g., caused by oil on the road, ice, snow, or aquaplaning. Similar to the human driver, the system could estimate friction in front with a camera [26].

The perception of position, size, speed, and acceleration of objects in subject, right, and left lanes, ahead of and behind the subject, is required for Rules 1, 4, 5, 6, 7, and 9. At night, at least objects with appropriate lighting should be detected by Rule 8. Object perception is possible with a variety of sensors such as the radar [27], LIDAR [28] and camera [29]. The camera is essential for indicator detection [30] of objects in the subject lane (behind and ahead of subject) for Rule 4. The knowledge of indicator status of objects in right and left lanes is not strictly needed according to traffic rules but helps in defensive driving. The camera also allows increasing the accuracy of lateral object position in the lane, which is determinant for subject trajectory optimality, as will be explained in Section IV.

Apart from information that comes from the aforementioned exteroceptive sensors (e.g., camera and radar), additional information from V2V and V2I communication can be integrated, if available. However, as explained in Section II, a legal safety system must also be capable of FA driving if other vehicles and infrastructure do not have communication equipment.

Perception combines subject, lanes, and objects description into a complete environment model, as shown in Fig. 3. The environment model is communicated to the decision component (see the continuous line in Fig. 2), and subject description is communicated to the control component (see the dotted lines in Fig. 2).

Providing a complete and robust environment perception is the main challenge of a legal safety system. Many requirements that were presented in this section cannot yet be met with state-of-the-art technology. However, research on this topic is intensifying. Reliability and accuracy increase under the impulse of first ADASs such as ACC, LDWS, and LKAS. The estimate is that legal safety perception could be achievable in medium terms.

D. Control Requirements

This section shortly mentions requirements on legal safety control and compares with state-of-the-art technology. For a natural feeling, Rules 10 and 11 require that control is performed through haptic feedback that can be overpowered by the human driver. The control component must be able to handle these disturbances.

Rules 4 and 5 imply lateral control for lane keeping and lane changing and longitudinal control, which, in the extreme case, performs emergency braking. Vehicle control is probably the domain that is most advanced with respect to legal safety. With state-of-the-art technology, limits of perception integrity are usually reached earlier than limits of control; for example, only slow lane changes ensure the integrity of lane tracking. In this case, vehicle dynamics can be assumed linear, which facilitates the task of control. Legal safety control can be based on longitudinal control [31] and lateral control [32], which are part of existing ADASs.

IV. Prediction of the Object and Phantom Trajectories

A. Overview of Approaches

One common approach for object trajectory prediction is to assume that the object will continue its current movement, without taking into account the lane structure. For example, a Kalman filter or one of its variants is used, together with motion models such as constant turning rate and acceleration [33]. In this approach, object behavior is assumed deterministic, i.e., one trajectory per object is computed.

Another approach is to calculate the probability of all possible object movements, e.g., with Gaussian distribution [34]. The subject trajectory is then calculated as a tradeoff between subject speed and the number of collisions with the randomly moving objects. This approach seems reasonable for collision mitigation and avoidance systems, which estimate all possible (i.e., realistic and nonrealistic) object trajectories to avoid premature system activation. For HA and FA driving, however, it is not clear what an acceptable threshold for this collision *risk* can be. It seems difficult to defend that reasonably foreseeable object behavior and not reasonably foreseeable object behavior are considered on an equal basis.

Object trajectory prediction approaches that do not take traffic rules into account frequently underestimate or overestimate the danger that an object represents. For example, when an object is moving straight and has its indicators activated, lane changing can be expected, but lane keeping is predicted according to a motion model. With the assumption of random object behavior, danger is usually overestimated in safe situations and underestimated in dangerous situations.

This paper proposes an approach to object prediction that is different from the aforementioned approaches. Section IV describes the legal safety prediction of object trajectories based on traffic rules. The legal safety decision component considers not only legal object behavior but also reasonably foreseeable nonlegal behavior, i.e., defensive driving is promoted. It should, however, not anticipate unforeseeable nonlegal 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) to allow sharing the road.

B. Lane Coordinate System

The curvilinear lane coordinate system UW, with the same origin as the subject coordinate system XY, U-axis parallel to the middle of each lane and W-axis perpendicular on U, is a natural environment for calculations with subject and object trajectories. The lane coordinate system UW and the subject coordinate system XY are illustrated in Fig. 3. In the lane coordinate system UW, lanes centers have a constant W-coordinate. Subject and object trajectories that target the lane center can be represented by a transient section (with a varying W-coordinate) and a permanent section (with a constant W-coordinate). Calculations with constant W-coordinates are much easier and faster than calculations in the actual lane geometry in XY, which is usually (but not necessarily) based on a combination of lines, clothoids, and circles [35].

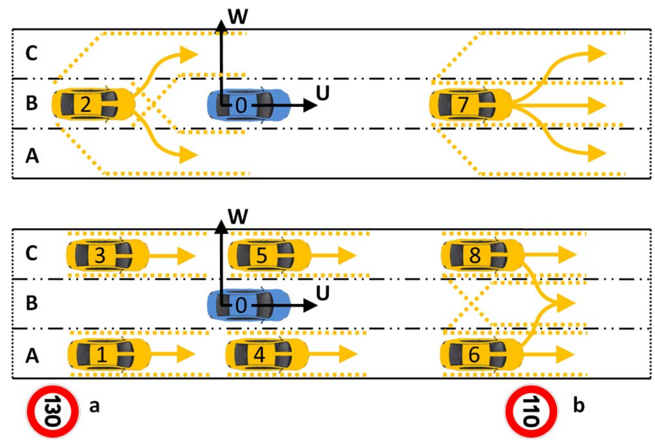

Fig. 4. Prediction of trajectories of objects (1–8) as a function of position with respect to subject (0). Overview of possibilities according to traffic rules. Mathematical zone model with minimum and maximum trajectories (dotted line) versus an exemplary actual trajectory (full line).

The first step of the decision algorithm consists of transforming the environment description by perception from XY to UW. All subject and object trajectory calculations are performed in UW. In the final step, the decision component applies an inverse transformation from UW to XY to describe trajectories for control and HMI.

C. Zone Model for Subject and Object Trajectories

Many alternatives exist for the mathematical description of subject and object trajectories, e.g., polynomials, circular arcs, splines, and sinusoids [36]. To ensure that trajectory descriptions are precise, these alternatives are usually based on a vehicle model such as a bicycle or a Dubins car [37]. However, no single exact trajectory can realistically describe subject movement due to perception and control errors (Rules 12 and 14). 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 uncertain. However, for HA and FA driving, an *unbounded* uncertainty on subject and object trajectories (e.g., with a Gaussian description) is difficult to defend; no threshold on the probability of collisions between subject and objects seems low enough. This paper proposes a zone model for subject and object trajectories, which represents a bounded and uniform uncertainty. In this paper, the zone model for the subject and objects is described by linear minimum and maximum speed profiles (for longitudinal movement, dotted lines in Figs. 5 and 7) and linear minimum and maximum trajectories (for lateral movement, dotted lines in Figs. 4, 6, and 8). This corresponds to a constant acceleration after a reaction time and to a constant lateral movement toward the target lane after a reaction distance. The lane-based zone model facilitates the implementation of traffic, human, and system rules, as described in Sections IV-D and V-B and C.

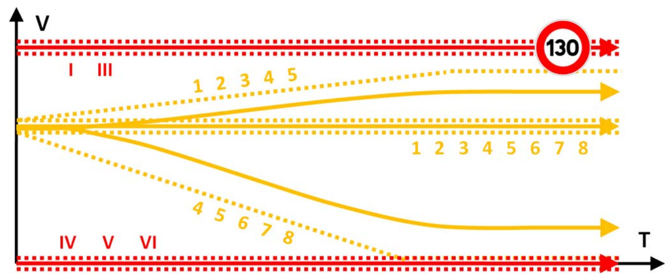

Fig. 5. Prediction of speed profiles of objects (1–8), phantoms behind (I, III), and phantoms ahead (IV, V, VI) as a function of position with respect to the subject (0). Overview of possibilities according to traffic rules. Mathematical zone model with minimum and maximum speed profiles (dotted line) versus an exemplary actual speed profile (full line).

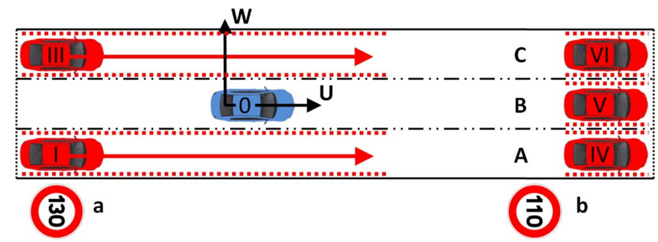

Fig. 6. Prediction of trajectories of phantoms behind (I, III) and phantoms ahead (IV, V, VI) as a function of position with respect to subject (0). Overview of possibilities according to traffic rules. Mathematical zone model with minimum and maximum trajectories (dotted line) versus an exemplary actual trajectory (full line).

D. Trajectory Prediction

Fig. 4 presents possible trajectories for the eight potential objects (1–8) around the subject (0) according to traffic rules. The default trajectory for objects corresponds to lane keeping. Only for 2 is the lane keeping trajectory not calculated. Object 2 is assumed to keep an appropriate distance from the subject (even if the subject performs emergency braking) according to Rule 5. Adapting to the lane-keeping trajectory of object 2 probably goes beyond reasonably limits of defensive driving.

According to Rule 4, objects 2 and 7 have priority on the subject when changing lanes if their indicators are activated and if subject indicators have not been activated. In this case, a lane change is predicted for these objects. Other objects that change lanes must give priority to the subject. As will be explained in Section V, this guarantees that a legal safety trajectory in the subject lane always exists, corresponding to lane keeping at a safe distance from object 7. In principle, lane-changing trajectories of objects other than 2 and 7 should not be predicted. However, to promote defensive driving, the subject also predicts that objects 2, 6, 7, and 8 nonlegally change lanes when they are crossing a lane marking, regardless of whether these lane markings are continuous. For objects 1 and 3–5 behind and on the side of the subject, lane-changing trajectories to B are not predicted for a similar reason as for the aforementioned lane-keeping trajectories of object 2.

The prediction of object trajectories illustrates the importance of an accurate estimation of lateral object position in the lane. Note that, for an object with a minimum/maximum trajectory for lane changing, the other maximum/minimum trajectory corresponds to lane keeping. The object evolves between both trajectories if it were expanding in the future. This reflects the uncertainty on whether the lane change will actually take place. Because the dynamism of the lane change cannot be known, a fast lane change is assumed.

Fig. 5 illustrates the prediction of object speed profiles. For objects behind and on the side of the subject (1–5), a minimum speed profile corresponds to keeping speed. If these objects are accelerating, their maximum speed profile continues the acceleration until the maximum speed. If objects behind or on the side are keeping speed or are decelerating, both minimum and maximum speed profiles correspond to keeping speed. The driving system is conservative by not relying on the fact that these objects keep decelerating. An opposite logic is followed for the prediction of speed profiles of objects on the side and ahead (4–8). These objects are either keeping speed or keep decelerating, as shown in Fig. 5.

The decision algorithm is more defensive than strictly needed by traffic rules. It assumes that objects can offend traffic rules, e.g., by overtaking other objects (including the subject) on the right and exceed speed limits.

Rule 5 stipulates that the subject must be able to avoid collisions with potential objects outside the perception zone. For this purpose, trajectories of phantoms, worst case objects at both ends of the perception zone, are calculated. Figs. 5 and 6 illustrate phantom speed profiles and trajectories. Because 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. By considering phantoms, the legal safety system limits its speed such that it can come to a standstill before a traffic congestion that appears at the end of the perception horizon, as will be explained in Section V.

Behind the subject, worst case phantoms I and III correspond to vehicles at the end of the perception zone that travel at speed limit. This prevents the subject from overtaking a slower vehicle when the subject speed and the perception horizon to the rear are low, as will be explained in Section V. In noncongested traffic, the phantom I on the right lane could be ignored, because no object is allowed to right overtake the subject by Rule 4. Phantom II is never considered, because the subject vehicle has priority over vehicles that come from behind on the subject lane by Rule 5.

V. Calculation of the Subject Trajectories

A. Overview of Approaches

Section V presents the calculation of subject trajectories based on the environment perception and object trajectory prediction discussed in Section IV. In the vast literature of trajectory planning, the following two types of algorithms can be distinguished: 1) sampling-based algorithms, and 2) direct algorithms [38]. Sampling-based algorithms such as sampling-based roadmap, rapidly exploring random tree, or grid algorithms allow a universal approach by first generating random samples in the trajectory space and then evaluating these samples. Direct algorithms such as expert, potential field, or control algorithms offer an application-specific approach that directly

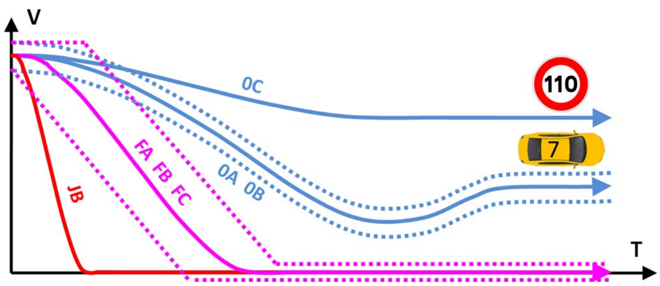

Fig. 7. Generation of seven speed profiles for the subject. Three for normal functioning (0A, 0B, 0C); three for failure functioning (FA, FB, FC); and one for emergency braking (JB). The zone model for speed profiles 0A, 0B, FA, FB, and FC is indicated with dotted lines. The figure corresponds to the situation in Fig. 8.

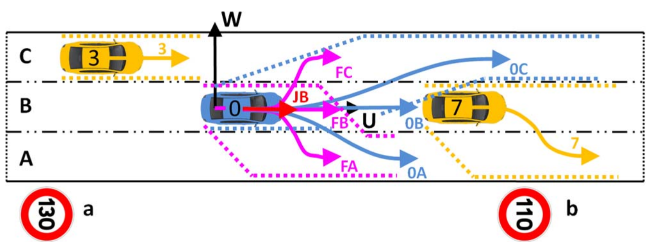

Fig. 8. Generation of seven trajectories for the subject. Three for normal functioning (0A, 0B, 0C); three for failure functioning (FA, FB, FC); and one for emergency braking (JB). The zone model for trajectories FA and 0C is indicated with dotted lines.

considers all driving aspects in the trajectory generation, without the need for an evaluation step. Direct algorithms find solutions that are more optimal and need fewer calculations than sampling-based algorithms. Sampling-based algorithms can solve complex problems that direct algorithms cannot (yet) solve.

The legal safety decision component presented in Section V combines direct and sampling-based trajectory planning. Direct calculations are used in the longitudinal direction to calculate subject speed profiles. Direct calculations are straightforward and precise for continuous variables such as longitudinal speed from zero to maximum speed and longitudinal acceleration from extreme braking to strong acceleration. Sampling-based calculations are used in the lateral direction, which has a discrete character by nature, by the lane structure. In the current implementation of the decision component, only trajectories toward the middle of the lanes are calculated.

B. Trajectory Generation

Figs. 7 and 8 give an example of the generation of seven speed profiles and trajectories. Three optimal trajectories, one per target lane, are calculated for normal system functioning: 0A, 0B, and 0C. In addition, three safe state trajectories, one per target lane, have a terminal speed of zero and can be used during system failure functioning or in situations of driver distraction or drowsiness: FA, FB, and FC. One trajectory for emergency braking in the subject lane, JB, is calculated for collision mitigation if an accident cannot be avoided, in certain cases of nonlegal object behavior.

TABLE I
NOTATIONS

Variable	t	Time
	d	Distance
	p, v, a	Position, speed, acceleration
	s	Slope
	k	Tuning parameter
	μ	Friction
	ρ	Curvature
Subscript	u, w	UW-coordinate
Superscript	-	Subject
	F	Failure
	G, H, I	Limit by friction, human, system
	J	Deceleration limits combined
	K	Acceleration limits combined
	L	Lane shape
	O	Object
	P	Phantom
	R	Reaction time
	S	Speed limit
Name	0	Subject (normal functioning)
	F	Subject (failure functioning)
	1 - 8	Object
	I - VI	Phantom
	A - C	Lane

The decision component first calculates speed profiles and then calculates trajectories. This approach is opposite to the classic path-velocity decomposition approach [39]. Section V-B presents several individual aspects of legal safety that apply to each of the seven subject speed profiles in (1)–(6). Each subject speed profile is calculated as the minimum of speed profiles for individual legal safety aspects. After the calculation of seven speed profiles, seven trajectories in UW are calculated as a maximum (in absolute value) of trajectories for individual legal safety aspects in (7)–(9). Table I gives an overview of the notations used in (1)–(9).

The first condition on subject speed profiles is that friction limits (superscript G), human limits (superscript H), and system limits (superscript I) are respected, in correspondence to human and system rules. Equations (1) and (2) present conditions on the transient section of a speed profile according to the longitudinal friction, human, and system limits. Equation (3) will present speed profile conditions according to lateral friction, human, and system limits.

Equation (1) presents the most extreme deceleration $-a_u^J$ on subject speed profiles. Extreme deceleration according to friction limits $-a_u^{G'}$ is calculated from the road friction estimated by perception. Extreme deceleration allowed by the human driver $-a_u^{H'}$ can be chosen according to the driving style. Higher values of $a_u^{H'}$ allow smaller distance to objects, as will be explained later. Extreme deceleration according to system limits $a_u^{I'}$ takes into account limits for perception integrity and control limits, i.e.,

$$\begin{cases} 0 \le v_u \\ -min\left(a_u^{G'}, a_u^{H'}, a_u^{I'}\right) = -a_u^J \le a_u. \end{cases} \quad (1)$$

Equation (2) presents a speed profile with maximum acceleration a_u^K toward maximum speed v_u^K. Similar to a_u^J, the value a_u^K is bounded by longitudinal friction, human, and system limits. Maximum acceleration $a_u^{H''}$ for the human driver depends on the driving style, e.g., sportive or comfort driving.

Note that values $a_u^{G''}$, $a_u^{H''}$, and $a_u^{I''}$ for the maximum speed profile (a_u^K) in (2) are usually smaller than values $a_u^{G'}$, $a_u^{H'}$, and $a_u^{I'}$ for the emergency deceleration (a_u^J) in (1). Maximum speeds v_u^H and v_u^I are the target speed set by the human driver and the maximum speed for which the system is designed. For speed profiles FA, FB, and FC for failure functioning, v_u^H is replaced by 0, and $a_u^{H'}$ is replaced by a deceleration value $-a_u^F$, which can be chosen between $-a_u^J$ and 0. For emergency speed profile JB, $a_u^{H'}$ is replaced by extreme deceleration value $-a_u^J$. For JB, (1) and (2) are identical

$$\begin{cases} v_u \leq min\left(v_u^H, v_u^I\right) \\ a_u \leq a_u^K = min\left(a_u^{G''}, a_u^{H''}, a_u^{I''}\right). \end{cases} \tag{2}$$

The second condition on speed profiles takes into account friction, human, and system limits in the lateral direction. Speed in a curved lane generates a centrifugal, lateral acceleration. In a similar way as maximum longitudinal acceleration a_u^K, maximum lateral acceleration a_w^K takes into account friction limits (a_w^G), human limits (a_w^H, depending on the driving style chosen by the human driver), and system limits (a_w^I, integrating limits on perception and control). Note that lateral a_w^G is a function of longitudinal $a_u^{G'}$ and $a_u^{G''}$ through the *friction ellipse* that models the friction between road surface and vehicle tires [40].

For a maximum lateral acceleration a_w^K and curve ahead with curvature ρ^L, the target speed v_u of speed profiles is described by (3). In straight lanes, ρ^L tends to zero, and v_u tends to infinity, which means that the condition does not represent a limitation. When approaching a curve, the subject speed must be reduced from the current speed v_{u_0} to v_u before reaching the beginning of the curve, at a distance p_u^L from the subject. The deceleration required for this is given by (3), and the equation takes into account the distance traveled during system reaction time t^R

$$\begin{cases} v_u \leq v_u^K = \sqrt{\frac{a_w^K}{\rho^L}} \\ a_u \leq -\frac{1}{2}\,\frac{(v_{u_0})^2-\left(v_u^K\right)^2}{p_u^L - v_{u_0}\,t^R}. \end{cases} \tag{3}$$

Equations (1)–(3) describe conditions on speed profiles according to friction, human, and system limits. This covers human and system rules. Conditions on speed profiles with respect to traffic rules are presented in (4)–(6).

The subject speed is adapted to the speed limit v_u^S in correspondence to traffic rules (Rule 5). Equation (4) for speed limits is similar to (3) for curves. The subject speed v_{u_0} is adapted to v_u^S within the distance to the speed limit p_u^S, i.e.,

$$\begin{cases} v_u \leq v_u^S \\ a_u \leq -\frac{1}{2}\,\frac{(v_{u_0})^2-\left(v_u^S\right)^2}{p_u^S - v_{u_0}\,t^R}. \end{cases} \tag{4}$$

Traffic rules (Rule 5) stipulate that the subject speed should be such that a collision with phantoms (Section IV) can be avoided. The target speed of speed profiles v_u must allow braking with a deceleration $-a_u^P$ for a still-standing object at a position p_u^P (end of the perception zone), leaving a minimum safety distance d_u^J. Deceleration $-a_u^P$ is to be chosen between $-a_u^J$ and 0. Higher values of a_u^P allow higher subject speeds v_u^P but cause harder braking for still-standing objects. Solving $v_u t^R + (v_u)^2/2a_u^P = p_u^P - d_u^J$ to v_u gives (5). As an example, 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) allow the subject speed $v_u^P = 36.1$ m/s $=$ 130.1 km/h. Similar to (3) and (4), (5) is identical for all seven subject speed profiles.

Phantoms behind (Section IV) are not considered in the trajectory generation step (Section V-B), only in the trajectory evaluation step (Section V-C).

In this paper, phantoms represent only worst case objects and not worst case curves or worst case speed limits. However, the subject speed should also be limited so that it allows decelerating in time for *phantom curves* and *phantom speed limits*. This paper 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 with zero speed always constitute a bigger constraint on speed profiles, i.e.,

$$\begin{cases} v_u \leq a_u^P\left(-t^R + \sqrt{(t^R)^2 + 2\,\frac{p_u^P - d_u^J}{a_u^P}}\right) \\ a_u \leq a_u^K. \end{cases} \tag{5}$$

Equation (6) describes constraints on speed profiles with respect to objects ahead. Subject variables are indicated without a superscript. An object in the equation (superscript O) denotes any object with trajectories toward the same target lane as the speed profile according to the prediction of object trajectories in Section IV. In noncongested traffic, the equation also includes objects with trajectories toward a lane left of the target lane of the speed profile to avoid overtaking an object on its right. Objects on the side and behind the subject are not considered in the generation step (see Section V-B) but are considered only in the evaluation step (see Section V-C).

The target distance to objects p_u^K in (6) takes into account the distance p_u^H desired by the human driver and safety distance p_u^I required by system limits. Distance p_u^H is generally proportional with speed. The time headway t^H can directly be set by the human driver through a lever or indirectly through the selection of driving style. Choosing a sportive driving style allows smaller distances to the object but leads to harder decelerations in case that the object brakes. Distance p_u^I is a function of system limits. Traffic rules (Rules 5 and 4) stipulate that the safety distance p_u^I should be such that a collision can be avoided in case that the object performs an emergency brake until standstill. This is expressed in (6). The system keeps a minimum distance p_u^I so that a small speed-dependent distance $(d_u^I + v_{u_0}, t^I)$ is left when object brakes with maximum deceleration $-\mu^L, g$ (with μ^L, the road friction) and subject brakes with maximum deceleration $-a_u^J$ after the system reaction time t^R. Minimum distance p_u^I mainly corresponds to the system reaction time t^R when making abstraction of the first two terms (the safety margin when the subject and the object come to a standstill after an emergency brake) and forth term (which only applies if the subject and the object have different braking capacity). The 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 interdistances to objects than typical human drivers, even

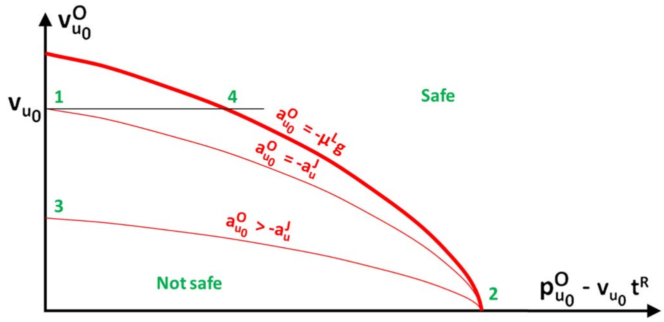

Fig. 9. Safety zone around the subject in the case of decelerating object.

with the requirements that it avoids accidents when the object performs an emergency brake. As the system reaction time decreases, safety distance to objects can be decreased. This increases traffic flow capacity and could ultimately decreases consumption through platoon driving as

$$\begin{cases} p_u^H = d_u^H + v_{u_0}\, t^H \\ p_u^I = d_u^I + v_{u_0}\, t^I + v_{u_0}\, t^R + \frac{(v_{u_0})^2}{2\, a_u^J} - \frac{\left(v_{u_0}^O\right)^2}{2\, \mu^L\, g} \\ p_u^K = max\left(p_u^H, p_u^I\right) \\ v_u \leq v_u^O \\ a_u \leq k_p\, \left(p_{u_0}^O - p_u^K\right) + k_v\, \left(v_{u_0}^O - v_{u_0}\right) + a_{u_0}^O. \end{cases} \tag{6}$$

Fig. 9 visualizes the safety zone around the subject vehicle, i.e., the combination of object positions $p_{u_0}^O$, speeds $v_{u_0}^O$, and decelerations $a_{u_0}^O$ for which the subject can avoid a collision through an emergency brake $-a_u^J$. An interesting use case is when an object with $p_{u_0}^O$, $v_{u_0}^O$, and $a_{u_0}^O$ performs a (nonlegal) sudden lane change toward the subject lane. If the object has a deceleration that equals the subject extreme deceleration $-a_u^J$, an accident can still be avoided if the object is at a distance of v_{u_0}, t^R and has a speed that is equal to the subject speed v_{u_0} (point 1 in Fig. 9). A collision with a still-standing object can be avoided if it is detected at a distance $v_{u_0}, t^R + (v_{u_0})^2/2, a_u^J$ (point 2 in Fig. 9). In this equation, the calculation of the subject speed with respect to phantoms ahead, in (5), can be recognized. If the object has less extreme decelerations, a collision can be avoided for lower object speeds (point 3 in Fig. 9). If the object adopts an emergency deceleration $-\mu^L, g$ (e.g., point 4 in Fig. 9), a collision can only be avoided at $v_{u_0}, t^R + (v_{u_0})^2/2, a_u^J - (v_{u_0}^O)^2/-\mu^L, g$, which corresponds to the calculation of p_u^I in (6), except for the additional safety distance $d_u^I + v_{u_0}, t^I$.

Equations (1)–(6) have presented constraints on subject speed profiles for longitudinal movement. Equations (7)–(9) present constraints on subject trajectories and speed profiles for lateral movement. The lateral target position p_w of trajectories always corresponds to the center of the target lane p_w^L. The zone model of subject trajectories (see Fig. 8) is defined by the slope s_w of the transient section of the trajectory.

Similar to subject speed profiles, subject trajectories must respect limits imposed by road friction, the human driver, and the driving system. Equation (7) presents the comfort trajectory slope s_w^K, which is specified by the human driver and the driving system. If the presence of objects ahead (9) does not put additional constraints, the subject trajectory slope equals s_w^K, i.e.,

$$max\left(s_w^H, s_w^I\right) = s_w^K \leq s_w. \tag{7}$$

Equation (8) describes the maximum trajectory slope s_w^J. Slope 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 (8) are higher than values for comfort trajectory slopes s_w^K in (7). The maximum trajectory slope also integrates friction limits s_w^G as

$$s_w \leq s_w^J = min\left(s_w^G, s_w^H, s_w^I\right). \tag{8}$$

Equations (1)–(8) represent constraints on either subject speed profiles or subject trajectories. Overtaking an object involves adapting both the speed profile and the trajectory. As for object following, a safety distance p_u^I (6) must be kept during object overtaking so that an accident can be avoided if the object performs an emergency brake. Equation (9) indicates that the trajectory slope s_w, speed profile target v_u, and acceleration a_u must meet certain constraints s_w^L, v_u^L, and a_u^L such that safety distance p_u^I is respected during the complete maneuver. The calculation of s_w^L, v_w^L, and a_u^L cannot directly be solved analytically. It is solved numerically by sampling s_w^L, v_w^L, and a_u^L and verifying the condition on p_u^I during the maneuver as

$$\begin{aligned} v_u &\leq v_u^L \\ a_u &\leq a_u^L \\ s_w^L &\leq s_w. \end{aligned} \tag{9}$$

Equations (1)–(9) define separate speed profiles by v_u and a_u and separate trajectories by s_w. Legal safety speed profiles are obtained by taking the minimum of separate speed profiles according to (1)–(6), and (9). Legal safety trajectories are found by taking the maximum (absolute values) of separate trajectories according to (7)–(9). This gives seven 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—as illustrated in Figs. 7 and 8.

C. Trajectory Evaluation

The decision component directly integrates most aspects of legal safety in the generation of subject speed profiles and trajectories, as presented in Section V-B. Section V-C presents the evaluation step, which evaluates the seven trajectories on legal safety aspects that were not considered in the generation step. A performance cost is attributed to each of the remaining legal safety aspects. The performance cost is binary (i.e., 0 or 1), except for the object collisions cost, which is proportional to the collision impact speed. This allows choosing the trajectory with minimum collision impact in situations where an accident cannot be avoided.

In the trajectory generation step, only phantoms and objects ahead have been considered. The trajectory evaluation step considers the prediction of trajectories of phantoms and objects behind and on the side. It checks if the subject speed on the

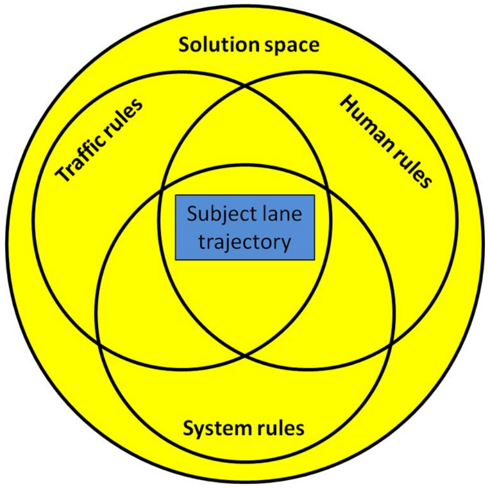

Fig. 10. At the intersection of traffic, human, and system rules, a legal safety trajectory in the subject lane can always be found.

speed profile allows phantoms to brake until subject speed with a reasonable deceleration $-a_u^P$. It verifies that objects from behind and on the side do not need to brake for the subject, according to Rule 4. The evaluation does only apply to lane-changing trajectories 0A, 0C, FA, and FC and not on lane-keeping trajectories 0B, FB, and JB. In the subject lane, the subject takes priority on phantoms and objects from behind and on the side, as explained in Section IV-D.

The evaluation step also considers the target lane type for lane-changing trajectories 0A, 0C, FA, and FC. Rule 7 stipulates that trajectories for normal functioning 0A and 0C must target *normal lanes* only and must not cross continuous lane markings. Trajectories for failure functioning FA and FC can end on either an *emergency lane* or a *normal lane* and can cross continuous lane markings. Lane-changing trajectories toward nonappropriate target lanes have not been excluded *a priori* (i.e., before trajectory generation), because these trajectories might help in avoiding accidents in cases of nonlegal object behavior. For example, a lane change toward an emergency lane is preferred to a collision with an object.

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, at least one subject trajectory must exist for control. This is the case for the legal safety decision component. In cases of legal object behavior, a safe subject lane trajectory 0B or FB is always found, as suggested in Fig. 10. The subject lane trajectory keeps a safety distance to the object ahead, which allows avoiding an accident if the object performs an emergency brake. The subject lane trajectory keeps the lane and has priority on objects in other lanes and on objects behind. In many cases of nonlegal object behavior, a collision-free subject trajectory can be found. In some cases, an accident cannot be avoided, and the trajectory with the lowest collision impact is chosen for collision mitigation. Note that decreasing constraints by human rules (e.g., allowing FA with automatic lane changes) and system rules (e.g., allowing faster lane changes) allow avoiding more accidents in cases of nonlegal object behavior.

The subject trajectories evaluation (presented in Section V-C) allows selecting the optimal subject trajectory 0A, 0B, 0C, or JB. Left lane trajectory 0C is suggested as the optimal trajectory if it has zero performance cost and allows increasing target speed compared with subject lane trajectory 0B. Right lane trajectory 0A is selected if it has zero performance cost and 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 indicated as the optimal trajectory. This selection scheme allows maximizing vehicle speed and encourages driving in the rightmost lane (Rule 3). The target lane and target speed of the optimal trajectory is communicated to the human driver through HMI.

One subject trajectory to be performed during normal functioning (0A, 0B, 0C or JB) and one trajectory to be performed during failure functioning (FA, FB, FC or JB) is selected and communicated to control, after translation to the subject coordinate system XY. In the case of FA driving, the performed subject trajectory for normal functioning corresponds to the optimal subject trajectory, i.e., optimal lane changes are automatically performed. In the automation modes DA, SA, and HA, the performed subject trajectory is the trajectory toward the lane specified by the human driver, unless it has a nonzero performance cost. In this case, the subject lane trajectory 0B is selected as the performed trajectory.

The performed 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 or subject lane trajectory FB is selected.

VI. Results on Vehicle and Simulator

A. Experiment Setup

Section VI discusses results on the simulator SiVIC [41] and demonstrator vehicle CARLLA on the Satory test track in Versailles, France. Four validation scenarios that combine HAVEit and ABV scenarios [14] and ISO test procedures [42], [43] are presented. Scenarios that involve subject lane changing are presented on the simulator, whereas other scenarios are presented on the vehicle. All tests are performed in HA driving, i.e., target speed and target lane are specified by the human driver, and vehicle control is performed by the driving system.

CARLLA is equipped with a camera for lane perception [23] and LIDAR for object detection. The perception of multiple lanes (i.e., right, subject, and left lanes) is currently under development. Currently, only lane-keeping scenarios are demonstrated on the vehicle. Curves and speed limit information, which cannot be detected by the camera or LIDAR, are delivered by a map or V2I and V2V communication based on positioning by the Global Positioning System (GPS) with normal precision. Precise localization with real-time kinematic (RTK)-based GPS is used only as reference for validation. For control, the vehicle has been equipped with actuators on the steering column, brakes, and motor valve.

The legal safety decision and control components are integrated on the automotive ECU to demonstrate their

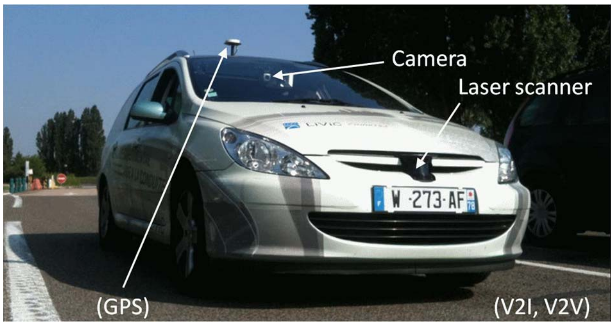

Fig. 11. Experimental vehicle CARLLA with a camera (CNB 36X) for lane perception and LIDAR (SICK LMS 400) for object perception. A GPS (Thales Sagitta 02), V2I communication, and V2V communication (NETGEAR WG121) are used for variables that cannot yet be detected by a camera or LIDAR.

Fig. 12. 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).

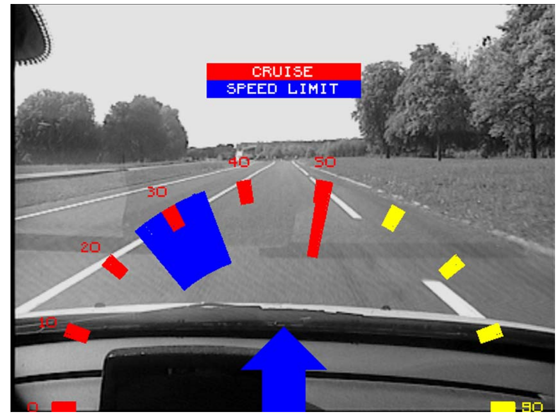

Fig. 13. Scenario *approaching a speed limit* on the vehicle. HMI at $t = 21$ s. The subject speed is 50 km/h, matching the human target speed. The current speed limit is 90 km/h. A future speed limit of 30 km/h has been detected.

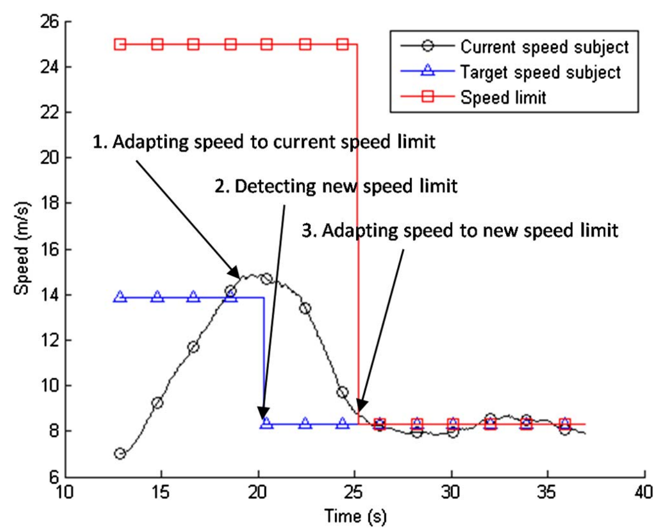

Fig. 14. Scenario *approaching a speed limit* on vehicle. Subject speed as a function of time. The zone model of the speed profile at $t = 20$ s is illustrated with dashed lines.

compatibility with series production platforms with limited memory and calculation power [44]. Figs. 11 and 12 show the ECU setup in a suit case. The ECUs, delivered by HAVEit partner Continental [45], have a SPACE 2FB30-M microcontroller with a clock frequency of 120 MHz, 3-MB Flash memory, and 100-kB RAM memory. They are based on the AUTomotive Open System ARchitecture (AUTOSAR) standard, version 2.1.0, which allows making abstraction of hardware implementation [e.g., controller area network (CAN) communication between ECUs] on the application level. On the ECU, decision and control components run within a cycle time of 25 ms, which includes reading and writing of data structures on the vehicle CAN. Perception and HMI components are implemented on a standard desktop PC.

B. Scenario Approaching a Speed Limit

Fig. 13 shows a snapshot of HMI during the scenario *approaching a speed limit* on the vehicle. System information is projected on the camera image. (Similarly, this information could be shown on a head-up display.) The HMI shows the automation mode HA. The vehicle speed is 50 km/h. This corresponds to the target speed set by the host driver, which is indicated by the numbers on the speed panel. The speed panel ranges from zero to the actual speed limit of 90 km/h. A new speed limit of 30 km/h is detected, which is indicated by a warning message and by the target speed recommended by the decision component. The proposed target lane is the subject lane, which is indicated with the arrow in the lower part of the image. This HMI is kept rudimentary, because the actual HMI design is not the focus of this paper. Several simple modifications could be considered to make the HMI easier to understand, e.g., using standard icons, rather than text, for automation mode and warning messages.

Fig. 14 shows the evolution of the vehicle speed (circle label) as a function of the actual speed limit (square label). The target

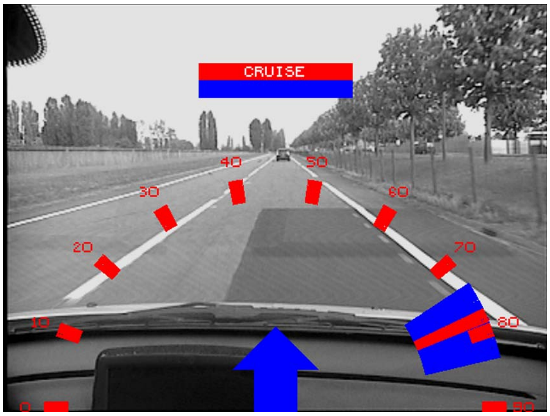

Fig. 15. Scenario *approaching a phantom* on the vehicle. HMI at $t = 36$ s. The object is not yet detected. The subject speed is 78 km/h, matching the maximum speed allowed by phantoms at 70 m, the end of the perception zone. The human target speed and speed limit are 90 km/h.

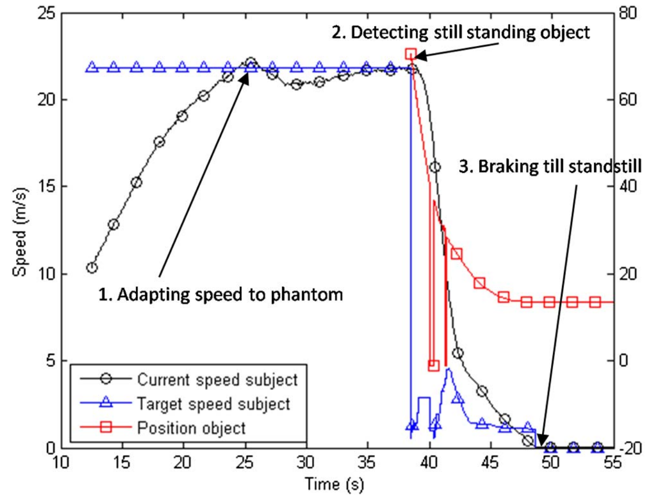

Fig. 16. Scenario *approaching a phantom* on vehicle. Subject speed and distance to the object as a function of time.

speed for the subject lane speed profile 0 B is labeled with a triangle. The vehicle accelerates and keeps the human target speed of 50 km/h (13.9 m/s), with an error of 3 km/h (0.8 m/s), at $t = 19$ s. At $t = 20$ s, a speed limit of 30 km/h (8.3 m/s) is detected at a distance of 60 m (this distance is not indicated in the figure). The driving system adapts the target speed (triangle label) to the speed limit. The deceleration on the speed profile is such that system reaches the limit with minimal braking, i.e., just in time, at $t = 25$ s. 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 light positive speed offset of 1.5 km/h (0.4 m/s). This offset should be easy to correct in the control component.

C. Scenario Approaching a Phantom

The scenario *approaching a phantom* shows how a legal safety system limits the vehicle speed to stop for a still-standing object outside the perception zone. Fig. 15 shows the HMI during the experiment on the vehicle. The speed limit and the human target speed are 90 km/h. The system, however, does not reach these target speeds. It limits the subject speed to 78 km/h to stop if a still-standing object would appear at 70 m, i.e., the perception horizon with LIDAR. The HMI snapshot was taken just before the actual detection of such an object.

Fig. 16 shows the subject speed as a function of time. At the beginning of the test, no object is detected. The subject speed is kept on the maximum speed allowed by phantoms, i.e., 78 km/h (21.7 m/s). At $t = 38$ s, an object at the end of the perception zone is detected (its position is square labeled). The target speed (triangle label) is adapted to the zero object speed. The system applies a deceleration of around -5 m/s^2 (which is close to the maximum deceleration allowed by the system) and comes to a standstill at 13 m from the object, i.e., with an error of 3 m on the target distance of 10 m. Note that there is some error on the estimation of object speed during hard braking and there are 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 multilayer LIDAR, which allows distinguishing horizontal objects (e.g., the road) from vertical objects (e.g., actual objects).

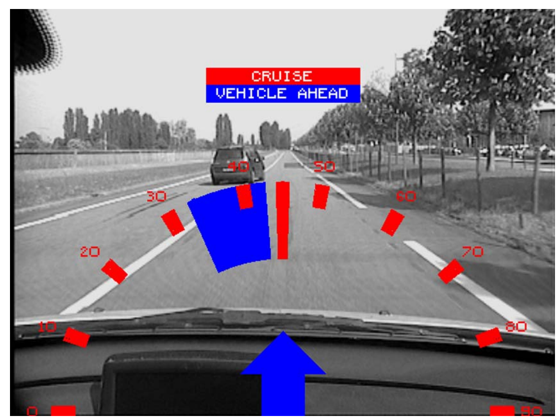

Fig. 17. Scenario *following an object* on the vehicle. HMI at $t = 60$ s. The subject speed is 45 km/h, and the target speed human driver and speed limit are 90 km/h. The object speed is 38 km/h. The object is crossing lane markings and predicted as *vehicle ahead*.

D. Scenario Following an Object

Fig. 17 shows the HMI during the scenario *following an object* on the vehicle. The system controls the distance to an object that varies its speed and that changes lanes between subject and left lanes. In the image, the object is on the left lane but crosses the lane marking toward the subject lane. The system predicts that the object will change lanes and announces a *vehicle ahead*.

Fig. 18 shows how the driving system adapts the subject speed (circle label) to the 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. The object also continuously changes speed. The safety distance between the subject and the object varies between 20 and 30 m. At this distance, a collision can be avoided by braking if the object would perform an emergency brake. Note that, during the test, the variation of subject speed

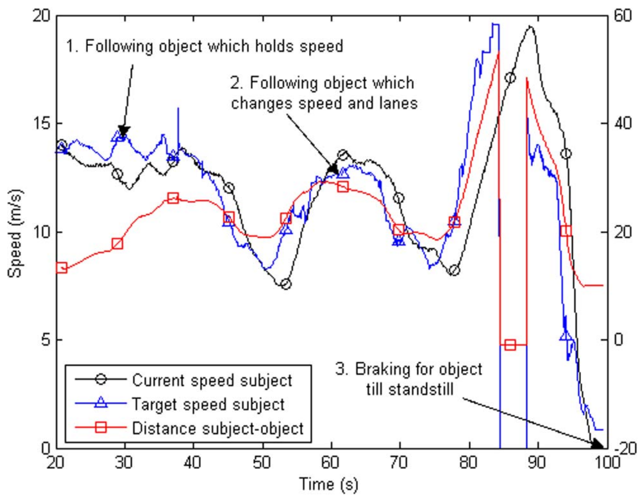

Fig. 18. Scenario *following an object* on the vehicle. Subject speed and distance to the object as a function of time.

is around 20% higher than the variation of the 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 Section V-B) for decreasing (instead of increasing) speed variations to avoid or flatten out traffic waves. At $t = 85$ s, the object is lost for 3 s. It is wrongly assigned outside the lanes. This perception problem could be tackled with more robust object tracking and with the use of a camera instead of LIDAR to determine the object-to-lane assignment. As the subject accelerates, the 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 until standstill at 10 m of the object, which is close to the minimum distance allowed by the human driver.

E. Scenario Overtaking an Object

Fig. 19 shows the HMI on the scenario *overtaking an object*. This scenario is performed on the simulator.

Fig. 20 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. At the beginning of the test, the object has its left indicators activated. It is predicted to either keep its lane (which is not indicated in the figure) or change lanes to the left (which 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. The driving system proposes a lane change, which is acknowledged by the human driver at $p = 250$ m. The zone model of the

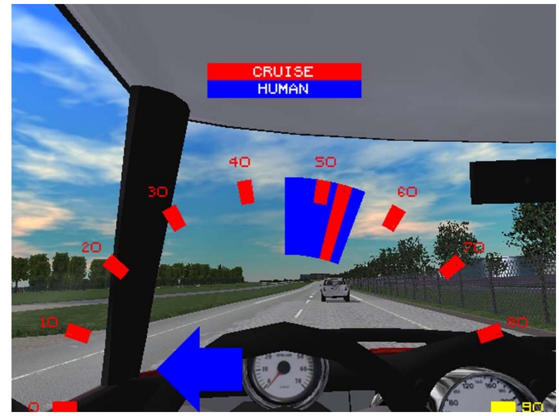

Fig. 19. Scenario *overtaking an object* on the simulator. HMI at $p = 260$ m. The subject speed is 52 km/h, the object speed is 50 km/h, the human target speed is 80 km/h, and the speed limit is 90 km/h. The overtaking maneuver has started.

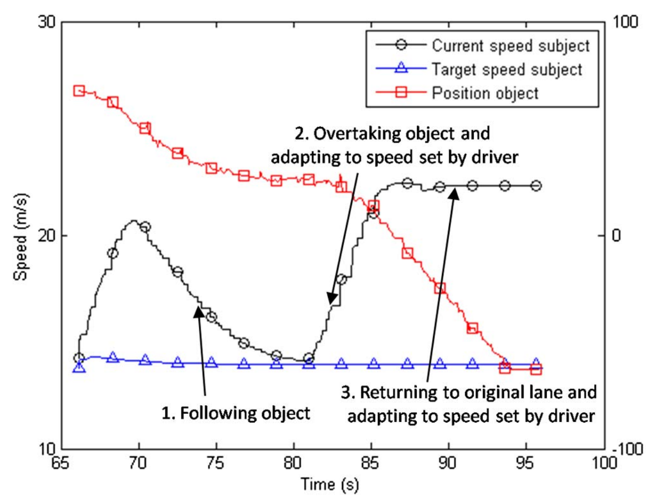

Fig. 20. Scenario *overtaking an object* on simulator. Subject speed and distance to the object as a function of time. The zone model of the trajectory at $p = 250$ m is illustrated with dashed lines.

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 lane changing but minimally keeps a safety distance from the object 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 change is acknowledged by the human driver and performed by the driving system at $p = 390$ m.

VII. Conclusion

This paper proposed driving system design based on traffic rules, which allows FA driving in traffic with human drivers, without necessarily changing equipment on other vehicles or infrastructure. The legal safety concept also facilitates the cooperation between driving system and host driver during HA driving according to current legislation.

Requirements for legal safety system design for driving on highways were presented in the following three sets of rules: 1) traffic rules for the interaction between driving system and environment; 2) human rules for the interaction between the driving system and the host driver; and 3) system rules for the interaction between system components. The discussion on perception and control stays on the requirement level and compares requirements to state-of-the-art technology. The main challenge is on legal safety perception, which might be available in medium term. For legal safety decision, an actual component design was presented. The decision component integrates traffic rules (including basic principles of defensive driving), human rules, and system rules and guarantees at least the existence of the subject lane trajectory. A curvilinear lane coordinate system and zone model were proposed as powerful mathematical tools for trajectory calculations. Decision and control components have been implemented on automotive ECUs, perception, and HMI components on a standard PC. Promising results on the demonstration vehicle CARLLA and in the simulation environment SiVIC have been discussed. A detailed presentation of this paper can be found in [46].

Future system development is twofold. First, the legal safety concept will be extended. A study will be on different driving styles for the driving system to match with the human driver style. Defensive driving will be refined, including the possibility of other types of nonlegal object behavior. The integration of nonlegal subject trajectories for safety or comfort reasons could be considered. Second, the application zone will be reduced in order to demonstrate FA driving with state-of-the-art technology, in traffic congestion on highways.

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