Fuzzy Mediating Control Systems for Automating Vehicle Driving Maneuvers: The Overtaking Case

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***Abstract*—A key challenge in automating vehicle driving maneuvers is to address uncertainty, mainly related to the interactions between the ego vehicle and all the surrounding traffic as well as the road infrastructure. In the case of an overtaking maneuver, the neighboring vehicles include the vehicle(s) moving in front of the ego vehicle – in particular, the vehicle(s) to be overtaken – and possibly other vehicles moving in the adjacent lane. In that case, the underlying research question is: how a driving automation system of an ego vehicle shall deal with occurring uncertainties to safely perform overtaking maneuvers, knowing that each of its neighboring vehicles is managerially and operationally independent, their disposition has been evolutionarily formed, and by their interactions, they jointly raise emergent behaviors. In fact, together, these vehicles compose a System-of-Systems (SoS). Recently, a novel formal language, called Fuzzy SosADL, has been specially conceived for modeling opportunistic SoS, while mastering uncertainty and interactions under uncertainty. This paper presents a case study of Fuzzy SosADL, in terms of Fuzzy Mediating Control Systems for safely supporting vehicle overtaking maneuvers in two-way roads, one of the hardest applications of driving automation systems.**

Keywords— vehicle overtaking maneuver, driving automation system, uncertainty, fuzzy control system, traffic system-of-systems

I. Introduction

Today, one of the toughest driving maneuvers for either manual or automated execution is vehicle overtaking, in particular in the case of two-way roads. Overtaking is indeed responsible for most of the traffic crashes today, e.g., almost a third of all people killed on country roads in France died in accidents involving overtaking in recent years.

The key challenge in overtaking maneuvers is how to deal with interactions under uncertainty, mainly regarding all the surrounding vehicles and the road infrastructure, as analyzed in [6]. In fact, when deciding to perform an overtaking in two-way roads, the overtaking ego vehicle lacks accurate information about the velocity and position of the related neighboring vehicles, including the one(s) to be overtaken in front of it in the same lane and the one(s) possibly moving in the opposite direction in the adjacent lane, among the others.

The consequent research question is: how a driving automation system of an ego vehicle shall deal with occurring uncertainties to safely perform overtaking, knowing that each of its neighboring vehicles is managerially and operationally independent, their alignments is the result of their independent evolutions, and by interactions, they raise emergent behaviors.

In fact, together they compose a System-of-Systems (SoS) [3], interacting to succeed often complex traffic maneuvers.

Indeed, uncertainty is an intrinsic characteristic of vehicles in traffic maneuvers, as sensing from and acting on physical environments have inherent uncertainties associated to the accuracy of the sensor and measurement devices (e.g., the position measured with a classical GPS has more uncertainty than the one measured with a GPS combined with Real Time Kinematic) as well as inherent uncertainties related to the actuation effects of actuator devices on the physical environment (e.g., due to tires slipping on the road surface, while turning the steering wheel).

In all those cases the issue is of epistemic uncertainty, i.e., the one that results from the lack of knowledge about an identified phenomenon (noting that epistemic uncertainty can be reduced by acquiring more refined data about the observed phenomenon, in contrast with aleatoric uncertainty).

Indeed, the importance of handling epistemic uncertainty in SoS design, such as the design of connected and automated driving maneuvers supported by intelligent transportation SoS, has been emphasized by the International Council on Systems Engineering (INCOSE) in its prospective vision for 2035 [1]. The identified challenge is thereby, predominantly, to be able to engineeringly model Cyber-Physical SoS, including opportunistically formed "systems" of vehicles that coordinate to succeed traffic maneuvers, in the presence of epistemic uncertainty, where each one of those vehicles is itself an independent system.

To address this challenge, we have developed a formal language, named Fuzzy SosADL [9]. To demonstrate its expressive power for automating vehicle driving maneuvers, this paper presents a case study of Fuzzy SosADL, in terms of Fuzzy Mediating Control Systems for safely supporting vehicle overtaking maneuvers in two-way roads, one of the hardest applications of driving automation systems.

The rest of this paper is organized as follows. Section II introduces Fuzzy SosADL. Section III presents the vehicle overtaking maneuver. Section IV specifies a fuzzy mediating control system, applying Fuzzy SosADL, for automating an overtaking maneuver under epistemic uncertainty. Section V briefly overviews the toolset implementing Fuzzy SosADL. Section VI compares our solution for overtaking with related work. To conclude, we summarize in Section VII the main contributions of this paper regarding the support for automated driving maneuvers, and in particular, overtaking.

II. Fuzzy SosADL in a Nutshell

This section introduces Fuzzy SosADL and its main underlying concepts for dealing with epistemic uncertainty when rigorously modeling Cyber-Physical SoSs in general.

SosADL [8], the predecessor of Fuzzy SosADL, was conceived to overcome limitations of existing Architecture Description Languages (ADLs) by providing the expressive power to model the architectural concerns of intrinsic SoS characteristics, and in particular to enable the description of emergent behaviors in opportunistic situations. Note that an SoS architecture description or model specifies how the different constituent systems should have their interactions mediated to achieve the intended emergent behaviors.

In SosADL, SoS models (according to the model-based systems engineering paradigm) are represented in abstract terms (as concrete systems which will become constituents of the SoS are not necessarily known) at design-time. Defined abstract SoS models will then be evolutionarily concretized at run-time, by identifying and incorporating concrete constituent systems (see [10] for details on the automated synthesis of concrete SoS models from abstract ones).

An abstract SoS model is described with SosADL in terms of abstract specifications of possible constituent systems, mediators, and their coalitions. The core concepts are hence the one of system to represent the constituents, the one of mediator to represent the possible connectors among constituents, and the one of coalition to represent their on-the-fly composition to form an SoS.

In particular, each mediator has the purpose to achieve a specific emergent behavior by mediating the interaction among different constituent systems. Based on mediators, a coalition constitutes a temporary alliance for combined action among constituent systems connected via mediators (it is dynamically formed to fulfill the SoS mission). In this context, different styles of mediation can be put in place, including coordination, cooperation, and collaboration among different constituent systems of an SoS.

To make possible to describe abstract SoS models subject to epistemic uncertainty in opportunistic situations, we defined Fuzzy SosADL by enhancing SosADL, passing from crisp logic to fuzzy logic [13], thereby supporting the specification of fuzzy control systems. The main difference between them is that fuzzy logic is an infinite-valued logic (any real number between 0 and 1 as degree of truthiness) while crisp logic is a bi-valued logic (0 or 1 for false or true).

Fuzzy SosADL extends SosADL with the following sorts of fuzzy language constructs: (i) fuzzification constructs; (ii) fuzzy values and fuzzy behavior constructs; and (iii) defuzzification constructs.

The fuzzification and defuzzification constructs are necessary to bridge fuzzy mediators with constituent systems (in concrete SoS models, mediators are dynamically created during SoS operation for raising suitable emergent behaviors).

Fuzzification enables to transform the real numbers inputted from constituent systems into fuzzy numbers used by the fuzzy operators and implication rules in fuzzy mediators. Defuzzification transforms the fuzzy numbers generated by the fuzzy inference rules into real numbers used to command or notify constituent systems.

A fuzzy rule is a fuzzy expression in the form of *if-then* where the *if* part declares the antecedent of the implication, and the *then* part the consequent. They involve fuzzy variables and operators. A fuzzy inference is the process that uses fuzzy logic to map a given input to an output based on fuzzy rules.

The nature of consequent part of fuzzy rules enables to define different kinds of fuzzy control systems [12], e.g., Mamdani, Takagi-Sugeno-Kang, Tsukamoto, and anYaRuleBase (see, e.g., [9], for more details).

III. THE VEHICLE OVERTAKING MANEUVER

This section presents the vehicle overtaking maneuver, which is the one of a vehicle (the overtaking ego vehicle) going to pass another slower moving vehicle (the overtaken vehicle), travelling in the same lane and direction, on a road (as shown, step by step, in Fig. 1, by the green vehicle). The lane used for overtaking another vehicle is an adjacent lane (the one that is further from the road shoulder). Thereby, the overtaking vehicle needs to move to the left in places that drive on right and to the right in places that drive on left.

Fig. 1. Vehicles in a typical overtaking maneuver in a two-way road

The specific case we study hereafter is of a typical overtaking scenario on a country road, where the ego vehicle drives in the right lane and the adjacent lane for overtaking is the left lane (as depicted in Fig. 1).

Note that in this typical overtaking scenario in a two-way road, the overtaking maneuver consists of one "lane change" from the right lane to the left lane of the road, one "lane keep" on the left lane, and a "lane change" back to the right lane after passing the to-be overtaken vehicle(s). These different phases of the overtaking maneuver are depicted in Fig. 1 above for the (green) ego vehicle. Between these two lane changes, the overtaking vehicle should move faster than the overtaken vehicle for passing it (the former on the left lane, the latter on the right lane).

IV. FUZZY MEDIATION FOR VEHICLE OVERTAKING

Now that we introduced Fuzzy SosADL and presented the problem statement of vehicle overtaking, in this section we study how, conceptually, Fuzzy SosADL can be applied to describe abstract SoS models to be concretized then enacted by the driving automation system equipping the ego vehicle, supporting thereby vehicle overtaking under epistemic uncertainty in two-lane two-way roads.

In our novel approach, based on the concept of opportunistic SoS (a novel perspective for automating traffic maneuvers), while coping with epistemic uncertainty, automated support for driving maneuvers is specified by abstract SoS models which are opportunistically (i.e., on the fly) concretized and then enacted by the different instantiated mediators for enforcing coordination, cooperation, or collaboration among the actors involved in traffic maneuvers.

It is worth noting here that the abstract SoS model for automated vehicle overtaking (illustrated by a concrete case) presented in this paper, was much simplified from the actual description in Fuzzy SosADL designed in the real pilot project from which this case was drawn. In particular, the abstract SoS model designed in that real pilot project (concretized in multiple testing scenarios) comprises several mediators (not only the one presented hereafter) as well as coordination actions deciding (possibly after negotiation) on dynamic driving tasks to be performed by other vehicles to guarantee the safety of the whole overtaking maneuver, e.g., a front vehicle creating an appropriate gap to the to-be overtaken vehicle, or to having two or more vehicles (the ego vehicle and some of its followers) concurrently performing the overtaking.

The remainder of this section introduces the notion of Vehicle Overtaking SoS and especially its intended emergent behavior to execute an overtaking maneuver by an ego vehicle, coordinated by a concrete fuzzy mediator, realized as a fuzzy mediating control system, between the ego vehicle and other involved vehicles.

Fundamentally, a Vehicle Overtaking SoS is the SoS evolutionary initiated by the ego vehicle that intends to execute an overtaking maneuver, including itself and all other surrounding vehicles possibly impacting the overtaking maneuver as constituent systems.

More precisely, in a Vehicle Overtaking SoS, the ego vehicle needs to execute different dynamic driving tasks (where a dynamic driving task comprises all the real-time operational and tactical automated functions required to operate the equipped vehicle safely in on-road traffic) to perform the intended overtaking maneuver, which includes in the selected scenario: (i) Prepare to initiate a safe overtaking of the to-be overtaken vehicle; (ii) Change lane to the left one (from the right lane); (iii) Keep to the left lane until the to-be overtaken vehicle has been passed; (iv) Change lane to the right one (from the left lane); and (v) Keep to the right lane.

Essentially, in a Vehicle Overtaking SoS, the application of the following microscale behaviors by the overtaking ego vehicle, depicted in Fig. 1, results in the emergent behavior of vehicle overtaking, possibly needing self-organization (see [7] for details of self-organizing SoSs): (i) By applying the lane change microscale behavior, the ego vehicle automatically steers to move from one lane to another adjacent lane, which involves lateral but also longitudinal control dynamics; (ii) By applying the lane keep microscale behavior, the ego vehicle automatically steers to keep moving on the lane it is, which involves longitudinal but also lateral control dynamics).

These microscale behaviors specify the different dynamic driving tasks to be performed. They sequentially combined (lane change followed by lane keep then by lane change), determine the velocity vectors that drive (phase by phase) the ego vehicle, where the speed of the ego vehicle is, by definition, the magnitude of the velocity vector and the angular offset of the velocity vector is the relative direction of the ego vehicle.

Let us now describe the fuzzy SoS model for the overtaking maneuver, by focusing on the fuzzy mediator expressed with Fuzzy SosADL.

With Fuzzy SosADL, the Vehicle Overtaking SoS is structured in terms of constituent systems and fuzzy mediators among those constituent systems. Constituent systems comprise all the vehicles related to the overtaking maneuver, and in particular the overtaking ego vehicle, the to-be overtaken vehicle and its possible front vehicles, the possible opposite vehicle and its possible lag vehicles. It may also include the vehicle that is just behind, i.e., the behind vehicle, and its possible lagging behind vehicles.

For mediating overtaking, possibly involving connected and automated vehicles, fuzzy mediators are defined in terms of fuzzy rulesets, which specify enabled microscale behaviors (which in the case under study are the lane change and the lane keep microscale behaviors).

Each fuzzy ruleset needs to handle data structures for representing the relative position and velocity of the ego vehicle, as well as of the other vehicles in the neighborhood. Based on all these relative positions and velocities (in particular of the to-be overtaken vehicle and the opposite vehicle, if any), the fuzzy mediator will evaluate if a safe overtaking maneuver can be initiated and performed.

For specifying the fuzzy overtaking mediator, let us first declare fuzzy datatypes and then corresponding fuzzy rulesets.

For defining the fuzzy datatypes, we apply the vehicle coordinate system defined by the international standard ISO 8855 [2]. In this coordinate system, the axes of longitudinal (X_V) and lateral (Y_V) motions are defined as drawn in Fig. 2. The identified vehicle reference point (indicated by ‘1’ in that figure) is used in the fuzzy datatypes defined hereafter for identifying the vehicle position with respect to the road plane (indicated by ‘2’ in the same figure).

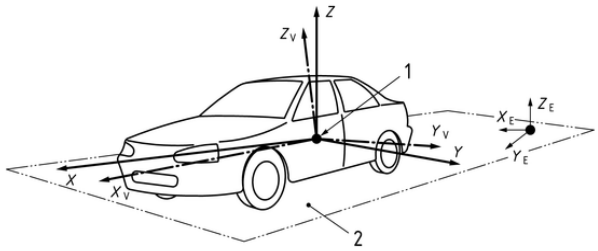

Fig. 2. Axes of longitudinal (X_V) and lateral (Y_V) motions acc. to ISO 8855

Note that according to the adopted vehicle coordinate system, the lateral motions to the left side of the center of the lane (with respect to the forward longitudinal motion of the vehicle) have positive real numbers and to the right side negative real numbers, where the vehicle reference point is at the center of the lane. This coordinate system will be applied hereafter locally at the right lane first and then locally at the left lane (per lane, then, of the same two-way road).

Using that coordinate system, angular motion is expressed in terms of positive degrees when counterclockwise (turning left) with respect to the direction of the lane, and thereby in terms of negative degrees when clockwise (turning right).

Recall that an ego vehicle equipped with a driving automation system for overtaking uses its sensors, in particular radars, lidars, or cameras to acquire information about its physical road environment and its immediate neighboring vehicles. Moreover, if other vehicles are connected vehicles, the ego vehicle being a connected and automated vehicle in our case, it can also wirelessly exchange information with the other connected vehicles, in particular by V2V (Vehicle-to-Vehicle) communication. In the case presented, we will leave out V2V communication.

Let us now set the fuzzy datatypes per lane, based on the case where each lane width is of 3.4 m in the two-way road, as largely recommended, knowing that crash frequencies increase once lane width exceeds 3.4 m [6].

First a fuzzy datatype is needed for expressing the possible lateral deviation of the ego vehicle intending to drive in the center of a lane, hereafter named `LateralDeviation`, and a second fuzzy datatype is needed for measuring the relative direction, i.e., the heading, of the ego vehicle in terms of angular offset in degrees with respect to the direction of the lane, named `AngularOffset`. For both, we adopt the vehicle coordinate system defined by ISO 8855, shown in Fig. 2.

Let us now set the membership functions of the necessary fuzzy values for those fuzzy datatypes, knowing that a typical vehicle is ca. 2.0 m wide (including wing mirrors) and the maximum width of a vehicle is 2.5 m wide (with mirrors).

Vehicles are recommended to keep to a lane by driving in the center of the lane. Thereby, the ego vehicle is expected to keep the right lane by moving in the center of the lane, as well as have a heading of 0° angular offset to the lane direction.

In automated driving for lane keeping, if the ego vehicle laterally deviates to the right, the steering actuator will compensate by steering the vehicle to the left and vice versa. Also, if the ego vehicle angularly deviates clockwise (towards the right), the steering actuator will compensate by steering the vehicle counterclockwise (towards the left) and vice versa. In all cases, the automated driving control system operating to keep the center of the right lane should be very reactive and thereby allowed deviations should be very small. Thereby, in this overtaking case study, the fuzzy mediating control system will allow lateral deviations from -0.7 m to 0.0 m and from 0.0 m to +0.7 m (considering a lane width of 3.4 m and vehicle width of 2.0 m, what means to tolerate lateral deviations where the ego vehicle does not exit the lane) and angular deviations of -3° to 0° and 0° to +3° (for smooth angular movements, until 110 km/h), knowing that physical angular limit is ca. ±30°. These values are typical ones obtained from automated driving experiments, but may vary according to different factors. In our overtaking pilot project, they were obtained via real driving experiments and varied according to road sections. They are used hereafter to define fuzzy datatypes.

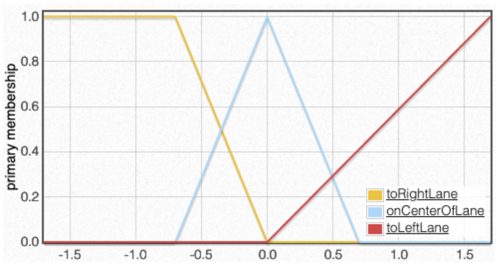

Fig. 3. Membership functions for Fuzzy `LateralDeviation`

Let us then define those two identified fuzzy datatypes: the first is for expressing the lateral deviation of a vehicle with respect to the center (of the width) of the lane, and the second for expressing the angular deviation of a vehicle with respect to the direction of the lane. The definition of `LateralDeviation` is shown in Fig. 3 and of `AngularDeviation` in Fig. 4, where fuzzy membership functions are defined for three fuzzy values regarding lateral deviation on a lane (namely `toRightOfLane`, `onCenterOfLane`, `toLeftOfLane`) and for three fuzzy values regarding angular deviation on a lane (namely `turningRight`, `straightOn`, `turningLeft`).

As depicted in Fig. 3, in `LateralDeviation`, the fuzzy value `onCenterOfLane` is defined in a triangular shape in the interval -0.7 m (membership value 0) to +0.7 m (membership value 0) and vertex at the middle of the lane width (with membership value 1); the fuzzy value `toRightOfLane` is defined in trapezoidal shape in the interval from -∞ to -0.7 m (with membership value 1) then decreases to 0.0 m in the middle of the lane (membership value 0); the fuzzy value `toLeftOfLane` is defined in trapezoidal shape, increasing from 0.0 m in the middle of the lane (membership value 0) to +1.7 m (membership value 1) and then from +1.7 m to +∞ (with membership value 1).

The interpretation of `LateralDeviation`, when the ego vehicle is in the right lane, is therefore that it is very well centered when its vehicle reference point is exactly in the center of the lane width. In that case, the membership value of `onCenterOfLane` is 1 and of `toRightOfLane` and `toLeftOfLane` are 0. Any deviation `toRightOfLane` will be reactively detected and a corrective action taken to drive back to `onCenterOfLane`. However, when there is a deviation `toLeftOfLane`, two situations may occur: if the target lane is the right one (i.e., lane keep), any deviation `toLeftOfLane` will be smoothly detected and a corrective action taken to come back to `onCenterOfLane`; if the target lane is the left one (i.e., lane change), any deviation `toLeftOfLane` will be smoothly detected and a reinforcement action taken to drive the ego vehicle towards `onCenterOfLane` of the adjacent left lane.

Indeed, once a decision is taken to change lane from the right one to the left one for initiating the overtaking maneuver, the fuzzy mediating control system will start smoothly turning the vehicle and thereby its lateral deviation will become higher `toLeftOfLane` and lower `onCenterOfLane`.

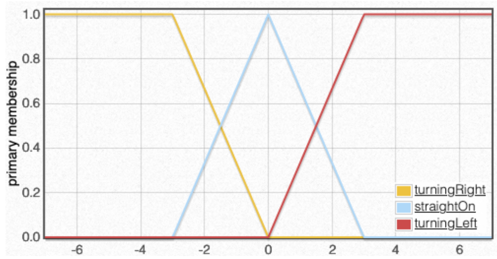

Fig. 4. Membership functions for Fuzzy `AngularDeviation`

As shown in Fig. 4, in `AngularDeviation`, the fuzzy value `straightOn` is defined in a triangular shape and the fuzzy values `turningRight` and `turningLeft` are defined in a trapezoidal shape.

The interpretation of `AngularDeviation` is therefore that a vehicle is very well directed straight on when its vehicle heading coincides with the longitudinal axis of the lane or is parallel to that axis. In that situation, the membership value of `straightOn` is 1 and of `turningRight` and `turningLeft` are 0.

In addition to the two identified fuzzy datatypes for automating the steering on a lane, let us now define a datatype for setting the target lane, which from the right lane becomes the left lane when the decision to change lane is taken.

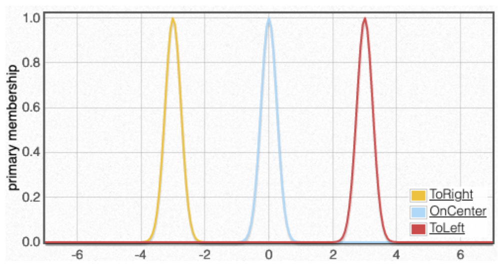

Fig. 5. Membership functions for Fuzzy `Steer` commands

Let us now declare the fuzzy datatype needed to command the ego vehicle by the mediator: the fuzzy datatype `Steer`, depicted in Fig. 5. Three fuzzy values are defined regarding the steering commands of a given ego vehicle during an overtaking maneuver: `toLeft`, `onCenter`, and `toRight`.

The interpretation of `Steer` commands is that the fuzzy mediating control system will smoothly steer the ego vehicle to the left, to the right, or to continue to move in the center. In the circumstances of steering to the left or to the right, the command for the steering wheel is set to ±3° to enforce smooth vehicle movements, knowing that the maximum clockwise / counterclockwise steering angle is ca. ±30°. These values are typical ones obtained from automated driving experiments too, but, as for other fuzzy datatypes, may also vary according to different factors.

Now that we have declared the fuzzy datatypes needed for specifying the fuzzy mediating control system, let us declare a fuzzy ruleset for supporting the needed dynamic driving tasks for performing an overtaking maneuver. As shown in Fig. 6, the fuzzy ruleset is defined by the fuzzy implications for computing the fuzzy command, i.e., `Steer`, according to the values of `LateralDeviation` and `AngularDeviation` as well as the `TargetLane`.

1. **If** LateralDeviation is toRightLane **then** Steer is ToLeft
2. **If** LateralDeviation is onCenterOfLane and TargetLane is RightLane **then** Steer is OnCenter
3. **If** LateralDeviation is onCenterOfLane and TargetLane is LeftLane **then** Steer is ToLeft
4. **If** LateralDeviation is toLeftLane and TargetLane is RightLane **then** Steer is ToRight
5. **If** LateralDeviation is toLeftLane and TargetLane is LeftLane **then** Steer is ToLeft
6. **If** AngularDeviation is turningRight **then** Steer is ToLeft
7. **If** AngularDeviation is straightOn and TargetLane is RightLane **then** Steer is OnCenter
8. **If** AngularDeviation is straightOn and TargetLane is LeftLane **then** Steer is ToLeft
9. **If** AngularDeviation is turningLeft and TargetLane is RightLane **then** Steer is ToRight
10. **If** AngularDeviation is turningLeft and TargetLane is LeftLane **then** Steer is ToLeft

Fig. 6. Fuzzy ruleset for mediating commands for lane keep or lane change

Note that, as expressed in Fig. 6, lateral deviation and angular deviation are computed separately. Regarding lateral deviation, rules 1 to 5 are potentially fired. Regarding angular deviation, rules 6 to 10 are potentially fired. Together, they form the resulting Mamdani fuzzy inference system created from the defined fuzzy datatypes. As shown in Fig. 7 and Fig. 8, in the resulting Mamdani fuzzy inference system, the output of each fuzzy rule is a fuzzy set which will contribute to computing the output of that Mamdani fuzzy control system.

Importantly, note that the fuzzy ruleset shown in Fig. 7 and Fig. 8, that defines the fuzzy mediating control system for overtaking, supports both the lane keep microscale behavior (when the ego vehicle is on the right lane and the target lane is the right lane too) and the lane change microscale behavior (when the ego vehicle is on the right lane and the target lane becomes the left lane).

Importantly too, note also that when the ego vehicle changes from the right lane to reach the left lane, the conjugated fuzzy ruleset is applied to keep the ego vehicle moving in the left lane until it has a gap to come back to the right lane after passing the overtaken vehicle(s), while ending the overtaking maneuver before achieving the cutoff point (point from which the maneuver becomes unsafe).

The conjugated fuzzy rule set is generated in Fuzzy SosADL by switching "left" and "right" values in the fuzzy datatypes and the defined fuzzy ruleset. The resulting conjugated fuzzy mediating control system thereby provides the lane keep microscale behavior for keeping the ego vehicle in the left lane (target lane set is left lane) while moving towards a viable gap to come back to the right lane, as well as the lane change microscale behavior for driving the ego vehicle towards the right lane (when the target lane becomes right lane), inserting itself in an identified gap, coming thereby back to the right lane.

Let us now very briefly illustrate the application of the resulting Mamdani fuzzy inference system in the fuzzy mediating control of the lane keep microscale behavior. Suppose that the ego vehicle is moving forward on the center of the right lane, then laterally deviates a little to the right (e.g., -0.5 m) as well as angularly deviates a little, turning to the right too (e.g., -1°). In that case, rules 1 and 2 shown in Fig. 7 are fired at -0.5 m as indeed the ego vehicle has slighted moved to the right side of the right lane, but at the same time it is yet closed to the center of the right lane. Also, rules 6 and 7 shown in Fig. 8 are fired as the heading of the ego vehicle turned -1°, i.e., 1° clockwise, thereby to the right too.

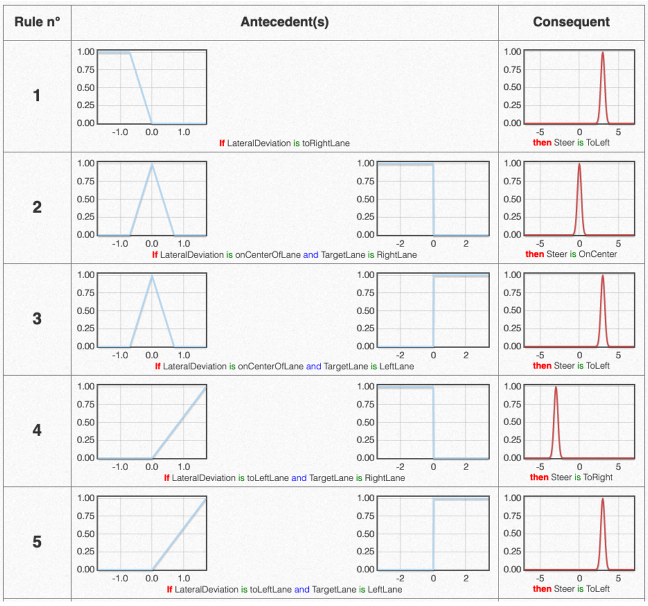

Fig. 7. Ruleset for lateral deviation in the res. Mamdani fuzzy control system

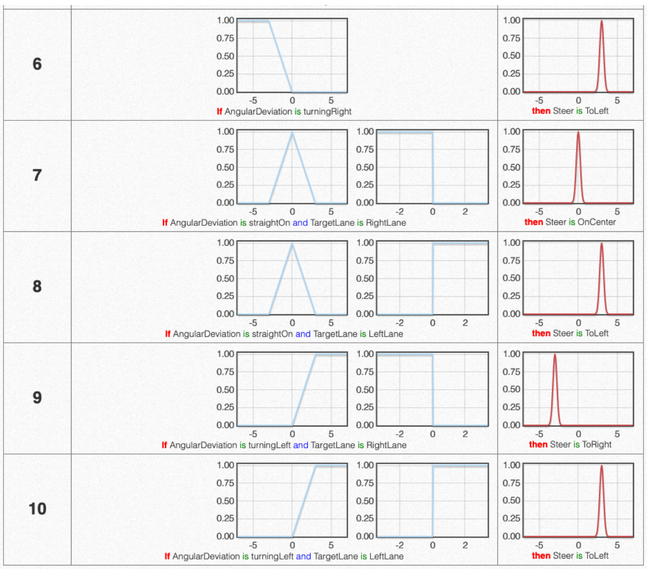

Fig. 8. Ruleset for angular deviation in the res. Mamdani fuzzy control system

The application of these fired fuzzy rules, i.e., 1, 2, 6, and 7, is aggregated in the fuzzy output Steer, shown in Fig. 9.

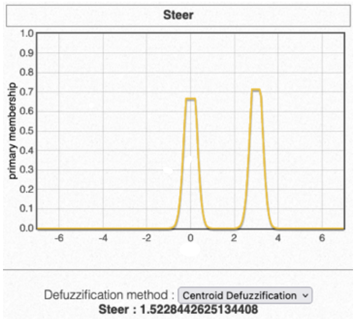

Fig. 9. Output of the application of the Mamdani fuzzy control system

The last step is to defuzzify the fuzzy output for delivering the crisp command necessary to safely steer the ego vehicle under control. As specified, the Centroid Defuzzification method was applied in this case. It returns a precise value (a real number) depending on the center of gravity of the fuzzy output. In the situation presented in Fig. 9, the defuzzified value for the Steer fuzzy result is 1.5228442625134408, which gives the angle in degrees to steer back the ego vehicle to the center of the right lane, in this case.

V. Fuzzy SosADL Toolset

This section very briefly presents the software toolset supporting Fuzzy SosADL, used in the overtaking case presented in this paper, named Fuzzy SosADL Studio.

The Fuzzy SosADL Studio has been constructed as plugins in Eclipse. For analyzing fuzzy SoS models, it applies DEVS-Suite (https://sourceforge.net/projects/devs-suitesim/) for verification and simulation of SoS models, constituted by fuzzy mediators and constituent systems (in DEVS-Suite, models can be both simulated and verified using DEVS and the Constrained DEVS variant). DEVS-Suite was extended with fuzzy reasoning based on the JFML library, coping with the Fuzzy Markup Language (FML) standard, which provides a sound basis for decentralized control.

Using Fuzzy SosADL Studio, driving automation systems architects designing an SoS model for supporting vehicle driving maneuvers proceed, iteratively, by modeling, simulating, and verifying fuzzy SoS maneuver models. It in particular supports guarantees of correctness [10].

VI. Related Work

Related work on the specification of control systems for automating vehicle driving maneuvers in general, and vehicle overtaking maneuvers in particular, can be classified in four categories.

The first category includes crisp standalone overtaking control systems, as presented in [11]. The second category includes fuzzy standalone overtaking control systems, as presented in [5]. The third category includes connected overtaking control systems, as presented in [4]. The approach that we have developed with Fuzzy SosADL is novel when compared with those state-of-the-art approaches. It is part of the fourth category.

Indeed, the different crisp and fuzzy control systems, for automating driving maneuvers, proposed in the literature (illustrated by those cited hereinbefore) are all specific solutions that are hard-coded in the different vehicles involved in the presented overtaking maneuvers.

Our approach, oppositely, provides a general solution, in terms of a formal language for defining specific solutions for automating vehicle driving maneuvers, being able to address uncertainty based on the fuzzy logic as well as to deal with crisp values, of which the vehicle overtaking maneuver presented in this paper is a demonstration case.

Another key difference of our approach when compared to those is that control systems for supporting driving maneuvers are not hard-coded in the vehicles, but instead they are dynamically concretized as mediators for coordinating the driving maneuvers, while being independent of the involved vehicles. Mediators are interfaced with the vehicles, being able to deal with different kinds of vehicle driving control systems. It is itself a sort of middleware for fuzzy mediating vehicles in order to automate vehicle driving maneuvers.

VII. Conclusion

In this paper, we have addressed the case of vehicle overtaking using a novel approach for safely automating the overtaking maneuver, described as an opportunistic SoS (in this case, a system composed of independent vehicles sharing the same operational environment, a two-way road, with the common goal of achieving safe overtaking).

Importantly, we approached that opportunistic SoS as composed of fuzzy mediators that coordinate the dynamic driving tasks of the different vehicles involved in the overtaking maneuver.

It was validated in a real pilot project in collaboration with a multinational company, and presented in this paper, concentrating on the essential points of the applied engineering approach as fuzzy mediating control systems.

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