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ORIGINAL PAPER

A review of fuzzy methods in automotive engineering applications

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Abstract
Purpose The paper addresses evolution of fuzzy systems for core applications of automotive engineering.
Methods The presented study is based on the analysis of bibliography dedicated to fuzzy sets and fuzzy control for ground vehicles. A special attention is given to fuzzy approaches used in the following domains of automotive engineering: vehicle dynamics control systems, driver and driving environment identification, ride comfort control, and energy management of electric vehicles.
Results The bibliographical analysis, supplemented with statistics of relevant research publications, has allowed to allocate the most important fuzzy application cases for each domain. In particular, it concerns driver identification, human-machine interface, recognition of road conditions, and controllers of vehicle chassis and powertrain systems. It is found out that fuzzy methods have the primary use most of all for tasks requiring identification and forecasting procedures, especially in conditions of limited informational space. Additional observation that can be also derived from the presented survey points to reasonable integration of fuzzy technique with other control engineering methods to improve the performance of automotive control systems.
Conclusions In the aggregate the performed review indicates that fuzzy computing can be considered as a versatile tool for automotive engineering applications of different nature.

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Keywords Fuzzy systems · Road vehicles · Automotive control systems · Vehicle dynamics control · Electric vehicles

1 Introduction

Fuzzy logic, among other computational intelligence methods, attracts increased attention of engineers and researchers involved in the development of complex control solutions for road vehicles and their subsystems. A possibility to overcome various nonlinear models and to use intuitive logical rules makes fuzzy control and fuzzy identification procedures useful tools by rapid system prototyping and on early design stages. It is of particular relevance for intelligent vehicle functions and systems requiring the prediction of manoeuvres dynamics, identification of driving environment parameters and objects, and interaction with the driver. For the mentioned topics, the development of models of objects and relevant controllers of on-board systems can meet essential problems with feasibility, sufficient level of complexity and other features demanded for real-time automotive applications. These issues can be efficiently handled with the computational intelligence methods, which are known as reasonable and powerful tools in solving non-well-posed analytical problems. Among different computational intelligence methods like neural networks, swarm intelligence computing et al. the fuzzy logic can be of special relevance for intelligent automotive systems. The reason is that the fuzzy logic has good applicability for identification tasks and pre-emptive control under strong presence of data and model uncertainty.

The above-listed arguments are motivated the study outlined in this paper. The main goal of the study is to give a survey of existing fuzzy methods and systems that are finding applications in the automotive area. Because the subject of the study is characterized by a high degree of interdisciplinarity, the discussed review can be of particular interest for researchers working on topics of Ground Vehicle Engineering, Control Engineering, and Computational Intelligence. Specific objectives of the presented work can be formulated as follows:

- Define research topics that are most relevant to automotive fuzzy systems and tools;
- Identify the main application cases for each defined topic;
- Estimate development trends for each defined topic;
- Analyse particular matters of automotive fuzzy systems from viewpoint of (i) industrial applications and (ii) integration with other control techniques.

The results of the performed survey are given in next sections in accordance with the listed objectives. The article includes also extensive bibliography aimed at the representation of various research schools around the world in context of the discussed topics.

2 Review background

The history of fuzzy systems in vehicle-related areas begins with several research works of founders of fuzzy logic dedicated to practical applications of fuzzy sets. An example is the intersection controller that reduced junction-related delay of vehicle driving proposed by Pappis and Mamdani in [1]. Later Sugeno and Murakami in [2] and Sugeno and Nishida in [3] have introduced the fuzzy realization of driver's logic for the cases of an automated car parking system and handling the desired vehicle trajectory. Then, from early 1990s, more and more automotive systems with fuzzy logic are subjected both to academic and industrial areas. This resulted in a considerable amount of publications and patents.

An analysis of the published studies and works allows to allocate a number of domains, where fuzzy logic has found the most acceptance. These domains can be conditionally called as "Driver", "Vehicle Dynamics", "Ride comfort", "Electric vehicles", and "Driving environment". Results of analysis of publications relevant to the fuzzy modeling and control of automotive systems in the listed engineering areas are further introduced in the paper.

The presented review uses the methodology proposed and partially implemented in [4]. The analysis uses only English-language scientific publications found in Scopus abstract and citation database of peer-reviewed literature (http://www.elsevier.com/online-tools/scopus). The following limitations of the analysis are accepted within the framework of this paper: The works are analyzed in relation to the ground and road vehicles only. Mobile robots and machines with non-holonomic constraints are excluded from the analysis due to their less relevance to automotive applications.

The overview is accompanied by statistics of peer-reviewed journal articles from two recent decades (dated 1994–2013) in each domain. (Conference papers are excluded from statistical analysis to avoid the consideration of duplicated content. The elimination has been also done for those papers, which content was already published in another journal. This is because it was observed that in particular cases the same content is repeated with minor variations in several conference papers published by the same authors.)

Additional section of the paper will analyse the publications of SAE International (http://www.sae.org) as one of the most recognized informational source worldwide for automotive engineering and presenting mainly the studies, which are providing experimental verification and close to industrial application.

3 Fuzzy methods for driver modelling and driver assistance systems

The domain "Driver", proposed for the classification, implicates topics related to the driver models, driver behavior, and driver assistance systems. These topics are of special relevance for fuzzy applications because almost emotional and psychological facets of human behavior carry more semantic as numerical uncertainty. It complicates the formulation of the driver in simulation and control tasks through non-soft computing methods. The first applications of fuzzy sets to the modeling of the driver are arisen in 1980s. In particular, Kramer and Rohr in [5] and Kramer in [6] proposed to use a fuzzy model for the representation of perception characteristics of the driver and illustrated this approach on the driving simulator. Nagai, Kojima and Sato [7] suggested the fuzzy driver model describing the subjective recognition, judgment and control of the vehicle speed. This model was built from the accident analysis data. Then Kageyama and Pacejka [8] and Ehara and Suzuki [9] developed the first fuzzy models of the human reasoning for more complex driving situations. Analysis of relevant journal publications, Fig. 1, and conference papers allows to allocate the most typical applications of fuzzy methods within the domain „Driver“:

- Identifications and classifications of the drivers regarding fatigue, emotions and other human attributes, including the procedures of driver state recognition and forecasting through monitoring of various physiological parameters like electroencephalography-estimated brain activity, eye movement, gestures et al. [10–15],
- Structure and controllers of driver assistance systems and devices of human machine interface [16–18],
- Models of driver actions on vehicle controlling devices (brake and throttle pedals, steering wheel) for authentic

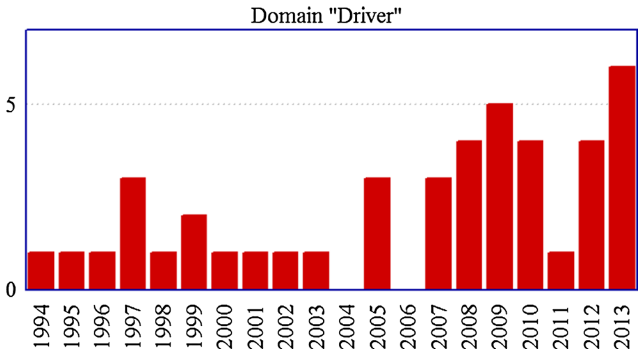

Fig. 1 Number of journal publications related to fuzzy methods in domain "Driver" and cited in Scopus database

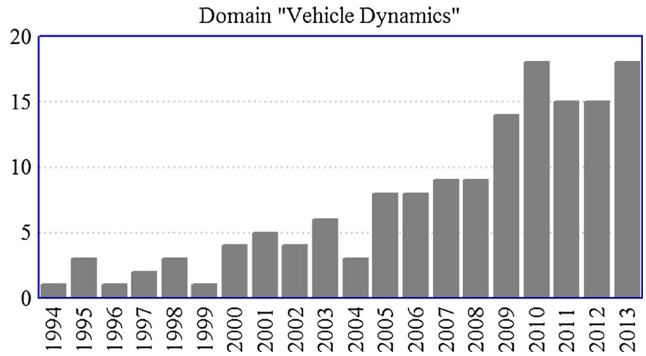

Fig. 2 Number of journal publications related to fuzzy methods in domain "Vehicle Dynamics" and cited in Scopus database

simulation of vehicle maneuvers on driving simulators; controllers of pedal and steering wheel robots [19–22],
- Simulation of driver reasoning for controllers of (semi-) automated and unmanned ground vehicles [23–25],
- Understanding of subjective evaluation of vehicle dynamics; driver feeling of vehicle dynamics parameters like velocity, road friction and other [26–29],
- Advisory functions of human-machine interface systems supporting the driver in eco- and low-emission vehicle operation [30–32].

From practical viewpoint, the fuzzy logic gives valuable opportunity to develop controllers of human machine interface and driver assistance, which can be integrated with other automotive systems responsible for active safety control through the correction of vehicle dynamics by active chassis and powertrain subsystems. The controllers of these subsystems can also implement different fuzzy methods that will be discussed in next section.

4 Fuzzy methods for vehicle dynamics control and ride comfort

Within the framework of the presented review the domain "Vehicle Dynamics" relates to the systems controlling the lateral and longitudinal vehicle motion. The corresponding representatives are anti-lock braking (ABS) and traction control systems, torque vectoring, electronic stability control, electronic differentials et al. The systems responsible for the vertical dynamics of the vehicle are allocated to another domain "Ride Comfort" due to considerable amount of relevant publications. Statistics of journal papers for both mentioned domains is depicted in Figs. 2 and 3.

The first applications of fuzzy methods to the vehicle dynamics were related to the formalization of tire parameters, which are used in the brake and acceleration control. It can be explained with the fact that automotive tires have nonlinear characteristics of friction and slip, which cannot be measured by on-board sensors and require therefore real-time estimation with the help of various numerical methods. Several early examples of fuzzy computing for tire parameters estimation are described in works of Stumpf, Arendt and Lux [33], and Madau, Yuan, Davis Jr. and Feldkamp [34]. Among vehicle dynamics control systems, ABS belongs to the classical examples of automotive control applications to verify and to define functional properties of different control methods, including fuzzy computing. In particular, Intel Corporation has proposed MCS 96 microcontroller family for the first fuzzy braking processors [35]. Later *Siemens AG* has applied fuzzy coprocessors C99A for brake-by-wire systems [36]. Progress in vehicle dynamics control (VDC) systems has given many opportunities for practical implementation of fuzzy logic. Whereas the first VDC systems have used only brakes and engine as actuators, the actual trend is to enable other chassis systems such as steering and suspension in an integrated control circuit. As a result, the domain "Vehicle Dynamics" includes a series of the research problems where fuzzy methods found use:

- Brake control including architecture and algorithms of anti-lock braking systems [37–40]
- Vehicle traction control including solutions for engine control, electronic differentials, powertrain and driveline control in general [41–43],
- Control of lateral vehicle dynamics, in particular, in terms of yaw rate and vehicle sideslip control [44–48],

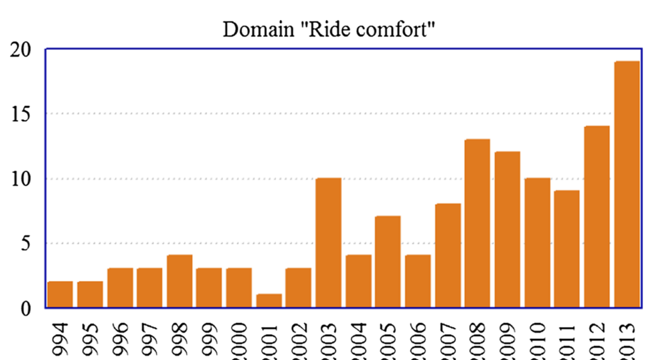

Fig. 3 Number of journal publications related to fuzzy methods in domain "Ride Comfort" and cited in Scopus database

- Steering control including solutions for electric power steering; active front and rear steering [49–51]
- Estimation of vehicle state (linear velocity, yaw rate, vehicle sideslip angle et al.) from the sensors and experimental data [52–54],
- Integrated sequential or parallel control on vehicle dynamics through independent subsystems (e.g. brakes, steering, suspension, driveline) [55–58],
- Identification and estimation of parameters of tire-road interaction [59–63].

It was found during the analysis of research literature that studies of semi-active and active suspension control take up a larger share comparing with publications in other of automotive systems based on fuzzy methods. The reason can be that the ride control systems are characterized by complex nonlinear oscillating behaviour influencing simultaneously several properties like comfort, handling, or NVH (noise, vibration, harshness). The use of soft computing methods can certainly simplify the control on these vehicle properties. The earliest variants of fuzzy architecture of active suspension controllers were proposed by *Yester and McFall* [64], and *Lin and Lu* [65]. Then many other studies related to the fuzzy applications in the domain "Ride comfort" are arisen with the trend to continuous growth of research in this area. The main topics within the domain "Ride comfort" can be subjected as follows:

- Methods of objective evaluation and control of the vehicle ride comfort [66–68],
- Control algorithms of suspension actuators and shock absorbers with adaptation to environmental and operational conditions such as road roughness, vehicle dynamic variables and other [69–73]
- Special control strategies of electrorheological, magnetorheological, and electrical dampers and specific suspension elements [74–77].

It should be noted that in spite of numerous publications in the domain "Ride comfort", there are few reports about industrial variants of fuzzy suspension controllers. Overwhelming majority of analyzed investigations belongs to the fundamental or conceptual applied research.

Now many classes of ground vehicles require the mandatory installation of VDC systems. This fact can encourage more intensive investigations on fuzzy approaches in vehicle dynamics and ride control.

5 Fuzzy methods and vehicle—environment interaction

Both driver assistance and vehicle dynamics control systems, discussed in previous sections, can benefit from new information and communication technologies allowing closer interaction of the vehicle with the driving environment. Impactful control solutions improving vehicle safety and energy efficiency are being proposed now with the help of various on-board and on-road sensors as well road infrastructure services. All these aspects including the technologies for (semi-)autonomous driving are subjected to the domain "Driving Environment", which has been also analysed in the presented study, Fig. 4. It should be mentioned that specific topics of traffic control and architecture of Intelligent Transport Systems are excluded from the review because they are related mainly to Transport Engineering, but not to Automotive Engineering.

The first research works relevant to fuzzy systems in the domain "Driving Environment" have investigated path planning algorithms for an autonomous vehicle supported by a navigation system or equipped with advanced set of sensors, which are able to percept external parameters like distance between the vehicles or to identify external objects. The studies of Hogle and Bonissone [78] and Freisleben and Kunkelmann [79] can be mentioned in this context. These and other topics are in scope of standing research interest from middle of 1990s and now the main subjects of fuzzy applications for the domain "Driving Environment" can be classified as follows:

- Adaptive cruise control for the vehicles controlled by the driver; road following control for automated driving; collision prevention systems [80–82],
- Processing sensor information; recognition of driving environment parameters; vehicle localization [83–89],
- Coordination of road vehicle platoon systems [90–92],
- Control architecture of autonomous vehicles [93–96];
- Specific problems of brake, traction and steering control systems of autonomous vehicles [97–99];
- Automated parking systems [100–102].

In accordance with the short- and long-term projection, the mass-produced cars with functions of autonomous driving

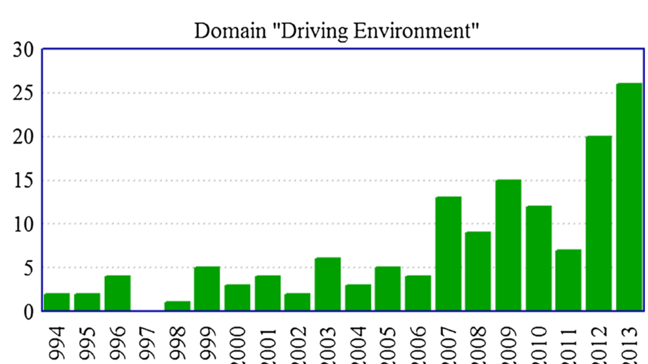

Fig. 4 Number of journal publications related to fuzzy methods in domain "Driving Environment" and cited in Scopus database

will be stepwise introduced on the market in coming decade. This fact should stimulate more intensive research in various topics of the domain "Driving Environment".

6 Fuzzy methods for electric vehicles

Hybrid electric vehicles, full electric vehicles, fuel cell electric vehicles are at the centre of permanent attention of researchers and developers of fuzzy systems. This tendency is growing now because of sweeping development of technologies for "Green Mobility", Fig. 5. Early studies have introduced fuzzy energy management (EM) of electric vehicles in general. In particular, Farrall and Jones in [103] and Cerruto, Consoli, Raciti and Testa in [104] have proposed different fuzzy EM systems for hybrid vehicle, which were responsible for efficient powertrain control. Then, comparing with other automotive applications, fuzzy methods found many-sided use in the domain "Electric vehicles". An analysis of relevant research works allows to mention the following applicative areas for fuzzy methods:

– Global energy management of electric vehicles; hybrid powertrain control of operational modes (internal combustion engine / electric motor) [105–110];
– Traction control, anti-lock braking and regenerative braking control of electric vehicles [111–113];
– Internal controllers of electric motors, starters, inverters; electric propulsion controllers [114–116];
– Forecast and optimization of driving range [117, 118];
– Estimation of battery performance and algorithms for battery charging [119–121].

A number of other aspects like interaction of electric vehicles with the road and urban infrastructure are among further promising fuzzy applications in this research area.

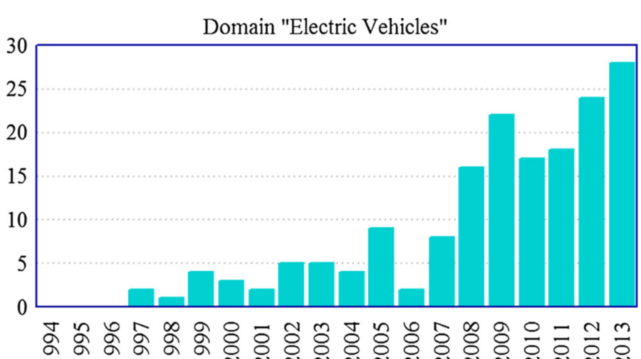

Fig. 5 Number of journal publications related to fuzzy methods in domain "Electric Vehicles" and cited in Scopus database

7 Fuzzy methods for miscellaneous applications

In addition to previously introduced domains, various unclassified or rarely studied examples of automotive fuzzy systems are also presented in analyzed research publications.

In particular, the most interesting variants cover the following topics: Transmission control including gear shifting algorithms and clutch control [122], Systems for diagnosing different vehicle systems and elements [123–125], Methods for the assessment of passive safety [126, 127], Thermal and NVH comfort control systems [128, 129], Vehicle body design [130], etc. Figure 6 shows the statistics of relevant journal publications. Hence, fuzzy methods can be considered as well-established research tools in different aspects of automotive engineering.

8 Fuzzy methods in applied and industrial research

One of the interesting results of the analysis is that a serious gap still persists between pure research and industrial applications of fuzzy methods in automotive engineering. To support this statement, Fig. 7 displays statistics of publications related to industrial or ready-to-installation specimens of road vehicle systems with fuzzy controllers or fuzzy models embedded into the processing units. This selection reflects the analysis of technical papers published by SAE International as one of the most recognized information sources worldwide for automotive engineering. The preliminary search has found only few publications every year with information about application of fuzzy methods in automotive area. The deep analysis detected neither the clear-cut growth of fuzzy applications nor their regularity in individual domains. The reason for the available gap between theoretical studies and industrial systems can be explained by the fact that most of traditional automotive control systems have well-established variants of system architecture and corresponding real-time functional

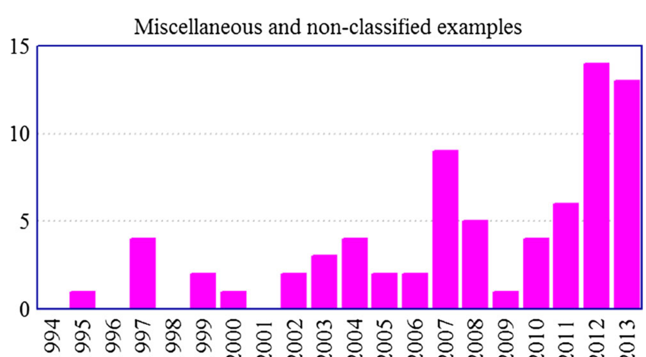

Fig. 6 Number of journal publications related to fuzzy methods for miscellaneous automotive applications and cited in Scopus database

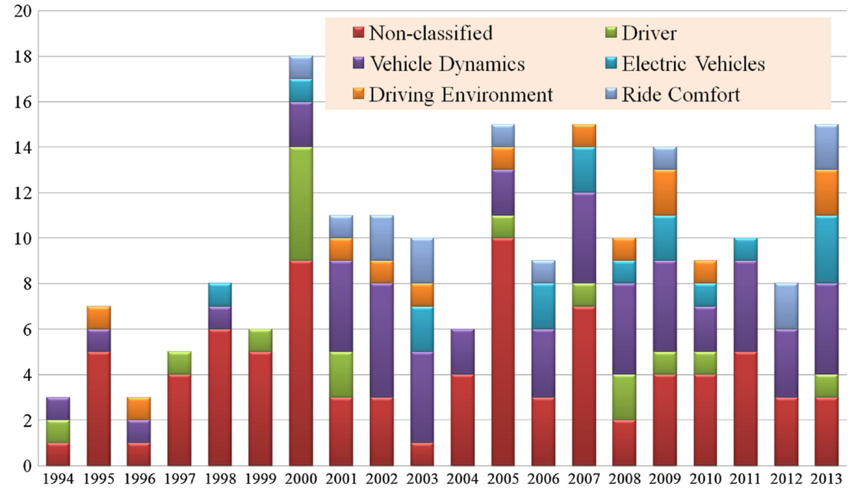

Fig. 7 Selected SAE publications related to fuzzy methods

realizations, which are most often based on rule-based, nonlinear, optimal and other control approaches that are not directly related to computational intelligence methods. Therefore, until recently the progress in the vehicle control systems has been related first of all to the implementation of more powerful and efficient hardware accompanied with cautious modification of software part. However an increased demand for on-board systems, communicating with the driver and performing adaptation and learning in accordance with human behaviour, shows certain limitations in traditional, non-soft computing control techniques.

Nevertheless, it should be noted that some applicative areas for fuzzy methods are especially most commonly addressed in published industrial research studies. This is particularly true for on-board systems like the cruise control, lane change assistant et al., which require identification of the driver behaviour. The research of Ford Motor on the driver characterization for the car following [131, 132] and for the vehicle destination prediction [133] can be mentioned in this regard. A reasonable applicability of fuzzy methods to this topic has been also demonstrated in studies with the participation of Centro Richerce Fiat for the driver distraction modelling [134]. Other work [135], performed under coordination of researchers from Renault, has indicated an efficient implementation of fuzzy sets and fuzzy space windowing for the psycho-physiological characterization of drivers within the context of the car following.

An analysis of industrial white papers and analytical publications indicates trends to further consistent growth of intelligent automotive systems with the logic based on fuzzy methods [136]. This statement can be also confirmed with numerous industrial patents for fuzzy algorithms and controllers, claimed by automotive OEMs and suppliers. It allows to expect that the mentioned gap between pure research and industrial applications should be overcome in near future.

9 About compatibility of fuzzy methods in automotive engineering

Eventual barriers for more intensive dissemination of fuzzy methods in automotive engineering can be removed through their integration with other analytical and numerical methods. In particular, such integration can improve robustness and adaptivity of controllers with simultaneous keeping of straightforward formalization of control tasks. The fact that fuzzy logic remains one of the most inviting approaches in basic and applied sciences it can be supported by the important indicator of high compatibility of fuzzy methods with other computing and control techniques. The analyzed research publications offer many examples of integration of fuzzy sets and fuzzy logic that are summarized in Table 1.

10 Conclusions

Analysis of research literature, especially results of published experimental works, demonstrates that fuzzy methods have solid background and good prospects for the implementation

Table 1 Examples of methods used in automotive applications

Conventional fuzzy methods	Methods / tools integrated with fuzzy technique
Takagi-Sugeno fuzzy model [137]	Sliding mode control [141]
Fuzzy linear regression [9]	Grey predictor [142]
Fuzzy preview control [138]	PI and PID control [91, 143]
Model reference adaptive fuzzy control [44]	Genetic algorithm [71, 144]
	Optimization gradient method [145]
Neuro-fuzzy method [123]	Multi-objective optimization [108]
Hierarchical fuzzy integral [24]	Variable structure control [146]
Fuzzy clustering [139]	Reinforcement learning [94]
Type-II fuzzy system [140]	Bayesian methods [147]

in automotive engineering applications. The following positions can be especially mentioned in this context:

– For the selected topics each—Driver, Vehicle Dynamics Control, Electric Vehicles, Driving Environment—the analysis has discovered a series of fuzzy application cases of different nature that points to good versatile and flexible feasibility of fuzzy methods for automotive engineering tasks;
– Relevant publication statistics indicates continuous growth of fuzzy-related research activities in the selected topics each;
– Despite the currently available gap between theoretical research and industrial implementations, a strong demand in automotive systems with intelligent functions and involving more intuitive interaction with the driver and environment will stimulate a more wide adoption of fuzzy tools and systems on serial vehicles.

The most feasible breakthrough in further development of fuzzy systems and tools for automotive engineering applications can be expected from two kinds of "fusion". From theoretical side, the fusion of fuzzy methods with other methods of soft computing or nonlinear control opens very promising prospects. From technological side, the fusion of many vehicle controllers and estimators on common fuzzy basis can get over numerical and linguistic uncertainties accompanying complex processes of vehicle dynamics and vehicle-driver-environment interaction. These trends would encourage the researchers and engineers in seeking for novel applicative fuzzy solutions in automotive engineering.

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