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VEHICLE PLATOONING: A BRIEF SURVEY AND CATEGORIZATION

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ABSTRACT

In this paper, the vehicle platooning literature published between 1994 and 2010 is categorized and discussed. The paper includes a general introduction and overview of vehicle platooning and a technical description of the methodology. Recent trends in Vehicle Platooning are presented and discussed. The results are reviewed and the vehicle platooning literature is categorized into subcategories within the broader division of application focused and theory focused results. Issues and challenges faced in platooning are discussed.

INTRODUCTION

Vehicle platooning is an important innovation in the automotive industry that aims at improving the safety, mileage, efficiency and the time needed to travel. Autonomous capable vehicles in tightly spaced, computer controlled platoons will lead to savings in fuel, increased highway capacity and increased passenger comfort. The introduction of automation into road traffic can provide essential solutions to the mainstream issues of accidents, traffic congestion, pollution and energy consumption [1, 2].

Under cooperative driving, automated vehicles drive like the migration of birds or a group of dolphins; the formation of birds in the migration is aerodynamically efficient, and dolphins swim without collision while communicating with each other. The cooperative driving, simulating the formation of birds or dolphins, will contribute to the increase in the road capacity as well as in the road traffic safety.

The concept of automated highways is not new. General Motors showed a working model as far back as in the 1939 World's Fair. Most of the research has led to and resulted in the Automatic Highway System (AHS) proof of technical feasibility put on by National Automated Highway System Consortium (NAHSC) in San Diego in August 1997. Even as far back as 1970, prototype equipment was operationally tested. Actual AHS research began in the early 1960's [3] and Shladover [4] has given a very extensive review of the AHS research done. A lot of advancement has taken place in this area since then. In 1995, a research report presented a detailed description on the aerodynamic performance of platoons revealing that the drag coefficient which accounts for both the vehicle size and velocity, experienced about 55 % reduction on average in 2, 3 and 4-vehicle platoons leading to reduction in fuel consumption, to the California Partners for Advanced Transit and Highways (PATH) [5].

The purpose of this paper is to provide a summary and review of the recent trends in Vehicle Platooning research from both application point of view and the theoretical point of view. We focus on the literature published between 1994 and 2010. Section I continues with a general introduction to Vehicle Pla-

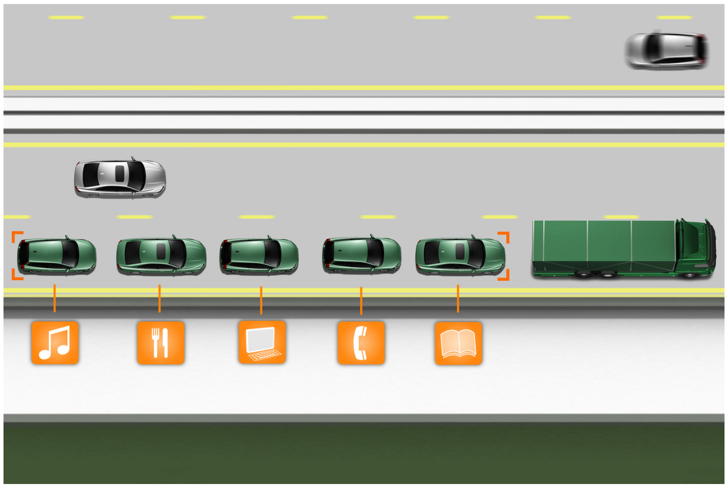

FIGURE 1. VEHICLE PLATOONING AS SHOWN BY THE SARTRE DEMO [8]

tooning and a technical description of the different methodologies that have been used. In Section II , we summarize the survey methodology that we used and present selected results from recent literature. Section III is the main part of the paper, where we separate the literature into applications-focused results and theory-focused results , giving detailed sub classifications of each of these broader categories. section IV presents the challenges and issues being faced in platooning. Section V presents some concluding remarks.

What Is vehicle platooning?

Platooning consists of creating platoons or "linked" vehicles which will travel along the AHS acting as one unit as shown in Fig. 1 (SARTRE Demo, [6–8]). These vehicles follow one another with a very small headway-vehicle spacing, as little as a couple of meters-and be "linked" through headway control mechanism, such as radar-based or magnetic-based systems. The first vehicle in the platoon, the leader, continuously provides the other vehicles, the followers, with information on the AHS conditions, and what maneuvers, if any, the platoon is going to execute.

In Vehicle Platooning, a group or platoon of vehicles travel in close co-ordination under fully automated longitudinal and lateral control. The vehicles maintain a constant fixed spacing between themselves at all speeds up to highway speeds. This short spacing results in increased highway capacity. Safety is increased by automation and close co-ordination between vehicles. Because of small relative speed between the vehicles, even extreme accelerations and decelerations cannot cause serious impacts on the vehicles, thus increasing passenger comfort [5]. This was shown to be true when the platooning scenario was presented by the PATH program [9]. Eight automated cars were platooned with inter-vehicle distances under ten meters and traveled in a single-file formation guided by magnets embedded in the roadways. This platoon demonstrated the ability to start, stop, accelerate and decelerate as a unit. Also demonstrated was the ability to split the platoon to allow for the entry of vehicles and then to rejoin as one platoon. A Heads-Up-Display unit was used to communicate to the driver information such a speed, distance to destination and whatever maneuver the vehicle is currently executing. Following the concept presented earlier, we can say that Vehicle Platooning is an approach to improve the current transportation system both economically and technologically. In [10], the author says there are 2 main approaches for the implementation of an AHS, hierarchical structure and autonomous vehicle approaches, of which the first approach is centered around the concept of platooning. In this approach, different layers of control hierarchy are responsible for performing different tasks needed to implement an AHS. Another definition of platooning is given in [11], where the author describes a vehicle platoon as a "tightly spaced string of vehicles, where the inter-vehicle distances are appropriately maintained as low as three to one meter at highway speeds depending on what sensors and communication devices that are applied. Since each vehicle knows the dynamics of its leading car and might also know the platoon's leading car, such short distances are safe enough for the vehicles. Usually, the vehicles need to use radar, laser sensor to directly measure the preceding car's speed and their gap. In many recent approaches, inter-vehicle communication is also employed to transmit the required messages, i.e. the speed and position of the platoon's leading vehicle".

Evolution of platooning

The present scenario which is seen in Automated Highway Systems has evolved over many years into what today is known as Vehicle Platooning. There is a very distinct order or pattern seen in this evolution. Initially, there was the independent Vehicle or Free Agent Concept which put all smart technology into the vehicle and let it act individually as a free agent, or a one vehicle platoon. Since there was no infrastructure support needed, this vehicle could use this technology on any existing highways. Then came the Cooperative Concept which added inter-vehicle communication to the Individual Vehicle Concept hence allowing for coordination of the vehicle's driving operation. This concept further evolved into the Infrastructure Supported Concept. This improved upon the Cooperative Concept by providing dedicated lanes for the operation of smart vehicles. Global system information needed for the vehicle decision making and operation was provided by Smart Infrastructure embedded into these lanes. This further gave way to the Infrastructure Assisted Concept which had the automated roadside system providing inter-vehicle communication at the entry, exit and merging maneuvers. Finally, there was the Adaptive Concept which accounted for the different requirements of each location, thus creating standards leaving the decisions and solutions open to the localities.

Currently, the ongoing project on Platooning is the European Union funded SARTRE (Safe Road Trains For Environment). Launched in 2009, the three year SARTRE project launched its first test in December 2010. This project will wind up in 2012. According to the project director of intelligent transport systems for Ricardo, technically the SARTRE platooning could be ready for rollout in 10 years [12].

Technical Overview of Vehicle Platooning

The feasibility of the usage of a vector field for autonomous navigation has previously been demonstrated in [13]. The technology of way points and obstacles was used in [5]. The waypoints exhibited attractive forces and obstacles exhibited repulsive forces which combined to produce a resultant vector indicating the desired velocity of the vehicle. At every point of space, navigational information is provided by this vector field. After obtaining the vector field of a specially designed track, the appropriate points were flagged as track elements and the velocity vector at each track element was set to be normalized distance vector between that element and the next closest track element. At every other point, the vector is taken to be the linear combination of the distance vector between that particular point and its projection onto the track and the the vector at the nearest track element [5].

$$v_{des}(r) = \alpha(proj_t(r) - r) + \beta v_t \tag{1}$$

where r is the point at which desired velocity vector v_{des} is calculated, v_t is the velocity vector at the nearest track element and

$$proj_t(r) = \frac{\langle r,t \rangle}{\langle t,t \rangle} t \tag{2}$$

is the projection of r onto the track vector, t.

Leader Navigation Leader Navigation was achieved by the feedback of the velocity error, attenuated by α and then supplied as acceleration $a(t)$ of the platoon leader at every time step as seen in equations (3) and (4).

$$v_{error} = v_{des}(t) - v_{veh}(t) \tag{3}$$

$$a(t) = \alpha v_{error}(t) - \frac{F_{friction}(t)}{m_{veh}} \tag{4}$$

The final positions of the vehicles are calculated using the standard equation of motion given as:

$$s_f = s_i + v_i \Delta t + \frac{1}{2} a (\Delta t)^2 \tag{5}$$

where Δt is the time step and v_i is the vehicle's velocity at the beginning of the time step.

Further, according to A. Kesting [12], the 'desired minimum gap' is given by:

$$s^*(v, \Delta v) = s_0 + vT + \frac{v \Delta v}{2\sqrt{ab}} \tag{6}$$

$\Delta v = v_\alpha - v_{\alpha-1}$, where α is the following vehicle and $\alpha - 1$ is the leader vehicle, s_0 is the minimum distance in case of congested traffic, a is the maximum acceleration and b is the 'comfortable deceleration'. The last term in (6) however, is significant only in non-stationary traffic, when $\Delta v \neq 0$. vT is a term more relevant to the resultant spacing in stationary traffic [14]
Also, according to [14], the formulation to determine road capacity , which can be increased by tighter spacing between vehicles, is given as:

$$C = V \frac{n}{ns + (n-1)d + D} \tag{7}$$

where d is intra-platoon spacing,D is inter-platoon spacing,s is vehicle length and V is the steady state speed in m/min.

Follower Spring Dynamics Demonstrations of the implementation of collision avoidance modeled on physical systems have been put forth by a lot of researchers, from potential fields in [15], to fluid dynamics in [16] and spring dynamics in [17]. However, in [5], the concept of spring dynamics is utilized wherein only the platoon's leader is provided with navigational information including the vector field and the following vehicles are linked together via spring dynamics. It was seen that although this method did manage to keep the vehicles on the track, the more desirable approach is to provide all the vehicles in the platoon with navigational information and have the spring forces act as either amplification or attenuation factors for the vector field, depending on vehicle proximity. Hooke's law for an ideal spring exerting a restoring force is given to be:

$$F = -kx \tag{8}$$

where x is the distance between two vehicles. The authors of [5] suggested the use of a critically damped spring with $\zeta = 1$ for the ideal case to avoid undesirable oscillations in vehicle spacing.

Inter-Platoon Dynamics For inter-platoon dynamics, a proportional controller was examined in [5] which activated when a threshold distance was reached between the lead vehicle of a platoon and the last vehicle of the platoon with which it wished to merge. Details on a non-linear approach to the inter-vehicle dynamics can be found in [5].

FROM 1994 TO 2010:AN OVERVIEW

In this section, we give an overview of the results obtained from our search for literature. The statistics presented in this section may vary because for resources like Ph. D Dissertations, 'Digital Library' does not include all the schools in the world, and we were not able to personally be aware of all the dissertations published everywhere on this topic. Nonetheless, we have tried to include all the Ph. D Dissertations of which we are aware.

Methodology of Literature Survey

There have not been many previous reviews and surveys on Vehicle Platooning. Of particular note however, is the survey conducted by Sadayuki Tsugawa [18] which gives a thorough analysis of the control algorithms in AHS with references through 1965.

The present survey began with a search on "IEEE Xplore", "Web of Science" and "ScienceDirect" sites conducted on October 2010. Table 1 shows the search results. As shown in tab. 1, from the keywords ("Vehicle AND Platooning "), we have a total of 284 publications. A broader search was also carried out using the keywords("Automated" AND "Highway" AND "Platoon" AND "System")from which we have a total of 134 publications. We also searched under a related topic using the keywords "Vehicle Strings" from which we obtained 231 publications, and "Platoon String Stability" from which we obtained a total of 110 publications. Given these large number of publications in this paper, our review is restricted to the literature obtained by searching under the phrases "Vehicle Platooning", "Inter-vehicle communication in vehicle platooning" and "Obstacle detection and collision avoidance in vehicle platoons". Other than IEEE conferences, we also include papers published in other conferences like SICE conference, Mechatronics Conference, IEICE Conference and the SAE Conferences. Figure 2 gives a graphical depiction of the number of Vehicle Platooning publications since 1994 in international conference proceedings and journals.

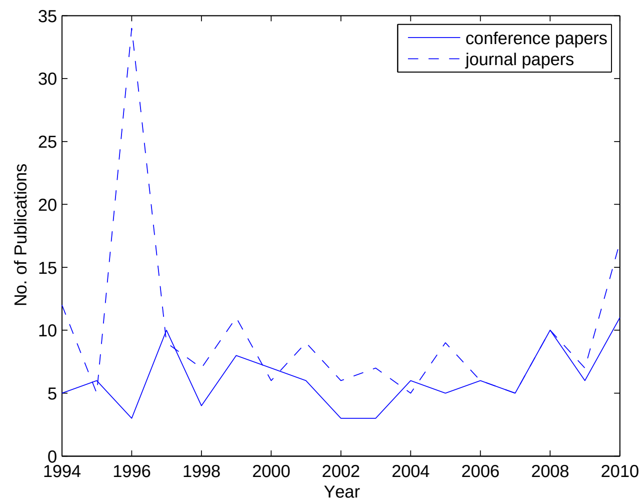

FIGURE 2. NUMBER OF VEHICLE PLATOONING RELATED PUBLICATIONS IN CONFERENCE PROCEEDINGS AND JOURNALS

TABLE 1. VEHICLE PLATOONING RELATED PUBLICATIONS FROM WEB OF SCIENCE, IEEE XPLORE AND SCIENCEDIRECT

Search options	From Web of Science	From IEEE Xplore	From ScienceDirect	Total
Vehicle+Platooning	37	86	161	284
Vehicle Platooning Dynamics	20	15	74	90
Platoon String Stability	23	37	50	110
Vehicle Platooning and Communication	10	43	93	146
Vehicle Platooning and Collision Avoidance	2	13	45	60

Vehicle Platooning Related Ph. D Dissertations And Master's Theses Since 1994. In this section, we will briefly review some Ph. D Dissertations and Master's theses published in the interval between 1994 and 2010. Table 2 gives an overview of some statistics in this regard. Platoon size remains limited by communication. So, there is a need for advances in low Bandwidth control techniques. In [19], decentralized, low bandwidth control of an arbitrarily large platoon of autonomous underground vehicles is investigated. In [20], the design and experimental results of low-cost lane-level positioning system that can support a large number of transportation applications are discussed. Using a Markov-based approach based on sharing information among a group of vehicles that are traveling within the communication range of each other, the lane positions of vehicles can be determined. The robustness and effectiveness of the system is shown in both simulations and real road tests. Also,

TABLE 2. VEHICLE PLATOONING RELATED Ph. D DISSERTATIONS AND MASTER'S THESES

Year	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	Total
Number	2	0	1	2	0	1	3	0	1	0	1	3	2	2	5	3	1	27

a decentralized approach to lane scheduling for vehicles with an aim to increase traffic throughput while ensuring the vehicles exit successfully at their destinations is presented in [20]. The work evaluates a proposed strategy which assigns vehicles to platoons by solving an optimization problem. A linear model for assigning vehicles to appropriate platoons when they enter the highway is formulated. Simulation results are presented to demonstrate that lane capacity can be increased effectively when platooning operation is used. In [21], the use of Computational Fluid Dynamics (CFD) for understanding convoy aerodynamics and airflow interaction between vehicles via CFD is investigated. In this study, time-averaged characteristics of a simplified, generic passenger vehicle, called the Ahmed car model was investigated computationally. Three different platoon combinations were analysed for the study which included a two, three and six model platoons for various rear end configurations of the Ahmed model geometry. In [22], intervehicle communication issues, such as sharing information via limited bandwidth channels and selecting network architecture to facilitate control design for an Autonomous Underwater Vehicle Platoon with Limited Communication is studied. The effects of various communication delays on string stability are analyzed in [23]. Longitudinal maneuvers for platoons in an AHS is analyzed in [24]. The interaction between control and communications portions of the vehicle software structure is defined. A complete nonlinear hybrid controller was developed to control the lead modes, follower modes, join transitions and split transitions of an automated vehicle.

A large amount of research work has been done on the Inter-Vehicle Communication Networks.In [25]the MAC solution is further enhanced by introducing a prioritization mechanism based on vehicle positions and the overall road traffic density, which further improves the throughput of both real-time and best-effort data traffic by focusing the communication resources to the most hazardous areas of the road infrastructure.Various MAC methods are also evaluated.In depth study of 5.9GHz DSRC has been done in [26].In this Master's thesis, a vehicular safety communication architecture is designed,an effective broadcast mes- sage distribution scheme is introduced, a channel-switch protocol is presented, and a communication stack is proposed.In [27],a simulation environment is developed in MATLAB for vehicle-vehicle and infrastructure communication based on IEEE 802.11p (WAVE). In [28],a hierarchical driving agent architecture based on three layers (guidance layer, management layer and traffic control layer) is proposed, which can be used to develop both centralized and decentralized platoons

FROM 1994 TO 2010:CATEGORIZATION

In this section, we separate the literature into two different parts. The first part is related to the literature that focuses on Vehicle Platooning applications and the second part is related to the literature focused on theoretical developments. It is difficult to separate the literature into these two parts, so the categorizations in this section are largely based on the authors' subjective opinions.

Literature Related to Vehicle Platooning Applications

Since it was very difficult to find a variety of applications related exclusively to platooning, we have widened our search to also include applications related to key concepts involved in platooning like 'inter-vehicle communication' and related issues like 'intelligent' and 'unmanned vehicles'. In [29], the application related to "image processing" is examined. The authors of [29] strike upon a solution to the problem of lane detection [30] in vehicle platooning which overcomes the problem faced by conventional methods when it comes to image processing of the image captured from a front camera. The proposed method has been implemented on the image processing hardware whose CPU satisfies on-board specifications. Another application of platooning was seen in "mobile robots" [31–36]. [37] described a robotic application where a co-ordinated team of mobile robots moves as a platoon. Particularly, the use of a real time operating system which implements the control algorithm that runs on-board on each robot was demonstrated as being able to assess the impact of real time parameters of computing tasks on the performance of the control application.

Platooning has some interesting applications to autonomous vehicles in intelligent transportation systems. In [38], the application concerning communication of information from infrastructure to the vehicles is analyzed. Use of magnetic markers [39] enables binary coding for information exchange from roadway to vehicle, to be utilized for all AHS subtasks.

In a platoon of vehicles, detection of overtaking vehicles plays an important role from the safety point of view. This application related to early detection of overtaking vehicles is analyzed in [40]. Related to this application, detailed categories were given as "blind spot monitoring" and "lane change support". Older people generally lose flexibility in their neck, making it harder to check before changing lanes . Intelligent sensors that monitor the blind spot can allow seniors to drive safely [41]. In addition, Military has increasing interest in intelligent vehicles. Scout vehicles typically operate in front of the main force, and are the first target of the opposition. It is hence desirable to have autonomous scouts that can investigate hazardous areas leading to increased safety of soldiers [41]. Furthermore, applications like "cooperative robot reconnaissance [42] and [43]manipulation " , "formation flight control" [44], "satellite clustering" [45], [46], and "unmanned vehicles" [47] have also been cited.

A major application of platooning is seen as roadside safety application [48].

"Automatic Car Parking" is also suggested as an application in [49]. In [50], a detailed survey of IVC based applications is conducted and examples of applications like "truck platooning", "co-ordinated braking", "runway incursion prevention", "vehicle formation control" and "adaptive traffic control" are cited. Applications are grouped into two types of classes according to the aim, such as "safety information services" or "findividual motion control". The authors of [50] have surveyed specific examples of applications in literature. They classified applications of inter-vehicle communications (utilized in platooning) into four classes which can be referred from [50].
Also included are applications of platooning in the agricultural sector [51–55]. Since the demands on agricultural productivity are increasing and there is a desire to decrease the labor force, automation of agricultural machinery plays an important role. Platooning of tractors for automation of agricultural tasks like ploughing and sowing is studied in [51]. Furthermore, aircrafts [56,57], spacecrafts [58], closely spaced parallel approaches [59] and separation control of arrival stream aircraft [60] have perhaps been the most active areas for research on control technologies. Platooning application can be extended to aerospace systems [46]. For example, flight formation control for uninhabited combat air vehicles (UCAV's), with fleet coordination and autonomy is talked about in [46]. [61] talks of a group of coordinated autonomous underwater vehicles which can search for a coastal area of mines more efficiently. Related to this application, detailed categories were given as "oceanographic surveys" [62], "operations in hazardous environments" [63], "underwater structure inspection" [64].
Application of platooning to railway systems has been proposed and studied in [65–68]. In case of rail-bound vehicles, only the control of the longitudinal dynamics is required with respect to drive control. The RailCab project, founded at the University of Padeborn in 1998 is studied, wherein the RailCab convoy is built from single RailCabs.

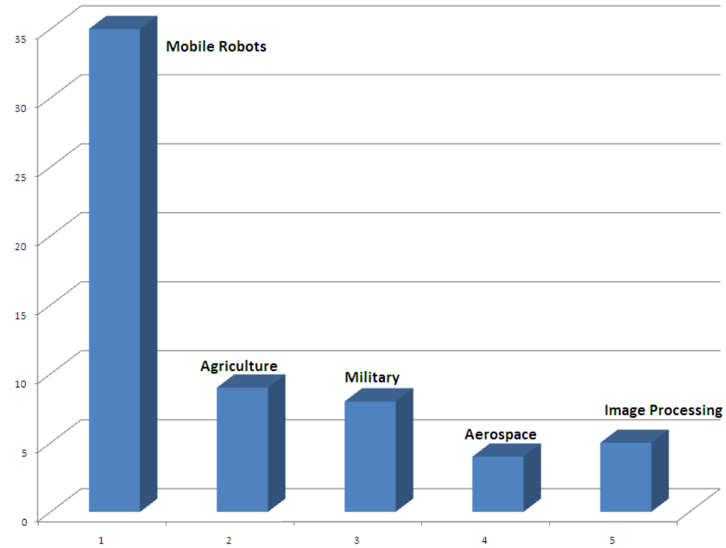

FIGURE 3. PUBLICATION NUMBER OF APPLICATION FOCUSED PLATOONING RESULTS

Literature Related to Vehicle Platooning Theories

It was seen that the literature related to theoretical developments was broadly classified into following subcategories listed below.

- Inter-Vehicle Communication Methodologies
- Collision Avoidance and Obstacle Detection Methodologies
- Design of Lateral and Longitudinal Control Systems for a Platoon.
- String Stability of a Platoon
- Trajectory Planning

Different techniques have been implemented so far for sensing and detection of obstacles, inter-vehicle communication and the control algorithm implemented. We present in this paper, a brief survey of these techniques.

Obstacle detection and collision avoidance. Inter platoon Cooperative Collision Avoidance(CCA) systems form an important aspect of 'vehicular ad-hoc networks' (VANET) safety applications. An efficient CCA strategy based on a risk-aware Medium Access Control (MAC) protocol tailored for VANET networks has been proposed in [69]. In this system, the vehicles were first clustered according to the features of their movement using information like direction of movement, inter-vehicle distance and relative speed. An emergency level was associated with each cluster, where the emergency level indicated the likelihood of a vehicle to experience an accident in the platoon. In yet another paper, a broadcast based packet forwarding mechanism for inter-platoon CCA using DSRC was proposed [70]. In [71], the concept of elastic Bands is proposed and analyzed for collision avoidance. The original elastic band approach was proposed by Quinlan and Khatib [17]. Forces acting on the elastic band are computed by taking the gradient of the potential energy at discrete path points. The repelling forces on the elastic band are produced by obstacles in the vicinity of the path. The path the leader follows is the initial path and obstacles in the environment exert forces on the band and move it into a final configuration. This is the path followed by the ego vehicles.

The development of a Rear End Collision Avoidance System has been analyzed in [72] where the system had automatic braking when the headway distance between the trailing vehicle and the selected vehicle crossed the safety threshold. It informs the driver of distance headway and warns the driver when there is a collision potential hazard.

While the problem of cruise control has been deeply explored by researchers, more work still needs to be done on the possibility of enriching the control system of the vehicles with the ability of autonomously reacting to the presence of any moving or static obstacles on the road. This issue is investigated in [73] where a cruise control system with collision avoidance features is proposed.

The concept used in [73] involved the idea of a supervisor for the control system of every vehicle in the platoon, which receives the data from the cars sensors. Whenever new data is collected by the sensors, the supervisor of each vehicle performs a collision detection test, which relies on the concept of collision cone [74]. On detection of the possibility of a collision, the control system switches from the normal “cruise mode” to “collision avoidance mode”, causing the involved vehicle to stop following the preceding vehicle. The decision involves which action to take from emergency braking and the generation of a collision avoidance manoeuvre. For this, two low level controllers were implemented and sliding mode control methodology was used for the two controllers.

Concerning automatic platooning, processing can be done based on:

- the use of radar only (ACC)
- the fusion of an active sensor(laser, radar, lidar) and monocular vision [75]
- monocular vision only.

A very widely used approach for monocular vision-based vehicle detection [76, 77] is to search for specific patterns [78] like shape [79,80], motion [81], color [75,79], symmetry [75,82], [83], shadow [75,83], texture [83], or the use of a specific model [84]. In [85], a stereo vision algorithm specifically tailored for Vehicle Detection has been developed [86, 87].
Model based vehicle detection is analyzed in [88], wherein a computer vision based system for vehicle detection is developed, based on a geometric model. The shape and symmetry of the vehicle along with the shadow it produces is used to obtain the energy function of the system. In [89], the processing is limited to image portion that is assumed to represent the road; borders that could represent a potential vehicle are looked for and examined. In [90], an edge detection process is enforced with obstacle modelization. This system is able to detect and track up to twelve objects around the vehicle. Analysis of *Optical Flow Fields* as regards Obstacle detection is dealt with in [91–94]. Using stereo images for the identification of free space in front of the vehicle is a robust method for obstacle detection [95].

Inter-Vehicle Communication. IVHS architecture also provides a communication system which allows vehicles on the highway to share driving information, such as the velocity and acceleration of each vehicle, road condition estimates, and obstacle detected by the lead vehicle [96].

One of the earliest studies on inter-vehicle communications was that started by JSK (Association of Electronic Technology for Automobile Traffic and Driving) in Japan in the early 1980s [97]. It was originally defined as flexible platooing of automated vehicles, which was also named super smart vehicle system(SSVS) at that time.Several different IVC models were designed,implemented and tested in the last decade such as COCAIN(Cooperative Optimized Channel Access for INter-vehicle communication) [98] ,TELCO (Telecommunication Network for Cooperative Driving) [99] and DOLPHIN [100]. A previous survey on Inter Vehicle Communications worth noting is that conducted by Sichitiu and Kihl [101] which also analyzes applications of IVC.

As the media for inter-vehicle communications, infrared and radio waves have been studied and employed for experimental systems. The radio waves include VHF waves, micro waves, and millimeter waves. The communications with infrared and millimeter waves are within the range of the line-of-sight and usually directional whereas those with VHF and microwaves are of broadcast type. Although VHF waves have been used because of their long communication distance, the mainstream nowadays is microwaves.

A system which uses 220MHz band (the VHF wave) has been proposed in [102]. Its objectives are safety related systems including incident warning system. Since the communication range is 1-2km, the system is feasible even if the penetration rate of communication unit is low. The communication system is also applied to a “chat” system among drivers relayed with a base station on the ground.

Mobile phones can also be used for the inter-vehicle communication. A consortium in Germany proposed a system that transmits the information on an accident or an incident detected by a vehicle to following vehicles through mobile phone with the localization data by the GPS [103].

The microwaves are used in several systems. In the platooning with automated vehicles during the Demo 97 in San Diego and in the truck platooning named “Chauffeur” developed by

DymlerCrysler [104], commercially available wireless radio was employed for the vehicle control. At the beginning of the Chauffeur Project, 2. 4 GHz wave was used for the inter-vehicle communications. The communication period was 40 msec, and the transmission rate was 230 kbps. Data transmitted included speed, acceleration, and the intention of joining or leaving the platoon. Later, the inter-vehicle communications for Chauffeur were updated to the use of 5. 8 GHz.

The 60 GHz band has also been applied to inter-vehicle communications by the group of Communications Research Laboratory in Japan [105]. The communications are a type of line-of-sight and thus the inter-vehicle communications are performed between vehicles with relatively small inter-vehicle distances. One of the applications is image transmission of high quality.

Another medium used for inter-vehicle communications is the infrared, which is again a type of line-of-sight. Infrared was employed in the cooperative driving phase I by JSK [106]. In this system, a preceding vehicle was equipped with infrared markers on the roof, one of which functioned as a transmitter, and both of which functioned for the inter-vehicle distance measurement with triangulation. The feature of this system was that the following vehicles could communicate as well as measure the inter-vehicle distances of preceding vehicles.

Yet another system was developed by the California PATH, wherein the communications were performed between the transceivers at the bumpers of the preceding and the following vehicle. The feature of this system was that the transmission rate was controlled by observing the bit error rate; if the inter-vehicle distance is short, that is, the bit error rate is small, then the transmission rate can be increased and vice-versa.

The cooperative communication of the vehicle-to-vehicle plays a key role in keeping the relative spacing of vehicles small in a platoon. Static platoon control, where the number of vehicles remains constant, is sufficient for the information to be transmitted in the suitably fixed interval, while the dynamic platoon control such a merge or split requires more flexible network architecture for the dynamical coordination of the communication sequence. In [107], a low cost, short range ISM band transceiver and 8 bit-microcontroller was used to implement the wireless communication device and the reliable protocol.

In a platoon, the information of the preceding vehicle can be obtained relatively by the range radar. This information is not available for other members of the platoon except the leader. This scheme guarantees that each vehicle in the platoon has a chance to transmit its information every one cycle in the case of static platoon control. However, for dynamical platoon control involving a merge or split, the maneuvering vehicle requires frequent update of the control input so more information should be transmitted to the maneuvering vehicle than others. The coordination of the communication sequence is achieved by RCS (remote control station) in [107].

The 433MHz RF-module, BIM-433, is used for the implementation of the wireless communication system of the TDMA (Time Division Multiple Access) with token passing architecture. The data transfer rate of this RF-module is 38Kbps and the carrier sense algorithm is not supported. Also, for stable movement of each vehicle, the sampling period of a vehicle should be less than 40ms [107]. Details on the hardware and software implementation can be found in [107].

It is generally more effective to use a time-division multiplexing (TDM) method or a round robin method to avoid collision and interference of packets during communication. However, since a TDM method requires to decide the maximum number of vehicles in a platoon in advance to prepare for the slots, this causes a problem in communication. A new data transmission algorithm is proposed in [108] to solve this problem. The algorithm is featured by that the order of data transmission from a vehicles to another one is not based the physical order of vehicles in a platoon. It is a round robin method. Details on the algorithm can be found in [108].

An experimental system of 60GHz millimeter wave band Inter-Vehicle Communication system implemented CSMA method based on DOLPHIN protocol [100] and CSMA used Spread Spectrum(SS) [109] was implemented in [110].

Protocol A list of the various protocols used in the different projects has been given in [111].A survey of both IVC and V-I communication protocols is also provided. There are two requirements on the protocol of the inter-vehicle communication system. The first one is that the protocol must be flexible to maintain a network among vehicles when a new vehicle leaves or joins the network. Second requirement is that the protocol should be able to deal with real time data transmission [112]. In the newly initiated European project employing the application of infrared CarTALK 2000, the protocol was based on IrDA. In the cooperative driving phase I with infrared communications by JSK, the protocol was based on a network-oriented one. Considering the importance of real time data transmission, the slotted ALOHA was employed in [106]. In the cooperative driving phase II with 5. 8 GHz Dedicated Short Range Communication (DSRC) developed by the authors, the protocol was based on CSMA (Carrier Sense Multiple Access) [100].

In [113], a comparison of TDMA, DS-CDMA, and MC-CDMA schemes in an AVCS platoon environment with Rician fading and Rayleigh interference. It was shown by the authors of [113], that CDMA undergoes fast fading while TDMA undergoes slow fading. Packet erasure rates were found in order to measure the performance of these multiple access schemes. It was also shown that bandwidth considerations must be taken into account in the performance of each scheme.

Control Strategies Much work has been done in the study of longitudinal control problem as a part of the AHS pro-

gram and a variety of solutions have been presented. A good overview of these activities is given in [114]. In [115, 116], feedback linearization techniques in combination with linear control laws are used to obtain a stable longitudinal vehicle platoon. Adaptive control methods are presented in [117] to cope with the nonlinear system behavior of heavy duty vehicles and to achieve string stability. In [118], a nonlinear sliding controller with a multiple surface technique is presented and the successful operation of the control system is demonstrated with practical results of a 4 car platoon. Demonstration of Robust Control using sliding mode controllers is also discussed in [119].
Longitudnal control by adaptive vehicle traction force control (force arising from tire/road interaction) is implemented in [120], wherein, two different traction force controllers, adaptive fuzzy logic control and adaptive sliding mode control are proposed and tested for stable but fast accelerations and decelerations of vehicle platoons.
An issue which if not considered, could be disastrous to a platoon system is that of control saturations. Vehicle platooning naturally implies a saturation problem when nonidentical vehicles are allowed. [121] presents a systematic design procedure for adapting a nominal controller, designed without regard to control saturation, to a higher performance nonlinear controller that explicitly accounts for the saturating nonlinearities while preserving stability [122]. A two layered control structure is proposed in [123]. The inner control loop includes a nonlinear acceleration controller linearizing a large part of the nonlinearities. A Robust Platoon controller is introduced for the outer control loop by the use of sliding mode control design. By the use of the proposed control concept, string stability can be achieved. Systems with combined lateral and longitudinal control systems is important for a well designed platoon system. It is shown that longitudinal controllers that directly control the wheel slip are inherently more stable, especially during lateral maneuvers on very slippery road conditions [10].

For a platoon of multiple vehicles, the lateral error propagation is a serious issue that can be solved if performance is compensated. Lateral control is generally achieved by the combined use of road and vehicle infrastructure such as magnet-magnetometer and lane marker-camera schemes. Lateral platoon stability remains an issue, since the systems are interconnected. Addition of inter-vehicle communication ensures lateral platoon stability and satisfactory performance since it eliminates the interconnection among the vehicles, provided that the communication delays are short.

In [124], an effective decentralized control technique for platoons is proposed and simulated for underwater vehicles. A lot of research is also being conducted in the application of fuzzy controller to design the Automatic Cruise Control (ACC) system. The ACC systems should be designed such that string stability can be guaranteed in addition to that every vehicle in a string of ACC vehicles which use the same control law must track any bounded acceleration and velocity of its preceding vehicle with a bounded spacing and velocity error. In [125], a fuzzy logic based ACC which guarantees string stability is designed. Furthermore, the use of learning control is also studied in [10], wherein a 'learning automata approach' was shown capable of capturing the dynamics of driver behavior. The controller learns the action in real time instead of learning the parameters or firing rules for deciding the best action to be taken for achieving a safe and optimal path. The 4-layer hierarchical control architecture consisting of network, link, planning and regulation as proposed by Varaiya [126] is used to propose an intelligent controller which can be seen as the planning layer of an autonomous vehicle. The communication between the planning and regulation layer was achieved by the issuing of a command by the planning layer to the regulation layer which in turn returned a reply when the command was carried out. A richer interface could be achieved if the planning layer were capable of sending multiple parameters to the regulation layer, which in turn would return parameters indicating 'success' or 'errors' and 'exceptions'. This, however, requires more research work to be carried out on how the regulation layer should switch from one control law to another. However, the system had the disadvantage of requiring extensive modifications even for minor changes in rules. The system also failed to handle unanticipated situations. Sadayuki Tsugawa [18] conducted a complete survey on Lateral and Longitudinal Control algorithms for the AHS with reference to systems developed since 1965.

String Stability. String stability in leader-follower platoons has been a topic of great concern. Intuitively, string stability implies uniform boundedness of all states of an interconnected system at all times if the initial states of the interconnected system are uniformly bounded [127]. Spacing errors should not amplify downstream from one vehicle to another of the platoon. String stability has proved to be an important tool in analyzing the stability of platoons of vehicles. Shladover [128] pointed out the need for lead vehicle information to obtain string stability with a linear static controller for spacing control. Without leader information, string stability is lost [129]. In [130], leader-to-formation stability is analyzed to address issues related to safety and performance due to error propagation in a platoon. The works of Peppard [131] already introduced the idea of string stability in connection to moving cell systems. Peppard defined string stability as the "ability of the vehicle string to attenuate disturbances as they propagate down the string". Conditions for string stability were also provided in the works of Peppard, [131], and Shiekholeslam and Desoer [132], in terms of the norm magnitude $(|G(j\omega) < 1|)$ and the impulse response $(g(t) > 0)$ of the linear operator $G(s)$, where $G(s)$ maps the deviation in the assigned distances between vehicle i and $i-1$.

String Stability is further studied in the works of Swaroop [133], wherein he introduced mathematical definitions for : *string stability, asymptotical string stability and l_p string stability*. Analysis of the the type of information and inter-vehicle spacing strategy that should be employed to achieve string stability has been debated by many authors [134–136]. In the works of [134] and [135] , they concluded that it was impossible to achieve string stability under autonomous operation when the desired inter vehicle spacing is constant.

In [137], definition of String stability is given by the relation:

$$e_j(s) = \prod_{l=1}^{j-1} G_1(s) \cdot e_1(s) = G(s) \cdot e_1(s), \forall j = 2,3.....n \quad (9)$$

that gives the transfer function of the backward error propagation, where $G_i(\cdot) : e_i \rightarrow e_{i+1}$. From this relation, we have:

$$\parallel e_i \parallel_\infty \leq \parallel g * e_1 \parallel_\infty \leq \parallel g \parallel_1 \parallel e_1 \parallel_\infty \quad (10)$$

where $g(t)$ is the inverse laplace transform of $G(s)$. A necessary and sufficient condition for error attenuation can be seen as:

$$\parallel g \parallel_1 \leq 1 \quad (11)$$

Also, if $g(t)$ is positive, then above condition equals:

$$\parallel G \parallel_\infty = max_\omega |G(j\omega)| \leq 1, g(t) \geq 0; \quad (12)$$

If $g(t)$ is not positive, then $\parallel G \parallel_\infty \leq 1$ only gives L_2 stability, because:

$$\parallel e_i \parallel_2 \leq \parallel G \parallel_\infty \parallel e_1 \parallel_2 . \quad (13)$$

. These conditions have already been presented in the works of Sheikholeslam and Desoer [132].
For details on linear control strategies based on whether the system is string unstable, l_2 string stable or string stable, refer to [137].

CHALLENGES AND ISSUES IN VEHICLE PLATOONING

A very interesting concept is examined in [138]. Although platooning can decrease travel time, it has certain security issues. The authors of [138] consider the problem of hackers using the system to cause accidents. Due to the utilization of Wireless Inter Vehicle communication in platooning, which is easily accessible, it exposes the system to computer security attacks. This wireless network can invite denial-of-service attacks and alteration attacks on legitimate network traffic, all of which could

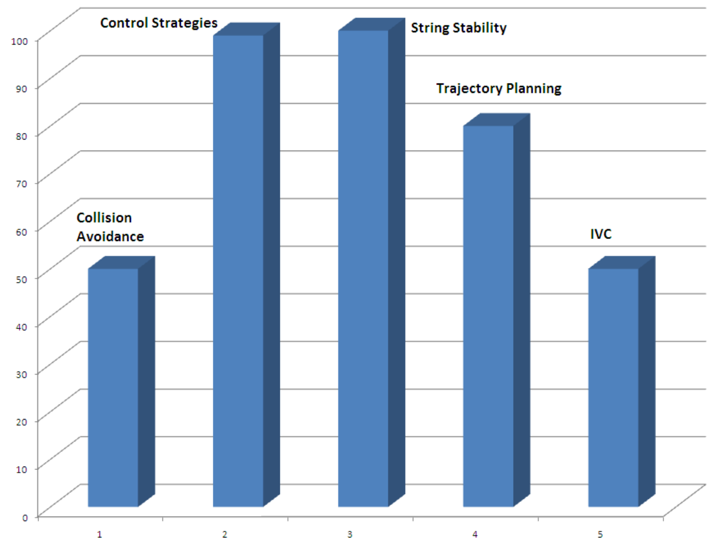

FIGURE 4. PUBLICATION NUMBER OF THEORY FOCUSED PLATOONING RESULTS

weaken the systems safety. Because of these weaknesses, attackers could exploit intelligent transportation systems to cause a new roadway danger with severe consequences“intelligent collisions”. One way to deal with this is to authenticate the information before it is used by the platoon by keeping a private key that is used to sign sensible information from sensors before it can be used by the system [139]. [138] explores the IVC networks potential susceptibilities to attack and emerging research targeted at reducing their impact.

Utilization of existing highways and infrastructure is vital to the idea of platooning. For platoons to be feasible, there should be minimal modifications on supporting infrastructure. The European Commission FP7 co-funded SARTRE project aims to examine issues for allowing platoons to operate on public motorways under these conditions [6], [7,8]. Hazards such as impaired drivers, altered driver behaviour, technical failures of the vehicles and new applications using an existing road infrastructure need to be analyzed. Consideration of the effects on the platoon if the lead vehicle has an accident need to be studied further. One important consideration is that of communication induced random delays. Hedrick et al [140] studied the effects of communication delays from the lead vehicle on string stability. They concluded that any delay in the communicated information using the existing control algorithms [141] will not be string stable over all conditions, and thus proposed the development of control algorithms that are robust to communication delays and to random dropouts. Similarly, measurement losses among satellites due to the shadowing effect was addressed in [58]. A method to handle communication dropouts is studied in [142], wherein, the lead state is propagated for control. In the event of loss of lead vehicle state, a propagation of the state is computed and used in the control law. Mathematically, this is written as:

$$\hat{v}^i_{l,k} = J^i_k v^{-i}_{l,k} + (1-J^i_k)\check{v}_{l,k}, \hat{s}^i_{l,k} = J^i_k s^{-i}_{l,k} + (1-J^i_k)\check{s}_{l,k} \tag{14}$$

where l stands for lead vehicle, $\hat{v}^i_{l,k}$ is the speed of the lead vehicle at the k^{th} time instant, s_i, v_i is the distance traveled and speed for a platoon, $\hat{v}$ is an estimate of v, $\check{v}$ is a measurement of v and $J^i_k = 1$ implies a lost link between the lead and i^{th}vehicle at time $k = 0$, and $J^i_k = 0$ implies a good link. The propagation is given as:

$$v^{-i}_{l,k+1} = \hat{v}^i_{l,k} s^{-i}_{l,k+1} = \hat{s}^i_{l,k} + \hat{v}^i_{l,k} T \tag{15}$$

which implies that each vehicle assumes that the lead vehicle travels at constant speed during losses. Vehicle-to-Vehicle Radio links are bound to suffer from multipath fading as well as interference from other vehicles. These communication links have to be extremely reliable. In [143] and [144], a vehicle-to-base station Rayleigh fading channel has been investigated whereas in [145] and [146], vehicle-to-vehicle Rayleigh fading channel has been investigated. However, in [113], the Rician fading channel is studied. From the media access control (MAC) point of view, the delay in the processing is a main cause of the packet loss. Multiple access schemes such as TDMA, DS-CDMA and frequency hopping with TDMA are investigated to determine their performance as regards Packet Erasure Rates and Reliability. It was shown that CDMA gives better results than TDMA. The authors of [113] also concluded that deep fades and large probabilities of packet losses can occur for distances less than 3m due to inherent cancelation of ground-reflected and direct Line-of-Sight wave. Consequences of Communication delays have already been shown in [147] and [148]. The effects of information delays on string stability has also been studied in [149]. Onboard sensors operate with a scan frequency between 3-10 Hz. This implies a potential information delay varying between 0.10 and 0.33 sec. [150]. Wireless Communication systems experience the problem of delays mainly because of packet losses, transmission time and the time to analyze and process the transmitted data [151]. Most designs of the longitudinal controllers do not take into account the effects of communication delays on string stability. In [152] this issue is analyzed in detail and the robustness of current longitudinal controller designs to communication delays is examined. The scarce radio spectrum directly limits the data rates on the wireless channel. As the signal commences through the channel, it undergoes random power fluctuations over time due to changing reflections and attenuations. These power fluctuations cause time-varying data rates and intermittent connectivity, thus introducing random delays and packet losses. In the following subsection, we analyze the effects of communication delays as is treated in [152].

System with Communication Delays

The longitudinal controller considered in [152] is of sliding mode control. The spacing error is defined as:

$$\varepsilon_i(t) = x_i(t) - x_{i-1}(t) + L_i \tag{16}$$

where x_i denotes the abscissa of the rear bumper of the i^{th} vehicle and L_i is the allotted slot to i^{th} vehicle, i. e, the desired spacing between vehicle i and $i-1$ from rear bumper to rear bumper. ε_i measures the deviation in the assigned distance between vehicle i and $i-1$.

Considering the feedback information contains relative position, velocity and acceleration of both the lead vehicle and preceding vehicles, define:

$$S_i = \dot{\varepsilon}_i + q_1\varepsilon_i + q_3(v_i - v_l) + q_4(x_i - x_l + \sum_{j=2}^{i} L_j) \tag{17}$$

where q_1, q_3, q_4 are design parameters. S_i is a function of ε_i. It is desired that S_i approaches zero that ε_i approaches zero. By setting

$$\dot{S}_i = -\lambda S_i \tag{18}$$

for some $\lambda > 0$, the control law is given as:

$$\begin{aligned} u_{i_d} = & \frac{1}{1+q_3}[\ddot{x}_{i-1} + q_3\ddot{x}_l - (q_1+\lambda)\dot{\varepsilon}_i - q_1\lambda\varepsilon_i \\ & -(q_4+\lambda q_3)(v_i - v_l) - \lambda q_4(x_i - x_l + \sum_{j=2}^{i} L_j)] \end{aligned} \tag{19}$$

The actuator lag and signal processing delay is modeled as a first order filter.

$$\tau\dot{u}_i + u_i = u_{i_d} \tag{20}$$

where τ is the 'time constant', taken here as 0.05. Differentiating both sides of (16), we get

$$\dot{\varepsilon_i}(t) = \dot{x}_i(t) - \dot{x}_{i-1}(t) = v_i(t) - v_{i-1}(t) \tag{21}$$

$$\ddot{\varepsilon}_i(t) = \ddot{x}_i(t) - \ddot{x}_{i-1}(t) = a_i(t) - a_{i-1}(t) \tag{22}$$

The i^{th} vehicle dynamics is given as:

$$\dot{v}_i = u_i \tag{23}$$

Substituting (16), (21), (22) and (23) into (20) gives:

$$\tau \frac{d^3 \varepsilon_i}{dt} + \ddot{\varepsilon}_i = u_{i_d} - u_{i-1_d} \tag{24}$$

The time delays in both the preceding and lead vehicle information are defined as:

- $\tau_{dp}^{(i)}$ is the timing delay of the preceding vehicle information seen by vehicle i.
- $\tau_{dl}^{(i)}$ is the timing delay of the lead vehicle information seen by vehicle i

Substituting (19) into (24) and taking Laplace transform to get transfer function yields:

$$\begin{aligned} H_{11} E_i(s) = & \frac{1}{1+q_3}[G_1 E_{i-1}(s) + G_2 A_l(s) \\ & + G_3 A_{i-1}(s) - G_4 A_{i-2}(s)] \end{aligned} \tag{25}$$

where

$$H_{11} = \tau s^3 + s^2 + (\lambda + \frac{q_1+q_4}{1+q_3})s + \frac{\lambda(q_1+q_4)}{1+q_3} \tag{26}$$

$$G_1 = \lambda q_1 \tag{27}$$

$$G_2 = \frac{1}{s^2}(e^{-\tau_{dl}^i s} - e_{dl}^{-\tau i-1} s)(q_3 s^2 + (q_4 + \lambda q_3)s + \lambda q_4) \tag{28}$$

$$G_3 = \frac{e^{-\tau_{dp}^i}}{s}(s + (\lambda + q_1)) \tag{29}$$

$$G_4 = \frac{e^{-\tau_{dp}^{i-1}}}{s}(s + (\lambda + q_1)) \tag{30}$$

For detailed discussion to distinguish the effects of communication delays in lead and preceding vehicle information, see [152]. Currently, there is no controller design that takes these communication delays into account and there is a need to design controllers that adapt to the communication delays.

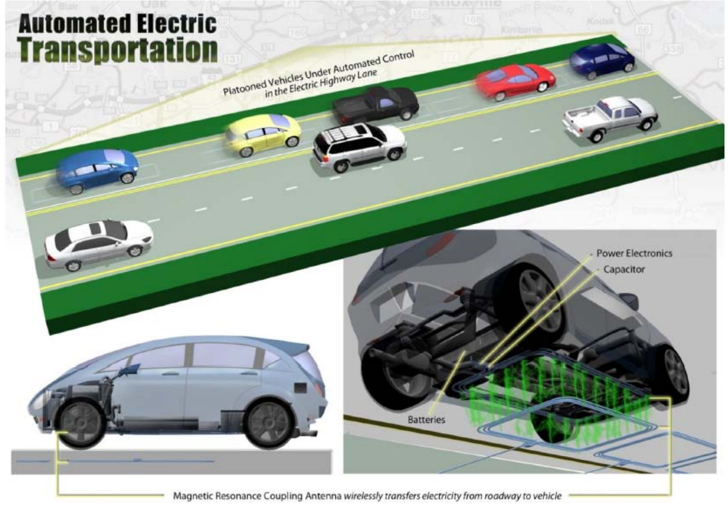

FIGURE 5. Platooning with AET [155]

AUTOMATED ELECTRIC TRANSPORTATION (AET)

This literature survey was conducted as a part of the ongoing DOE (Department of Energy) project which aims at developing a system that will:

a Provide energy directly to vehicles from electric highways, thus dramatically reducing their fuel consumption and CO_2 emission, and
b Automate control of the vehicles while on highways, reducing congestion, improving safety by removing the human element in driving, and produce new in-vehicle services.

This section describes this new concept briefly, which can be considered as an extension of the Intelligent Transportation System. AET is a new approach to transportation that integrates energy, vehicle, highway and communication infrastructures into a flexible, convenient, and Automated Electric Transportation system. Along with platooning, AET has the potential to reduce fuel consumption, carbon emissions, air pollution, traffic congestion and highway accidents. The AET concept centers around delivering energy on demand and in real time to moving vehicles, which facilitates increased research on wireless energy transfer using a phenomenon known as 'wireless inductive coupling'. This concept suggests that upgrading infrastructure by electrifying highway networks may be possible by eliminating the use of overhead wires which are in use today [153, 154]. Compared to present automobile scenario,the AET benefits will be seen as being faster,cheaper, greener,safer,comfortable,higher capacity and less congestion.

Potential Research Challenges

In developing a disruptive technological revolution like AET, significant technical, financial, institutional, and political

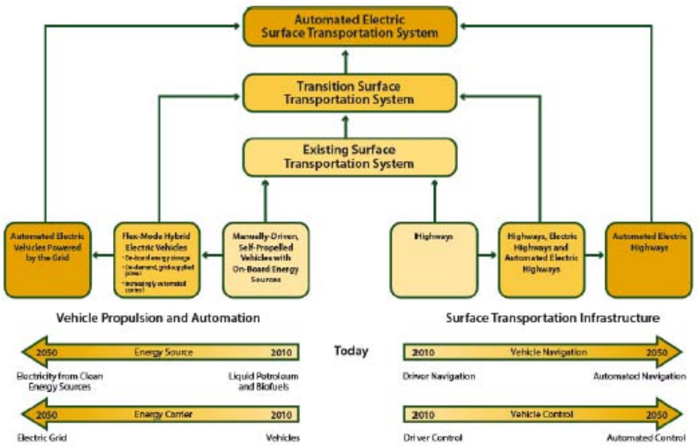

FIGURE 6. The Road to AET [155]

risks are inherent. Safe and efficient energy transfer from roadways to vehicles is in itself a fundamental challenge, and needs further research on "Inductive Power Transfer" methods. AET will also require the development of sophisticated software for performing critical safety related functions on road vehicles operating under a wide range of complicated operating conditions.

Apart from these technical challenges, there is a challenge posed by the architecture level change, which is more difficult for networked systems. Previous attempts of system level change in the transportation sector have failed partly because of inability to provide backwards compatibility to previous systems. Thus, a key challenge will be to develop ways to facilitate smooth transition from current system to an automated electrified transportation system [156–159].

CONCLUDING REMARKS

In this review article, we have categorized and discussed the Vehicle Platooning literature published between 1994 and 2010. Following a general introduction to platooning and a technical description of the concept, selected results were reviewed and we then classify the platooning literature into two broad divisions: application based and theory based.

From the categorization of application based results, we have found that platooning applications are mainly related to mobile robots, military, agriculture, underwater vehicles and aerospace.

From the survey of theory focused results, it is seen that platooning theory focuses broadly on inter-vehicle communication techniques in platoons, obstacle detection and collision avoidance techniques, lateral and longitudnal control strategies for platoons, trajectory planning methods and achieving string stability for a platoon.

The concept of platooning is a relatively new one and will take time to be accepted and incorporate into everyday life by common man. Furthermore, introduction of vehicle platooning without modifying existing infrastructure poses a challenge.

As a disclaimer, we would note again that while we tried to include as many Vehicle Platooning publications as we could find, the literature survey was more focused on the words 'vehicle platooning'. Thus, it is certain that we may have missed many important platooning publications. Nonetheless, we hope that the survey work performed in this paper can help the reader understand the overall trend of Vehicle Platooning in both applications and theory. We would like to repeat that research in platooning applications is still not active as compared with the purely theoretical works. We also agree that it is very difficult to have new industrial applications other than those which already exist but we still hope to see more publications that include successful platooning based applications. Finally, we hope to see the concept of platooning being incorporated in our every day life in the near future.

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