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A Review of Motion Planning Techniques for Automated Vehicles

David González, Joshué Pérez, Vicente Milanés and Fawzi Nashashibi

Abstract—Intelligent vehicles have increased their capabilities for highly, and even fully, automated driving under controlled environments. Scene information is received using on-board sensors and communication network systems—i.e. infrastructure and other vehicles. Considering the available information, different motion planning and control techniques have been implemented to autonomously driving on complex environments. The main goal is focused on executing strategies to improve safety, comfort and energy optimization. However, research challenges such as navigation in urban dynamic environments with obstacle avoidance capabilities—i.e. Vulnerable Road Users (VRU) and vehicles—and cooperative maneuvers among automated and semi-automated vehicles still need further efforts for a real environment implementation. This paper presents a review of motion planning techniques implemented in the intelligent vehicles literature. A description of the technique used by research teams, their contributions in motion planning and a comparison among these techniques is also presented. Relevant works in the overtaking and obstacle avoidance maneuvers is presented, allowing to understand the gaps and challenges to be addressed in the next years. Finally, an overview of future research direction and applications is given.

Index Terms—Motion planning, automated vehicles, path planning, intelligent transportation systems.

I. INTRODUCTION

The application of intelligent transportation systems is significantly aiding drivers, reducing some driving-associated tedious tasks. Specifically, highway driving has become safer thanks to the development of the Cruise Control (CC), Adaptive CC (ACC) and, lately, the Cooperative ACC (CACC) where both longitudinal actuators, throttle and brake pedals, are controlled using a pre-defined gap with the preceding vehicle [1]. For urban environments, systems like emergency braking with assistance of active suspension [2], automatic parking [3] or blind angle vehicle detection [4] are also contributing toward a safer driving in populated areas.

These systems improve safety, comfort, transport time and energy consumption. Such systems are known as advanced driving assistance system(ADAS). Fully automated driving capabilities, that is, vehicles able to drive by themselves without human interventions are an extension of current partial automated ADAS. As a matter of fact, recent demonstrations on automated driving are facing complex real scenarios. Implementations from Google (with more than 700.000 hours of automated driving in different environments), Daimler and Karlsruhe Institute of Technology (KIT), recreating the first cross-country automobile journey in history, in an autonomous way [5]; and Vislab and the University of Parma, showing

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automated driving capabilities in the PROUD project demo on 2013 [6], are some of the recent demonstrations with promising results regarding automated driving technologies. Despite of some remarkable results obtained up to now, there is still a long way to go before having fully automated vehicles on public roads, including technical and legal unsolved challenges [7].

Some initiatives launched between governments and manufacturers are currently creating the framework for the new standards and regulations for automated driving. As a matter of fact, some ongoing European initiatives address legal matters and promote the standardization of these technologies, as Citymobil2 project [8]. They got permission from local authorities for vehicle demonstrations, and some certification procedures were developed. In United States, already four states (Nevada, Florida, California and Michigan) and the District of Columbia recognize the importance of these technologies for future sustainable mobility and have enacted specific laws to allow automated driving in common traffic [9].

When it comes to develop automated vehicles, a literature review shows different proposed control architectures. Stanford and Carnegie Mellon University (CMU) [10] pioneered the implementation of fully automated vehicles in the Grand and Urban DARPA challenges. In Europe, the VIAC project [11] and Daimler with KIT [5] described the different processing stages needed for the control architecture of automated vehicles, where perception, decision and control are the most important. Figure 1 shows a general architecture for automated vehicles that can be extracted from earlier developments, including interconnections based on previous real automated vehicle implementations.

This work pays special attention to the decision stage in automated vehicles, presenting a state of the art in motion planning strategies. This topic has been extensively investigated in the literature, starting from the first developments in mobile robotics applications [12]. It is considered a key aspect for robot navigation since it provides global and local trajectory planning to describe the behavior of the robot. It considers the dynamic and kinematic models of the robot to go from a starting position to a final one. The main difference between vehicles and robots for carrying out motion planning are in the fact that the former addresses road networks where traffic rules have to be obeyed; whereas the latter has to cope with open environments without much specific rules to follow, only to reach the final destination.

This paper makes an overview of the state of the art implementation of motion planning techniques for automated driving. Section II presents an in-depth review of path planning techniques. Section III presents developments in automated driving by research groups worldwide, focusing in the description of the planning techniques applied in real demonstrations.

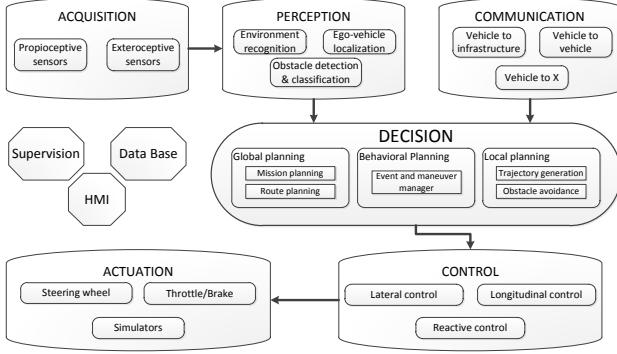


Fig. 1. Control architecture for automated vehicles. General abstraction based on: [5], [6], [10], [15], [16], [17] and [18].

An overview of the tendencies and orientation of the state-of-the-art according to research centers and industry developments is included. Finally, Section IV presents remaining challenges, current research direction from important researchers and manufacturers, including future steps in motion planning developments.

II. MOTION PLANNING STATE-OF-THE-ART

Intelligent vehicles development was very limited before the 90s because reduced investments in the field [13]. Thanks to evolution of information technology applicable to vehicle automation, the Intelligent Transportation Systems (ITS) concept was created. Different research centers around the world were oriented to this end (e.g. California PATH, Parma University, among others), improving intelligent vehicle systems. An overview of some important development events in automated navigation systems is presented in Section III.

A description of the first automated vehicles—[dating back to the late 80's and beginning of the 90's \(see also Fig. 3\)](#)—are mentioned by [13] and [14]. Shladover et al. [13] describe longitudinal control systems (including vehicle following control, inter-vehicular communications and a comparison between different methods), and lateral control systems (considering vehicle lateral dynamics and magnetic sensors as path reference with no path planning involved), in order to improve the Advance Highway Systems (AHS). Behringer et al. [14] describe the architecture proposed for the VaMoRs-L vehicle in the PROMETHEUS project. A vehicle that was able to perform automated driving, aided by vision and path generation algorithms.

Following these first implementations, different control architectures have been proposed for automated driving. In Fig. 1, perception, decision and control are the three main components of the software configuration. The main focus of this work is related to the decision component of the architecture, specifically path planning techniques in automated vehicles.

Path planning in mobile robotics has been a subject of study for the last decades. Most of the authors divide the problem into global and local planning. A review of the different approaches and concept definitions (as global, local or reactive motion planning) can be found in [19], [20] and [21].

A great amount of navigation techniques have been taken from mobile robotics and modified to face the challenges of road networks and driving rules. These planning techniques were classified in four groups, according to their implementation in automated driving: graph search, sampling, interpolating and numerical optimization (see Table I). The most relevant path planning algorithms implemented in motion planning for automated driving are described below.

A. Graph search based planners

In automated driving, the basic idea is to traverse a state space to get from point A to point B. This state space is often represented as an occupancy grid or lattice that depicts where objects are in the environment. From the planning point of view, a path can be set implementing graph searching algorithms that visit the different states in the grid, giving a solution (that not necessarily is the optimal one) or not (there is no possible solution) to the path planning problem. Some of these algorithms have been applied to the automated vehicles development.

Dijkstra algorithm: It is a graph searching algorithm that finds single-source shortest path in the graph. The configuration space is approximated as a discrete cell-grid space, lattices, among others (e.g. [22], [23]).

Description of the concept and implementation of the algorithm can be found in [24] and [25]. In automated driving, it has been implemented by [26] in multi-vehicles simulations, in the Little Ben vehicle (Ben Franklin racing team's entry to the Darpa Urban Challenge [27]) and also team VictorTango [28]. [An urban implementation is shown in Fig. 2a \[29\]](#).

A-star algorithm (A^{*}): It is a graph searching algorithm that enables a fast node search due to the implementation of heuristics (it is an extension of Dijkstra's graph search algorithm). Its most important design aspect is the determination of the cost function, which defines the weights of the nodes. It is suitable for searching spaces mostly known *a priori* by the vehicle [30], but costly in terms of memory and speed for vast areas.

Several applications in mobile robotics have used as basis for improvement, such as the dynamic A^{*} (D^{*}) [31], Field D^{*} [32], Theta^{*} [33], Anytime repairing A^{*} (ARA^{*}) and Anytime D^{*} (AD^{*}) [34], among others. Ziegler et.al. [35] implemented the A^{*} algorithm along with Voronoi cost functions for planning in unstructured spaces and parking lots. In [36] (hybrid A^{*}) and [37] (A^{*}), it served as part of the DARPA Urban Challenge in Junior ([Stanford University automated vehicle, see Fig. 2d](#)) and AnnieWAY (KIT) respectively. In [16] AD^{*} was used by Boss, the winning vehicle of the DARPA Urban Challenge.

State Lattice algorithm: The algorithm uses a discrete representation of the planning area with a grid of states (often a hyper-dimensional one). This grid is referred as *state lattice* over of which the motion planning search is applied [46]. The path search in this algorithm is based in local queries from a set of lattices or primitives containing all feasible features, allowing vehicles to travel from an initial state to several others. A cost function decides the best path between

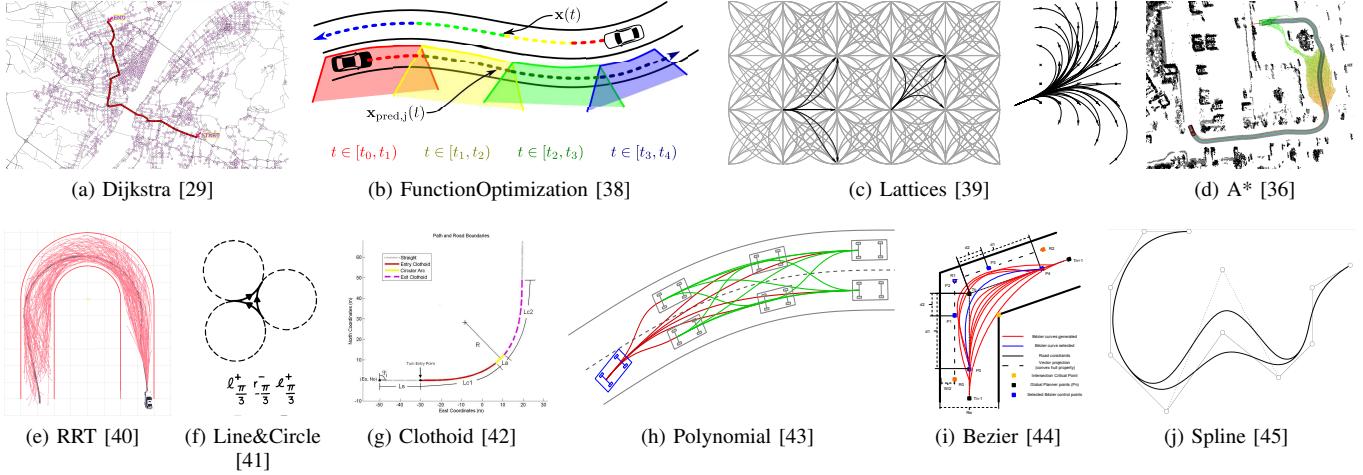


Fig. 2. Planning algorithms as presented in the literature. a) Representation of a global path by the Dijkstra algorithm in [29]. b) Trajectory optimization from [38], taking into account a vehicle in the other lane. c) Lattices and motion primitives as presented in [39]. d) Hybrid A* as implemented in the DARPA Challenge by Junior [36]. e) RRT* as showed in [40]. f) Optimal path to turn the vehicle around as proven in [41]. g) Planning a turn for the Audi TTS from Stanford [42]. h) Different motion states, planned with polynomial curves as presented in [43]. i) Evaluation of several Bézier curve in a turn, as showed in [44]. j) Spline behavior when a knot changes place, as presented in [45].

the precomputed lattices. A node search algorithm is applied in different implementations (e.g. A* in [47] or D* in [48]).

Howard and Kelly applied state lattices in rough terrains for a wheeled mobile robot [49], where simulations give promising results of global and local planning. Table I shows the authors reference for automated driving implementations divided in state and spatio-temporal lattices. Most of the works consider time and speed dimensions as [39] and [50]. A good example is presented in Fig. 2c from [39], where the nontemporal lattice is presented on the left and a finer discretization, on the right, also includes curvature.

B. Sampling based planners

These planners try to solve timing constraints—i.e. planning in high dimensional spaces—that deterministic methods can't meet. The approach consists on randomly sampling the configuration space or state space, looking for connectivity inside it [21]. The downside is the fact that the solution is suboptimal. The most commonly used methods in robotics are the Probabilistic Roadmap Method (PRM) [93] and the Rapidly-exploring Random Tree (RRT) [94]. The latter has been extensively tested for automated vehicles.

Rapidly-exploring Random Tree (RRT): It belongs to the sampling-based algorithms applicable to on-line path planning [95]. It allows a fast planning in semi structured spaces [94] by executing a random search through the navigation area. It also has the ability to consider non-holonomic constraints (such as maximum turning radius and momentum of the vehicle).

In [21] and [95] descriptions, applications and improvements of these algorithms are reviewed. In automated driving, it has been used for the MIT team at DARPA Urban Challenge [61]. However, the resulting path is not optimal, jerky and not curvature continuous. In Karaman et.al. [96] a new approach of this algorithm was developed, named RRT* (See Fig. 2e from [40]). This new implementation converges to an optimal solution but having the same disadvantages. First results are

shown in [64]. Further developments and implementations in automated vehicles are mentioned in Table I.

C. Interpolating Curve Planners

Techniques as Computer Aided Geometric Design (CAGD) are often used as path smoothing solutions for a given set of way-points [73]. These allow the motion planners to fit a given description of the road by considering feasibility, comfort, vehicle dynamics and other parameters in order to draw the trajectory.

Interpolation is defined as the process of constructing and inserting a new set of data within the range of a previously known set (reference points). This means that these algorithms take a previously set of knots (e.g. a given set of way-points describing a global road map), generating a new set of data (a smoother path) in benefit of the trajectory continuity, vehicle constraints and the dynamic environment the vehicle navigates [97]. In the presence of obstacles, it suffices to generate a new path to overcome the event and then re-enter the previously planned path. The interpolating curve planners implement different techniques for path smoothing and curve generation, being the most common in the automated driving field those indicated in Table I and II (see also Fig. 2f-j).

Lines and circles: Different segment road network can be represented by interpolating known way-points with straight and circular shapes. It is a simple mathematical method to approach the planning problem in car-like vehicles [41], [98]. An example is presented in Fig. 2f for the shortest path to turn around a vehicle to perform forward and backward driving.

Clothoid Curves: This type of curve is defined in terms of Fresnel integrals [73]. Using clothoid curves is possible to define trajectories with linear changes in curvature since their curvature is equal to their arc-length; making smooth transitions between straight segments to curved ones and vice versa (see Fig. 2g [42]). Clothoids have been implemented in

TABLE I
TAXONOMY OF MOTION PLANNING TECHNIQUES APPLIED IN AUTOMATED DRIVING SCENARIOS

Algorithm group	Technique	Technique description	Implemented in
Graph search based planners	Dijkstra's Algorithm	Known nodes/cells search space with associated weights	[27], [51], [52], [53]
		Grid and node/cells weights computation according to the environment	[28], [26]
	A* algorithm family	Anytime D* with Voronoi cost functions	[10], [16], [30]
		Hybrid-heuristics A*	[36], [54]
		A* with Voronoi/Lattice environment representation	[37], [35], [51]
		PAO* as in [55]	[56]
Sampling based planners	RRT	Environment decomposed in a local variable grid, depending on the complexity of the maneuver.	[16], [30], [46], [57]
		Spatio-temporal lattices (considering time and velocity dimensions)	[50], [58], [39], [59], [47], [60]
		Physical and logical bias are used to generate the random-tree	[61], [62], [63]
Interpolating curve planners	Line and circle	Anytime planning with RRT*	[64], [40], [53], [65].
		Trajectory coordination with RRT	[66]
		Road fitting and interpolation of known waypoints	[41], [67]
	Clothoid Curves	Piecewise trajectory generation with straight, clothoid and circular segments	[68], [42], [69], [70], [71], [72]
		Off-line generation of clothoid primitives from which the best will be taken in on-line evaluation	[73], [74], [14]
	Polynomial Curves	Cubic order polynomial curves Higher order polynomial curves	[75], [50] [76], [77], [78], [79], [80]
Numerical optimization approaches	Bézier Curves	Selection of the optimal control points location for the situation in hand	[81], [44], [82], [83], [79], [84]
		Rational Bézier curves implementation	[85], [86]
		Polynomial piecewise implementation Basis splines (b-splines)	[15], [76], [28] [87], [88], [89]
	Function optimization	Trajectory generation optimizing parameters such as speed, steering speed, rollover constraints, lateral accelerations, jerk (lateral comfort optimization), among others	[90], [91], [54], [5], [38], [92]

the design of highways and railways and are also suitable for car-like robots [99].

The implementation of clothoid primitives was tested in the VIAC project. In [69] the current curvature is taken from the steering wheel position and then the other profiles are evaluated taking into consideration the dynamic limitations (e.g. fishtailing) and the physical ones (e.g. the steering wheel).

Polynomial Curves: These curves are commonly implemented to meet the constraints needed in the points they interpolate, i.e. they are useful in terms of fitting position, angle and curvature constraints, among others. The desired values or constraints in the beginning and ending segment will determine the coefficients of the curve. For the computation of the polynomial coefficient, the reader is referred to [79], [76] and [77].

The Laboratory on Interactions between Vehicles, Infrastructure and Drivers (LIVIC) [77] implemented these curves for line change scenarios. Fourth degree polynomials were used for longitudinal constraints and fifth degree polynomials

for the lateral constraints, meeting the desired parameter for different scenarios. Also in [75] cubic polynomials where used to generate safe trajectories for overtaking maneuvers. In [43], **cubic (green line) and quartic (red line) polynomial curves are implemented with a state lattice planner (see Fig. 2h).**

Bézier Curves: These are parametric curves that rely on control points to define their shape. The core of Bézier curves are the Bernstein polynomials. These curves have been extensively used in CAGD applications, technical drawing, aeronautical and automotive design.

The advantage of this kind of curves is their low computational cost, since the curve behavior its defined by control points. The constraints at the beginning and the end of the curvature can be met by correctly placing these control points according to different properties described in [81], [100].

A good example of the modularity and malleability of Bézier curves is presented in [101], interconnecting circular shapes and also interconnecting Bézier curves with continuous curvature profiles in [102]. These curves are often used to

TABLE II
COMPARISON OF BENEFITS AND DISADVANTAGES IN MOTION PLANNING TECHNIQUES

Technique	Advantages	Disadvantages
Dijkstra's algorithm	Finds the shortest path in a series of nodes or grid. Suitable for global planning in structured and unstructured environments (Fig. 2a).	The algorithm is slow in vast areas due to the important amount of nodes. The search is not heuristic. The resulting path is not continuous. Not suitable for real time applications.
A* family	Based on the Dijkstra algorithm. The search is heuristic reducing computation time (Fig. 2d).	The resulting path is not continuous. The heuristic rule is not straightforward to find most of the times.
State lattices	Able to handle several dimensions (position, velocity, acceleration, time). Suitable for local planning and dynamic environments (Fig. 2c).	Computationally costly due to the evaluation of every possible solution in the database. The planner is only resolution complete (lattice discretization).
RRT family	Able to provide a fast solution in multi-dimensional systems. The algorithm is complete and always converges to a solution (if there is one and given enough time). Suitable for global and local planning, see Fig. 2e.	The resulting trajectory is not continuous and therefore jerky. The optimality of the path strongly depends of the time frame for the RRT* case.
Interpolating curve planner	Optimization of the curvature and smoothness of the path is achieved through the implementation of CAGD techniques (compared here below). Suitable for local planning oriented to comfort and safety in structured environments.	Depends on a global planning or global waypoints. Time consuming when managing obstacles in real time because the optimization of the path and consideration of road an ego-vehicle constraints.
Line and circle	Low computational cost. Simple to implement. Assures the shortest path for a car-like vehicle, see Fig. 2f.	The path is not continuous and therefore jerky, making non-comfortable transitions between segments of the path. The planner depends on global waypoints.
Clothoids	Transitions to and from curves are done with a linear change in curvature. Highways and road designs implement these curves. Suitable for local planning (see Fig. 2g).	Time consuming because of the integrals that define the curve. The curvature is continuous but not smooth (linear behavior). The planner depends on global waypoints.
Polynomials	Low computational cost. Continuous concatenations of curves are possible (Suitable for comfort).	Curves implemented are usually of 4th degree or higher, difficulting the computation of the coefficients to achieve a determined motion state.
Béziers	Low computational cost. Intuitive manipulation of the curve thanks to the control points that define it. Continuous concatenations of curves are possible (Suitable for comfort). See Fig. 2i.	Loss of malleability when increasing the curve degree, as well as the computation time increases (Thus, more control points have to be evaluated and correctly placed). The planner depends on global waypoints.
Splines	Low computational cost. The result is a general and continuous curvature path controlled by different knots (see Fig. 2j).	The solution might not be optimal (from the road fitness and curvature minimization point of view) because its result focuses more on achieving continuity between the parts than malleability to fit road constraints.
Function Optimization	Road and ego-vehicle constraints as well as other road users can be easily taken into account (Fig. 2b).	Time consuming since the optimization of the function takes place at each motion state. Therefore, the optimization is stopped at a given time horizon. The planner depends on global waypoints.

approximate clothoid curves [103], [104], or implementing rational Bézier curves for fast planning as in [85], [86]. In [81], [83] and [44] 3rd and 4th degree Béziers (see Fig. 2i) are implemented in automated vehicles, evaluating the best applicable curve to the situation in hand (i.e. turns, roundabouts, lane change, obstacle avoidance, among others).

Spline Curves: A spline is a piecewise polynomial parametric curve divided in sub-intervals that can be defined as polynomial curves [76], [28], b-splines [88], [89] (that can also be represented in Bézier curves [105]) or clothoid curves [99]. The junction between each sub-segment is called knot and they commonly possess a high degree of smoothness constraint at the joint between the pieces of the spline. An example of a b-spline with a changing knot is shown in Fig. 2j.

D. Numerical Optimization:

These methods aim to minimize or maximize a function subject to different constrained variables. In path planning is often used to smooth previously computed trajectories

as in [54] and also to compute trajectories from kinematic constraints [5].

Function optimization: This technique finds a real valued function's roots (minimize the variables outcome). It has been implemented to improve the potential field method (PFM) in mobile robotics for obstacles and narrow passages, obtaining C_1 continuity [106]. In [5], [38] it also aimed to find C_2 continuous trajectories by minimizing a function that considers position, velocity, acceleration and jerk as planning parameters (see Fig. 2b).

In Table I, a taxonomy of motion planning techniques implemented in automated vehicles is presented. It classifies the planning technique in each contribution according to the previously described algorithms. Table II complements Table I, giving a comprehensive review about the pros and cons of each planner technique.

These implementations show that the first steps for automated driving have already been set. Different architectures implement motion planners in order to have a safe and continuous path to follow. To mitigate or eliminate risky

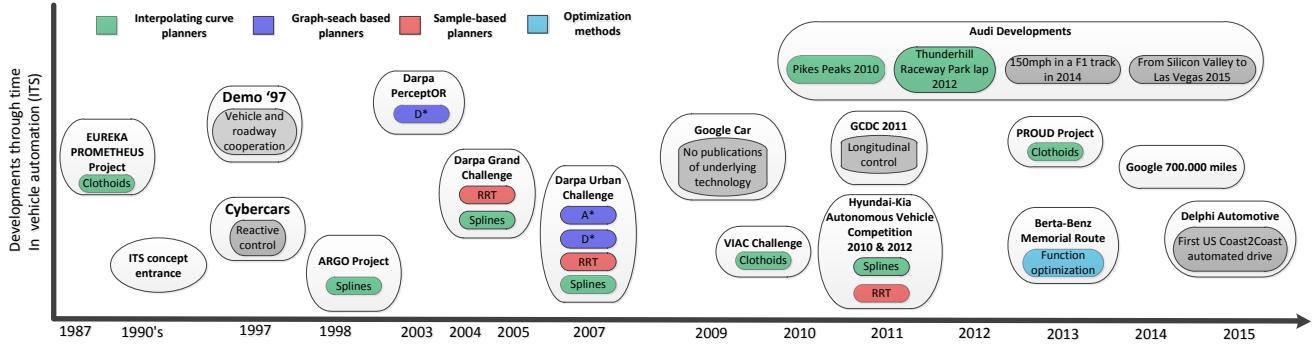


Fig. 3. Timeline with important automated vehicle demonstrations through time and their associated planning techniques.

situations (such as dynamic obstacle avoidance, emergency situations, intersection and merging negotiation, among others) is the current focus in the literature. The consideration of perception limitations (uncertainty in measurements) and control needs for safety and comfort are key aspects in future steps. Some works have already considered such parameters, by generating driving corridors and trajectory proposals that can be communicated to the driver by an HMI [77], [107]. Others consider the uncertainty in data acquisition [108], communications [109] and even future behavior prediction [110] to avoid situations like the MIT-Cornell collision in the Darpa Urban Challenge [111].

III. MOTION PLANNING DEVELOPMENTS BY ITS GROUPS WORLDWIDE

Although the idea of intelligent vehicles began in 1939 at New York world fair with GM's *Futurama* presentation, it took decades to become the idea in a reality. Figure 3 shows a timeline with important demonstrations and developments in vehicle automation up to this date. The EUREKA-PROMETHEUS project pionnered in Europe this research between 1987 and 1994, where different vehicles from industrial partners such as Volvo and Daimler were automated. Clothoid paths were implemented in curved segments to aid the control system to follow the route [14].

The PATH program presented its platooning demonstration as part of the Demo '97 at San Diego CA, in cooperation with GM [112]. It consisted on an eight vehicle platoon in a dedicated lane with vehicle inter-distances of 6m. Carnegie Mellon University participated as well, providing the free agent demonstration with their Navlab vehicles [113]. Also in the same year, a presentation in The Netherlands introduced the first operational service of CTS [114], using shuttle services at Schiphol airport. CTS addressed the last mile problem providing a door-to-door and on-demand service [115]. In the systems above described, reactive control and vehicle-roadway cooperation were preferred over path planning techniques.

One of the first projects to test path planning techniques was the ARGO project from VisLab [76]. With a vision-based system, the planning technique consisted in adjusting quintic polynomial splines into the lane markings detected by the front camera. Later, the Darpa PerceptOR program stimulated

the development of automated navigation techniques for off-road vehicles [116],[117]. This was achieved by the Darpa Challenges (Grand and Urban challenge) that encouraged the research in automated navigation systems, developing path planning techniques (see Fig. 3).

The first Google Car made its entrance in 2009. Google driverless cars have carried out several public exhibitions showing the automated capabilities of their vehicles, achieving more than 700.000¹ miles of travel without accidents attributed to automation. Google also pushed for the legislation of this kind of technology, receiving the first license for an automated vehicle in May 2012 (two months after the state of Nevada enacted the first automated vehicle law) [118]. Unfortunately there are no publications about the motion planning or control techniques that have been used to achieve those results.

The VisLab International Autonomous Challenge (VIAC) was carried out in 2010 [11]. 13.000km traveled from Italy (Parma) to China (Shanghai) in autonomous mode, where the planning consisted on a cost function that considered clothoid curve generation [69]. In the same year and also in 2012, the Hyundai Motor Group organized their own automated vehicle competitions in Korea. The 2010 challenge focused in path following and obstacle avoidance. The 2012 challenge focused in understanding urban driving and detecting traffic signals [17]. Motion planning techniques included clothoids [119],[18], RRT [120], among others.

The European Grand Cooperative Driving Challenge (GCDC) in 2011 promoted longitudinal vehicle control [143]. Nonetheless, some teams have already developed path planning strategies (such as state lattices by AnnieWAY [131]). In this sense, there is a call for a second edition of the GCDC Challenge in 2016², where lateral control in platoon, busy road merging and urban environments will be considered.

Recently, Audi presented high performance vehicle control in a conjoint effort with Stanford [42], [144], implementing clothoids to plan curved segments. Among the demonstrations: 1) the climb of Pikes Peak in 2010; 2) a racing lap at the Thunderhill Raceway Park in 2012, reaching 150mph in a F1 track in 2014³; and 3) automated driving in real scenarios from

¹ Available online at: <http://goo.gl/a90d1l>

² Available online at: <http://www.gcdc.net/>

³ Available online at: <http://goo.gl/g2eJ50>

TABLE III
INTERNATIONAL ITS RESEARCH GROUPS

Team / Program	Main Focus	Related work
Carnegie Mellon University	One of the first robotic center to focus in ITS. Key player of Demo '97 and different Darpa Challenges. Motion planning research is focused in graph search algorithms as D* and state lattices.	Demo '97 [113], DARPA PerceptOR [116], Grand Challenge [121], Urban Challenge[10],[16], D* [31], [32], state lattices [46], [57], [50], [92], [58], automated driving platform [122], [123], [108]
Google	Automated driving in urban and highway navigation, where many challenges are still unsolved. Their vehicles rely on extensively mapped driveways for motion planning.	Publications only by videos or talks, however their results are remarkable enough to be considered as the main private developer of automated vehicles [118].
Hanyang University	Winners of the Hyundai Motor Group 2012 Autonomous vehicle competition (their vehicle is called A1). Laser and camera data fusion with spline interpolation as its main motion planning technique.	[119], [120], [18], [17]
Inria	Research in perception, control, communications and traffic modeling for sustainable mobility. Planning methods focus in polynomial, Bézier curves, clothoids and RRT. Door-to-door and on-demand applications (Cybercars)	Clothoids [68], RRT [124], [125], Cybercars [115], [126], control architecture [127], overtaking maneuvers [128], [75], [44],
Karlsruhe Institute of Technology	Participants of the Darpa Urban Challenge. Motion planning research begins with graph search algorithms (A* and spatiotemporal lattices) and recent implementations move toward numerical optimization approaches.	Behavioral planning [129], Darpa Urban Challenge [35], [37], state lattices [39], [59], cooperation with Stanford [130], Grand Cooperative Driving Challenge [131], Berta-Benz Memorial route [5]
Massachusetts Institute of Technology	Rapidly-exploring Random Tree has been the motion planning technique implemented by MIT since its entry to the Darpa Urban Challenge. Today its knowledge is applied to industrial and safety applications with some spin-offs as nuTonomy.	Darpa Urban Challenge [132], [61], industrial [64] and safety applications [53], [65].
Parma University / Vislab	Focused in perception by vision, this group has been around since the Eureka-Prometheus project. Motion planning techniques include splines (ARGO), RRT (Darpa Challenges), and more recently clothoids (VIAC and PROUD projects)	The Argo project [133], [76], Darpa Grand Challenge [62], Urban Challenge [51], VIAC project [134], [69], [11], future vision [6], PROUD project [135], [136]
California Path	One of the first ITS research center in the world (focused in automated highways systems), and key participant in Demo '97. Motion planning is mostly infrastructure dependent, with robust control techniques for path following.	Demo '97 [112], [113], Path at 2007 [137]
Stanford University	From Darpa Grand and Urban challenges to an automated Audi TTS that can drift, is clear Stanford is present in the ITS development. Motion planning techniques include the A* family, optimization via conjugate gradient and more recently interpolation by clothoids	Darpa Grand Challenge [15], Urban Challenge [36], [54], [138], automated driving platform [139], [42], cooperation with other research institutes [130], [140]
OEMs	Automakers that have contributed in the ITS development. Planning strategies include interpolation by Bézier and clothoid curves, state lattices, the A* family, RRT, numerical path optimization, among others.	Toyota [83], BMW [141], [59], GMC [112], [113], [10], [50], [58], [78], Daimler [14], [80], [5], Volkswagen Group [15], [36], [42], [60], Hyundai-Kia Group [120], [119], Renault [70], Oshkosh Truck Corp. [51], [62], Volvo Group [142].

Silicon Valley to Las Vegas in 2015⁴. Also in 2015, Delphi Automotive made the first coast to coast driving in the US⁵, going from San Francisco to New York in 9 days. In Table III an overview of international research groups is presented.

IV. DISCUSSION

The development of intelligent planning algorithms is one of the key issues when designing robotic architectures [20], [21]. The associated constraints in the automated vehicle research area—i.e. traffic rules, high speeds or road layout—turn real-time motion planning in a critical aspect for achieving

automated driving on complex environments. This work has reviewed the motion planning state of the art from two points of view: 1) considering the different techniques (see Table I), there are four main algorithms: graph-search, sample-based, interpolation and numerical optimization; 2) considering the worldwide research groups that have implemented motion planning techniques on automated vehicles, testing the behavior on real roads (see Table III).

There are two main algorithms that have been recently used by research groups in real implementations:

- Most of research groups implement interpolation to solve the planning problems. Specifically, recent demonstrations have used clothoids (Audi, Parma/Vislab or Stan-

⁴ Available online at: <https://goo.gl/voT0cb>

⁵ Available online at: <http://www.delphi.com/delphi-drive>

ford), Bézier curves (Inria) and polynomial curves (Daimler or Inria). The main reason for choosing this technique is because an enhanced map in structured environments can provide the needed way-points—i.e. GPS data. Then, optimal curves in terms of smoothness, continuity, vehicle constraints, speed and comfort are generated.

- Graph search is the second algorithm most applied when dealing with real implementations. Specifically, state lattices is the most used one—i.e. CMU, KIT, GMC. The main reason for choosing this technique is because a fast search of the optimal path can be performed in real-time, considering comfort, safety and vehicle constraints although the solution is only resolution complete (depends on the resolution of the underlying grid/lattice).

Current challenges are associated to real-time planning calculation on dynamic environments. Urban scenarios where multiple agents—i.e. pedestrians, cyclists, other vehicles—have to be taken into account, require a continuous evaluation (and re-calculation) of the determined trajectories. The limited time for generating a new free collision trajectory with multiple dynamic obstacles is an unsolved challenge. This is mainly caused by the time-consuming perception algorithms [145], reducing dramatically the motion planning decision window. Current implementations are not able to overcome this limitation yet.

Since planning stage is the link between perception and control, current works considers both: perception uncertainties and control constrains when developing new path planning algorithms. Recent developments in path planning aim to properly handle the uncertainty in the data acquisition process for dynamic environments. This permits to have a better environment understanding in real-time, giving the planning process the ability to prevent dangerous situations by considering uncertainties on the acquisition/perception stages of the architecture. From the control point of view, multiple constrains have to be considered, ranging from vehicle kinematic limitations up to passengers' comfort. Recent developments aim to consider some of these constrains in the planning stage leading to smooth and achievable trajectories, reducing control stage constrains. Next steps should be focused on developing algorithms able to fuse perception uncertainties with control constraints. This work has been already started by KIT [5] and CMU [108].

A new trend on the automated vehicle research is to add the driver in the control loop. From the path planning research perspective, the trajectory is communicated to the driver using an HMI, acting as an ADAS [77], [107]. This creates a new research challenge by multi-fusing perception uncertainties, control constrains and driver knowledge when generating safe, smooth and achievable trajectories.

ACKNOWLEDGMENT

Authors wants to thank to the ARTEMIS project DESERVE and FP7 CityMobil2 for its support in the development of this work.

REFERENCES

- [1] V. Milanés, S. Shladover, J. Spring, C. Nowakowski, H. Kawazoe, and M. Nakamura, "Cooperative adaptive cruise control in real traffic situations," *Intelligent Transportation Systems, IEEE Transactions on*, vol. 15, no. 1, pp. 296–305, Feb 2014.
- [2] J.-S. Lin and W.-E. Ting, "Nonlinear control design of anti-lock braking systems with assistance of active suspension," *Control Theory Applications, IET*, vol. 1, no. 1, pp. 343–348, January 2007.
- [3] T. hua Hsu, J.-F. Liu, P.-N. Yu, W.-S. Lee, and J.-S. Hsu, "Development of an automatic parking system for vehicle," in *Proc. IEEE Vehicle Power and Propulsion Conf. VPPC '08*, 2008, pp. 1–6.
- [4] R. OMalley, M. Glavin, and E. Jones, "Vision-based detection and tracking of vehicles to the rear with perspective correction in low-light conditions," *IET Intelligent Transport Systems*, vol. 5, no. 1, pp. 1–10, 2011.
- [5] J. Ziegler, P. Bender, M. Schreiber, H. Lategahn, T. Strauss, C. Stiller, T. Dang, U. Franke, N. Appenrodt, C. Keller, E. Kaus, R. Herrtwich, C. Rabe, D. Pfeiffer, F. Lindner, F. Stein, F. Erbs, M. Enzweiler, C. Knoppel, J. Hipp, M. Haueis, M. Trepte, C. Brenk, A. Tamke, M. Ghanaat, M. Braun, A. Joos, H. Fritz, H. Mock, M. Hein, and E. Zeeb, "Making bertha drive —an autonomous journey on a historic route," *Intelligent Transportation Systems Magazine, IEEE*, vol. 6, no. 2, pp. 8–20, Summer 2014.
- [6] A. Broggi, M. Buzzoni, S. Debbattisti, P. Grisleri, M. Laghi, P. Medici, and P. Versari, "Extensive tests of autonomous driving technologies," *Intelligent Transportation Systems, IEEE Transactions on*, vol. 14, no. 3, pp. 1403–1415, Sept 2013.
- [7] M. Van Schijndel-de Nooitj, B. Krosse, T. Van den Broek, S. Maas, E. Van Nunen, H. Zwijnenberg, A. Schieben, H. Mosebach, N. Ford, M. McDonald, and J. Sanchez, "Definition of necessary vehicle and infrastructure systems for automated driving," *SMART 2010/0064 European Commission*, 2011.
- [8] J. van Dijke and M. van Schijndel, "Citymobil, advanced transport for the urban environment: Update," *Transportation Research Record: Journal of the Transportation Research Board*, no. 2324, pp. 29–36, 2012.
- [9] B. Walker Smith, "Automated driving: Legislative and regulatory action," *The Center for Internet and Society, Tech. Rep.*, 2013.
- [10] C. Urmson, J. Anhalt, D. Bagnell, C. Baker, R. Bittner, M. Clark, J. Dolan, D. Duggins, T. Galatali, C. Geyer *et al.*, "Autonomous driving in urban environments: Boss and the urban challenge," *Journal of Field Robotics*, vol. 25, no. 8, pp. 425–466, 2008.
- [11] M. Bertozzi, L. Bombini, A. Broggi, M. Buzzoni, E. Cardarelli, S. Cattani, P. Cerri, A. Coati, S. Debbattisti, A. Falzoni *et al.*, "Viac: An out of ordinary experiment," in *Intelligent Vehicles Symposium (IV), 2011 IEEE*. IEEE, 2011, pp. 175–180.
- [12] S. Han, B. Choi, and J. Lee, "A precise curved motion planning for a differential driving mobile robot," *Mechatronics*, vol. 18, no. 9, pp. 486 – 494, 2008. [Online]. Available: <http://www.sciencedirect.com/science/article/pii/S0957415808000512>
- [13] S. E. Shladover, C. A. Desoer, J. K. Hedrick, M. Tomizuka, J. Walrand, W.-B. Zhang, D. H. McMahon, H. Peng, S. Sheikholeslam, and N. McKeown, "Automated vehicle control developments in the path program," *Vehicular Technology, IEEE Transactions on*, vol. 40, no. 1, pp. 114–130, 1991.
- [14] R. Behringer and N. Muller, "Autonomous road vehicle guidance from autobahnen to narrow curves," *Robotics and Automation, IEEE Transactions on*, vol. 14, no. 5, pp. 810–815, 1998.
- [15] S. Thrun, M. Montemerlo, H. Dahlkamp, D. Stavens, A. Aron, J. Diebel, P. Fong, J. Gale, M. Halpenny, G. Hoffmann *et al.*, "Stanley: The robot that won the darpa grand challenge," *Journal of field Robotics*, vol. 23, no. 9, pp. 661–692, 2006.
- [16] D. Ferguson, T. M. Howard, and M. Likhachev, "Motion planning in urban environments," *Journal of Field Robotics*, vol. 25, no. 11–12, pp. 939–960, 2008.
- [17] K. Jo, J. Kim, D. Kim, C. Jang, and M. Sunwoo, "Development of autonomous car–part i: Distributed system architecture and development process," *Industrial Electronics, IEEE Transactions on*, no. 12, Dec 2014.
- [18] ———, "Development of autonomous car–part ii: A case study on the implementation of an autonomous driving system based on distributed architecture," *Industrial Electronics, IEEE Transactions on*, 2015.
- [19] V. Kunchev, L. Jain, V. Ivancevic, and A. Finn, "Path planning and obstacle avoidance for autonomous mobile robots: A review," in *Knowledge-Based Intelligent Information and Engineering Systems*. Springer, 2006, pp. 537–544.

- [20] Y. K. Hwang and N. Ahuja, "Gross motion planninga survey," *ACM Computing Surveys (CSUR)*, vol. 24, no. 3, pp. 219–291, 1992.
- [21] M. Elbanhawi and M. Simic, "Sampling-based robot motion planning: A review," *Access, IEEE*, vol. 2, pp. 56–77, 2014.
- [22] F. Marchese, "Multiple mobile robots path-planning with mca," in *Autonomic and Autonomous Systems, 2006. ICAS '06. 2006 International Conference on*, July 2006, pp. 56–56.
- [23] S. LaValle and S. Hutchinson, "Optimal motion planning for multiple robots having independent goals," *Robotics and Automation, IEEE Transactions on*, vol. 14, no. 6, pp. 912–925, Dec 1998.
- [24] S. M. LaValle, *Planning algorithms*. Cambridge university press, 2006.
- [25] J. Y. Hwang, J. S. Kim, S. S. Lim, and K. H. Park, "A fast path planning by path graph optimization," *Systems, Man and Cybernetics, Part A: Systems and Humans, IEEE Transactions on*, vol. 33, no. 1, pp. 121–129, Jan 2003.
- [26] R. Kala and K. Warwick, "Multi-level planning for semi-autonomous vehicles in traffic scenarios based on separation maximization," *Journal of Intelligent & Robotic Systems*, vol. 72, no. 3-4, pp. 559–590, 2013. [Online]. Available: <http://dx.doi.org/10.1007/s10846-013-9817-7>
- [27] J. Bohren, T. Foote, J. Keller, A. Kushleyev, D. Lee, A. Stewart, P. Vernaza, J. Derenick, J. Spletzer, and B. Satterfield, "Little ben: The ben franklin racing team's entry in the 2007 darpa urban challenge," *Journal of Field Robotics*, vol. 25, no. 9, pp. 598–614, 2008. [Online]. Available: <http://dx.doi.org/10.1002/rob.20260>
- [28] A. Bacha, C. Bauman, R. Faruque, M. Fleming, C. Terwelp, C. Reinholz, D. Hong, A. Wicks, T. Alberi, D. Anderson *et al.*, "Odin: Team victortango's entry in the darpa urban challenge," *Journal of Field Robotics*, vol. 25, no. 8, pp. 467–492, 2008.
- [29] Q. Li, Z. Zeng, B. Yang, and T. Zhang, "Hierarchical route planning based on taxi gps-trajectories," in *Geoinformatics, 2009 17th International Conference on*, Aug 2009, pp. 1–5.
- [30] M. Likhachev and D. Ferguson, "Planning long dynamically feasible maneuvers for autonomous vehicles," *The International Journal of Robotics Research*, vol. 28, no. 8, pp. 933–945, 2009.
- [31] A. Stentz, "Optimal and efficient path planning for partially-known environments," in *Robotics and Automation, 1994. Proceedings., 1994 IEEE International Conference on*. IEEE, 1994, pp. 3310–3317.
- [32] D. Ferguson and A. Stentz, "Using interpolation to improve path planning: The field d* algorithm," *Journal of Field Robotics*, vol. 23, no. 2, pp. 79–101, 2006.
- [33] A. Nash, K. Daniel, S. Koenig, and A. Felner, "Theta^{*}: Any-angle path planning on grids," in *Proceedings of the National Conference on Artificial Intelligence*, vol. 22, no. 2. Menlo Park, CA; Cambridge, MA; London; AAAI Press; MIT Press; 1999, 2007, p. 1177.
- [34] M. Likhachev, D. Ferguson, G. Gordon, A. Stentz, and S. Thrun, "Anytime search in dynamic graphs," *Artificial Intelligence*, vol. 172, no. 14, pp. 1613–1643, 2008.
- [35] J. Ziegler, M. Werling, and J. Schroder, "Navigating car-like robots in unstructured environments using an obstacle sensitive cost function," in *Intelligent Vehicles Symposium, 2008 IEEE*. IEEE, 2008, pp. 787–791.
- [36] M. Montemerlo, J. Becker, S. Bhat, H. Dahlkamp, D. Dolgov, S. Etinger, D. Haehnel, T. Hilden, G. Hoffmann, B. Huhnke *et al.*, "Junior: The stanford entry in the urban challenge," *Journal of field Robotics*, vol. 25, no. 9, pp. 569–597, 2008.
- [37] S. Kammel, J. Ziegler, B. Pitzer, M. Werling, T. Gindole, D. Jagzent, J. Schröder, M. Thuy, M. Goebel, F. v. Hundelshausen *et al.*, "Team annieway's autonomous system for the 2007 darpa urban challenge," *Journal of Field Robotics*, vol. 25, no. 9, pp. 615–639, 2008.
- [38] J. Ziegler, P. Bender, T. Dang, and C. Stiller, "Trajectory planning for bertha—a local, continuous method," in *Intelligent Vehicles Symposium Proceedings, 2014 IEEE*. IEEE, 2014, pp. 450–457.
- [39] J. Ziegler and C. Stiller, "Spatiotemporal state lattices for fast trajectory planning in dynamic on-road driving scenarios," in *Intelligent Robots and Systems, 2009. IROS 2009. IEEE/RSJ International Conference on*. IEEE, 2009, pp. 1879–1884.
- [40] J. hwan Jeon, R. Cowlagi, S. Peters, S. Karaman, E. Frazzoli, P. Tsotras, and K. Iagnemma, "Optimal motion planning with the half-car dynamical model for autonomous high-speed driving," in *American Control Conference (ACC), 2013*, June 2013, pp. 188–193.
- [41] J. Reeds and L. Shepp, "Optimal paths for a car that goes both forwards and backwards," *Pacific Journal of Mathematics*, vol. 145, no. 2, pp. 367–393, 1990.
- [42] J. Funke, P. Theodosis, R. Hindiyeh, G. Stanek, K. Kritatikarana, C. Gerdes, D. Langer, M. Hernandez, B. Muller-Bessler, and B. Huhnke, "Up to the limits: Autonomous audi tts," in *Intelligent Vehicles Symposium (IV), 2012 IEEE*, June 2012, pp. 541–547.
- [43] W. Xu, J. Wei, J. Dolan, H. Zhao, and H. Zha, "A real-time motion planner with trajectory optimization for autonomous vehicles," in *Robotics and Automation (ICRA), 2012 IEEE International Conference on*, May 2012, pp. 2061–2067.
- [44] D. Gonzalez, J. Perez, R. Lattarulo, V. Milanes, and F. Nashashibi, "Continuous curvature planning with obstacle avoidance capabilities in urban scenarios," in *Intelligent Transportation Systems (ITSC), 2014 IEEE 17th International Conference on*, Oct 2014, pp. 1430–1435.
- [45] R. T. Farouki, *PythagoreanHodograph Curves*. Springer, 2008.
- [46] M. Pivtoraiko and A. Kelly, "Efficient constrained path planning via search in state lattices," in *International Symposium on Artificial Intelligence, Robotics, and Automation in Space*, 2005.
- [47] A. Kushleyev and M. Likhachev, "Time-bounded lattice for efficient planning in dynamic environments," in *Robotics and Automation, 2009. ICRA'09. IEEE International Conference on*. IEEE, 2009, pp. 1662–1668.
- [48] M. Rufli, R. Siegwart, R. Y. Siegwart, and R. Y. Siegwart, "On the application of the d* search algorithm to time-based planning on lattice graphs," *ECMR*, vol. 9, pp. 105–110, 2009.
- [49] T. M. Howard and A. Kelly, "Optimal rough terrain trajectory generation for wheeled mobile robots," *The International Journal of Robotics Research*, vol. 26, no. 2, pp. 141–166, 2007. [Online]. Available: <http://ijr.sagepub.com/content/26/2/141.abstract>
- [50] M. McNaughton, C. Urmson, J. Dolan, and J.-W. Lee, "Motion planning for autonomous driving with a conformal spatiotemporal lattice," in *Robotics and Automation (ICRA), 2011 IEEE International Conference on*, May 2011, pp. 4889–4895.
- [51] Y.-L. Chen, V. Sundareswaran, C. Anderson, A. Broggi, P. Grisleri, P. P. Porta, P. Zani, and J. Beck, "Terramax: Team oshkosh urban robot," *Journal of Field Robotics*, vol. 25, no. 10, pp. 841–860, 2008. [Online]. Available: <http://dx.doi.org/10.1002/rob.20267>
- [52] B. J. Patz, Y. Papelis, R. Pillat, G. Stein, and D. Harper, "A practical approach to robotic design for the darpa urban challenge," *Journal of Field Robotics*, vol. 25, no. 8, pp. 528–566, 2008. [Online]. Available: <http://dx.doi.org/10.1002/rob.20251>
- [53] S. J. Anderson, S. B. Karumanchi, and K. Iagnemma, "Constraint-based planning and control for safe, semi-autonomous operation of vehicles," in *Intelligent Vehicles Symposium (IV), 2012 IEEE*. IEEE, 2012, pp. 383–388.
- [54] D. Dolgov, S. Thrun, M. Montemerlo, and J. Diebel, "Path planning for autonomous vehicles in unknown semi-structured environments," *The International Journal of Robotics Research*, vol. 29, no. 5, pp. 485–501, 2010. [Online]. Available: <http://ijr.sagepub.com/content/29/5/485.abstract>
- [55] D. Ferguson, A. Stentz, and S. Thrun, "Pao for planning with hidden state," in *Robotics and Automation, 2004. Proceedings. ICRA '04. 2004 IEEE International Conference on*, vol. 3, April 2004, pp. 2840–2847 Vol.3.
- [56] I. Miller, M. Campbell, D. Huttenlocher, F.-R. Kline, A. Nathan, S. Lupashin, J. Catlin, B. Schimpf, P. Moran, N. Zych, E. Garcia, M. Kurdziel, and H. Fujishima, "Team cornell's skynet: Robust perception and planning in an urban environment," *Journal of Field Robotics*, vol. 25, no. 8, pp. 493–527, 2008. [Online]. Available: <http://dx.doi.org/10.1002/rob.20253>
- [57] T. M. Howard, C. J. Green, A. Kelly, and D. Ferguson, "State space sampling of feasible motions for high-performance mobile robot navigation in complex environments," *Journal of Field Robotics*, vol. 25, no. 6-7, pp. 325–345, 2008. [Online]. Available: <http://dx.doi.org/10.1002/rob.20244>
- [58] T. Gu, J. Snider, J. Dolan, and J. woo Lee, "Focused trajectory planning for autonomous on-road driving," in *Intelligent Vehicles Symposium (IV), 2013 IEEE*, June 2013, pp. 547–552.
- [59] M. Werling, S. Kammel, J. Ziegler, and L. Grll, "Optimal trajectories for time-critical street scenarios using discretized terminal manifolds," *The International Journal of Robotics Research*, 2011.
- [60] P. Furgale, U. Schwesinger, M. Rufli, W. Derendarz, H. Grimmelt, P. Muhlfellner, S. Wonneberger, J. Timpner, S. Rottmann, B. Li, B. Schmidt, T. Nguyen, E. Cardarelli, S. Cattani, S. Bruning, S. Horstmann, M. Stellmacher, H. Mielenz, K. Koser, M. Beermann,

- C. Hane, L. Heng, G. H. Lee, F. Fraundorfer, R. Iser, R. Triebel, I. Posner, P. Newman, L. Wolf, M. Pollefeyns, S. Brosig, J. Effertz, C. Pradalier, and R. Siegwart, "Toward automated driving in cities using close-to-market sensors: An overview of the v-charge project," in *Intelligent Vehicles Symposium (IV), 2013 IEEE*, June 2013, pp. 809–816.
- [61] Y. Kuwata, S. Karaman, J. Teo, E. Frazzoli, J. How, and G. Fiore, "Real-time motion planning with applications to autonomous urban driving," *Control Systems Technology, IEEE Transactions on*, vol. 17, no. 5, pp. 1105–1118, Sept 2009.
- [62] D. Braid, A. Broggi, and G. Schmiedel, "The terramax autonomous vehicle," *Journal of Field Robotics*, vol. 23, no. 9, pp. 693–708, 2006. [Online]. Available: <http://dx.doi.org/10.1002/rob.20140>
- [63] J.-H. Ryu, D. Ogay, S. Bulavintsev, H. Kim, and J.-S. Park, "Development and experiences of an autonomous vehicle for high-speed navigation and obstacle avoidance," in *Frontiers of Intelligent Autonomous Systems*. Springer, 2013, pp. 105–116.
- [64] S. Karaman, M. R. Walter, A. Perez, E. Frazzoli, and S. Teller, "Anytime motion planning using the rrt*," in *Robotics and Automation (ICRA), 2011 IEEE International Conference on*. IEEE, 2011, pp. 1478–1483.
- [65] G. S. Aoude, B. D. Luders, D. S. Levine, and J. P. How, "Threat-aware path planning in uncertain urban environments," in *Intelligent Robots and Systems (IROS), 2010 IEEE/RSJ International Conference on*. IEEE, 2010, pp. 6058–6063.
- [66] R. Kala and K. Warwick, "Planning of multiple autonomous vehicles using rrt," in *Cybernetic Intelligent Systems (CIS), 2011 IEEE 10th International Conference on*, Sept 2011, pp. 20–25.
- [67] M. F. Hsieh and U. Ozguner, "A parking algorithm for an autonomous vehicle," in *Intelligent Vehicles Symposium, 2008 IEEE*, June 2008, pp. 1155–1160.
- [68] T. Fraichard and A. Scheuer, "From reeds and shepp's to continuous-curvature paths," *Robotics, IEEE Transactions on*, vol. 20, no. 6, pp. 1025–1035, Dec 2004.
- [69] A. Broggi, P. Medici, P. Zani, A. Coati, and M. Panciroli, "Autonomous vehicles control in the vislab intercontinental autonomous challenge," *Annual Reviews in Control*, vol. 36, no. 1, pp. 161 – 171, 2012. [Online]. Available: <http://www.sciencedirect.com/science/article/pii/S1367578812000132>
- [70] H. Vorobieva, N. Minoiu-Enache, S. Glaser, and S. Mammar, "Geometric continuous-curvature path planning for automatic parallel parking," in *Networking, Sensing and Control (ICNSC), 2013 10th IEEE International Conference on*, April 2013, pp. 418–423.
- [71] H. Vorobieva, S. Glaser, N. Minoiu-Enache, and S. Mammar, "Automatic parallel parking with geometric continuous-curvature path planning," in *Intelligent Vehicles Symposium Proceedings, 2014 IEEE*, June 2014, pp. 465–471.
- [72] H. Fuji, J. Xiang, Y. Tazaki, B. Levedahl, and T. Suzuki, "Trajectory planning for automated parking using multi-resolution state roadmap considering non-holonomic constraints," in *Intelligent Vehicles Symposium Proceedings, 2014 IEEE*, June 2014, pp. 407–413.
- [73] M. Brezak and I. Petrovic, "Real-time approximation of clothoids with bounded error for path planning applications," *Robotics, IEEE Transactions on*, vol. 30, no. 2, pp. 507–515, April 2014.
- [74] D. Coombs, K. Murphy, A. Lacaze, and S. Legowik, "Driving autonomously off-road up to 35 km/h," in *Intelligent Vehicles Symposium, 2000. IV 2000. Proceedings of the IEEE*, 2000, pp. 186–191.
- [75] P. Petrov and F. Nashashibi, "Modeling and nonlinear adaptive control for autonomous vehicle overtaking," *Intelligent Transportation Systems, IEEE Transactions on*, vol. 15, no. 4, pp. 1643–1656, Aug 2014.
- [76] A. Piazzì, C. G. Lo Bianco, M. Bertozzi, A. Fascioli, and A. Broggi, "Quintic g2-splines for the iterative steering of vision-based autonomous vehicles," *IEEE Transactions on Intelligent Transportation Systems*, vol. 3, pp. 27 – 36, August 2002.
- [77] S. Glaser, B. Vanholme, S. Mammar, D. Gruyer, and L. Nouveliere, "Maneuver-based trajectory planning for highly autonomous vehicles on real road with traffic and driver interaction," *Intelligent Transportation Systems, IEEE Transactions on*, vol. 11, no. 3, pp. 589–606, 2010.
- [78] J. woo Lee and B. Litkouhi, "A unified framework of the automated lane centering/changing control for motion smoothness adaptation," in *Intelligent Transportation Systems (ITSC), 2012 15th International IEEE Conference on*, Sept 2012, pp. 282–287.
- [79] A. Simon and J. Becker, "Vehicle guidance for an autonomous vehicle," in *Intelligent Transportation Systems, 1999. Proceedings. 1999 IEEE/IEE/JSAT International Conference on*, 1999, pp. 429–434.
- [80] C. G. Keller, T. Dang, H. Fritz, A. Joos, C. Rabe, and D. M. Gavrila, "Active pedestrian safety by automatic braking and evasive steering," *Intelligent Transportation Systems, IEEE Transactions on*, vol. 12, no. 4, pp. 1292–1304, 2011.
- [81] J. Perez, R. Lattarulo, and F. Nashashibi, "Dynamic trajectory generation using continuous-curvature algorithms for door to door assistance vehicles," in *Intelligent Vehicles Symposium Proceedings, 2014 IEEE*, IEEE, 2014, pp. 510–515.
- [82] J. Pérez, J. Godoy, J. Villagra, and E. Onieva, "Trajectory generator for autonomous vehicles in urban environments," in *IEEE International Conference on Robotics and Automation (ICRA)*, May 2013, pp. 409 –414.
- [83] L. Han, H. Yashiro, H. T. N. Nejad, Q. H. Do, and S. Mita, "Bezier curve based path planning for autonomous vehicle in urban environment," in *Intelligent Vehicles Symposium (IV), 2010 IEEE*. IEEE, 2010, pp. 1036–1042.
- [84] Z. Liang, G. Zheng, and J. Li, "Automatic parking path optimization based on bezier curve fitting," in *Automation and Logistics (ICAL), 2012 IEEE International Conference on*, Aug 2012, pp. 583–587.
- [85] N. Montes, A. Herraez, L. Armesto, and J. Tornero, "Real-time clothoid approximation by rational bezier curves," in *Robotics and Automation, 2008. ICRA 2008. IEEE International Conference on*, May 2008, pp. 2246–2251.
- [86] N. Montes, M. Mora, and J. Tornero, "Trajectory generation based on rational bezier curves as clothoids," in *Intelligent Vehicles Symposium, 2007 IEEE*, June 2007, pp. 505–510.
- [87] P. G. Trepagnier, J. Nagel, P. M. Kinney, C. Koutsougeras, and M. Dooner, "Kat-5: Robust systems for autonomous vehicle navigation in challenging and unknown terrain," *Journal of Field Robotics*, vol. 23, no. 8, pp. 509–526, 2006.
- [88] Z. Shiller and Y.-R. Gwo, "Dynamic motion planning of autonomous vehicles," *Robotics and Automation, IEEE Transactions on*, vol. 7, no. 2, pp. 241–249, Apr 1991.
- [89] T. Berglund, A. Brodnik, H. Jonsson, M. Staffanson, and I. Soderkvist, "Planning smooth and obstacle-avoiding b-spline paths for autonomous mining vehicles," *Automation Science and Engineering, IEEE Transactions on*, vol. 7, no. 1, pp. 167–172, 2010.
- [90] L. B. Cremean, T. B. Foote, J. H. Gillula, G. H. Hines, D. Kogan, K. L. Kriechbaum, J. C. Lamb, J. Leibs, L. Lindsey, C. E. Rasmussen et al., "Alice: An information-rich autonomous vehicle for high-speed desert navigation," *Journal of Field Robotics*, vol. 23, no. 9, pp. 777–810, 2006.
- [91] D. Kogan and R. Murray, "Optimization-based navigation for the darpa grand challenge," in *Conference on Decision and Control (CDC)*, 2006.
- [92] T. Gu and J. M. Dolan, "On-road motion planning for autonomous vehicles," in *Intelligent Robotics and Applications*. Springer, 2012, pp. 588–597.
- [93] L. E. Kavraki, P. Svestka, J.-C. Latombe, and M. H. Overmars, "Probabilistic roadmaps for path planning in high-dimensional configuration spaces," *Robotics and Automation, IEEE Transactions on*, vol. 12, no. 4, pp. 566–580, 1996.
- [94] S. M. LaValle and J. J. Kuffner, "Randomized kinodynamic planning," *The International Journal of Robotics Research*, vol. 20, no. 5, pp. 378–400, 2001.
- [95] S. Karaman and E. Frazzoli, "Sampling-based algorithms for optimal motion planning," *The International Journal of Robotics Research*, vol. 30, no. 7, pp. 846–894, 2011. [Online]. Available: <http://ijr.sagepub.com/content/30/7/846.abstract>
- [96] —, "Optimal kinodynamic motion planning using incremental sampling-based methods," in *Decision and Control (CDC), 2010 49th IEEE Conference on*, Dec 2010, pp. 7681–7687.
- [97] L. Labakhua, U. Nunes, R. Rodrigues, and F. S. Leite, "Smooth trajectory planning for fully automated passengers vehicles: spline and clothoid based methods and its simulation," in *Informatics in Control Automation and Robotics*. Springer, 2008, pp. 169–182.
- [98] J. Horst and A. Barbera, "Trajectory generation for an on-road autonomous vehicle," in *Defense and Security Symposium*. International Society for Optics and Photonics, 2006, pp. 62 302J–62 302J.

- [99] D. Walton and D. Meek, "A controlled clothoid spline," *Computers & Graphics*, vol. 29, no. 3, pp. 353 – 363, 2005. [Online]. Available: <http://www.sciencedirect.com/science/article/pii/S0097849305000488>
- [100] J.-w. Choi, R. Curry, and G. Elkaim, "Path planning based on b閦ier curve for autonomous ground vehicles," in *World Congress on Engineering and Computer Science 2008, WCECS'08. Advances in Electrical and Electronics Engineering-IAENG Special Edition of the IEEE*, 2008, pp. 158–166.
- [101] D. Walton, D. Meek, and J. Ali, "Planar i_i g_i/i_i sup_i $2_i/sup_i$ transition curves composed of cubic b閦ier spiral segments," *Journal of Computational and Applied Mathematics*, vol. 157, no. 2, pp. 453–476, 2003.
- [102] K. Yang and S. Sukkarieh, "An analytical continuous-curvature path-smoothing algorithm," *Robotics, IEEE Transactions on*, vol. 26, no. 3, pp. 561–568, 2010.
- [103] L. Wang, K. Miura, E. Nakamae, T. Yamamoto, and T. Wang, "An approximation approach of the clothoid curve defined in the interval $[0, /2]$ and its offset by free-form curves," *Computer-Aided Design*, vol. 33, no. 14, pp. 1049 – 1058, 2001. [Online]. Available: <http://www.sciencedirect.com/science/article/pii/S0010448500001421>
- [104] J. S醘nchez-Reyes and J. Chac髇, "Polynomial approximation to clothoids via s-power series," *Computer-Aided Design*, vol. 35, no. 14, pp. 1305 – 1313, 2003. [Online]. Available: <http://www.sciencedirect.com/science/article/pii/S0010448503000459>
- [105] L. Romani and M. Sabin, "The conversion matrix between uniform b-spline and bzier representations," *Computer Aided Geometric Design*, vol. 21, no. 6, pp. 549 – 560, 2004. [Online]. Available: <http://www.sciencedirect.com/science/article/pii/S0167839604000597>
- [106] J. Ren, K. McIsaac, and R. Patel, "Modified newton's method applied to potential field-based navigation for mobile robots," *Robotics, IEEE Transactions on*, vol. 22, no. 2, pp. 384–391, April 2006.
- [107] J. Hardy and M. Campbell, "Contingency planning over probabilistic obstacle predictions for autonomous road vehicles," *Robotics, IEEE Transactions on*, vol. 29, no. 4, pp. 913–929, 2013.
- [108] W. Xu, J. Pan, J. Wei, and J. Dolan, "Motion planning under uncertainty for on-road autonomous driving," in *Robotics and Automation (ICRA), 2014 IEEE International Conference on*, May 2014, pp. 2507–2512.
- [109] J. Lee and B. Park, "Development and evaluation of a cooperative vehicle intersection control algorithm under the connected vehicles environment," *Intelligent Transportation Systems, IEEE Transactions on*, vol. 13, no. 1, pp. 81–90, 2012.
- [110] F. Havlak and M. Campbell, "Discrete and continuous, probabilistic anticipation for autonomous robots in urban environments," *Robotics, IEEE Transactions on*, vol. 30, no. 2, pp. 461–474, 2014.
- [111] L. Fletcher, S. Teller, E. Olson, D. Moore, Y. Kuwata, J. How, J. Leonard, I. Miller, M. Campbell, D. Huttenlocher *et al.*, "The mit-cornell collision and why it happened," *Journal of Field Robotics*, vol. 25, no. 10, pp. 775–807, 2008.
- [112] S. Shladover, "The gm-path platoon scenario," *Intellimotion. Vol. 6, no. 3, 1997.*
- [113] C. Thorpe, T. Jochem, and D. Pomerleau, "Automated highways and the free agent demonstration," in *Robotics Research*. Springer, 1998, pp. 246–254.
- [114] K. Malone, J. van der Wiel, and B. Saugy, "Cybernetic transport systems: lessons to be learned from user needs analysis and field experience," in *Intelligent Vehicle Symposium, 2002. IEEE*, vol. 2, June 2002, pp. 551–556 vol.2.
- [115] M. Parent, "Advanced urban transport: Automation is on the way," *Intelligent Systems, IEEE*, vol. 22, no. 2, pp. 9–11, 2007.
- [116] A. Kelly, A. Stentz, O. Amidi, M. Bode, D. Bradley, A. Diaz-Calderon, M. Happold, H. Herman, R. Mandelbaum, T. Pilarski *et al.*, "Toward reliable off road autonomous vehicles operating in challenging environments," *The International Journal of Robotics Research*, vol. 25, no. 5-6, pp. 449–483, 2006.
- [117] E. Krotkov, S. Fish, L. Jackel, B. McBride, M. Perschbacher, and J. Pippine, "The darpa perceptor evaluation experiments," *Autonomous Robots*, vol. 22, no. 1, pp. 19–35, 2007.
- [118] J. M. Anderson, K. Nidhi, K. D. Stanley, P. Sorensen, C. Samaras, and O. A. Oluwatola, *Autonomous Vehicle Technology: A Guide for Policymakers*. Rand Corporation, 2014.
- [119] K. Chu, M. Lee, and M. Sunwoo, "Local path planning for off-road autonomous driving with avoidance of static obstacles," *Intelligent Transportation Systems, IEEE Transactions on*, vol. 13, no. 4, pp. 1599–1616, Dec 2012.
- [120] K. Jo, M. Lee, D. Kim, J. Kim, C. Jang, E. Kim, S. Kim, D. Lee, C. Kim, S. Kim *et al.*, "Overall reviews of autonomous vehicle al-system architecture and algorithms," in *Intelligent Autonomous Vehicles*, vol. 8, no. 1, 2013, pp. 114–119.
- [121] C. Urmson, C. Ragusa, D. Ray, J. Anhalt, D. Bartz, T. Galatali, A. Gutierrez, J. Johnston, S. Harbaugh, W. Messner *et al.*, "A robust approach to high-speed navigation for unrehearsed desert terrain," *Journal of Field Robotics*, vol. 23, no. 8, pp. 467–508, 2006.
- [122] J. Wei, J. M. Snider, J. Kim, J. M. Dolan, R. Rajkumar, and B. Litkouhi, "Towards a viable autonomous driving research platform," in *Intelligent Vehicles Symposium (IV), 2013 IEEE*. IEEE, 2013, pp. 763–770.
- [123] T. Gu and J. M. Dolan, "Toward human-like motion planning in urban environments," in *Intelligent Vehicles Symposium Proceedings, 2014 IEEE*. IEEE, 2014, pp. 350–355.
- [124] C. Fulgenzi, C. Tay, A. Spalanzani, and C. Laugier, "Probabilistic navigation in dynamic environment using rapidly-exploring random trees and gaussian processes," in *Intelligent Robots and Systems, 2008. IROS 2008. IEEE/RSJ International Conference on*. IEEE, 2008, pp. 1056–1062.
- [125] C. Fulgenzi, A. Spalanzani, and C. Laugier, "Probabilistic motion planning among moving obstacles following typical motion patterns," in *Intelligent Robots and Systems, 2009. IROS 2009. IEEE/RSJ International Conference on*. IEEE, 2009, pp. 4027–4033.
- [126] L. Bouraoui, C. Boussard, F. Charlot, C. Holguin, F. Nashashibi, M. Parent, and P. Resende, "An on-demand personal automated transport system: The citymobil demonstration in la rochelle," *IEEE Intelligent Vehicles Symposium*, vol. 4, pp. 1086 – 1091, 2011.
- [127] D. Gonz醈ez and J. Perez, "Control architecture for cybernetic transportation systems in urban environments," in *Intelligent Vehicles Symposium (IV), 2013 IEEE*. IEEE, 2013, pp. 1119–1124.
- [128] P. Petrov and F. Nashashibi, "Adaptive steering control for autonomous lane change maneuver," in *Intelligent Vehicles Symposium (IV), 2013 IEEE*. IEEE, 2013, pp. 835–840.
- [129] M. Werling, T. Gindele, D. Jagasz, and L. Groll, "A robust algorithm for handling moving traffic in urban scenarios," in *Intelligent Vehicles Symposium, 2008 IEEE*. IEEE, 2008, pp. 1108–1112.
- [130] M. Werling, J. Ziegler, S. Kammel, and S. Thrun, "Optimal trajectory generation for dynamic street scenarios in a frenet frame," in *Robotics and Automation (ICRA), 2010 IEEE International Conference on*. IEEE, 2010, pp. 987–993.
- [131] A. Geiger, M. Lauer, F. Moosmann, B. Ranft, H. Rapp, C. Stiller, and J. Ziegler, "Team annieway's entry to the 2011 grand cooperative driving challenge," *Intelligent Transportation Systems, IEEE Transactions on*, vol. 13, no. 3, pp. 1008–1017, 2012.
- [132] Y. Kuwata, G. A. Fiore, J. Teo, E. Frazzoli, and J. P. How, "Motion planning for urban driving using rrt," in *Intelligent Robots and Systems, 2008. IROS 2008. IEEE/RSJ International Conference on*. IEEE, 2008, pp. 1681–1686.
- [133] A. Broggi, M. Bertozi, A. Fascioli, C. G. L. Bianco, and A. Piazz, "The argo autonomous vehicles vision and control systems," *International Journal of Intelligent Control and Systems*, vol. 3, no. 4, pp. 409–441, 1999.
- [134] A. Broggi, P. Medici, E. Cardarelli, P. Cerri, A. Giacomazzo, and N. Finardi, "Development of the control system for the vislab intercontinental autonomous challenge," in *Proc. 13th Int Intelligent Transportation Systems (ITSC) IEEE Conf*, 2010, pp. 635–640.
- [135] A. Broggi, P. Cerri, S. Debattisti, M. C. Laghi, P. Medici, M. Panciroli, and A. Prioletti, "Proud-public road urban driverless test: Architecture and results," in *Intelligent Vehicles Symposium Proceedings, 2014 IEEE*. IEEE, 2014, pp. 648–654.
- [136] A. Broggi, S. Debattisti, M. Panciroli, and P. P. Porta, "Moving from analog to digital driving," in *Intelligent Vehicles Symposium (IV), 2013 IEEE*. IEEE, 2013, pp. 1113–1118.
- [137] S. E. Shladover, "Path at 20-history and major milestones," *IEEE Transactions on intelligent transportation systems*, vol. 8, no. 4, pp. 584–592, 2007.
- [138] R. Kummerle, D. Hahnel, D. Dolgov, S. Thrun, and W. Burgard, "Autonomous driving in a multi-level parking structure," in *Robotics and Automation, 2009. ICRA'09. IEEE International Conference on*. IEEE, 2009, pp. 3395–3400.

- [139] J. Levinson, J. Askeland, J. Becker, J. Dolson, D. Held, S. Kammler, J. Z. Kolter, D. Langer, O. Pink, V. Pratt *et al.*, "Towards fully autonomous driving: Systems and algorithms," in *Intelligent Vehicles Symposium (IV), 2011 IEEE*. IEEE, 2011, pp. 163–168.
- [140] D. Dolgov and S. Thrun, "Autonomous driving in semi-structured environments: Mapping and planning," in *Robotics and Automation, 2009. ICRA'09. IEEE International Conference on*. IEEE, 2009, pp. 3407–3414.
- [141] M. Aeberhard, S. Rauch, M. Bahram, G. Tanzmeister, J. Thomas, Y. Pilat, F. Homm, W. Huber, and N. Kaempchen, "Experience, results and lessons learned from automated driving on germany's highways," *Intelligent Transportation Systems Magazine, IEEE*, vol. 7, no. 1, pp. 42–57, 2015.
- [142] D. Madas, M. Nosratinia, M. Keshavarz, P. Sundstrom, R. Philppsen, A. Eidehall, and K.-M. Dahlen, "On path planning methods for automotive collision avoidance," in *Intelligent Vehicles Symposium (IV), 2013 IEEE*. IEEE, 2013, pp. 931–937.
- [143] E. van Nunen, R. Kwakernaak, J. Ploeg, and B. D. Netten, "Cooperative competition for future mobility," *Intelligent Transportation Systems, IEEE Transactions on*, vol. 13, no. 3, pp. 1018–1025, 2012.
- [144] K. Kritayakirana and J. C. Gerdes, "Autonomous vehicle control at the limits of handling," *International Journal of Vehicle Autonomous Systems*, vol. 10, no. 4, pp. 271–296, 2012.
- [145] T. Gandhi and M. Trivedi, "Pedestrian protection systems: Issues, survey, and challenges," *Intelligent Transportation Systems, IEEE Transactions on*, vol. 8, no. 3, pp. 413–430, Sept 2007.



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