A Survey on the Coordination of Connected and Automated Vehicles at Intersections and Merging at Highway On-Ramps

Jackeline Rios-Torres, *Member, IEEE*, and Andreas A. Malikopoulos, *Member, IEEE*

***Abstract*—Connected and automated vehicles (CAVs) have the potential to improve safety by reducing and mitigating traffic accidents. They can also provide opportunities to reduce transportation energy consumption and emissions by improving traffic flow. Vehicle communication with traffic structures and traffic lights can allow individual vehicles to optimize their operation and account for unpredictable changes. This paper summarizes the developments and the research trends in coordination with the CAVs that have been reported in the literature to date. Remaining challenges and potential future research directions are also discussed.**

***Index Terms*—Connected and automated vehicles (CAVs), vehicle coordination, intersection control, merging highways, vehicle-to-vehicle (V2V) communication, vehicle-to-infrastructure (V2I) communication, cooperative driving.**

Notation

S	Intersection/merging zone length
L	Control zone length
x	Vehicle position
v	Vehicle speed
u	Control input
j, p	Road index
i, q	Vehicle index
t	Time
ΔT_a	Minimum time allowed to cross the intersection
δ	Desired following distance
a	Maximum between the times that vehicles i and $i+1$ take to enter the intersection
b	Minimum between the times that vehicles i and $i+1$ take to exit the intersection
v^d	Desired speed
H	Total number of horizons
k	Horizon index
T	Horizon length
CS	Critical set
w	Penalty weight
ϕ	Navigation function
τ	Expected arrival time at intersection
J	Vehicle inertia

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I. Introduction

CONGESTION is created by driver responses to various disturbances [1]. In 2014, congestion caused people in urban areas to spend 6.9 billion hours more on the road and to purchase an extra 3.1 billion gallons of fuel, resulting in a total cost estimated at \$160 billion [2]. Limitations in mobility may also generate driver frustration, irritation, and stress, which may encourage more aggressive driving behavior and further slow the process of recovering free traffic flow [3].

The typical US highway capacity is 2,200 vehicles per hour per lane or 750 trucks per hour per lane, and the vehicles occupy only 5% of the road surface at the maximum capacity [4]. Safety and environmental issues are also attributed to the transportation. In 2012, 2.2 million nonfatal injuries and 35,000 deaths were reported, and around 1.7 billion metric tons of CO_2 was released to the environment [4]. Such factors, along with stronger governmental regulations, are contributing towards focusing on more sustainable transportation technologies.

Connected and automated (CAVs) can provide shorter gaps between vehicles and faster responses while improving highway capacity by identifying appropriate target speeds. The overarching goal of these technologies is the improvement of safety while reducing fuel consumption, emissions and traffic congestion.

A. Development of Connected and Automated Vehicles on Highway Systems

In 1970, Fenton [5] reported the state of the art in vehicle automatic guidance and control and emphasized its significance in addressing both traffic-related problems and accidents. A few years later, Pue [6] investigated communication requirements in the longitudinal control of vehicles for the allocation of control computation and the associated trade-offs for maintaining an acceptable level of vehicle performance in automated guideway transit systems. The same year, Caudill *et al.* [7] discussed the hierarchy of controller functions in vehicle management for an automated vehicle system and provided the economics of system-owned communication and control packages for automated highway systems (AHS). The goals of AHS are to alleviate congestion, reduce energy use and emissions, and improve safety. One of the ways these can be achieved is through significantly higher traffic flow as a result of closer packing of automatically controlled vehicles in platoons. However, to accomplish these goals, vehicles need to be able to communicate with each other and exchange information; namely, they need to be connected.

Forming platoons of vehicles traveling at high speed, accelerating or braking simultaneously, was a popular system-level approach to address traffic congestion that gained momentum in the 1980s. Shladover *et al.* [8] summarized the work on automating vehicle lateral and longitudinal control in the Program on Advanced Technology for the Highway at the University of California, Berkeley. Sheikholeslam and Desoer [9] proposed a longitudinal control policy for a platoon of vehicles without requiring communication of lead vehicle information. Varaiya [10] discussed extensively the key features of automated intelligent vehicle-highway systems. Rajamani *et al.* [11] reported on the integrated control system that was implemented in eight fully automated vehicles traveling together as a platoon.

Over the years, the necessity for CAVs has become pervasive. Many stakeholders intuitively see the benefits of multiscale vehicle control systems and have started to develop business cases for their respective domains, including the automotive and insurance industries, government, and service providers. It seems clear that vehicle-to-vehicle (V2V) communication has the potential to reduce traffic accidents and ease congestion by enabling vehicles to more rapidly account for changes in their mutual environment. Likewise, vehicle-to-infrastructure (V2I) communication, e.g., communication with traffic structures, nearby buildings, and traffic lights, should allow for individual vehicle control systems to account for unpredictable changes in local infrastructure.

B. Objectives and Contributions of the Paper

There is a solid body of research now available for optimizing vehicle system efficiency both for conventional [12] and hybrid powertrain systems [13]. The question is whether we could take advantage of CAVs and optimize transportation efficiency. What if we would consider the problem of optimizing fuel economy and emissions by coordinating a transportation system consisting of CAVs (Fig. 1)? What would be the appropriate conceptual approaches for modeling and optimization?

Several research efforts reported in the literature have aimed at addressing these questions. Li *et al.* [14] recently surveyed relevant research on improving transportation safety and efficiency using traffic lights and V2I communication. There have been also significant efforts in developing analytical approaches to coordinate CAVs for improving both safety and traffic flow on specific transportation segments, e.g., intersections, merging roadways.

This paper has two main objectives: (1) to summarize research efforts related to the coordination of CAVs on specific

Fig. 1. Vehicles able to communicate with each other and infrastructure, e.g., buildings and traffic lights.

transportation scenarios, e.g., intersections and merging at highway on-ramps, reported in the literature to date; and (2) to discuss a potential research direction addressing some of the unanswered questions. The approaches are presented in their approximate chronological order. We report related efforts in vehicle coordination according to the nature of the control scheme, i.e., centralized or decentralized.

The contribution of this paper is the collection and review of papers in the area of vehicle coordination. Any such effort has obvious limitations. Space constraints limit the description of the various approaches in detail, and thus, extensive discussions are included only where they are important for understanding the fundamental concepts or explaining significant departures from previous work. In all cases, objectivity has been a high priority.

C. Organization of the Paper

The structure of the paper is as follows. In Section II, we introduce and formulate the problem of coordination of CAVs for (1) intersections, and (2) merging at highway on-ramps. In Sections III and IV we cover the literature related to coordination of CAVs using centralized and decentralized approaches respectively. Finally, in Section V, we present conclusions and a discussion of the main issues and the gaps that provide opportunities for further research.

II. Coordination of Connected and Automated Vehicles

Significant research efforts using either centralized or decentralized approaches have focused on coordinating CAVs in intersections and merging at highway on-ramps. In this paper, we categorize an approach as centralized if there is at least one task in the system that is globally decided for all vehicles by a single central controller. In decentralized approaches, the vehicles are treated as autonomous agents that attempt, through strategic interaction, to maximize their cooperative efficiency. In this framework, each vehicle obtains information from other vehicles and roadside infrastructure to optimize specific performance criteria (e.g., efficiency, travel time) while satisfying the transportation system's physical constraints (e.g., stop signs, traffic signals).

Ramp metering is a common method used to regulate the flow of vehicles merging into freeways to decrease traffic congestion [15]. Although it has been shown that it can help improving the overall traffic flow and safety on freeways, some problems like interference with the traffic on adjacent roads may arise because of the short length of the on-ramps. Different strategies to address these challenges, including the use of feedback control theory [16]–[20], optimal control [21]–[23] and heuristic algorithms [24], [25], have been explored before [26].

Given the recent technological developments, several paths to address traffic congestion caused by merging roadways have been considered. In these efforts, it is assumed that the vehicles on the road are connected and have some level of autonomy. This assumption facilitates the design of strategies to achieve safe and efficient coordination of the merging maneuvers avoiding the undesirable stop-and-go operation of the vehicles. One of the very early work in this direction was proposed in 1969 by Athans [27] who formulated the merging problem as a linear optimal regulator.

For intersections, on the other hand, traffic lights are considered one of the most efficient ways to control the traffic and attempts are still being made in order to increase their effectiveness. In 2004, Dresner and Stone [28] proposed an approach for automated vehicle intersection control based on the use of a reservation algorithm. Since then, numerous approaches have been reported in the literature to achieve safe and efficient autonomous control of traffic through intersections using centralized and decentralized control algorithms. Note that the intersection control problem and the merging control problem are very similar in nature and most of the approaches proposed for intersection control, can be easily adapted for merging coordination and vice versa. In the following subsections we formulate both problems and discuss the various approaches that have been proposed to date.

A. General Problem Formulation

Typically, the crossing sequence on an intersection is controlled by traffic lights, or stop signs. In the case of merging highways, ramp metering is a common method used to regulate the flow of vehicles merging into freeways, however it also implies that the vehicles on the secondary way will have to stop to decrease traffic congestion. Figs. 2 and 3 illustrate these two scenarios.

The region at the center of the intersection, or merging of the roadways, is called *merging zone* and has a length S. There is also a *control zone* inside of which the vehicles can communicate with each other. The distance between the entry of the control zone and the entry of the merging zone is L. For

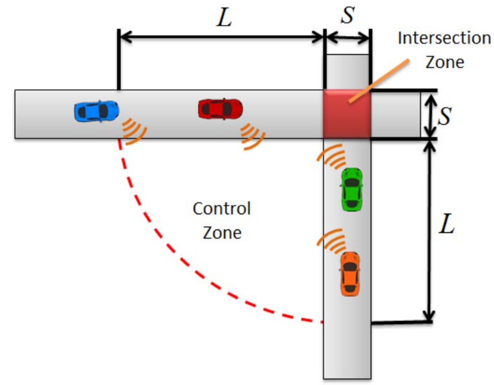

Fig. 2. Intersection with CAVs.

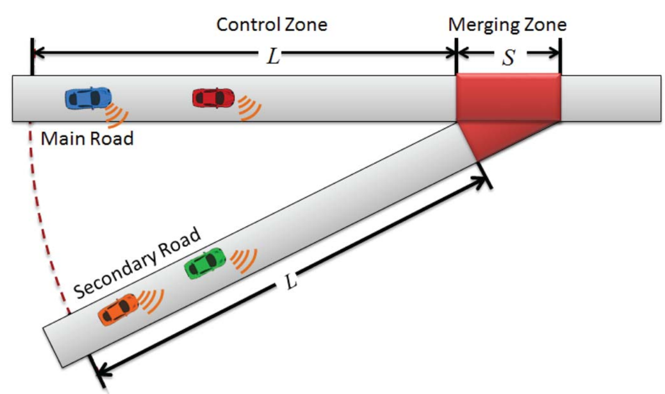

Fig. 3. Merging roadway scenario with CAVs.

simplicity, we assume that each vehicle is governed by a second order dynamics

$$\begin{aligned} \dot{x}_{j,i} &= v_{j,i} \\ \dot{v}_{j,i} &= u_{j,i} \end{aligned} \tag{1}$$

where $j = 1, 2, \ldots, m$, $m \in \mathbb{N}$, indexes the road, $i = 1, 2, \ldots, n$, $n \in \mathbb{N}$, indexes each vehicle, x is the position of each vehicle, v is its speed, and u is the control input (acceleration/deceleration). Eventually, when it is necessary to differentiate among the two roads and the respective vehicles on each road, the subscripts p and q will be used for the second road and the vehicles traveling on it, respectively.

The objective here is to coordinate the vehicles to cross the intersection (or to merge) without either rear-end, or lateral collision at the merging zone. There are two main approaches that have been proposed in the literature to address this problem: 1) centralized and 2) decentralized approaches.

III. Centralized Approaches

In centralized approaches, there is at least one task in the system that is globally decided for all vehicles by a single central controller. In this section we discuss the centralized approaches that have been proposed in the literature to address coordination of vehicles at intersections and merging at highways on-ramps.

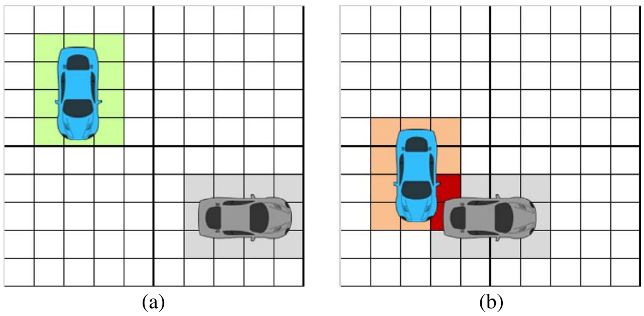

Fig. 4. Cell reservation process at time t (as proposed in [29]). (a) Successful reservation. (b) Reservation request rejected due to conflict with a cell already reserved by another vehicle.

A. Approaches Based on Heuristic Rules

1) Reservation Scheme: In this approach there is a centralized controller or intersection manager that coordinates the reservation or crossing schedule based on the requests and information received from the vehicles located inside the communication range. The intersection is divided into cells, or points, which are to be assigned, or reserved, for only one vehicle at each instant of time to avoid collisions (Fig. 4). The main challenges in this case are associated with the heavy communication requirements and the possible occurrence of deadlocks. The communication becomes a critical issue, particularly when vehicles are required to communicate several times with the central controller until their reservation request is approved.

Intersection coordination: In [28] Dresner and Stone proposed the use of the reservation scheme to control a single intersection of two roads with vehicles traveling with similar speed on a single direction on each road, i.e., no turns are allowed. In their approach, each vehicle is treated as a driver agent which request the reservation of the space-time cells to cross the intersection at a particular time interval defined from the estimated arrival time to the intersection. Once the centralized reservation system receives the request, it accepts if there is no conflict with the already accepted reservations; otherwise, the request is to be rejected. In case of rejection, the driver agent is required to decelerate and send a new reservation request. Note that in this case, each driver agent has autonomy to decide the best trajectory to fulfill the assigned crossing time interval. To test the efficiency of the proposed system, the authors measured the delay incurred by the vehicles due to the deceleration required until the reservation request is accepted. This work was later extended [29] to consider turning as well as including improvements like allowing the central controller: (1) to estimate the positions of the cars to prioritize the requests made for the vehicles which are closer to the intersection (reducing probability of deadlocks), (2) to impose the required acceleration profile inside the intersection zone, and (3) to send a counter offer for the arrival time and trajectory when rejecting a request. Huang *et al.* [30] further extended the solution proposed in [29] by (1) centralizing the computation of the vehicle trajectories to reduce the possibilities of reservation cancelation due to inability to fulfill the initially reported arrival time, (2) adopting a hierarchical processing of the reservation request which accounts for the implementation of different priority assignations, and (3) evaluating metrics related to environmental benefits. The reservation scheme have been also explored by Au and Stone [31], De la Fortelle [32], and Zhang *et al.* [33], [34].

2) Other Heuristics:

Intersection coordination: The vehicle intersection control proposed by Wuthishuwong *et al.* [35] consists of a two-level control. In the lower level an intersection agent uses estimation of the traffic flow to define a control policy that guarantees traffic flow stability in the intersection. In the upper level, information about traffic density for the incoming and outgoing streets is shared among the connected intersection neighborhoods to improve system throughput. At this level, a consensus algorithm is used by each intersection agent to compute desired traffic density based on the information received from connected neighbors. This desired traffic density is then used to determine the vehicle speed. The reported results showed that the adopted average vehicle velocity allows the system to maintain stability.

Jin *et al.* [36] considered platoon formations for intersection control. In their approach, the intersection controller communicates with the platoon leader, and the leader with the followers. The platoons are defined according to the gap between adjacent vehicles and/or the size limit. Once a platoon is set, the leader calculates the time of arrival at the intersection for each vehicle and sends the information to the controller along with the request to cross the intersection. If the request is accepted, the platoon leader calculates the required vehicle trajectories to satisfy the assigned schedule and safety constraints. Simulations were performed in SUMO for a two roads intersection and the results showed reduction in fuel consumption and travel time when compared with respect to traffic light-based and non-platoon-based approaches.

On-ramp coordination: Schmidt *et al.* [37] proposed a two-layer control approach based on heuristic rules that were derived from observations of the non-linear system dynamics behavior. In the first layer, the merging sequence is defined according to the time for each vehicle to merge in the control zone, which is estimated by assuming that each vehicle is traveling at a constant speed value. In the second layer, the required constant acceleration value for each vehicle is computed by following heuristic rules according to the conflicts found during the merging sequence. Another solution approach using different layers of control have been proposed by Ran *et al.* in [38].

B. Optimization and Control Approaches

1) Optimizing Travel Time: Increasing the throughput at an intersection is one desired goal to reduce traffic congestion and it can be achieved through the optimization of the travel time for all the vehicles located inside the control zone. For the scenario illustrated in Fig. 2, allowing only one vehicle at the intersection at a time, the optimization problem can be formulated as follows:

$$\min_{u} \frac{1}{2} \sum_{j=1}^{m} \sum_{i=1}^{n} \left[t_{j,i}^{\mathrm{out}} - t_{j,i}^{\mathrm{in}}\right]^2 . \tag{2}$$

Subject to:

$$\begin{aligned}
\dot{x}_{j,i} &= v_{j,i}\\
\dot{v}_{j,i} &= u_{j,i}\\
t^{\text{out}}_{j,i} - t^{\text{in}}_{j,i} &\geq \Delta T_a\\
o < v_{j,i}(t,u) &\leq v^{\max}\\
x_{j,i}(t) &\leq x_{j,i+1}(t) + \delta \quad \forall t\\
x_{j,i}(t) &\leq x_{p,q}(t) + S \quad \forall t,\ j \neq p,\ i \neq q
\end{aligned}$$

where $t^{\text{in}}_{j,i}$ and $t^{\text{out}}_{j,i}$ are the times that the vehicle i on road j enters and exits the merging zone, ΔT_a is the minimum allowed time to cross the intersection at maximum speed $v^{\max}$, and δ is the desired safe distance between vehicles on the same road.

Intersection coordination: The approaches proposed by Li *et al.* [39], Yan *et al.* [40], Zohdy *et al.* [41], Jin *et al.* [42], Wu *et al.* [43] and Zhu *et al.* [44], focus on the formulation of an optimization problem in which the objective function involves the travel time. The constraints, which are different in each work, are formulated with the goal of avoiding collisions. Dynamic programming (DP) is applied in [43] to solve the formulated optimization problem. As the complexity of DP increases with the addition of lanes, the authors proposed an alternative heuristic solution in which the system is modeled using Petri nets and the main goal is to minimize the sum of the lengths of the two queues. It was found that platoon-based vehicular control improves traffic flow and based on this formulated rules to control the vehicle crossing sequence. A mathematical proof of this approach was presented by Wu *et al.* in [45].

On-ramp coordination: Raravi *et al.* [46] and Awal *et al.* [47] formulated and solved optimal problems involving the travel time for the case of merging coordination.

2) Minimizing the Vehicles Overlap: Assuming that the vehicles in the system follow the dynamics in (1) and that they are served on a first come first serve basis, the optimization problem considers minimizing the overlap of the vehicles position inside the intersection zone. Namely, the objective is to derive the acceleration profiles of the vehicles such that only a limited number of vehicles are present inside the intersection at each instant of time. The total number of vehicles depends on the size of the vehicles, the length of the intersection area and the minimum safest following distance. Fig. 5 illustrates the general idea of this approach, where a is the maximum time between the times, t_i^{in} and t_{i+1}^{in}, that the vehicles i and $i+1$ enter the intersection, and b is the minimum time between the times, t_i^{out} and t_{i+1}^{out}, that the vehicles i and $i+1$ exit the intersection. The problem is formulated as to minimize the overlap of the vehicles inside the intersection

$$\min \sum_{i=1}^{n} \int_a^b \sqrt{1 + x_i(t)^2}\, dt \tag{3}$$

where several constraints are imposed to satisfy the minimum and maximum speed limits and acceleration as well as to keep a safe inter-vehicular distance between vehicles on the same road.

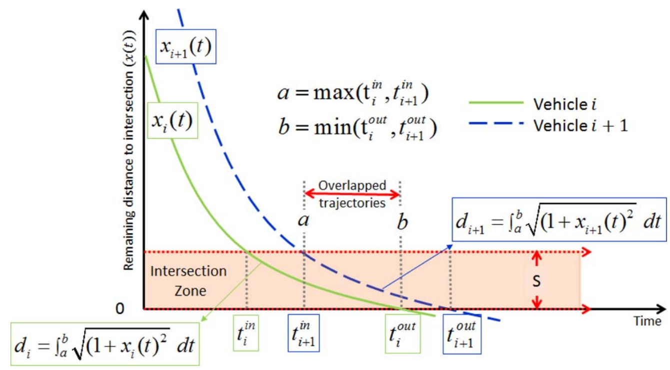

Fig. 5. Illustrative example of trajectories overlap for two vehicles traveling on two intersecting roads.

Intersection coordination: This approach was first proposed by Lee and Park in [48] where they considered the case of a two-roads intersection with two lanes and turning capabilities using of a phase conflict map as a part of the problem formulation. Simulation results showed that the system is not only able to reduce total travel time and delays but also able to reduce fuel consumption. This work was later extended to the case of an urban corridor [49].

3) Multi-Objective Optimization: A number of approaches have been proposed to address this problem by including multiple criteria in the objective function. In this case, it is common to assume that the vehicles have already been assigned a driving schedule, thus the problem consists of minimizing the error between the actual vehicle speed $v_{j,i}(t)$ and the desired speed $v^d(t)$, and the acceleration $u_{j,i}(t)$. The multiobjective optimization problem can be solved as a receding horizon control problem, in which the objective function is minimized for a number of time horizons of equal length T. Additional terms can be added to the cost function to guarantee avoidance of collisions. In general, this problem can be formulated as follows:

$$\min_u \sum_{k=1}^{H} \int_{t(0)+kT}^{t(0)+T+kT} \Bigg[\sum_{j=1}^{m} \sum_{i=1}^{n} \Big(w^v \left(v_{j,i}(t) - v^d(t)\right)^2 + w^u \left(u_{j,i}(t)\right)^2 + w^c \left(f(t, u_{j,i})\right)^2 \Big) \Bigg] dt \tag{4}$$

where H is the total number of horizons, k indexes horizon, T is the length of each horizon, w denotes weighting factors and the superscripts v, u corresponds to speed and acceleration respectively. Finally, $f(t,u)$ is an additional function that can be used to quantify the risk of collisions in the system. The constraints vary for each formulation but in general the most common constraints are related to the speed and acceleration limits and safest following distance or time.

Intersection coordination: This multiobjective optimization framework was used by Campos *et al.* [50], Kamal *et al.* [51], [52] and Dai *et al.* [53]. The formulation in [50] includes speed tracking error and acceleration in the objective function to find safe trajectories while satisfying local constraints, like the avoidance of control inputs which belong to the critical set as defined in Hafner *et al.* [54]. The set of constraints is later modified for a decentralized version of the controller in which a reservation scheme is used. Model Predictive Control (MPC) is used in [51] and [52] to solve the problem that includes a risk factor function to quantify the risk of collision at the intersection and constraints related to safe velocity and acceleration values.

4) Other Optimization and Control Approaches:

Intersection coordination: Charalampidis and Gillet [55] derived closed-form solutions to the problem of intersection control. The authors used a second-order kinematic model to describe the vehicle dynamics and assumed all the vehicles initially travel at a maximum speed. Employing this approach, the collision avoidance strategy finds the appropriate deceleration/acceleration pattern. Once the first vehicle reaches the communication range of the intersection manager, it calculates the time required to leave the intersection and sets a reservation. Once the second vehicle is detected, it is forced to adjust speed to an optimal speed value to ensure it reaches the intersection only after the first one has already crossed it. The optimal speed is calculated by minimizing the delay due to deceleration. This approach only allows one vehicle on the intersection at a time.

Zohdy and Rakha [56] used game theory, where a manager agent receives information from the vehicles in the road network and selects one of them to optimize its trajectory. At the same time, based on the available information, every vehicle agent optimizes its own trajectory. Using Monte Carlo simulations, it was shown that the proposed system is able to reduce the total delay compared to a traffic-light-controlled intersection.

The use of queuing theory was proposed by Miculescu and Karaman [57]. In their approach, the system is modeled as a polling system with two queues and one server. The customers (vehicles) are coordinated to cross the intersection without collisions. The polling system determines the sequence of times assigned to the vehicles on each road. Then, a coordination algorithm finds the safe trajectories for all the vehicles inside the control region using the time each vehicle should arrive to the intersection and the trajectory of the leading vehicle. Differential constraints are used to enforce safety. Simulations for light-, medium-, and heavy-load cases were performed using MATLAB. The results showed that the switching times needed to reassign the right of way from one road to another are reduced in the case of heavy loads, thus promoting platoon formations.

On-ramp coordination: Assuming a given merging sequence, Athans formulated the merging problem as a linear optimal regulator (as it was proposed by Levine and Athans [58] to control a single string of vehicles) with the aim of minimizing the speed errors that will affect the desired headway between each consecutive pair of vehicles. In this approach, he formulated three main constraints: (1) adjacent vehicles should keep a minimum separation distance, (2) each vehicle must follow a given string velocity, and (3) high acceleration and/or decelerations are penalized except in emergency situations. The author evaluated different merging sequences to determine the best one, i.e., the sequence with less errors and minimum

TABLE I
SUMMARY OF RESULTS FOR CENTRALIZED COORDINATION CONTROL (I: INTERSECTION, O: ON-RAMP)

Category		**Fuel Consumption Improvement [%]** 20% to 30%	35% to 45%	45% to 50%	Not Reported
Heuristic	I	[36]	[49], [48]	[30],	[28], [29], [31], [32], [33], [34], [35]
	O				[37], [38]
Optimization and Control	I				[39], [40], [41], [42], [43], [44], [45], [50], [51], [52], [53], [55], [56], [57],
	O			[60], [61]	[46], [47], [58], [59]
Evaluated Through Simulation	I	[36]	[49], [48]	[30]	[28], [29], [31], [32], [33], [34], [35], [39], [41], [42], [43], [44], [45], [50], [51], [52], [53], [56], [57]
	O			[60], [61]	[37], [38], [46], [47], [58], [59]
Theoretical Approach	I				[40], [55]

control efforts. However, no consideration was given to the average delay produced in the traffic network. In 1997, Kachroo and Li [59] used sliding mode control and designed longitudinal and lateral controllers to guide the vehicle until the merging maneuver is completed, assuming that a gap has been already assigned to the merging vehicle. Most recently, the problem of coordinating vehicles that are wirelessly connected to each other at merging roads was addressed in [60] and [61]. A closed-form solution was developed aimed at optimizing the acceleration profile online of each vehicle in terms of fuel economy while avoiding collision with other vehicles at the merging zone. The proposed solution was validated through simulation and it was shown that coordination of connected vehicles can reduce fuel consumption at merging roads by up to 50%.

Table I summarizes the main results in centralized control, related to fuel consumption reduction reported in the literature. None of the papers have reported field tests results for centralized solutions.

IV. DECENTRALIZED APPROACHES

In decentralized control, each vehicle determines its own control policy based on the information received from the other vehicles on the road, or some coordinator. One of the main challenges faced in the implementation of decentralized approaches is the possibility of having deadlocks in the solutions as a consequence of the use of local information. Various heuristic- and optimization-based decentralized control approaches have been reported in the literature to date.

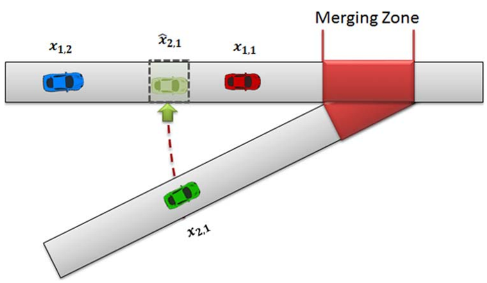

Fig. 6. Virtual vehicle/slot mapped onto main road.

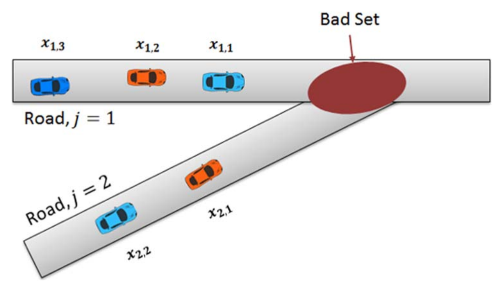

Fig. 7. Intersection collision avoidance scenario illustrating the bad set.

A. Heuristic Control

1) Virtual Vehicle/Platooning:

On-ramp coordination: The concept of virtual vehicle/platooning for autonomous merging control was used by Uno *et al.* [62] in 1999. In the proposed approach, a virtual vehicle is mapped onto the main road (Fig. 6) before the actual merging is supposed to occur, to allow the vehicles perform smoother and safer control actions. This concept was later explored by Lu and Hedrick [63], and Lu *et al.* [64], [65]. The approach proposed by Marinescu *et al.* [66], builds upon the concept of slot-based traffic management, in which the intelligent vehicles drive inside a virtual slot. The authors extended the model to consider V2V communication and V2I communication, where a traffic management system communicates with the vehicles inside its range. The proposed cooperative merging control outperformed a scenario in which the vehicles are controlled by human drivers when evaluated with respect to the throughput and the average delay of the vehicles on the on-ramp.

2) Fuzzy Logic:

Intersection coordination: Milanes *et al.* [67] designed a controller based on fuzzy logic, that allows a fully automated vehicle to yield to an incoming vehicle in the merging zone, or to cross if it is feasible and lateral collision cannot occur. The fuzzy controller controls the throttle and brake pedals of the automated vehicle. Milanes *et al.* also compared in [68] three heuristic intersection control schemes: 1) fuzzy logic, 2) partial motion planner, and 3) heuristic static rules. The schemes were implemented in automated cars and experimental results showed they could safely interact in a cooperative environment working under a specific communication protocol. When operating in the presence of manually operated cars, the three autonomous vehicles were able to yield and stop before the intersection.

The work described by Milanes *et al.* [67] was extended by Onieva *et al.* in [69]. The proposed control scheme consists of a three-layer fuzzy control system. The first layer, detects whether a turn or a straight path through the intersection is required. The second layer determines a feasible speed value to safely cross the intersection; in this layer the fuzzy algorithm is optimized by means of a genetic algorithm. The third layer determines the accelerator and brake commands required to track the speed reference given by the second layer. Simulation results showed the system was able to coordinate the vehicles without collisions.

On-ramp coordination: A similar approach to the one proposed in [67] was implemented and evaluated for the case of an on-ramp in [70].

3) Use of a Critical/Invariant Set:

Based on the scenario illustrated in Fig. 7 and under the dynamics in (1), it is possible to demonstrate that the system is monotone, if the following assumptions are made: 1) the control input has a unique minimum and a unique maximum, i.e., $u_{\min} \leq u_{j,i} \leq u_{\max}$ and the system (1) is non-decreasing in $u_{j,i}$, 2) the system (1) has unique solutions, 3) only positive speeds are allowed: $v_{\min} < v_{j,i} \leq v_{\max}$, 4) $|\dot{v}_{j,i}|$ is bounded for all $v_{j,i} \in [v_{\min}, v_{\max}]$, and 5) all the vehicles on the same path follow the same dynamics, i.e., $x_{j,i} = x_{j,q}$, $v_{j,i} = v_{j,q}$ $\forall\, j \in \{1, 2\}$, $i, q \in \{1, 2, \ldots, n\}$.

From the monotonicity of the system it follows that the hierarchical sequence of the vehicles is kept as long as $x_{j,i} \geq x_{j,q}$, $v_{j,i} \geq v_{j,q}$, and $u_{j,i} \geq u_{j,q}$ and this property allows the definition of a critical set. Also, according to the geometry of the intersecting roads in Fig. 7, it is possible to have rear-end collisions when the vehicles travel on the same road, or side collisions when two vehicles from different roads are entering the intersection zone at the same instant of time. The intersection zone can be represented by the interval $[x_{j,i}^{\text{in}}, x_{j,i}^{\text{out}}]$ which can be defined according to the vehicle length. Then, the critical set is defined as the set of all the states in which the collisions are unavoidable.

Intersection Coordination: Hafner *et al.* [54], [71] used the definition of the critical set in such a way that if the current vehicle trajectories are close to the critical set, the control scheme is activated and inputs selected to lie outside the critical inputs set are applied to accelerate one vehicle and decelerate the other. Similarly, Colombo and Del Vecchio [72] proposed to find the set of control inputs that would avoid collisions. The problem is translated into a scheduling problem where exact and approximated solutions can be derived. The controller only modifies the trajectory of a vehicle if it detects that the current control input is outside the set of safe control actions. These approaches do not involve optimization, and the control scheme is deactivated after the current vehicles have safely crossed the intersection.

In a similar approach, Qian *et al.* [73] proposed an algorithm to integrate legacy vehicles in the coordination system, i.e., manually driven vehicles with not V2V nor V2I communication capabilities. In this case, sensors located on the road will notify the intersection controller about the potential presence of legacy vehicles and by following predefined rules the legacy vehicles will be notified by means of a traffic light whether they are allowed or not to cross. The safety operation of the coordination algorithm was proved through simulation results.

4) Other Approaches:

Intersection coordination: Alonso *et al.* [74] proposed two conflict resolution schemes in which an autonomous vehicle could make a decision about the appropriate crossing schedule to avoid collision with other manually driven vehicles on the road. To safely cross the intersections, the vehicles are assumed to have V2V capabilities, to share information regarding their position, speed, driving direction, and identification. The first scheme is based on the use of priority tables. Thus, by implementing a look-up table including all the possible combinations of occupancy of the intersecting roads, a signal is defined which indicates whether the vehicle should continue moving or coming to a full stop until the intersection is cleared. In the second scheme, each vehicle determines its own priority level and the look-up table is created that yields whether the vehicle should stop or cross the intersection. The approach was implemented and tested with three automated vehicles that were able to safely interact in two different real-world scenarios.

Khoury *et al.* [75] proposed a decentralized system which rely on information obtained only from local sensors to coordinate the vehicles crossing an intersection. Wu *et al.* [76] proposed decentralized approach, the best sequence for the vehicles to cross the intersection is decided by wirelessly sharing the estimated arrival time among the vehicles on the queue. If any vehicle has an arrival time shorter than the current shared arrival time, it sends a message to prevent the current vehicle from crossing. Additional logic is included for simultaneous crossing of vehicles traveling on non-conflicting lanes. The authors did not focus on optimizing a particular performance metric and the approach involves stop and go operation.

On-ramp coordination: Antoniotti *et al.* [77], [78] proposed a decentralized hybrid controller with the aim of keeping a safe headway between the vehicles in the merging process. In this work, there was not V2V communication. Instead, each vehicle decides when to merge, yield or exit the freeway according to the local information it receives from its own sensors. The controller inside each vehicle manages the decision of merging, yielding or exiting as a discrete process while the vehicle acceleration is computed continuously according to the discrete decisions and the required constraints to achieve safe maneuvers. This approach allows vehicles to stop and the main focus is on the safety. While this work is one of the earliest attempts to develop decentralized control for this problem, the authors reported that accidents were still detected in some of their simulations. Additional attempts to develop decentralized systems which rely on information obtained only from local sensor have been proposed by Yang *et al.* [79].

Ntousakis *et al.* [80] proposed two decentralized algorithms for automated merging control in which each vehicle uses information of the vehicles inside a cooperation area to determine the appropriate sequence to merge into the main road. The first algorithm is based on a "first come, first serve" basis while in the second additional rules are included to reduce unnecessary decelerations. Once the sequence is defined, a car following model is used to determine the acceleration/deceleration commands to achieve a safe merging maneuver and keep the chosen merging hierarchy. Results showed that both algorithms performed safely and the traffic flow was kept at reasonable rates.

The interaction of vehicles with different levels of automation is the focus of the strategy proposed in [81]. The authors developed an algorithm based on a Bayesian driving intention recognition model to predict the future behavior of the surrounding agents in the system as a response to the decisions made by an autonomous agent, thus enabling it to have a "cooperative social behavior." A similar approach, in which the automated vehicles cooperate to allow a smooth merging for manually driven vehicles was proposed by Pueboobpaphan *et al.* in [82].

B. Optimization and Control Approaches

1) Multiobjective Optimization: For the intersection problem, a multi-objective optimization framework for time horizons of equal length T has been proposed. As in the centralized case, in the decentralized approaches it is also common to assume that each vehicle i has already been assigned a driving schedule, thus one of the terms in the objective function attempts to minimize the error between the speed of vehicle i, $v_i(t)$, at time t, and the desired speed, v^d. Minimizing the acceleration, $u_i(t)$, and other terms that can be related to collision avoidance, $f(t, u_i(t))$, is also common in the formulations. The main difference with respect to the centralized case is the local nature of the information used to solve the optimization problem, i.e., each vehicle solves its own optimization problem based on the local information and the one from the vehicles located inside a particular radius from its current position. In general, the decentralized optimization problem can be formulated as follows:

$$\min_u \sum_{t=1}^{T} \left(w^v \left(v_i(t) - v^d\right)^2 + w^u u_i^2(t) + w^c f_i^2\left(t, u_i(t)\right) \right) \tag{5}$$

where w^v, w^u, and w^c are weight factors.

The common constraints found in the literature are related to the minimum safe distance/time gap between vehicles approaching the intersection, minimum following distance (for vehicles on the same lane) and speed and acceleration limits.

Intersection coordination: The approaches presented in [83]–[87] formulate multi-objective optimization problems. Makarem and Gillet [85] proposed a method that assumes each vehicle travels at a desired vehicle speed, and thus the expected time of its arrival at the intersection can be previously calculated. Then, the control input is computed from a navigation function that attempts to minimize the error between the desired speed and the actual speed of each vehicle while keeping a safe time gap among the vehicles attempting to cross the intersection. The function assigns smaller acceleration values to heavier vehicles compared to lighter vehicles. This last characteristic results in smoother trajectories for heavier vehicles, thus reducing energy consumption. A two-road intersection was simulated, and the performance of the approach was evaluated by measuring the total energy consumption and traffic flow, and comparing them with those for an intersection controlled by traffic lights and by a centralized approach. The results showed that the proposed strategy is more efficient than using traffic lights.

Using MPC to solve the local optimization problem has been proposed by Makarem *et al.* [86], Qian *et al.* and Kim and Kumar [87]. In the approach proposed by Makarem *et al.* [86] each vehicle defines its constraints by using local information from other vehicles inside the communication range. Then, each of them solves a linear quadratic optimal control problem according to its dynamics and constraints to avoid collision. Each vehicle calculates the time required to arrive at the intersection for all the vehicles in the network so that the priority to modify the acceleration control can be given to the one that is closest to the intersection. The effectiveness of the system is confirmed through simulations. Qian *et al.* [88] proposes to solve the problem in two levels. In a high level, the vehicles are coordinated based on some predefined priority scheme. Then, a low level control solves a multi-objective optimization problem based on the information of its current system state and short time prediction of the states' evolution of the vehicles in front.

On-ramp coordination: The concept of cooperative merging, in which the vehicle(s) on the main road adjust its speed to facilitate the merging process of the vehicle attempting to merge, was used in [89]. The cooperative merging path is optimally generated for the relevant vehicles on two merging single-lane roads by using MPC. The formulation was later extended for the case of multiple lanes in [90].

2) Other Optimization-Based Approaches:

Intersection coordination: The problem formulation proposed in [61] was reformulated as a decentralized problem of coordinating online a continuous flow of CAVs crossing two adjacent intersections in [91]. The solution of this problem, when it exists, allows the vehicles to cross the intersections without the use of traffic lights, without creating congestion, and under the hard safety constraint of collision avoidance. The effectiveness of the proposed solution was validated through simulation considering two intersections located in downtown Boston, and it was shown that coordination of CAVs can reduce significantly both fuel consumption and travel time. Part of the analytical solution of the constrained problem at a single intersection was presented in [92].

Tlig *et al.* [93] proposed a decentralized approach in which the vehicles are allowed to cross an intersection alternately. The proposed approach still requires a centralized controller in charge of synchronizing the vehicles to achieve an alternated crossing sequence. After receiving approval to cross the intersection, each vehicle adjusts its own speed according to a previously defined ideal velocity profile that contains three zones: a deceleration zone, a constant speed zone, and an acceleration zone. The vehicle has to decide the optimal velocity value for the constant velocity zone and the time horizon it needs to keep such speed is computed according to the arrival time. The acceleration and deceleration rates are assumed to be fixed and equal for all vehicle. A two-road intersection was simulated and total crossing time and energy consumption were used as performance metrics. The simulation results showed that the proposed approach outperformed the standard traffic light-based intersection control approach. In [94], the authors proposed a two-level control system for interconnected intersections. In the first level, a control agent coordinates the vehicles to allow them crossing alternately and deciding their own speed. In the second level, each intersection control agent shares information with its neighbor agents to optimize the flows inside the road network. This is achieved by optimizing the phases of each intersection so that the desired optimal speeds for each road segment can be calculated. Simulation of a traffic network with 6 roads and 12 intersections showed that the approach allows the vehicles to cross the intersections avoiding collisions.

TABLE II
SUMMARY OF RESULTS FOR DECENTRALIZED COORDINATION CONTROL (I: INTERSECTION, O: ON-RAMP)

Category		References
Heuristic	I	[54], [67], [68], [69], [71], [72], [73], [75], [74], [76]
	O	[62], [63], [64], [65], [66], [70], [77], [78], [79], [80], [81], [82]
Optimization and Control	I	[83], [84], [85], [86], [87], [88], [93], [94]
	O	[89], [90], [91], [92]
Evaluated Through Simulation	I	[72], [73], [75], [76], [83], [84], [85], [86], [87], [88], [93], [94]
	O	[62], [66], [77], [78], [79], [80], [81], [82], [89], [90], [91], [92]
Evaluated Through Field Test	I	[54], [67], [68], [69], [71], [74]
	O	[63], [64], [65], [70],

The decentralized solutions are amenable for online implementation and field tests have been reported in the literature. Table II groups the decentralized solutions according to the type of approach and whether they have been tested through simulations or field tests.

V. OUTLOOK AND FUTURE DIRECTION

A. Concluding Remarks

Several efforts in coordinating CAVs for improving both safety and traffic flow on specific transportation segments have been reported in the literature. The use of reservations is one of the first approaches applied to address this problem. The main challenge in this approach is related to the heavy communication requirements and the possibility of deadlocks. The optimization of the travel time appears to be the most commonly addressed problem. Alternative formulations include the minimization of vehicles overlap in the intersection zone. In addition, multi-objective optimization criteria have been also explored including the speed tracking error, acceleration, and the risk of collisions. Another path in this direction is the use of estimation of the traffic flow to generate control inputs guaranteeing traffic flow stability in the intersection. In this case, the solution is used to coordinate interconnected intersections. Solutions based on queuing theory and game theory have also been found in the literature.

Although the research efforts reported to date have aimed at enhancing our understanding of coordination of CAVs, there are still open issues to be addressed. For example, in the optimization-based approaches, depending on how the problem is formulated, it could only be solved numerically at the expense of a high computational load limiting its potential for real-time implementation. While these approaches can still be very helpful to assess the performance of decentralized solutions and the design of eco-driving systems, this becomes a major drawback for their implementation. Furthermore, there is a limited amount of effort in attempting to generate a closed-form solution for this problem. The latter would be helpful to expand the problem in interconnected and interdepended transportation segments, e.g., intersections, merging roadways, and facilitate further traffic analysis and improvement at the network level. In this direction, complex systems theory [95] appears to be a viable framework for modeling and analysis.

B. Future Research

Over the last years, there has been a significant progress in the area of CAVs and many simulation studies have been reported in the literature [96]. While much progress has been made in coordinating vehicles and improving traffic flow, it appears that the current state of the art is now at a point where new and significantly different approaches are needed. One particular question that still remains unanswered is "how much can we improve the efficiency of the powertrain in vehicles, if we assume that the vehicles are connected and can exchange information with each other and with infrastructure?"

In this new environment of massive amounts of data from vehicles and infrastructure, what we used to model as uncertainty becomes additional input or extra state information. It appears that future research needs to be devoted to considering optimizing vehicle operation at an even larger scale. Such large-scale optimization will require the acquisition and processing of additional information from the driver and conditions outside the vehicle itself. This is likely to require addition of new sensors and/or better utilization of information generated by existing sensors. However, the processing of such multiscale information will require significantly new approaches in order to overcome the curse of dimensionality. Thus the question is "can we exploit unique "rapid learning" technologies, e.g., Perturbation Analysis [97], successfully used in other domains to address this problem?"

Another question is directly related to connected vehicles operated by drivers. If we assume that we have available an efficient optimization framework and control algorithms for online coordination of a fleet of connected vehicles, how we can combine driver feedback systems and connected vehicles to provide instructions to the drivers? What kind of incentives (or penalties) we need to provide to motivate (or reinforce) the drivers to follow the suggested instructions or optimal routing directions? What is the minimum number of vehicles that need to be connected so that to start realizing the potential benefits? What are the implications in the transportation network if a certain number of drivers just ignore these instructions? These are some of the questions that the authors believe the community should attempt to address over the next years, as CAVs will become a reality.

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