OVERVIEW OF COORDINATION ALGORITHMS FOR VEHICLES AT AN URBAN INTERSECTION

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For my family
and my friends

-Luis K. González G.-
Summary

The purpose of this thesis is to present a critical survey of the most advanced strategies currently available to coordinate autonomous and semi-autonomous vehicles approaching an intersection.

The thesis is composed by 3 chapters:

Chapter 1 contains the problem statement.

Chapter 2 discusses the current state of the art on coordination of autonomous vehicles at an intersection.

Chapter 3 discusses existing techniques to coordinate semiautonomous vehicles at an intersection. These are vehicles driven by human drivers, but with the ability to override their drivers commands and act autonomously when necessary.
Sommario

Lo scopo di questa tesi è quello di presentare una rassegna critica delle strategie più avanzate attualmente disponibili per coordinare veicoli autonomi e semiautonomi che si avvicinano ad un incrocio.

La tesi è composta da 3 capitoli:

Capitolo 1 contiene la dichiarazione del problema.

Capitolo 2 illustra l’attuale stato dell’arte relativo al coordinamento dei veicoli autonomi ad un incrocio.

Capitolo 3 discute tecniche esistenti per coordinare i veicoli semiautonomi a un incrocio. Si tratta di veicoli guidati da autisti umani, ma con la possibilità di ignorare i loro driver comandi e agire autonomamente quando necessario.
Acknowledgments

I would like to thanks God firs, for countless blessings, to my family who provided me support, help, encourage-ment and faith in each step i gave, to the universities POLITECNICO DI MILANO and PONTIFICIA UNIVERSIDAD JAVERIANA Which give me the opportunity to follow new life’s challenges, to my tutor Professor Alessandro Colombo, without him nothing of this could be possible, his patience and guidance built the base of this work. To my friends that have become my new family by helping me all the time to grow toward my success, and bide this process of Master together. I hope to make them proud. To my godparents, their remembrance is our memory, it will remain forever.

-Luis Kewin González González-
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Introduction

The human capability of migration and the ability to change place by walking and running contributed to the colonization of the earth. Developments in Transportation are at the core of these enterprise and may be the most important and vital environment on the actual society.

0.1 Historical context

It is a reality that with the increasing population and urbanization, the traffic congestion is a pressing issue in current society. Thirty years ago, there were fewer cars and people did not have the same worries about traffic. However, it has become harder for traffic control to provide a safe and efficient traffic movement on the streets at the same time.

An early approach to the automation in the field of vehicles starts with the Automated Highway System (AHS) research program [18], it was focused on the improvement of the capacity and the safety of the highway traffic (see Figure 1). It began in 1989 with the support of the company named Caltrans, then, the University of California Partners for Advanced Transit and Highways (PATH) program, developed the basic tools for hybrid system design, simulation, and verification, in order to carry out AHS research (i.e. the hybrid system simulation language and run-time system SHIFT [12]). In 1994, the U.S. Department of Transportation formed the National Automated Highway Systems Consortium (NAHSC) with the idea to investigating alternative AHS designs as well as to test its key elements. In August 1997, the NAHSC successfully demonstrated several AHS technologies, including an eight-vehicle platoon-based system, on I-15 in San Diego, CA, more than 1700 people enjoyed rides in automated vehicles. The NAHSC was dissolved in 1998. With the support of Caltrans, PATH continues to develop the AHS technology and related spinoffs. In 2011, an study made by Tientrakool et al. [31] showed that the capacity of an ex-
existing highway system has the possibility to be increased by approximately 300%, when the coordination between vehicles and the use of the sensors to avoid collisions are introduced.

Figure 1: An example of Highway with 3 lines in each direction that have an intersection in the right.

The connections of different paths make intersections, where the possibilities of collision are critical without control. If the highways have an improve in the throughput the bottleneck will be presented in the intersections due to the number of vehicles and the meeting of paths. Those places are the main reason for this work. The cars approaching to intersections need an efficient control or supervisor, the lights implemented years ago could have an important update with the help of technology (i.e. the sensors in the cars, the computers in the intersection, the automated highway, etc) and the new resources can give better and more efficient coordination of vehicles approaching to the intersections implementing safety constraints with the goal to reduce the chances of a collisions as well as the throughput.

0.2 Related Work

Recent developments in information systems lead us to believe that autonomous vehicles will be widely adopted in the future. The wireless communication makes more efficient the dialog between devices and, if a car is taken as a device, it is possible to create affordable protocols of communication. In this way, the Vehicle To Vehicle communication (V2V), Vehicle To Intersection (V2I) or, in other words, Vehicle To Environment (V2X) and Vehicle Infrastructure Integration (VII) have been developed, whose aim is to create intelligent and autonomous traffic environment and open new
statements in the next step of thoughts about comfort in transportation. Autonomous vehicles approaching an intersection use Dedicated Short Range Communications (DSRC) and Wireless Access in a Vehicular Environment (WAVE) [42] to periodically broadcast information such as position, heading and intersection crossing intentions to other vehicles. The vehicles then decide among themselves resolving questions like who crosses first, who goes next and who waits.

The literature shows innovative methods which manage intersections without using traffic signals to implement new control methods. Most researches determine the vehicle passing sequence based on the control policy "First In First Out" (FIFO) [7] [30], that allows a direct answer about the scheduling to pass the intersection but the requirements of very low computational cost are overshadowed, limiting the potential capacity in the intersection. Wang et al. [25] covered all the feasible vehicle passing sequences and through trajectory planning algorithms tried to find the most efficient one, but, they admitted that the algorithms were not efficient enough because their complexity increases exponentially with the number of vehicles and lanes. Wu et al. [41], proposed an efficient dynamic programming algorithm to schedule vehicles at a two-lane intersection, with just $O(n^2)$ operations of computational cost and with the limitation that the case was not generalized. Yan et al. [44] proposed an efficient branch and bound algorithm for the problem, but the results are strongly limited by the number of vehicles [45]. Some heuristic and metaheuristic algorithms were also presented for the large scale version of the same problem in [40] and [43], that will be treat in the next chapter.

Raravi et al. [29] proposed an automatic merge control system for intelligent vehicles under a cooperative vehicle to infrastructure environment that ensured safe vehicle maneuver at road intersections, with the optimization through constraints the safety is guaranteed and the optimal maneuvers for merging vehicles were obtained by doing the minimization of the maximum driving time to intersection for every vehicle coming from two conflicting approaches. Uno et al. [32] also studied the merge control application based on V2V communication under the concept of virtual vehicles which is used to map vehicles from one lane to the other for ensuring safe distance criteria.

Dresner et al. [14] presented the idea of autonomous intersection management (AIM) as an alternative to the traditional traffic signal control mechanism. In the AIM, the vehicles and intersections are treated as autonomous agents in a multiagent system. By dividing the intersection into
a number of cells, an intersection manager program coordinates the reservation requests for temporal cell occupancies from every vehicle, offering right-of-way for each vehicle and ensuring safe crossing. Then, autonomous vehicles exchange the information of their states continuously communicating with each other and with roadside infrastructures, which can be seen as a controller, to ensure the driver’s safety and increasing the travel efficiency. Advanced sensors collect the data from vehicles such as the arrival time to the intersection and the time needed to pass it by sending it to the center controller in real-time. In other words, instead of using the traditional traffic lights, this kind of traffic control strategy considers each vehicle individually and vehicles can get through the intersection which have received their individual right-of-way.
Chapter 1

Problem Statement

The intersections are common places where vehicles change their speed, their path and where the possibilities of collision increase, even more when the advertising banners take more attention than they should, see Figure 1.1.

The transportation nowadays presents a good number of possibilities to create algorithms to avoid crashes and accidents, considering the influences that different sizes of vehicles bring to the roads, the elements on the street that control and regulate the environment of the drivers and pedestrians, such as the traffic lights, traffic signals, the intersections, the roundabouts, the places where pedestrians cross the streets and all the conditions that can be measure in some way.

Figure 1.1: Cars and street

An example of a T intersection is in Figure 1.1 and a intersection with 2 roads is in Figure 1.2

From the Figure 1.2 the paths are shown as colored shadows of the vehi-
cles in time and show that both cars share roads in different times, so, the challenge of correct approaching in the right moment defines the optimal coordination.

Depending of the city planning those elements of control can be seen more frequently, meaning that in the big cities you can find streets with so many intersections, diagonal intersections, and roundabouts before or after the intersection that could lead to road bottlenecks, traffic jams, etc.

The cars approaching to intersections is a worldwide worrisome, everywhere drivers have to face an intersection at least once throughout the day. Therefore, considering the high number of collisions presented in intersections, engineers and scientists are working with sensors and processors capable of taking control of the vehicle and skip the uncertainties of human decisions.

Many countries focus on the development of new materials, better sensors, faster processors, in other words better hardware, but the software to manage this new and improved machines, should be able of keep up with new needs as much as possible. The new algorithms imply mathematical procedures that should work fast and in most cases, in real time. This overview show the different methodologies already made by the researches over the years.

The importance of these investigations in the transport sector relates to safety, comfort, save time and space for the driver and a better exploitation of the streets already made.
After the implementation of the technology, the drivers can trust in the computer to take control of the vehicle, it will calculate the speed, decide the best order to arrive to the intersection and the best option in case of probability of collision (i.e. natural disaster). The mothers could give attention to the kids while going to the kindergarden and help themselves on a journey. A great number of vehicles crossing an intersection on the same time will have an important improvement, reducing the roads bottleneck and the time of travel. The efficiency of the fuel will be increase due to the constant speed and the number of stops.

Existing approaches for automating an intersection can be categorized as being either centralized or decentralized. Centralized solutions keep the same approach as the traffic lights but include V2I (Vehicle to Infrastructure) communication [13]. These typically involve an intersection agent (IA) that receives requests from vehicles to cross the intersection, do the scheduling and decides the best crossing sequence. On the other hand, the decentralized solutions use the inter-communication vehicle to vehicle (V2V) cooperation to coordinate them but without traffic lights or manager, instead allow the vehicles to cross the intersection without having to predict the future trajectory while crossing the intersection.

The number of approaches made for the authors in their investigations does not converge in an specific idea, the quantity of information and algorithms require an organization and therefore is this thesis, the overview of the main methodologies will be covered, as the main methods developed during the current society that search the future of automated vehicles. The division is in two big chapters, the first one is Coordination of autonomous vehicles at intersections and the second is Supervision of Human - Driven Vehicles at intersections.
Chapter 2

Coordination of autonomous vehicles at intersections

2.1 Introduction

The cars have sensors and computers in different places of the vehicle, the function of the computer is to process the information taken from the sensors and give a response, this can be a light showing and warning of a situation or the activation of an actuator, the term autonomous is introduced in the moment that the car has enough technology to be its own authority in the activation of the actuators, which means that it, can accelerate, brake and turn independently of the people inside.

But the decisions of the vehicle are influence by the other ones, therefore in an intersection the car should have the correct way to pass in the precise time in order to avoid collisions and following predefined rules. The following papers show that depending of the rules developed for this purpose is possible group them. The groups will have the following names: Platoon, Reservation Algorithm, Vehicle scheduling using Genetic Algorithm and Vehicle Scheduling using Job Scheduling. The first one is a term used when is defined a division by groups of vehicles in the algorithm, that is, they are divided in bunches depending how close are between one to another and with respect to the distance to the intersection; the second one is a new term that will be introduced in order to define a set of algorithms which take decisions changing as less as possible the trajectory defined by the vehicles when are taking the decisions based on the requirements; the third one takes the order of crossing the intersection in base of the decisions made for the genetic algorithm, the order of arrival of the vehicles to the intersection
Chapter 2. Coordination of autonomous vehicles at intersections

depend on the conditions given for the GA selection; and the fourth one of collision avoidance or scheduling, is defined as a set of times in which the vehicle should arrive and cross the intersection.

The common relationship between these groups is the absence of human-driver in the vehicles approaching to intersections. Then, by using automated vehicles through the methodologies presented, it can improve the throughput and/or the collision avoidance at intersections.

The differences between this groups are: in the platoons the vehicles are taken in bunches, the intersections divided by cells and the state of the cell is the one which implies if the collision can appear, in the reservation algorithms, the trajectories are predicted or pre-programed in order to be followed for the vehicle during the approaching and crossing the intersection. In the genetic algorithm, an intersection manager agent is required in order to do the computations using the genetic algorithm for the correct scheduling, and the job scheduling, take the intersection manager agent as a single machine and the vehicles as jobs, scheduling to cross the intersection.

2.2 Platoons

Platoons is the name used to refer vehicles in groups. When the approach considers individual vehicles, the average trip delay is increased, especially when many vehicles from different approaching lanes need to cross a busy intersection, therefore the grouping solution could improve the throughput of the intersection and the crossing order could have different solutions depending of the implemented rules or by heuristic scheduling. An example of grouping is showing in the Figure 2.1, where depending of the distance to the intersection the group is formed for the closer cars.

In the literature the last authors to use this approximation are:


• In 2015 Guang Chen, Kyoung-Don Kang with Win-Fit: Efficient Intersection Management via Dynamic Vehicle Batching and Scheduling [6].
In the same year Alejandro Ivan Morales Medina, Nathan van de Wouw, Henk Nijmeijer with Automation of a T-intersection using virtual platoons of cooperative autonomous vehicles [28].

The first 3 papers follow the idea of divide the intersection by cells (i.e. The Figure 2.1 has 4 enumerated cells), depicting in this way the occupation area depending of the path of the vehicles. However, the fourth one use coordinates in a curvi-linear path, this means that the initial point of the zone of the trajectory is determinate by the radius from the center of the intersection, the straight and the turn are considered in terms of coordinates by arcs and evaluated depending on the direction of the vehicle (In the Figure 2.2 is showed the curvilinear path beginning from S1 and with the possibilities to turn left (t1,l) or right t1,r respectively). The differences are in the way that the order in which the vehicles pass the intersection are solved.

Azimi et al. [4], divide the intersection in cells and classify each one in order to have a representation of the state (busy, free, possible collision). With the space well defined, the vehicles follow V2V protocols through safety messages (Enter, Cross, Exit) deciding if it crosses or not with the trajectories. In these protocols we have Minimal Concurrency Protocols (MCP), High Concurrency Protocols (HCP) and High Concurrency Protocols with Slow-down (HCPS); the first one allows the cross of the intersection even if the possibility of crashing is close, depending to the priority, the second increases the parallelism inside the intersection area by allowing more vehicles to cross the intersection at the same time and the last one allows a low priority con-
Chapter 2. Coordination of autonomous vehicles at intersections

Conflict between vehicles, therefore slows down the vehicle while approaching to an intersection and prior the conflicting cell to provide the higher priority-vehicle with necessary time gap to cross. Thus minimizes the complete stop, and also the total number of stops and startups that the vehicle do in the way.

With the idea of the HCP, in 2015 they established the Ballroom Intersection Protocol: Synchronous Autonomous Driving at Intersections [3], where take as example the synchronization of the people dancing, maximizing the area of the intersection using parallelism.

In the BRIP, a predefined traffic arrival pattern is assigned to each intersection. This pattern depends on the intersection geometry and considers parameters such as the number of entering/exiting roads and turning restrictions. Therefore, the approaching vehicle has to be in the appropriate lane before entering the intersection box and enter the intersection area during a permitted arrival time slot maintaining a certain speed while crossing. They refer these information as the Synchronized Intersection Arrival Pattern (SIAP). So, the SIAP takes the parameters but the BRIP use the provided information to simulate the state of the vehicles as is defined in the memory, keeping the distances and avoiding collisions. The main problem in this protocol is the precision of the GPS and the low robustness to a random external conditions because if one wheel explodes, for example, or something affect the movement of the vehicles the small spaces make the cars collide as in a ballroom concert, having the entire group a collision and stop the traffic in all directions.

Chen et al. [6] used the Win - Fit approach, decreasing the average trip delay to cross a simulated intersection by a percentage of 31% - 95% compared to several baselines. In Win algorithm, the first group that results after the operation of grouping of the vehicles using the distance to the intersection is declared as the winner, only if the group can entirely pass the intersection as one batch incurring the shortest average waiting time for the cars in the other approach lanes. So, doing this instead of handling individual cars from all directions one by one, decreases the chance for collisions/conflicts between cars coming from different directions and required waiting times for safety, of course avoiding potential starvation of the cars in the low priority (non-winner) groups. Besides the Fit algorithm cooperates with Win to allow some vehicles of the low priority groups enter safely in the cells of the intersection unoccupied by the winner group during its idle
2.2. Platoons

time slots (if any) decreasing the overall intersection trip delay. Then, the concept of Intersection Management Agent (IMA) is introduced and now the communication have another member who broadcasts the intersection trip schedule derived by Win-Fit to the first group in each approach lane. Right before the winner group leaves the intersection the program is executed again from the beginning.

In Morales Medina et al. [28] the platoon is created in a virtual way: a virtual platoon is formed by defining a virtual inter-vehicle distance between vehicles driving on different lanes and realizing the virtual inter-vehicle distance by Cooperative Adaptive Cruise Control (CACC) [17] on the individual vehicles. This approach allows to leave the “gap-making” task (i.e. to ensure safe passage of a vehicle with higher priority) solely in the hands of the CACC system.

The curvilinear path created for the inter-vehicle distance is showed in Figure 2.2 and is defined using the four zones (named cooperated zones, CZ), of the intersection and the radius. For example generically in the left-turn trajectory exists two straight sections with lengths: 

\[ s_0 = rcz - 1/2 \times wf, \]

and 

\[ sl = rcz - rl + 1/4 \times wo, \]

where \( wo \) is the width of the road on which the vehicle enters the CZ and \( wf \) is the width of the road on which the vehicle exists the CZ, a left turn about an angle of \( \pi/2 \) radians with constant radius \( rl = 3/4 \times wf \).
2.3 Reservation Algorithms

The papers grouped here has in common the fact that the trajectory is predicted or established, the possibilities that the car can follow are determined for the presence of existing Intelligent Transportation System (ITS) technologies that make the management system adaptive to constantly changing traffic. Then the order to arrive to the intersection keep as much as possible the path on the premise of ensuring certain fairness.

In the literature the last authors to use this approximation are:

- In 2012 Ismail H. Zohdy, Raj Kishore Kamalanathsharma, Hesham Rakha with Intersection Management for Autonomous Vehicles using iCACC [46].
- In 2013 Laleh Makarem, Denis Gillet with Model predictive coordination of autonomous vehicles crossing intersections [26].
- In the same year Kyoung - Dae Kim with Collision Free Autonomous Ground Traffic: A Model Predictive Control Approach [20].
- In 2014 Gabriel R. Campos, Paolo Falcone, Henk Wymeersch, Robert Hult, Jonas Sjöberg with Cooperative receding horizon conflict resolution at traffic intersections [5].
- In the same year Xin Wei, Guozhen Tan and Nan Ding with Batch-Light: An Adaptive Intelligent Intersection Control Policy for Autonomous Vehicles [33].

Starting with the Adaptive Cruise Control (ACC) systems which have the ability to accelerate and decelerate based on the lead-vehicle speed and system set-speed [21] and the integration with new technologies applied in vehicles concern to communication systems as Vehicle-to-Infrastructure (V2I) and Vehicle-to-Vehicle (V2V) information transfer are being developed using Dedicated Short-Range Communication (DSRC) and other wireless
technologies, bring the idea of the Cooperative Adaptive Cruise Control (CACC), adding the grouped part and placed a supervisor (i.e. the intersection manager), to pass through an intersection devoid of signal controllers or stop/yield signs. The flowchart of the behavior of the CACC protocol is showed in the Figure 2.3 where the wireless communication starts with the information gathered from the group of vehicles in the cooperation zone in the Supervisory level and with the Host vehicle in the execution level, the ref is the system set-speed, the virtual inter-vehicular distance is calculated and the control reconfiguration supervises the target vehicle assignment that should be followed by the CACC protocol, returning the signals that change the acceleration as it is required.

Therefore Ismail et al. [46] with CACC in intersections (iCACC), stands for Intersection Management using Cooperative Adaptive Cruise Control and aims optimizing speed profiles, minimizing delay and preventing crashes. Also it has the capability to capture the physical characteristics of the environment at intersections. Moreover, the algorithm has the ability to optimize a time step ahead to speed up the process and overcome any uncertainty in the simulation. In the work the system is analyzed for two basic measures of effectiveness: average delay per vehicle and average fuel consumed by a vehicle to pass the intersection.

As is showed in the figures 2.4 and 2.5 the fuel savings due to inertia and a higher average speed save of 77% in fuel for the iCACC case over
Chapter 2. Coordination of autonomous vehicles at intersections

Figure 2.4: Delay per vehicle (s) comparison between conventional control and the proposed iCACC control.

Figure 2.5: Fuel consumed per vehicle (l) comparison between conventional control and the proposed iCACC control.
2.3. Reservation Algorithms

conventional approaches.

In the work made for Makarem and Gillet in 2013 [26], the use of soft-constrains allows violations of constrains related to collision avoidance at early stages, this make more approximations and not so rigid behavior in the MPC control of the vehicles. The Model Predictive Control (MPC) method’s first introducer is unknown (See García et al. [27] for a review of this literature), it is a form of control in which the current control action is obtained by solving at each sampling time a finite horizon optimal control problem, taking the current state as the initial state. The optimization produces an optimal control sequence, but just the first control value in this sequence is applied to the system. In most approaches, every vehicle solves an optimal control problem taking into account its dynamics, dynamic constrains and constraints related to collision avoidance. In this way every vehicle formulates the collision avoidance constraints using the local information gathered from the nearby vehicles.

The constraints are formulated using all the predicted trajectories of the other vehicles, therefore at each time step the optimal controller computes the solution for the full control horizon. These rules depends on the behavior.

Through the cooperative vehicle intersection control (CVIC) system [23], the algorithm minimized the overlaps of the projected trajectories of conflicting vehicles in the intersection area, avoiding the presence of any pair of conflicting vehicles. However, the presence of two conflicting vehicles just at the outside of intersection is considered safe, that means that such condition may cause collision at some corner in the intersection depending on the lengths of the vehicles. Imura et al. [19] takes the CVIC algorithm and consider the states of all vehicles together, based on avoidance of their projected cross-collision risks around the intersection. Moreover, the introduction of relevant constraints ensures the scheme free from any collisions and enables to manage turning movements of the cars under a safe velocity limit without using any auxiliary lanes. But now, an intersection coordination unit (ICU), is assumed to be installed and uses two-way communication to receive basic driving information from the approaching vehicles, e.g., current position, velocity and destination at the next intersection, and send back guidance to them after computing their control inputs.

However, the prediction of the trajectory is a problem of heavy computation. One solution was proposed by Campos et al. [5] as a decentralized solution where the problems are divided in two parts: an infinite horizon
solution, calculated offline and a finite-time optimal control problem where collision avoidance is enforced as terminal constraints. In this way, its agent complexity with respect to the number of agents remains constant since collision avoidance is enforced through local state constraints at given time steps.

On the other hand the automate intersections allow more considerations, the ones already working use lights and the change to traffic less-lights will not be instantaneous, what it means that the change between completely automated vehicles and intersections will pass through a moment where the co-existence with human driver vehicles is present. Wei et al. [33] proposed a policy called Batch-Light which can make full use of existing Intelligent Transportation System (ITS) technologies to make the management system adaptive to constantly changing traffic through a greedy-based Conflict Matrix decision algorithm, getting more vehicles reserve successfully on the premise of ensuring certain fairness. Besides, one algorithm is proposed to help the vehicles who are not include in the early steps to pass through the intersection by acceleration or deceleration, named a k-Shift optimization.

In the experiment the results show that Batch-Light outperforms FCFS and traditional traffic signal control policy both in balanced and unbalanced traffics.

Elhenawy et al. [15], inspired by chicken-game and taking CACC in the vehicles, but doing the assumption that the generation of the CACC is not responsible for maneuverability, instead the analysis of collision is avoided and is scheduled the payoff for the vehicles using the acceleration or constant velocity. The chicken game is a model of conflict for two players in game theory: ”The principle of the game is that while it is for both players beneficial if the other player yields, their own optimal choice depends on what their opponent is doing, if their opponent yields, the player should not, but if the opponent fails to yield, the player should” [36]. The equilibrium of the conciliation between the players is known as Nash equilibrium and the main idea is that all the gamers arrive without lost, in the vehicle context, without collision.

### 2.4 Vehicle Scheduling using Genetic Algorithm

GA is an adaptive heuristic optimization approach related to the evolutionary concepts where the evolution process in natural systems is simulated, ”genetic algorithm” (GA) is a metaheuristic inspired by the process of natu-
2.5 Vehicle Scheduling using Job scheduling

In this section the vehicle sequencing problem is modeled as a single machine where the cars are treat as jobs, each job has a release moment and a deadline as boundaries where should start and finish respectively. The intersection acts as the controlling entity that give the order in where the vehicles arrive to the intersection and the vehicles are grouped depend of their positions and the similarities.

In the Figure 2.6 the single machine shows 3 different schedules, there are $J_1$, $J_2$ and $J_3$, jobs that are processed with the order: first $J_2$, then $J_1$ and last $J_3$, is possible seeing that Schedule 1 is not feasible because $J_1$ terminates after its deadline, Schedule 2 is not feasible as well due to the order of $J_1$ and $J_2$ violating the defined constraint and the Schedule 3 is
Both papers show the NP-hardness proof of the algorithms developed, in Colombo et al. [9] is proposed a least restrictive supervisor based on the exact solution and an approximate supervisor with quantified approximation bounds.

In the literature the last authors to use this approximation are:


- In 2014 Fei Yan, Jia Wu and Mahjoub Dridi present A Scheduling Model and Complexity Proof for Autonomous Vehicle Sequencing Problem at Isolated Intersections [44].

In the first two papers by Colombo et al. [9] [8] the objective is to determine a minimally restrictive supervisor, which allow agents to choose all possible control actions that keep the system without collisions. This is achieved by determining the maximal controlled invariant set, and then by determining control actions that keep the system state inside this set.

Therefore through results from the scheduling literature and computational complexity theory is showed that the exact solution of the problem is NP-hard. The complexity is combinatorial and the running time of the approximate algorithm scales polynomially as the number of agents, the authors provide tight upper bounds on the error introduced by the approximation.

The supervisor acts as a filter between a desired input, if the scheduling algorithm arrives to a solution after a desired input, it returns the desired
2.5. Vehicle Scheduling using Job scheduling

input, unless this could cause a collision at some future time, if so, the supervisor returns a safe input.

In the case presented by Yan et al.

paths is showed in Figure 2.7 where a controller is located in the center of intersection and is informed by the vehicles approaching the intersection about their data after entering the control range. Pedestrians are not considered and vehicle overtaking on same lane is not allowed.

Figure 2.7: Schematic of intersection under the control strategy with vehicle infrastructure integration

The paths used by traffic streams to pass the intersection are illustrated with dashed lines in Figure 2.8, depending on the direction there exist compatible and incompatible streams, which determine whether the trajectories crossed or not. If the trajectories of two traffic streams do not cross, they can pass through the intersection. In this example, the partition is possible, the 12 streams are divided into four compatible stream groups (see Figure 2.8).

Now suppose that at a start time to = 0, there are vehicles in the control range approaching the intersection from different directions and the data of all vehicles is received by the controller informing from each vehicle:

- Vehicle identification (ID): is used to identify each vehicle.
- Stream number: identified which stream the vehicle belongs to, i.e. which lane it is moving on.
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Figure 2.8: Grouped vehicles

- Vehicle arrival time: the precise time vehicle arrives at the stop line from to without interference.

- Vehicle passing time: time interval vehicle needs to get.

A function that evaluates the minimum overall evacuation time to make all the vehicles in the control range get through the intersection area is required. The isolated intersection is consider as a single machine, each vehicle is treated as a job and its arrival time and passing time can be modeled as the job release date and processing time, respectively. Also, the time a vehicle passes the intersection can be modeled as the job completion time and jobs are partitioned into different families (CSGs) according to their positions. For example, the vehicles in Figure 2.8 can be treated as four families corresponding to the four compatible stream groups. Vehicles on same lane should traverse intersection in FIFO way but vehicles in the same stream are treated as jobs in the same chain. Jobs in different chains but same family can be processed in parallel. The lost time between two stages can be considered as the family setup time, which is only decided by the following family. The similarities between the vehicle sequencing problem and the single machine scheduling problem presented are given in Table 2.1.
### Table 2.1: Similarity Between Vehicle Sequencing Problem and Single Machine Scheduling Problem

<table>
<thead>
<tr>
<th>Vehicle sequencing</th>
<th>Scheduling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isolated intersection</td>
<td>Single machine</td>
</tr>
<tr>
<td>Intelligent vehicles to sequence</td>
<td>Jobs to process</td>
</tr>
<tr>
<td>Vehicle in different CSGs</td>
<td>Jobs in different families</td>
</tr>
<tr>
<td>Vehicle arrival time</td>
<td>Job release date</td>
</tr>
<tr>
<td>Vehicle passing time</td>
<td>Job processing time</td>
</tr>
<tr>
<td>All red time between different CSGs</td>
<td>Setup time between families</td>
</tr>
<tr>
<td>FIFO rule on same lane</td>
<td>Chain constraints</td>
</tr>
<tr>
<td>Overall evacuation time</td>
<td>Makespan</td>
</tr>
</tbody>
</table>

The scheduling model has a distinct structure, so this problem can be seen as processing jobs in Processing Groups (PG). These can be defined as a set of jobs from the same family and processed on the machine without the interruption of jobs in any other families. Note that only jobs in the same family can be put into same PG. Therefore, jobs in the same chain should be processed consecutively and jobs in different chains may be processed simultaneously. Thus, the processing time of the PG does not equal the sum of processing time of jobs in it, nor the maximum processing time of all jobs.
Chapter 2. Coordination of autonomous vehicles at intersections
Chapter 3

Supervision of Human - Driven Vehicles at intersections

The common aspect of the papers covered in this chapter is the human-diver, here the technology implemented in the vehicles does not command the machine at 100% but allows in most cases avoid the orders of the driver when the supervisor do the process deciding which is the best option that optimizes the order of approach or avoid collisions at intersections.

In this way the safety not only depends on the human-driver but also allow better collision avoidance results, different ways of scheduling to cross the intersections increase the efficiency of time delay and throughput time without the fully automation of the cars.

The topics below are divided beginning with the literature of risk assessment, where the evaluation of a risk situation is based on distinguishing safe behaviors and the driver’s intention at the intersection, then, the Discrete Event Model is used to built a safe, non-blocking and maximally permissive supervisor at road intersections and finally the collision avoidance.
Chapter 3. Supervision of Human - Driven Vehicles at intersections

3.1 Risk Assessment

3.1.1 Introduction

Driving has a risk, the forces at fast speed can accumulate enough energy to end a person’s life in a few moment, although the quantity of studies each year permit the implementations of tools which reduce more and more this misfortunes. With respect to the statistics of crashes, between 40 and 60 percent are produced in intersections, is led only by rear end collisions. [2]

In the intersections the visibility is not clear and sometimes the light or the mirror effect affect who drives. Most of this crashes occur due to the human error, the driver wants to arrive on time to work, he is not focused in what he is doing, involving bad decisions or distractions, this means that it is possible to reduce and optimize the prevention of collisions in an important percentage.

In the literature the last authors to use this methodologies are:

- In 2012 Stéphanie Lefèvre, Christian Laugier, Javier Ibañez - Guzmán made Evaluating Risk at Road Intersections by Detecting Conflicting Intentions [2]

- Ismail H. Zohdy, Raj Kishore Kamalanathsharma, Hesham Rakha with Intersection Management for Autonomous Vehicles using iCACC [46]

- In 2016 Jianqun Wang, Xiaoqing Xue, Rui Chai, Ning Cao with ATemporal-spatial Collision Warning Method at Non-signalized Intersection [2]

- Yuchuan Fu, Changle Li, Bing Xia, Weiwei Dong, Yulong Duan and Lei Xiong with A Novel Warning/Avoidance Algorithm for Intersection Collision Based on Dynamic Bayesian Networks [16]
3.1. Risk Assessment

The first approach with respect to the risk assessment defines a set of rules with the objective of detecting danger. With technology it is easier the use of the context and the current observations of the state of the vehicles and the rules can include weather conditions, location, level of fatigue of the driver, percentage of distractions, a hole in the street or another real factors. [39]

Later, through accumulation of information and learning patterns, the possibility to detect potential configurations that imply risk and makes procedures to react solving the situations in different ways than the usual crash could be increased, as in the literature where the neural network was used in [7] and in [30], applying the Expectation-Maximization algorithm to cluster data. However, the bunch of information continues being an issue because the acquisition of data is not perfect and the programs for the simulations does not cover all the possibilities that can be involved in the real behavior of the cars. Therefore, the trajectory prediction and collision detection was presented, in which at first, motion models are used to predict the future for the objects in the scene, in order to later check the possibilities where the trajectories can collide. Nonetheless, the algorithms base on a physical motion model of vehicles are able to just predict short-term collision.

On the other hand, using estimations, the driver intentions and expectations can be analyzed from the joint motion of the vehicles, starting with the layout of the intersection and taking into account the traffic rules at the intersection. Lefèvre et al. [2] have proposed an approach with two vehicles involved in typical collision scenarios, where through the collision prediction horizon it is possible to characterize the efficiency of the approaching in different situations evaluating in this way the potential of different strategies and avoiding accidents after dangerous situations are detected.

Nonetheless Wang et al. [2] show the atemporal-spatial warning method. This is based on the analysis of conflicts in the road intersections and simplified the vehicle model. First, a calculation of the time region when the vehicle pass the conflict zone can be used to decide whether the accident can occur or not, and then, the relationship between the safety breaking distance and the actual distance can be considered to establish a correction in the algorithm. Furthermore, according to the features of the drivers, a division into three categories can be established: normal, negative and positive; for the negative drivers the warning of danger should be released earlier than the one for positive drivers. However, in order to simplify the algorithm, for
all the cases some parameters must be kept constant, as is the case of the speed and deceleration.

The issue with the trajectories is that there are algorithms that brings complex paths and some of them are not useful, therefore the idea of using stochastic process helps. In the Dynamic Bayesian Network (DBN) \(^1\), the vehicles state evolution is analyzed, therefore, with this information and the inter-vehicle communication a warning algorithm to avoid intersection collision is designed. The evaluation of a risk situation is based on distinguishing dangerous and safe driver behaviors.

### 3.2 Collision Avoidance using Discrete Event Model

The real life is a continuous process but the quantity of information can make an important modification working in the discrete event level.

By doing series of executions or through dividing by sets, it is possible to measure the size of the allowed execution space and therefore obtain the restrictiveness when the control is designed.

Most of the complexity scenarios from the composite control specifications can be tackled in a relatively simple way at the discrete level, while at the same time the restrictiveness of the resulting controller can be measured in terms of size of the allowed execution space, compared with the set of all possible executions.

In 2013, Dallal, Alessandro Colombo, Domitilla Del Vecchio and Stéphane Lafortune in the Supervisory Control for Collision Avoidance in Vehicular Networks with Imperfect Measurements [11] analyze the problem of collision avoidance at road intersections in vehicular networks in the presence of uncontrolled vehicles, in this case a disturbance, and measurement uncertainty. The aim is to build a supervisor of the continuous time system that is safe, non-blocking and maximally permissive with respect to the discretization, taking the presence of a disturbance and measure uncertainty but assuming perfect measurement of position, is proceeding in the follow steps:

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\(^1\)A Dynamic Bayesian Network (DBN) represents a set of random variables and their conditional dependencies via directed acyclic graph (DAG) which relates variables to each other over adjacent time steps [37]
3.3. Collision Avoidance

1. Defining a discrete event system (DES) abstraction of the continuous time system, using uncontrollable events to model the uncontrolled vehicles and the disturbance.

2. Translating safety and non-blocking requirements to the DES level.

3. Solving at the DES level.

4. Translating back the resulting supervisor from the DES level to the continuous level.

In order to establish if the observer of this discrete automaton is the “right” abstraction of an optimal continuous estimator based on the continuous dynamics and the measurement equation, is introduced the notions of state reduction and exact state reduction, which are akin to the notions of simulation/alternating simulation and alternating bisimulation in the hybrid systems literature, but adapted to the specific context under consideration in the paper. These new notions are then leveraged for proving that the solution at the abstracted DES level, when implemented at the continuous level, does meet the three requirements of safety, non-blockingness, and maximal permissiveness. Under this set-up, the DES problem can be solved on the observer of the discrete automaton, by computing the supremal controllable sub-language.

The DES abstraction by introducing a finite set of observable but uncontrollable “measurement events”, showed that this abstraction was a state reduction of a system defined over state estimates, and used this abstraction to obtain the desired supervisor for the continuous domain system.

The problem in this work is the assumption of perfect measures of the GPS which compromise the robustness of the algorithm in presence of imperfect positions.

3.3 Collision Avoidance

In 2015, Heejin Ahn, Andrea Rizzi, Alessandro Colombo, and Domitilla Del Vecchio presented an Experimental Testing of a Semi-autonomous Multi-vehicle Collision Avoidance Algorithm at an Intersection Testbed [2] which describes the implementation of a multi-vehicle supervisor to prevent collisions at intersections using experiments on an intersection testbed with three RC cars.
Chapter 3. Supervision of Human - Driven Vehicles at intersections

The testbed is present with 3 paths where 2 controlled cars are in presence of a third uncontrolled, so:

\[ \text{Figure 3.2: Testbed} \]

\(a\) Three prescribed paths on which three RC cars run. The paths are defined as a sequence of points in the global coordinates with an origin \(O\). The shaded area in the middle is the intersection, is represented on each path by an interval \((\alpha_i; \beta_i)\) for \(i = \{1; 2; 3\}\). The black circles represent two controlled cars while the grey circle represents the uncontrolled car.

\(b\) The intersection testbed. The orange lines on the ground correspond to the prescribed paths in (a).\(^2\)

The way that the supervisor acts is by overriding the controlled cars only when it detects possible future collisions, in the meantime the cars are programmed to maintain a constant motor input, called desired input. In the experiments, car 1 and car 2 are controlled by the supervisor, while car 3 is driven by a human and is not controlled by the supervisor.

An over-head vision system is used to measure the position and direction of all cars, a computer collects all the available information including the positions, speeds, and directions of all cars, which are measured by the vision system and the encoders, and the local information of each controlled car, such as the desired input. This information is then distributed to the controlled cars through a 802.11b wireless communication network. All cars follow the prescribed paths by implementing a feedback controller for the steering input using information from the vision system. The supervisor can override the motor input, but cannot change the steering input.

\(^2\)Image taken from the paper in order to show the problem statement and explain the method.
The supervisor is executed in discrete time $\tau$ and has the high-level structure shown in Figure 3.3. In this section, each function of the supervisor is introduced, and the formal integration of these functions is provided.

![Figure 3.3: The structure of a supervisor](image)

At step $k$, the supervisor receives a state measurement ($x_{m}; 1; x_{m}; 2; x_{m}; 3$) and a desired input ($u_{\text{desire}; 1}(k\tau); u_{\text{desire}; 2}(k\tau)$) from the controlled cars. These are used to compute a one-step-ahead state prediction $X^{k+1}(u_{\text{desire}}(k\tau))$. Then, the verification function determines whether it exists a safe input signal for this state prediction to avoid future collisions. If the answer is “yes” with a schedule ($T_{1}; T_{2}$), a safe input signal $u^{k+1}$ is generated and stored for possible use at the following step, and the supervisor does not override the cars. Otherwise, the supervisor overrides the controlled cars using the safe input $u^{k}$, which was computed and stored at the previous step.\(^3\)

The dynamics of the cars were studied with several sources of disturbances taken in consideration to design the compensator and therefore reduce their effects.

As results of the experiment just the 7.2% of the times the prediction was incorrect but the control is programmed to stop the car. After 591 trajectories where at least one car cross the intersection, in 208 the supervisor intervenes, no collisions presented and 15 stops.

An important computation of the supervisor is taken because all possible routes of vehicles have to be considered and progressively discard unfeasible ones, also the prediction of the state depends on the dynamics of the vehicle, so, when the size of the devices for the experiments increases it is necessary

\(^3\)Image taken from the paper in order to show the problem statement and explain the method.
to add sensors that correct the model of the dynamics in real-time, leading to reduce the uncertainty of the trajectories and increasing the performance, this supervisor has the limitation depending on the number of vehicles and has constraints with the uncontrolled vehicles because the number of entrances is increased as well as the AND gates that should be used in the tree of decision on scheduling.
Chapter 4

Conclusions

In conclusion, the literature about vehicles approaching to intersections is essentially arranged around two main families of approaches. The first one is Coordination of Autonomous Vehicles at Intersections, where the main characteristic of this division is that all the algorithms are developed in base to the new technologies that implied human-driverless of the vehicles. The second one is Supervision of Human - Driven Vehicles at Intersections, where the human continues as the main driver but can have help from the technology, in the sense that, a supervisor gives the scheduling that the driver has to follow in the intersection or take the control of the car in a dangerous situation in order to avoid collisions could exist. The methodologies are present in this way:

1. Coordination of autonomous vehicles at intersections:

   - Platoons: The vehicles are grouped in order to cross the intersection, in this way the main algorithms are:
     - STIP: Spatio-Temporal Intersection Protocol, where the intersection is divided by cells and through V2V communication the decision of the order to cross is made.
     - WIN-FIT: Two algorithms co-working, the first one (WIN) classifies in groups the cars using the distance to the intersection, the closest group is the winner, passing through certain path and, depending of the area in the intersection used for the group passing, allows the second one (FIT) to make other cars cross through the free one, keeping the safety distances.
Virtual platoon in T intersections, where the virtual grouping vehicles follow curvilinear paths after the definition of the virtual inter-vehicular distance through the Cooperative Adaptive Cruise Control (CACC) method.

- **Reservation Algorithms:** The trajectory is predicted, these algorithms are characterized by the arrival order to the intersection, keeping as much as possible the path on the premise of ensuring certain fairness.

- **Intersection Management for Autonomous Vehicles using iCACC:** The CACC takes the physical characteristics and manages them through the Intersection Agent (IA) following the speed advises to cross the intersection.

- **MPC - Model Predictive Control:** The vehicles formulate the collision avoidance constraints using the local information gathered from the nearby vehicles through the prediction of the trajectories.

- **CVIC - Cooperative Vehicle Intersection Control:** Considers the states of all vehicles together, it is based on avoidance of their projected cross-collision risks around the intersection, using a Intersection Coordination Unit (ICU) to receive the driving information and send back the guidance.

- **Cooperative receding horizon conflict:** The problems are divided in two parts: an infinite horizon solution, calculated offline and an infinite-time optimal control problem, where collision avoidance is enforced as terminal constraints.

- **Batch-Light,** which through the Intelligent Transportation System (ITS) technologies manage the system adaptive to constantly changing traffic, due to Conflict Matrix decision algorithm. Besides, one algorithm named k-Shift optimization, is proposed to help some unlucky vehicles to pass through the intersection as much as possible by acceleration or deceleration.

- **Chicken - Game:** Characterized by the decision of ”go straight”
or "turn", the analysis of collision is avoided and the payoff is scheduled for the vehicles using the acceleration or constant velocity.

- Vehicle Scheduling using Genetic Algorithm (GA): Uses the GA, which is an adaptive heuristic optimization approach, related to the evolutionary concepts where the evolution process in natural systems is simulated arriving to the order of scheduling to cross the intersection.

- Vehicle scheduling using Job scheduling: The isolated intersection is considered as a single machine, each vehicle is treated as a job and its arrival and passing times can be modeled as the job release date and processing time, respectively.

2. Supervision of Human - Driven Vehicles at intersections

- Risk Assessment: Uses of the supervisor to reduce the collisions in human-driven vehicles by:
  - Detecting intentions, the continuous observation of the current state of the driver could detect possible dangerous situations.
  - Atemporal: Based on the analysis of conflicts in the road intersections and simplified the vehicle model, classifying the drivers in normal, negative and positive depending on the driver’s skills and reaction time.
  - DBN - Dynamic Bayesian Network: The vehicles’ state evolution is analyzed, therefore, with this information and the inter-vehicle communication a warning algorithm to avoid intersection collision is designed.

- Collision Avoidance using Discrete Event Model: Introduces a finite set of observable but uncontrollable measurement events, showing that this abstraction was a state reduction of a system defined over state estimates, and used this abstraction to obtain the desired supervisor.
• Collision Avoidance in a testbed: Describes the implementation of a multi-vehicle supervisor to prevent collisions at intersections, by means of experiments on an intersection testbed with three RC cars. The way that the supervisor acts is by overriding the controlled cars only when it detects possible future collisions, otherwise they are programmed to maintain a constant desired motor input.

The development of the algorithms in the collision avoidance field, will be complemented with new materials and mechanical technical which allow better dynamics and behaviors in the streets.
Bibliography


