Optimizing driverless vehicles at intersections

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Abstract

Recently, several artificial intelligence labs have suggested the use of fully driverless vehicles with the capability of sensing the surrounding environment to enhance the roadway safety. The idea of having fully automated vehicles running in streets was inapplicable for many years until recently when researchers succeeded in releasing fully automated vehicles (without human drivers). Consequently, the paper develops a heuristic optimization algorithm for driverless vehicles at unsignalized intersections using a multi-agent system. The proposed system models the driverless vehicles as autonomous agents controlled by the intersection controller (manager agent). The input information of the system consists of vehicles' current location, speed and acceleration in addition to the surrounding environment (weather, intersection characteristics, etc.). The intersection controller processes the input information using a built-in simulator: "OSDI" (Optimization Simulator for Driverless vehicles at Intersections). The simulator objective is to optimize the movements of vehicles to reduce the total delay time for the entire intersection and prevent crashes simultaneously. Thereafter, the intersection controller uses the simulator output for controlling the speed profile of the driverless vehicles within the intersection study zone. The proposed system is compared to two different intersection control scenarios: an All-way stop control (AWSC) and an Intersection manager with built-in OSDI. For both scenarios, it is assumed that there are four driverless vehicles (one vehicle per approach) willing to cross a four-legged unsignalized intersection concurrently. The results show using Monte Carlo simulation show that the proposed system reduces the total delay by 35 seconds on average compared to traditional AWSC. This research is considered as a first step in developing an unmanned vehicle technology system.

Keywords

Driverless, Agent modeling, Optimization

Introduction

Every year in the United States, about six million traffic accidents occur due to automobile crashes. In 2003 alone, these accidents accounted for $230 billion in damaged property, 3 million nonfatal injuries, and 43,000 deaths [1]. While different factors contribute to vehicle crashes, such as vehicle mechanical problems and bad weather, driver behavior is considered to be the leading cause of more than 90 percent of all accidents due to human distraction and/or misjudgment [1]. There are several traditional (e.g. using warning signs and signals) and nontraditional (e.g. providing vehicles with sensors and cameras) countermeasures for reducing the number of accidents; especially at intersections. Many companies in the vehicle industry (e.g. GM and Volvo) are working at enhancing the safety of their vehicles by adding driver assistance components. Many technologies for driver assistance are already available in the market for example: rear-view alarms, front collision warning systems, lane departure warning systems, etc.

In addition, several artificial intelligence labs have suggested the use of fully driverless vehicles with the capability of sensing the surrounding environment to enhance roadway safety. A driverless – also known as autonomous or unmanned – vehicle will control all aspects of driving including following the speed limit, staying in its lane, detecting pedestrians and choosing the best route. A driverless vehicle can much more accurately judge distances and velocities, and react instantly to situations that could cause an accident due to a delayed human reaction.

The arrival of driverless vehicles is not as far away as some might believe. The idea of having autonomous vehicles running in streets was inapplicable for many years till recently when some researchers succeeded in releasing fully automated vehicles. An autonomous vehicle must be able to reliably detect, classify, and track various objects that may be in the roadway. As an example, Stanley is an autonomous vehicle created by Stanford University in cooperation with the Volkswagen Electronics Research Laboratory. Stanley won the 2005 DARPA (the Defense Advanced Research Projects Agency) Grand Challenge [2]. Also, the Google Driverless Car – the project of Google and the Stanford Artificial Intelligence Laboratory – succeeded to run for half an hour beginning on Google's campus 35 miles south of San Francisco on October 2010 [3]. One of the tested Google Driverless cars was a Toyota Prius equipped with a variety of sensors and following a route programmed into the GPS navigation system [3]. Consequently, after the successful test of the Google driverless vehicle, Nevada passed a law that could let self-driving cars on the road as soon as March 1, 2012. The new legislation directs the DMV to implement regulations for the operation of autonomous vehicles on highways within the State of Nevada. According to the law, an autonomous vehicle is "*one that uses artificial intelligence, sensors and global positioning system coordinates to drive itself without the active intervention of a human operator*." The law asks the DMV to create a driver's license endorsement for such vehicles [4].

As a result, it is anticipated in the future that many (or most) of the vehicles will be fully automated; thus the movements of those vehicles will need to be optimized in the network. Imagine that all running vehicles are unmanned and controlled by highly sophisticated equipment, there will be a need for innovative optimization algorithms for controlling these driverless vehicles. This research effort attempts to focus on optimizing the movements of the future intelligent (driverless/autonomous/unmanned) vehicles at unsignalized intersections by controlling these vehicles as agents that have certain goals and limitations.

Study Objective and Paper Layout

The purpose of this study is to develop a heuristic optimization algorithm for controlling driverless vehicles at unsignalized intersections using a built-in simulator: **O**ptimization **S**imulator for **D**riverless vehicles at **I**ntersections (OSDI). The main objective of the optimization algorithm is to minimize the total delay for all vehicles crossing the intersection by adjusting the trajectory of each vehicle. The vehicles are modeled as agents interacting with the controller agent and obeying the controller's orders.

In terms of the paper layout initially an overview of the agent-based applications followed by the layout for the proposed multi-agent system is presented. Subsequently, the built-in OSDI simulator is presented and the testing of the optimization algorithm is then discussed. Finally, the conclusions of the paper and the future research are presented.

Agent-Based Applications Overview

Transportation systems are considered an interaction of many complex entities that communicate with each other such as drivers/vehicles, traffic signals, and advisory signs. For the case of driverless vehicles, the agent-based modeling is the most suitable (recommended) method to present the interaction of autonomous entities (i.e. driverless vehicles) as was suggested in many literatures (e.g. [5-8]). One of the main reasons for using agent-based approaches for modeling driverless vehicles are: (1) they are at least to some extent capable of autonomous actions or decisions and (2) they are capable of interacting with other agents by cooperation, coordination and negotiations [9].

There are a growing number of agent-based applications in a variety of fields and disciplines, like: the stock market (e.g. [10, 11]), molecular self-assembly (e.g. [12]), biological science (e.g. [13-15]) in addition to many transportation-related agent-based applications. Chen and Cheng (2010) [9] presented a general overview of agent-based modeling techniques applied to many aspects of traffic and transportation systems, including decision support systems, dynamic routing and congestion management, and intelligent traffic control.

Agent-based modeling concepts have been used in many transportation applications including traffic management, traffic control, route choice, traffic information systems, decision support, etc. In this paper, it is proposed to use the multi-agent approach for modeling the interaction between driverless vehicles movements and the controller installed at the intersection study zone. The driverless vehicles are modeled as “autonomous” agents and the controller as the “manager” agent. The autonomous agents (vehicles) are inspired by the research done in robotic control [10], behavior-based robotics [11] and microscopic traffic simulation [16]. The interaction between autonomous agents and the manager agent is described in the following section.

Proposed Multi-Agent Modeling Layout

An agent-based modeling and simulation is a relatively new approach for modeling the coordination of autonomous or interacting agents in transportation systems. The proposed multi-agent system (MAS) consists of two types of agents: autonomous agents (driverless vehicles) and a manager agent (intersection controller). The main idea of the proposed system is that the manager agent communicates with the autonomous agents in the intersection study zone (ISZ) and determines the optimum movement for each autonomous agent. The ISZ is the zone area around the intersection where the autonomous agents begin to exchange information with the manager. The ISZ in this research was set to be 200 m from the intersection in each direction for demonstration purposes. This value can be easily modified.

The proposed layout for the MAS gives the authority to the manager agent to control the movements of the autonomous agents in the ISZ. The reason for giving complete authority to the manager is to overcome any selfish behavior by an autonomous vehicle or in other words to seek the global benefit for all vehicles in the ISZ. The global benefit for all vehicles is defined as reducing the total delay while preventing vehicle collisions. Therefore, the main task for the manager agent is to determine the optimum speed and acceleration for each autonomous agent at each time step by processing the input data through a real-time simulator. The MAS layout consists of three main components for controlling the movements of autonomous agents in the ISZ: Input, Data processing and Output.

The input data for the manager agent consists of: intersection characteristics, weather station input and autonomous agent input. The intersection characteristics contain the speed limit of the intersection and number of lanes of each approach. The weather station provides the instantaneous weather condition to take into account the roadway surface condition (dry or wet) in simulating the autonomous agents’ movements. At each time step, all autonomous agents that are within the ISZ report their physical characteristics, current speed, location and acceleration to the manager controller.

All input information is received by the manager agent; thereafter, the information is processed and optimized by the built-in simulator “OSDI”. The optimization process accomplished by the OSDI simulator is explained in detail in the following section. The OSDI output is the optimum speed and acceleration for each autonomous agent in the ISZ for every time step. Consequently, the manager agent uses the OSDI output to control the movements (speed and acceleration) of autonomous agents using wireless communication. Figure 1 summarizes the layout of the proposed multi-agent system (MAS) for driverless vehicles.

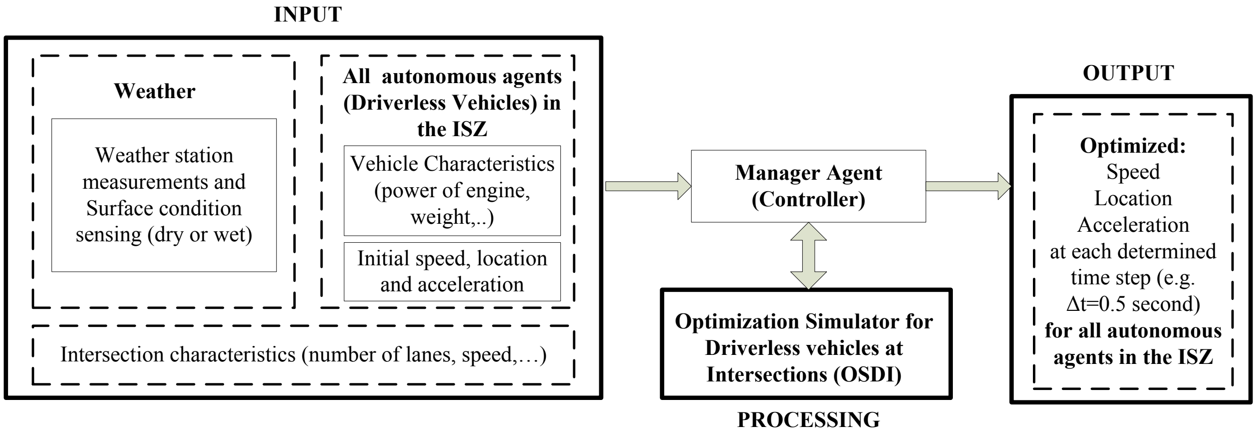


Figure 1: The layout of the proposed MAS for driverless vehicles at intersections

The communication between the manager agent and autonomous agents in our proposed MAS could be considered as V2I (vehicle to infrastructure) communication. Consequently, a suitable wireless communication is required that provides high availability and low latency. The DSRC (Dedicated Short Range Communication) appears to provide the required functionality [17-19]. In summary, the proposed MAS layout is developed to direct vehicles through intersections more efficiently, it assumes that each vehicle is an autonomous agent and the agents’ movements are optimized by the OSDI simulator.

Proposed Real Time Simulator For Driverless Vehicles (OSDI)

A few attempts have been done for creating simulators (or simulation software) in the literatures for modeling driverless vehicles. For example, Reece and Shafer (1991) [20] developed a driving program called Ulysses. The Ulysses goal is to prevent the simulated robot from having or causing accidents, and from unnecessarily constraining itself to stop.

Also, Dresner and Stone [7, 21, 22] proposed an intersection control protocol called Autonomous Intersection Management (AIM) and built their custom simulator which has gone through four major versions. Dresner and Stone showed that with autonomous vehicles it is possible to develop intersection control much more efficient than the traditional control mechanisms such as traffic signals and stop signs. The AIM custom simulator is based on the reservation paradigm, in which vehicles “call ahead” to reserve space-time in the intersection under the FCFS (a First Come, First Served) policy [21]. The main concept is each autonomous vehicle sends a request to the intersection manager and asks the permission to pass through the intersection. Thereafter, the intersection manager decides whether to grant or reject requested reservations according to an intersection control policy and FCFS.

It could be stated that previous research has made simplifying assumptions and failed to capture the impact of various aspects in simulating driverless vehicles at intersections, for example:

1- All current simulators do not optimize the movements of driverless vehicles for the global benefit (total delay minimization) at intersections;
2- All current simulators do not account for weather condition impacts;
3- Most of the simulators do not use the vehicle physical characteristics (e.g. vehicle power, mass and engine capacity) in the simulation process;
4- Most of the simulators do not allow the intersection manager to control the movements of driverless vehicles and only grant the permission to pass or not.

Therefore, this research effort is a modest attempt to address some of the issues not covered by previous research and to develop a new real-time simulator. Consequently, in order to present the interaction of driverless vehicles together with the intersection controller, a new simulator entitled: "OSDI" (**O**ptimization **S**imulator for **D**riverless vehicles at **I**ntersections) is built. Figure 2 shows a screen shot of the visualization interface for the new simulator OSDI.

OSDI Concept

This section describes the state-of-art of the built simulator OSDI. The simulator is considered the first version for the realization of a driverless vehicle optimization framework at unsignalized intersections. The simulator models the intersection study zone (ISZ) of 200 meter in each direction from the center of the intersection. In general, the concept of OSDI is to determine the optimum location, speed and acceleration of the approaching vehicles that ensure that no conflicts occur while at the same time minimizes the total delay at the intersection each time step (e.g. 0.5 sec).

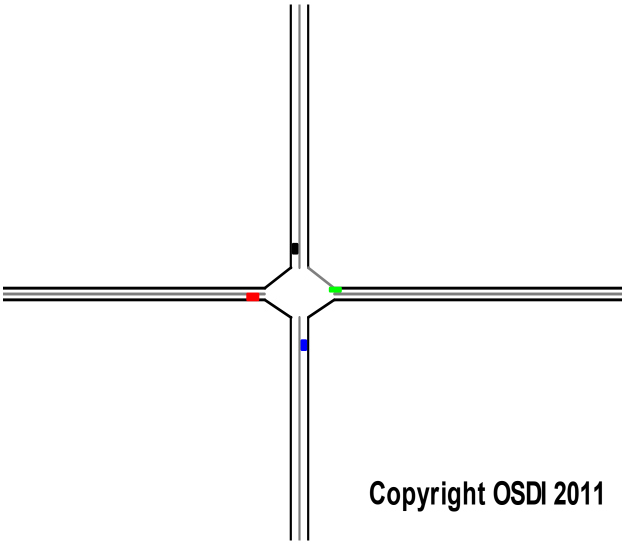


Figure 2: A screen shot from the OSDI used for simulating driverless vehicles

The OSDI is considered as a first attempt at optimizing the movements of driverless vehicles at unsignalized intersections; however, it has some limitations and assumptions that will be addressed in future research. The current model assumptions and limitations are:

1- All vehicles in the ISZ are fully autonomous;
2- The intersection is equipped with an intersection controller that has the ability and authority to control the movements of the vehicles in the ISZ;
3- All wireless connections are secure and support low latency communication;
4- All vehicles update their infornation to the controller each time step;

5- The intersection manager can change the speed profile of only one vehicle (the most critical one) at each time step;
6- All vehicles are through vehicles (no turns) at intersections. This assumption will be relaxed in future versions of the system. However, the intent in this paper is to provide a framework that can be enhanced and to demonstrate the potential for such an application.

The OSDI has a built-in vehicle dynamics (acceleration and deceleration) model that takes into account the tractive and resistance forces acting on vehicles at each time step. Consequently, the OSDI reflects the physical characteristics (power of engine, mass, etc.) and the weather condition (wet or dry) affecting the movements of vehicles.

OSDI Optimization Process

As mentioned previously, the OSDI main objective is to optimize the movements of driverless vehicles through the intersection in order to reduce the total delay and prevent crashes. The total delay is defined by the summation of all delay times for all driverless vehicles crossing the studied intersection. The delay time is considered the time difference between the actual crossing time and crossing time traveling at the free-flow speed. In order to simulate vehicles, the required input information for the OSDI is: 1) the physical characteristics of all vehicles in the ISZ, 2) The initial location, speed, acceleration of all vehicles, 3) the weather condition (dry or wet) and 4) the intersection characteristics (number of lanes, lane width, etc.).

After having the input information and determining the existing vehicles in the ISZ for the current simulation time step, the OSDI uses a heuristic optimization process divided into three stages, as follows: 1) Calculate the Conflict Zone Occupancy Time (CZOT) for each conflict area, 2) Choose one vehicle for the current time step to be adjusted, 3) Finalize the decision for the existing vehicle then go to the next time step. These stages are described in more detail in the following sub-sections.

1- Calculate the Conflict Zone Occupancy Time at each conflict area

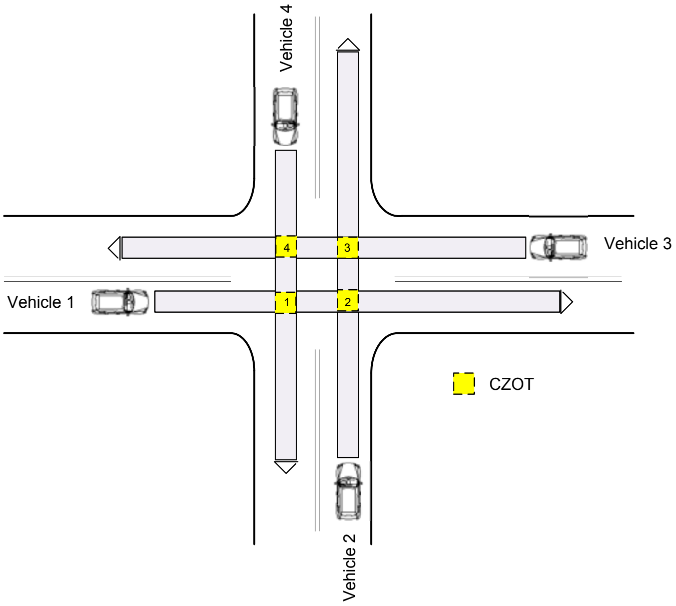
The OSDI assumes that all vehicles will accelerate to the maximum speed (if their speed is less than the maximum) as an "initial decision" to reduce the total travel time for each vehicle and consequently the total delay will be minimized. Thereafter, the OSDI determines the Conflict Zone Occupancy time for each expected conflict point as explained next.The critical point at the intersection area is the point where it could be occupied by two different crossing vehicles at the same time interval. Therefore, the **C**onflict **Z**one **O**ccupancy **T**ime (CZOT) term is introduced to in the optimization process. The CZOT is the time interval where the two intersecting vehicles will occupy the same conflict area. The OSDI uses the input information to simulate the trajectory of the vehicles; therefore estimates the time needed to enter and leave the conflict zone. If the CZOT value is positive, it is an indication that by accepting the initial decision for both intersecting vehicles, they will crash with each other at the conflict area. Alternatively, if CZOT is equal to zero that means that the approaching vehicles will not be conflicting with each other and it is safe to accept the initial decision until the vehicles exit the ISZ.

As an illustrative example, in case of having a four-legged intersection, it would have four critical areas (with only "going through" movements) as shown in Figure 3 (a). Consequently, the OSDI estimates the CZOT value for each critical (conflict) area, CZOT1, CZOT2, CZOT3 and CZOT4. Subsequently, the OSDI plots the CZOT diagram as shown in Figure 3 (b) where each rectangle presents the occupancy time of the conflict area by each vehicle. As mentioned before, the current implementation of the OSDI assumes that the trajectory of a single vehicle can be modified (by changing the vehicle speed and acceleration) for each time step.

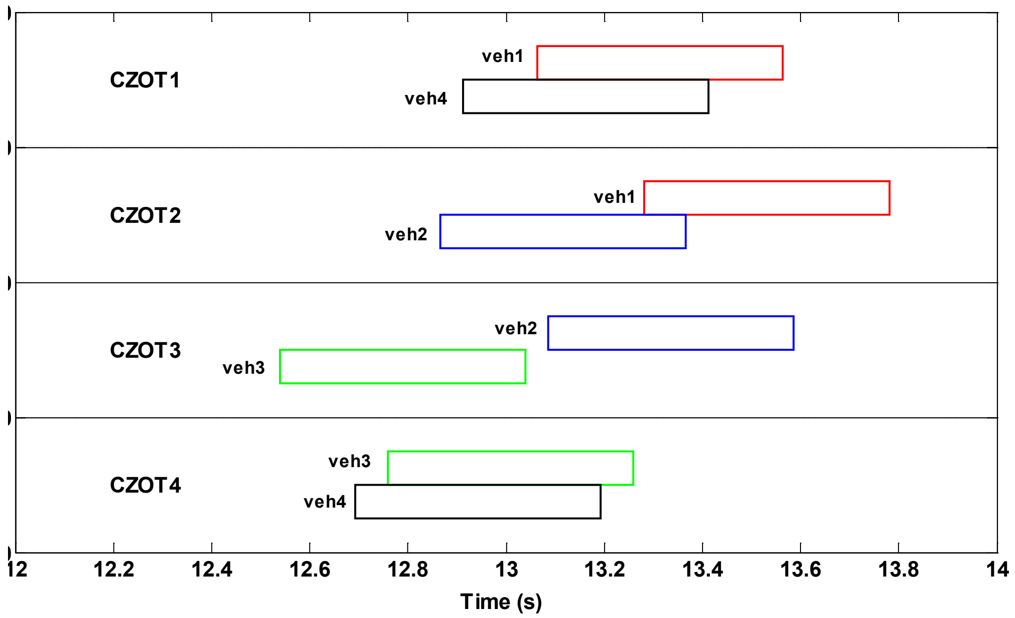
Therefore the following stage is to select the appropriate vehicle to prevent a crash while minimizing the total delay. In case of having all CZOT values equal to zero, the OSDI simply skips the following stages, and accepts the initial decision (accelerate all vehicles to maximum speed) then go to the next time step.

2- Choose one vehicle for the current time step to be adjusted

The initial decision for the OSDI was accelerating all vehicles to their desired speed and that could result in vehicle conflicts (i.e. CZOT>0) at some point in space and time. Therefore, at this stage, the OSDI selects one conflicting vehicle to force it to reduce its speed or to maintain its current speed (zero acceleration) in order to avoid a crash. First, the OSDI determines how many conflict points have CZOT values greater than zero (i.e. crash possibility). Second, if there are multiple points, the OSDI determines the conflict point with the least CZOT value and then lists the two conflicting vehicles at this point. Third, the OSDI chooses the vehicle with the minimum required time to lose while preventing a crash, in other words, the vehicle shifted to the right of the CZOT diagram, as will be illustrated next.



(a)



(b)

Figure 3: Conflict Zone Occupancy Time (CZOT) output example from OSDI simulator

As an example, in Figure 3 (b), the OSDI first determines the conflict points with CZOT values greater than zero at the current time step, which are: CZOT1, CZOT2 and CZOT4. The OSDI then finds the point with the least CZOT value and in this example it is conflict point 2 with a CZOT value equal to 0.1 seconds (approximately). At CZOT2, veh1 will reach the conflict area at simulation time 13.3 seconds and leave at 13.8 seconds. For veh2, it will reach at 12.9 seconds and leave at 13.4 seconds. In other words, if we accept the initial decision of OSDI, both vehicles will be occupy the same conflict area for a common 0.1 seconds. Consequently, the OSDI should selectg one vehicle (veh1 or veh2) to alter its trajectory (by making it cruise or decelerate). If the OSDI selects veh1, then it would be forced to lose (arrive late by) 0.1 seconds in order to begin the occupancy time at 13.4 seconds instead of 13.3 seconds to avoid a crash. On the other hand, if the OSDI selects veh2, it would have to occupancy the conflict zone at time 13.8 seconds (after the passage of veh1) which means veh2 would lose (i.e. be delayed by) 0.9 seconds. Therefore, the OSDI would select veh1 to decelerate to reduce the total loss (delay) time. Hence, it could be stated that by simply choosing the vehicle arrivals to the right at the least CZOT value, it would produce the minimum delay time at the current time step.

3- Finalize the decision for the existing vehicles

After determining the chosen vehicle that should be decelerated or maintained at the current speed, the OSDI accepts -for this time step- the initial decision for all other vehicles (accelerate to desired speed) and check the current speed of the chosen vehicle. If the current speed is the desired speed, then force the chosen vehicle to decelerate based on its vehicle dynamics model, if not, the chosen vehicle to maintained at the current speed (do not accelerate). Thereafter, the OSDI simulates all vehicles with the final decisions and estimates the new position, speed and acceleration for the next time step (i.e. after Δt). The OSDI continues updating the vehicle trajectories until the vehicles leave the ISZ. All OSDI stages are summarized in the flow chart presented in Figure 4.

Testing The Proposed Simulator "OSDI"

In order to test the proposed OSDI system, a comparison is made to an AWSC intersection control. The first scenario uses an AWSC and the second scenario uses an intersection manager provided with the OSDI simulator. The case study intersection consists of 4 approaches and each approach is one lane per direction as shown in Figure 3 (a). Each lane width is 3.5 meters and the speed limit for the intersection is 35 mph (approximately 16 m/s).

For illustration purposes we considered the Toyota Prius 2010 model as a typical driverless vehicle (similar to the tested vehicle in the Google Driverless experiment [3]) crossing the intersection. The vehicle has an engine power of 134 Horse Power (hp). The analysis assumes that the vehicle travels on a good flat asphalt surface (grade 0%) and the current weather condition is dry.

For the comparison between the two scenarios, four driverless vehicles (one vehicle per approach) were assumed to arrive at the unsignalized intersection. For both scenarios, the entrance time of each vehicle to the ISZ was randomly selected, as was the initial speed and acceleration. A time step (Δt) of 0.5 s was assumed. Thereafter, the total delay was computed for both scenarios as the summation of all delay time for the four driverless vehicles.

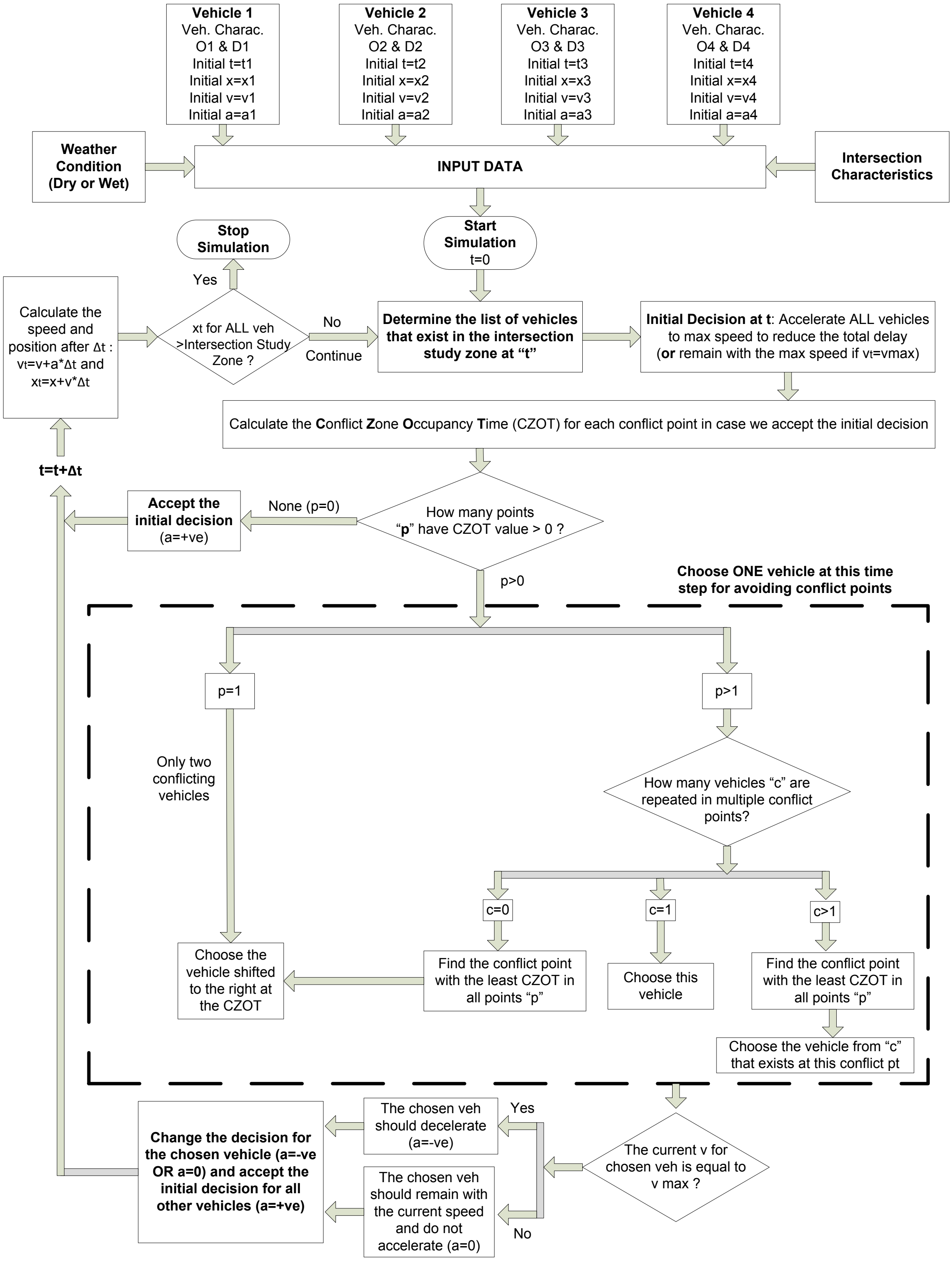


Figure 4: OSDI stages

This procedure was repeated 1000 times using a Monte Carlo Simulation and the total delay time was recorded at each time for both scenarios. Figure 5 shows the total delay time distribution for both scenarios for the 1000 simulations. It is observed that for all simulations, the OSDI scenario reduces the total delay when compared to the AWSC scenario. The average total delay for the OSDI scenario is approximately 19 seconds and for the AWSC is 54 seconds. Thus, for the case of only four crossing vehicles, there is on average delay reduction of 35 seconds through the OSDI implementation.

It could be stated that by applying the proposed optimization control OSDI, the total delay is significantly less than the traditional control for an unsignalized intersection (AWSC). The above example is just a simple example illustration to demonstrate the potential merits of the proposed system. Clearly more development is needed to consider a full stream of vehicle arrivals with different movements. The developed system will also be compared to not only unsignalized control but also signalized control.

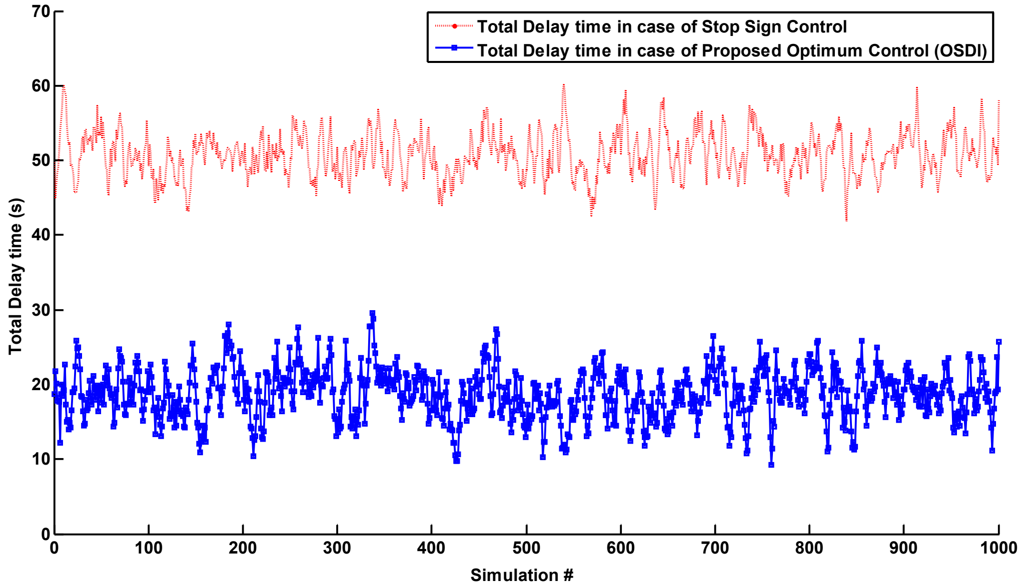


Figure 5: Total Delay comparison between AWSC and proposed control OSDI

Conclusions and Future Work

Driverless vehicles are considered one of the future reliable intelligent transportation systems for reducing number of crashes. Having fully automated vehicles in the streets, is necessary to replace traditional intersection control (stop-sign) control at unsignalized intersections. Therefore, this research attempts to present an innovative algorithm for optimizing the movements of driverless vehicles at unsignalized intersections using a multi-agent system (MAS). The research introduces the concept of the intersection manager for not only crash prevention but also for the minimization of the total intersection delay.

The proposed layout for the MAS gives the authority to the manager agent to control the movements of the autonomous agents in the intersection study zone (ISZ). The reason for giving the complete authority to the manager is to overcome any selfish behavior by an autonomous vehicle or in other words to seek the global benefit for all vehicles in the ISZ. The manager agent processes the input (vehicles information and surrounding environment) data using the OSDI simulator for choosing the optimum vehicle trajectory for each vehicle in the ISZ. The OSDI uses a heuristic optimization algorithm that consists of four stages. The main concept of the OSDI is to manage the movements of vehicles by minimizing the CZOT value for conflict areas per time step. The proposed algorithm is repeated for each time step until all vehicles clear the ISZ. This framework lends itself to transit signal priority where a vehicle might be given a higher weight depending on its occupancy in computing the person delay as opposed to vehicle delay. The system would then minimize the total person delay at the intersection as opposed to minimizing the vehicle delay.

Although, the OSDI is still in its initial stages, it does present some significant savings compared to an AWSC intersection control. The OSDI showed that by applying the proposed algorithm on only four crossing vehicles, the total delay was reduced by approximately 35 seconds, which is equivalent to a 65 percent reduction in the total intersection delay.

This research effort is an initial attempt at developing a flexible and expandable driverless optimization framework. The built OSDI is a first version for a simulator and will be developed to capture all types of intersection control strategies considering different vehicle movements (left, through, and right turners). It is anticipated that this research will contribute to the future of intelligent transportation systems (ITSs), connected vehicle technology systems, and unmanned vehicle applications.

Acknowledgement

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