ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE ENGINEERING AND TECHNOLOGY

MULTI AGENT INTERSECTION MANAGEMENT CONSIDERING ENERGY CONSUMPTION

M.Sc. THESIS

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Department of Control and Automation Engineering

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

ENERJİ TÜKETİMİNİ GÖZ ÖNÜNDE BULUNDURAN ÇOK ETMENLİ KAVŞAK YÖNETİMİ

YÜKSEK LİSANS TEZİ

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Tez Danışmanı: Prof. Dr. M. Turan SÖYLEMEZ

ARALIK 2017

Ferit Hacıoğlu, a M.Sc. student of ITU Graduate School of Science Engineering And Technology student ID 504141112, successfully defended the thesis/dissertation entitled “MULTI AGENT INTERSECTION MANAGEMENT CONSIDERING ENERGY CONSUMPTION”, which he prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

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Date of Submission : 17 Nov 2017
Date of Defense : 18 Dec 2017

It's not who we are underneath,
it's what we do that defines us.

FOREWORD

I would like to express my gratitude to my advisor, Prof. Dr. Mehmet Turan Söylemez, for sharing his knowledge during this research. It was a great pleasure for me to study with his guidance and support.

I would like to thank my parents and my sister for their endless support and effort keeping me motivated in every step of my life.

Finally, I also would like to thank my friends and 002, especially Mr. Ahmet Sakallı and Mr. Mertcan Ciboоğlu for their support and sharing their experiences.

November 2017 Ferit Hacıoğlu

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ABBREVIATIONS

AIM : Autonomous Intersection Management
FCFS : First Come – First Served
LICP : Look-ahead Intersection Control Policy
V2V : Vehicle-to-Vehicle
V2I : Vehicle-to-Infrastructure

SYMBOLS

δ	: Steering angle
l_f	: The distance from front axle to center of gravity
l_f	: The distance from rear axle to center of gravity
L_d	: The distance between center of rear axle and look ahead point
ψ	: Yaw angle / Vehicle orientation
v	: Longitudinal velocity
β	: Velocity angle to the longitudinal axis of the vehicle
F_r	: Rolling resistance force
F_w	: Aerodynamic drag force
F_g	: Grading resistance force
F_T	: Traction force
M:	: Mass of the vehicle
g	: Gravitational acceleration
C_d	: Drag coefficient
f_r	: Rolling resistance
A_f	: Frontal area of the vehicle
ρ	: Air density
α	: Road angle
t_d	: Delay time for a vehicle
e_d	: Energy loss for a vehicle
T_d	: Total delay time for a sequence
E_d	: Total energy loss for a sequence
T_{pctg}	: Percentage time loss for a sequence
E_{pctg}	: Percentage energy loss for a sequence

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MULTI AGENT INTERSECTION MANAGEMENT CONSIDERING ENERGY CONSUMPTION

SUMMARY

Traffic congestion is one of the main reasons of increasing pollution and fuel consumption in the cities. According to recent urban mobility reports, traffic congestions cost up to $121 billion in USA every year due to productivity and time loss. Approximately 38-40 hours are spent by an average citizen in the traffic. Additionally, 25 billion kilograms of carbon dioxide is emitted due to congestions. Increasing number of vehicles on the urban roads leads congestions at the intersections. Traditional intersection management methods such as stop signs, traffic officer control and traffic lights, are getting insufficient. Traffic light timing depending on day time is a common application; however, it is not an adaptive method for changing traffic flow density.

Traffic density can be measured by cameras, piezo and infrared sensors. Intelligent traffic light timing can be achieved using the traffic information gathered from the units integrated to the roads. Vehicle to vehicle and vehicle to infrastructure communication technologies allow us to gather information directly from vehicles, and analyze traffic congestion. Besides, vehicles can be informed about the traffic ahead or can be conditioned to reduce effect of congestions. Intersections can be managed by using information from the vehicles. One way to manage intersections is to integration of an intersection manager unit. Vehicles request reservation from intersection manager to pass the intersection. Another approach is interactive multi agent intersection management by the help of autonomous vehicles.

Autonomous intersection management uses estimated trajectories provided by the vehicles to detect any possible crash at the intersection. Estimated position of a vehicle at a time can easily be simulated for a given velocity profile. Estimated position and time information of vehicles are compared and estimated collisions are detected. Possible collisions must be resolved before the vehicles arrive at the intersection. Most common approach is the first come – first served method, which allows the first vehicle that requests reservation first to pass the intersection, allocate the intersection. Other vehicles' trajectories must be adjusted to avoid the collision at the intersection. This adjustment is done by assigning delay to the arrival time of the vehicles at the intersection.

Giving the priority to the vehicle that requests reservation first may not always be the most efficient decision in terms of total delay time. A method called look ahead intersection control policy is explained in the next sections. Look ahead intersection management policy assigns the priorities based on total delay time minimization. This method aims to reduce consecutive effect when the head vehicle of a convoy is delayed.

In this study, we proposed an intersection management method searching the passing sequence from the collision point to minimize defined cost functions. First intersection

model is explained to specify communication zone, velocity adjustment zone and grid structure at the center of intersection. Communication protocols are given for the communication zone. Crash detection and intersection management algorithm are executed in communication zone by all vehicles. Vehicles' estimated trajectories are transformed into time – space occupation at the intersection using grids to easily isolate possible collisions.

Passing sequences of the vehicle, which are estimated to pass the collision point, are found. For each sequence, different vehicles' arrival are delayed by different amount of time. Therefore, each sequence results in different total delay time. Selection between possible passing sequences is done by minimizing total delay time. Another performance criterion is energy loss of the vehicle. Vehicle longitudinal dynamics are explained for energy loss calculation. Delay time is realized by deceleration and acceleration. Acceleration requires an increase in traction force, this leads energy loss compared to the nominal state. Since vehicle dynamics are different for different vehicles, the same velocity rate may result in different energy losses. Hence, each passing sequence has a different energy loss value associated with it. This difference is used to select the sequence with minimum energy loss. Energy loss and total delay based costs are then combined in one cost function using a rating parameter.

After specifying cost functions, intersection management is simulated for different cases. A simulation framework is created in MATLAB. Vehicle kinematic bicycle model, which is used in the simulation environment, is explained. Vehicles with different masses and paths are simulated in different case studies. The case studies show that total delay based sequence selection distributes minimum delays to the vehicles only aiming to resolve estimated crashes. On the other hand, energy loss based method gives the priority to heavier vehicles to minimize energy loss. Thus, the total delay time increases in energy loss based method. The combined cost based selection method reduces energy loss of the total delay time based method. Similarly, it reduces total delay time of the energy loss based method.

In this thesis, literature survey and motivation of the study is given. Then vehicle models are explained for further use in the thesis. The intersection model including communication protocols and crash detection are stated. Afterwards, the intersection management algorithm is explained. The total delay time, energy loss and combined cost functions are given. Finally, simulation environment is explained and results of case studies are discussed.

ENERJİ TÜKETİMİNİ GÖZ ÖNÜNDE BULUNDURAN ÇOK ETMENLİ KAVŞAK YÖNETİMİ

ÖZET

Şehirlerdeki trafik sıkışıklığı yakıt tüketiminin ve kirliliğin artmasındaki ana sebeplerden biridir. Araştırmalara göre trafik sıkışıklığı, her sene Amerika Birleşik Devletleri'nde verimliliğin düşmesi ve zaman kaybından dolayı 121 milyar dolara yakın maliyete sebep olmaktadır. Kişiler, ortalama 38-40 saatlerini trafikte kaybetmektedirler. Bu da yaklaşık haftalık çalışma saati kadardır. Buna ek olarak, trafik sıkışıklığı yılda 25 milyar kilogramlık karbondioksit salımına sebep olmaktadır. Şehir içi yollardaki araç sayısının artması geleneksel trafik yönetimi sistemlerinin yetersiz kalmasına yol açmaktadır. Trafik işaretler, trafik memurlarının müdahaleleri ve trafik ışıkları geleneksel çözümler arasında sayılabilir. Trafik ışıklarının kontrolü sabit zamanlı olarak yapılmaktadır. Günün farklı saatlerinde oluşabilecek tahmini trafik sıkışıklığına göre trafik ışığı zamanlaması yapılmaktadır. Ancak, bu yöntem değişen trafik yoğunluğuna göre güncelleme yapılmadığı için yetersiz kalmaktadır. Bu da trafikte gereksiz ve verimsiz beklemelere yol açmaktadır.

Trafik yoğunluğu yollara kurulabilecek çeşitli kamera ve sensör sistemleriyle ölçülebilir. Yollara kurulan sistemlerden alınan trafik bilgisi, akıllı trafik ışığı sistemlerinin kurulması için kullanılabilir. Böylece anlık trafik yoğunluğuna göre trafik akışını arttıracak şekilde trafik ışığı zamanlaması ayarlanabilir. Bunun yanında araçlar arası ve araçlar ile saha üniteleri arası haberleşme de trafik yoğunluğunun analizi için kullanılabilir. Araç haberleşmesi sürücüler ilerideki trafik yoğunluğu hakkında bilgilendirilebilir. Bunun da ilerisinde, otonom araçlar için kavşak geçiş sistemleri oluşturulabilir. Otonom araçlar için trafik ışıklarına ihtiyaç duymadan kavşak kontrolü sağlanabilmesi için çeşitli yöntemler sunulmuştur. Bunlardan en yaygın olanı, araçların geçiş için kavşakta bulunan bir kavşak yönetim sisteminden rezervasyon istemelerine dayalı çalışmaktadır. Bunun yanında araçların birbirleri ile haberleşerek kavşak yönetimini gerçekleştirmeleri de başka bir yaklaşımdır.

Otonom kavşak yönetim sistemleri araçların kavşaktan tahimin rotalarını kullanarak muhtemek kazaları tespit eder. Günümüz araç kontrol üniteleri ile araçların verilen hız profilleri ile tahmini rotaları kolaylıkla oluşturululabilir. Araçların kavşaktaki tahmini bulunma anları ve konumları karşılaştırılarak muhtemel kazalar tespit edilir. Araçlar kavşağa ulaşmadan mumtemel kazalar çözümlenmelidir. Kazaların çözümlenmesi için kullanılan en yayğın yöntem, basitçe uygulanabilir olamasından da dolayı, ilk gelen alır prensibidir. Bu prensibe göre kavşaktan geçmek için rezervasyon isteyen araçlar arasında öncelik, ilk rezervasyon isteyene verilir. Daha düşük önceliğe sahip araçlar hızlarını belirli bir zaman gecikmesini sağlamak üzere ayarlarlar.

Geçiş önceliğini ilk rezervasyon isteyen araca vermek her zaman toplam zaman gecikmesi anlamında en verimli yöntem olmayabilir. İlk gelen alır prensibine göre daha verimli çalıştığı belirtilen ve ileriye bakan kavşak yönetimi oalrak adlandırılan bir yöntem sunulmuştur. Bu yönteme göre kavşaktan geçiş önceliğinin verilmesi düşük

önceliğe sahip olacak araçların üzerinde oluşacak toplam zaman geçikmesini minimize edecek şekilde yapılmaktadır. Konvoy halinde ilerleyen bir grup araç arasında en öndeki aracın geciktirilmesi onu takip eden araçların da geciktirilmesi anlamına geldiği için, konvoyun tamamı tek araç olarak düşünülmüştür. Böylece konvoydaki ardışık gecikmenin azaltılması amaçlanmıştır.

Bu çalışmada, kavşaktan araçların geçiş sıralamasını belirlenmiş maliyet fonksiyonlarına göre düzenleyen bir algoritma sunulmuştur. Kavaşkta tespit edilmiş muhtemel kaza noktası üzerinden geçecek araçların geçis sıralamaları araç sayısına bağlı permütasyon olarak ortaya konur. Bunlardan gerçekleşmesi muhtemel olmayanlar elenir. Muhtemel geçiş sıraları arasından bir maliyet fonksiyonuna göre seçim yapılır. Seçilen sıralamanın gerçeklenmesi için araçların kavşağa varış süreleri gecikmelerle ayarlanır. Bunun için öncelikle kavşak modeli açıklanmıştır. Kavşak dört yoldan oluşmaktadır ve haberleşme, yavaşlama ve hızlanma olmak üzere üç temel bölüme ayrılmıştır. Haberleşme bölümünde araçlar birbileri ile haberleşerek tahmini rotalarını karışılatırır ve olası kazaları tespit eder. Kazaların tespitinin kolaylaştırılması için kavşak merkezi ızagara sistemi ile bölünmüştür.

Her bir geçiş sıralaması için araçlara farklı zaman gecikmeleri atanmaktadır. Dolayısıyla her bir sıralama toplamda farklı bir gecikmeye sebep olmaktadır. Bu toplam gecikme miktarı geçiş sıralamaları arasından minimum gecikmeye sebep olanın seçilebilmesi için kullanılabilir. Bu yaklaşım toplam zaman gecikmesine bağlı maliyet olarak belirtilmiştir. Araçların kavşağa geliş zamanlarının arttırılması, yavaşlama ve hızlanmalarla sağlanmaktadır. Dinamik araç modeli verilerek, hızlanma sırasında gerecek ekstra enerjinin hesaplanması anlatılmıştır. Araçların dinamik model parametrelerinin birbirinden farklı olduğu durumlarda, araçlar başlangıçta eşit hızlarla hareket ediyor ve her birine atanan gecikme eşit olsa bile gerekli yavaşlama ve hızlanmanın sağlanması için harcanacak enerji farklı olacaktır. Bu farklılıktan yola çıkarak her geçiş sıralaması için farklı bir enerji kaybı hesaplanabileceği söylenebilir. Olası geçiş sıralamaları arasından, minimum enerji kaybına sebep olması beklenen sıralamanın seçilmesi ikinci bir yöntem olarak sunulmuştur. Bu seçim kriteri enerji kaybına bağlı maliyet olarak adlandırılmıştır. Sunulan iki maliyet hesabı, bir oran ile birleştirilerek birleşik maliyet fonksiyonu ortaya konulmuştur. Bu sayede, olası geçiş sıralamaları arasından seçim yapılırken zaman gecikmesi ve enerji kaybının aynı anda göz önünde bulundurulabilmesi amaçlanmıştır.

Maliyet fonksiyonlarının belirlenmesinden sonra MATLAB tabanlı bir simülasyon ortamı oluşturularak kavşak yönetimi algoritması farklı örnek durumlar için test edilmiştir. Araçların hareketi, kinematik bisiklet modeli ve *"pure pursuit"* yol takip algoritması verilerek açıklanmıştır. Farklı kütlelere ve yörüngelere sahip araçlardan oluşan örnek durumların, daha önceden açıklanan üç farklı maliyet fonksiyonuna bağlı, simülasyonu incelenmiştir. Simülasyon sonuçlarına göre toplam zaman gecikmesine bağlı geçiş sıralaması seçiminin, olası çarpışmaların çözümlenmesi için gereken en az gecikmeyi araçlara atayarak kavşak yönetimini sağladığı görülmüştür. Öte yandan, enerji kaybına bağlı geçiş sıralaması seçimi, geçiş önceliğini daha ağır araçlara vererek enerji kaybını azaltmaya çalıştığı gözlenmiştir. Birleşik maliyet fonksiyonuna bağlı kavşak yönetimi ile, toplam zaman gecikmesine bağlı seçime göre daha fazla zaman kaybedilirken daha az enerji harcandığı görülmüştür. Benzer şekilde, enerji kaybına bağlı seçime göre de daha az zaman kaybedildiği görülmüştür.

Tezin ilerleyen bölümlerinde öncelikle literatür araştırması ve çalışmanın motivasyonu anlatılmaktadır. Daha sonra enerji kaybı hesabı ve araç hareketi simülasyonu için kullanılmak üzere araç modelleri verilmiştir. Haberlerşme protokolleri ve kaza tespiti dahil olmak üzere kavşak modeli açıklanmıştır. Daha sonra kavşak yönetimi algoritması, toplam zaman gecikmesi, enerji kaybı ve birleşik maliyet fonksiyonları ile birlikte anlatılmıştır. Simülasyon ortamının oluşturulması açıklanıp farklı örnek durumlar için kavşak yönetimi test edilmiştir. Son olarak, simülasyon sonuçları açıklanıp yorumlanmıştır.

1. INTRODUCTION

Traffic congestion is one of the main reasons of increasing pollution and fuel consumption in the cities. In USA, $121 billion is lost every year depending on the productivity and time loss because of the traffic congestions. Average time spent in the traffic is 38-40 hours for an American citizen. Besides, 25 billion kilograms of carbon dioxide emission is caused by the traffic congestion [1, 2].

Rapidly increasing vehicle numbers on the intercity roads leads traffic congestions in the intersections; thus, traditional traffic management methods are getting less sufficient to organize traffic flow. Stop signs, traffic lights and traffic officers can be considered as traditional traffic regulation methods. Static traffic light scheduling may cause unnecessary stops if the intersection is not crowded. Traffic light timing adjustment for different times of the day is a common application.

Intelligent solutions for the traffic congestion are possible thanks to developments in vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) technologies. Cameras, piezo and infrared sensors can be easily integrated to the roads to detect traffic. Data gathered from these units can be analyzed. Siemens ACS Lite Adaptive Control Solution technology is deployed in Tyler, Texas. With this software, all traffic data gathered from different field units, are analyzed and quick response are generated to such as adjusting speed limits, opening new lanes. 22% reduction in travel time, 49% in traffic delays, $1,628,000 benefit is obtained by the smart traffic management system in Texas [1]. Another application called Surtrac System is set up in Pittsburgh, Pennsylvania. Surtrac is an artificial intelligence system that uses camera and radar data to build a timing plan for traffic lights. Difference between the Surtrac and ACS Lite is that Surtrac is decentralized method. Idling time in the intersection is reduced by 40% with the Surtrac system [2].

In Germany, Adaptive and Cooperative Technologies for the Intelligent Traffic (AKTIV) initiated a research in 2010, bringing together automobile manufacturers, suppliers and research institutions. Developed in-vehicle cooperative-traffic-light module channels the traffic optimally by providing individual supports to drivers [3].

In 2012 Volvo signed a Memorandum of Understanding with the CAR 2 CAR Communication Consortium to implement V2V and V2I communication units in its vehicles. They aim to connect vehicles and infrastructures in a predetermined radius. Potential benefits of this initiation are stated by Volvo as green light optimum speed advise, traffic jam or accident warning, road work warning [4]. They aim to inform the driver to adjust the vehicle velocity according to an optimal trajectory so that the driver could pass at the green light.

Figure 1.1 : Volvo's Vehicle Communication [4].

Traffic light control can be considered as the first step of the autonomous intersection management, since the intersections are currently managed by the traffic lights. There are several works regarding intersection management with traffic light scheduling. An optimal traffic light control for single intersection is given by B. De Schutter with model derivation for the evolution of the queue lengths [5]. A fuzzy logic based traffic light control method is proposed by J. Cai and B. M. Nair for an isolated intersection including traffic abnormality such as road blocks and accidents [6]. They took the number of vehicles arriving to the intersection and the number of vehicles waiting in the queue at red light and calculated the green light timing. Lyapunov function-based analysis and maximal weight matching algorithm are given for an isolated intersection in [7]. X. H. Yu and A. R. Stubberud used Markovian decision control theory to control traffic lights for an intersection [8]. A traffic signal management method with genetic algorithm to reduce queue size at the intersections is presented in [9, 10]. D. Helbing and S. Lämmer proposed a self-organized traffic light control method calculating optimum green light times based on dynamic priorities of queues [11].

Intersection managements method which are described above are based on controlling already planted traffic lights. Another approach is to make the intersections traffic light clear. In order to remove traffic lights completely, there may be a field unit at the intersection to organize all on coming vehicles or all vehicles travel collaboratively to maintain order.

A multi agent reservation based intersection management method, called Autonomous Intersection Management (AIM), is introduced by K. Dresner and P. Stone in [12, 13, and 14]. In that method, vehicles approaching intersection send a reservation request to a field unit as an intersection manager. Reservation request is evaluated by the intersection manager. Reservation request includes the future path of the vehicle. Since almost every vehicle is equipped with a Global Positioning System (GPS) and at least one vehicle control unit, future position calculation can be conducted easily. The future path is compared with the other requests by the intersection manager. If there is no confliction, the request is approved. A reservation based approach for the situations when autonomous vehicles meet human drivers is explained in [15]. They also stated learning opportunities for the agents and the intersection manager with the basic requirements to allow machine learning [16]. An application of AIM is also given for multi – intersection system, which consists four intersections [17].

In case of confliction in the future paths of the vehicles which send a reservation request to the intersection manager, a prioritization mechanism is executed. Most common way to decide which request has the priority is First Come – First Served (FCFS) principle. FCFS is introduced for AIM [12]. The request of the vehicle, which is to pass the intersection area first, is approved, if more than one reservation are requested at the same time. Besides the FCFS policy, predetermined priorities are used to establish a passing sequence as described in [18, 19]. In case of existence of an emergency vehicle such as ambulance or fire truck, highest priority can be assigned to the emergency vehicle [20].

Q. Jin et al. proposed a platoon based multi agent intersection management method [21]. Only the leader vehicle communicates with the intersection management agent. Leader agent requests a reservation by sending the estimated arrival and clearance time of the platoon to the intersection manager. Other vehicles of the platoon follow the trajectories which are created by the leader. They also introduced an optimal traffic scheduling method to reduce maximum total travel time of the agents in [22]. Some other optimal control approaches for multi agent intersection management are given in [23, 24, and 25].

G. Sharon and P. Stone proposed a protocol for connected vehicles and traditional traffic lights [26]. Green lights are used as traditional way by allowing vehicles on the green light given lane. When the light is red, only the vehicles with the reservation are allowed to pass. M.A.S. Kalam et al. introduced a centralized intersection management method with model predictive control (MPC) for fully automated vehicles by using position and velocity and destination information of the vehicles [27].

A time based scheduling algorithm called Look-ahead Intersection Control is given by M. Zhu et al [28]. In that method, vehicles are scheduled depending on the delay time which they will cause during a safe travel through the intersection. In case of multiple agents communicating at the same time to get permission to pass the intersection, there are more than one permutation of scheduling. Each sequence causes different total delay time for the vehicles. Selecting the sequence with the minimum total delay time is proposed as a decision method.

Intersection management can be considered as an upgrade for traffic light systems in terms of reduction in $\boldsymbol{CO_2}$ emission and fuel consumption. However, if it is desired to design a traffic light free intersection, crash prevention is taken under consideration, as well. In the related works, intersection is modelled with grids so that the possible conflicts of the vehicles' future positions can be isolated [12, 19, 28, and 29]. In order to determine when V2I or V2V communication starts, communication boundary is introduced in [22]. In addition to the communication boundary, velocity adjustment boundaries are introduced in [29]. Since the vehicle with the lower priority is expected to adjust its velocity to avoid possible collisions in the intersection. Vehicle velocities are adjusted to arrive at the intersection with calculated average speed in [19]. Vehicles are decelerated and accelerated to the initial speed to obtain delay time in [29].

Detecting collisions, making passing sequence decision to prevent crash and adjusting speed profiles constitute the intersection management. In this thesis, we focused on decision problem in terms of power consumption. Since the delay time is fulfilled with velocity trajectory adjustment, power consumption loss is inevitable. Power loss varies for the different vehicles, even the vehicles have the same delay time due to the vehicle dynamic parameters. Power loss minimization approach is proposed to schedule vehicles. Combination of the total delay time and power loss in one cost function is also simulated and discussed. A simulation framework is designed using MATLAB to simulate proposed method. According to following parts of the thesis, the first part will cover the literature and market survey on the intelligent intersection management problem. Afterwards, both longitudinal and lateral vehicle model, which are used in the studies, will be introduced in the Section-2. In Section-3, intersection model, communication policy and intersection management method will be presented. In Section-4, intersection simulation frame work will be explained. Simulation results will be discussed in Section-5. Finally, the conclusion and future study plans will be given in the last section.

2. VEHICLE MODEL

In this section, the longitudinal and lateral vehicle models are explained. Lateral dynamics are used for the simulation of the vehicle motion, while the longitudinal dynamics are used to simulate required power for traction. Integration of the lateral movement will be explained in the simulation framework section, and the longitudinal dynamic equations will be referred for the proposed intersection management method.

2.1 Kinematic Bicycle Model

Kinematic vehicle model gives information about the position of the vehicle on a Cartesian space depending on a speed and steering angle. Kinematic bicycle model illustration is seen in Figure 2.1. Vehicle is represented with two wheels connected by an axle through the center of gravity. Only the front wheel supports the steering as the traditional vehicle architectures.

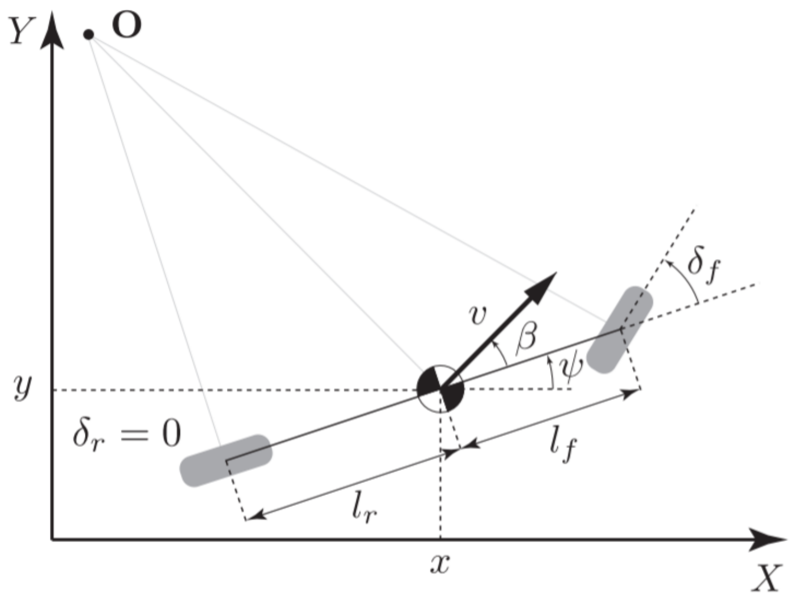


Figure 2.1 : Kinematics of lateral vehicle motion for bicycle model [30].

Here, δ_f is the front wheel angle which is the control input for the vehicle motion. Rear wheel angle δ_r is set to zero, since it does not any effect on the steering. l_f and l_r are the distances to the center of gravity from the front wheel and the rear wheel, respectively. v and ψ are the vehicle velocity and the steering angle of the vehicle. β represents the velocity angle to the longitudinal axis of the vehicle.

In the kinematic bicycle model, tire slip is neglected. Equations of the lateral motion is given below [30]:

$$\frac{dx}{dt} = v\cos(\psi + \beta) \tag{2.1}$$

$$\frac{dy}{dt} = v\sin(\psi + \beta) \tag{2.2}$$

$$\frac{d\psi}{dt} = \frac{v}{l_r}\sin(\beta) \tag{2.3}$$

$$\beta = \tan^{-1}\left(\frac{l_r}{l_r + l_f}\tan(\delta_f)\right) \tag{2.4}$$

2.2 Longitudinal Dynamic Model

Longitudinal vehicle dynamics are interested in velocity and acceleration of the vehicle contrary to vehicle kinematics. Forces acting on a vehicle are seen in Figure 2.2.

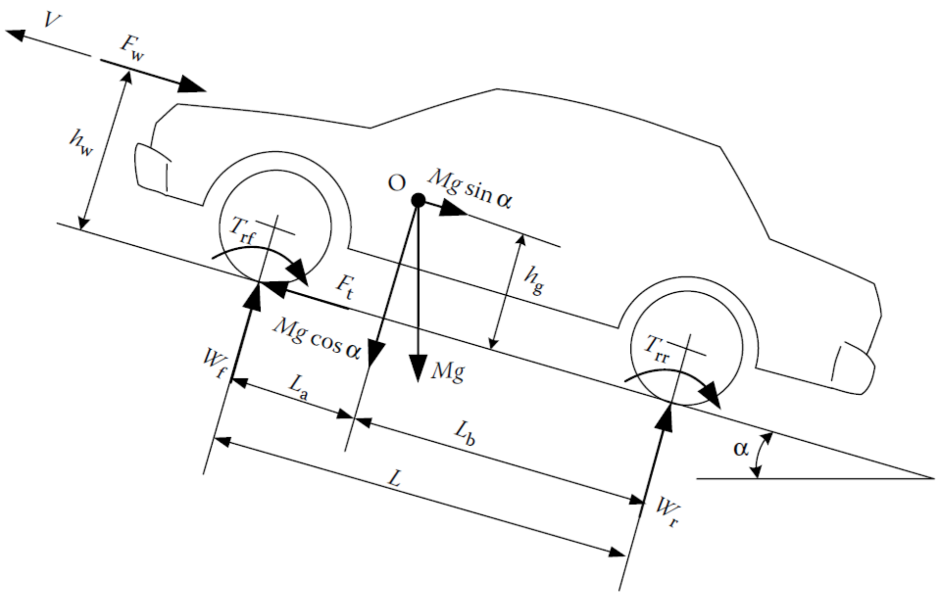


Figure 2.2 : Forces effecting vehicle movement [31]**.**

Vehicle is affected by rolling resistance, aerodynamic drag and gravitational force. The rolling resistance is caused by the contact between the tires and the surface. Rolling resistance force is dependent on the vehicle weight and a rolling resistance coefficient as described in equation 2.5. Rolling resistance coefficients for different road and tire types are given in [31].

$$F_r = Mgf_r \tag{2.5}$$

The rolling resistance is modified with the road slope as follows, since the normal force acting on the wheels depending on the vehicle mass changes on a slope road.

$$F_r = Mgf_r \cos(\alpha) \tag{2.6}$$

Here, α denotes the road angle. M is the vehicle mass and g is the gravitational acceleration. f_r represents the rolling resistance coefficient.

Aerodynamic drag is the result of air pressure which effects on the vehicle during motion; thus, it is a function of the vehicle speed. Aerodynamic drag equation is given below:

$$F_w = \frac{1}{2}\rho A_f c_d v^2 \tag{2.7}$$

where, A_f denotes the frontal area of the vehicle. c_d represents the drag coefficient, which differs for different vehicle shapes. ρ is the air density.

Gravitational force, which is also called as grading resistance affects the vehicle on the slope road. It is the only force which can support traction in case of negative road gradient. Grading resistance is given below:

$$F_g = Mgsin(\alpha) \tag{2.8}$$

Longitudinal dynamic equation for vehicle motion can be derived as seen in equation 2.9.

$$M\frac{dv}{dt} = F_T - \left(F_r + F_w + F_g\right) \tag{2.9}$$

$$M\frac{dv}{dt} = F_T - Mgf_r\cos(\alpha) - \frac{1}{2}\rho A_f c_d v^2 - Mgsin(\alpha) \quad (2.10)$$

Here, F_T is the traction force, which is generated by the propulsion source of the vehicle. Propulsion source can be internal combustion engine or electric motor. Propulsion source dynamics and powertrain losses are not considered in the scope of this thesis. It is assumed that the requested traction force can be supplied by the propulsion sources.

Vehicle dynamic equation parameters are given in Table 2.1 [31]. A regular sedan type vehicle frontal area value and asphalt road rolling resistance value are selected.

Table 2.1 : Vehicle dynamic equation parameters.

Parameter	Value
ρ_{air}	1.24 kg/m^3
$c_d \cdot A$	$0.6m^2$
f_r	0.0012
g	9.81 m/s^2

3. INTERSECTION MODEL

In this section, intersection model and vehicle communication policy are explained. An intersection model is required to be defined before developing and applying an intersection management algorithm. Addition to the physical structure of the intersection, communication protocols for vehicles or field units should be identified.

An isolated cross road intersection is used for this study. Intersection area includes specific length of the roads in both directions. Each section consists of 4 lanes; two for one direction and two for the opposite direction. Turns are allowed in the intersection. Intersection representation is seen in Figure 3.1.

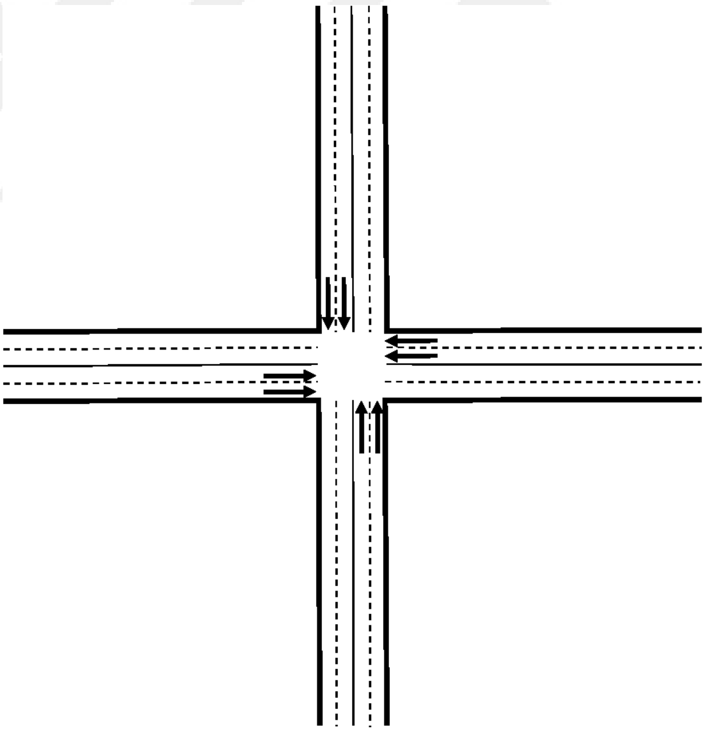


Figure 3.1 : Intersection.

The intersection is separated in three main parts as seen in Figure 3.2:

- Zone I: Communication area
- Zone II: Deceleration area
- Zone III: Acceleration area

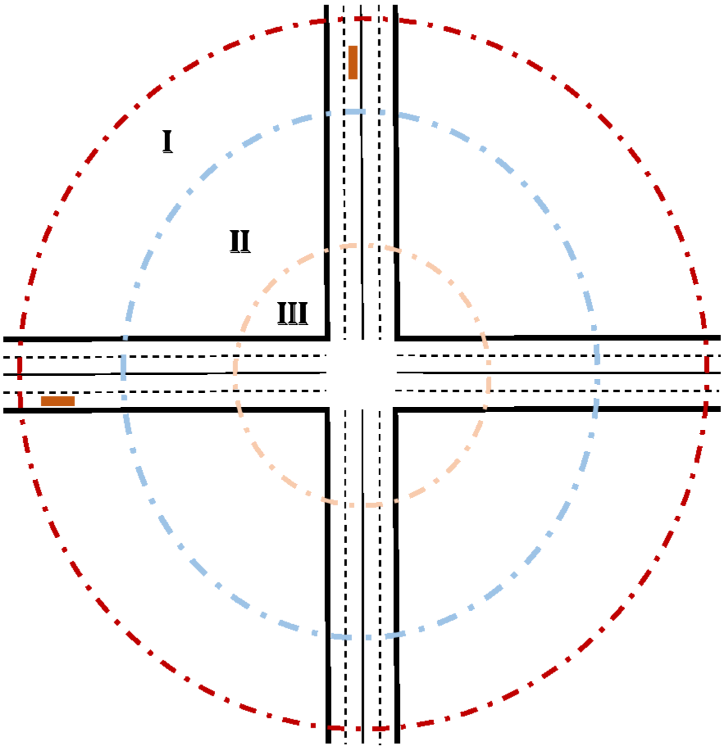


Figure 3.2 : Intersection parts.

Zone I is where a vehicle is taken under consideration for the first time. In this area, vehicles communicate by transmitting information regarding their estimated trajectories. Intersection management is conducted, and safe velocity trajectories are assigned to the vehicles in this zone. Other parts of the intersection are Zone II and Zone III, which are the deceleration and acceleration zone, respectively. Safe velocity trajectories, which are defined in Zone I, are realized in Zone II and III by deceleration and acceleration. Zone II and Zone III together can be named as trajectory adjustment area.

Section lengths are defined as $200m$. Lane widths are set as $3m$ accoding to examples in [34]. Since the intersection starts with Zone I, Zone I radius can be selected, such that it surrounds whole intersection. Therefore, Zone I radius is defined as equal to the summation of section length and width of two lanes $206m$. Radius of Zone II and Zone III are defined as $126m$ and $66m$, respectively. Due to the fact that Zone II and III are velocity adjustment areas, radius of Zone II and Zone III are directly related to the maximum deceleration, acceleration capability and velocity of the vehicles. The maximum speed limit for urban roads changes between $50 - 60km/h$. Under the assumption that maximum speed limit shall not be exceeded by a vehicle entering an intersection in urban roads, deceleration distance to stop from $60km/h$ $(16.6m/s)$ is given in equation 3.1. Maximum deceleration is selected as $2.4m/s^2$ according to the studies in [35].

$$x_{decel} = \frac{v^2}{2a_d} = \frac{16.6^2}{2 \cdot 2.4} = 57.4m \tag{3.1}$$

Thus, required deceleration distance for full brake is rounded to $60m$ for simplicity. Communication, deceleration and acceleration distances are seen in Figure 3.3.

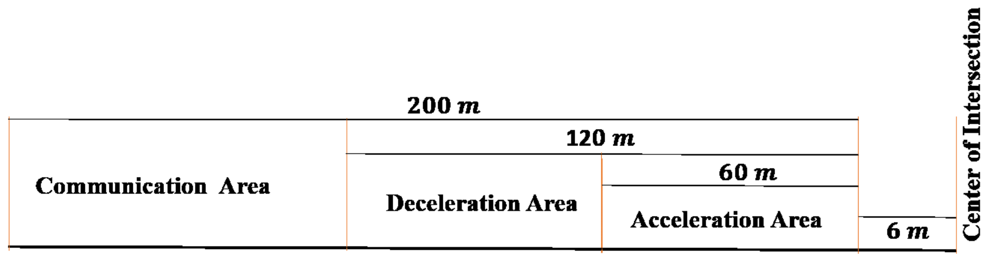


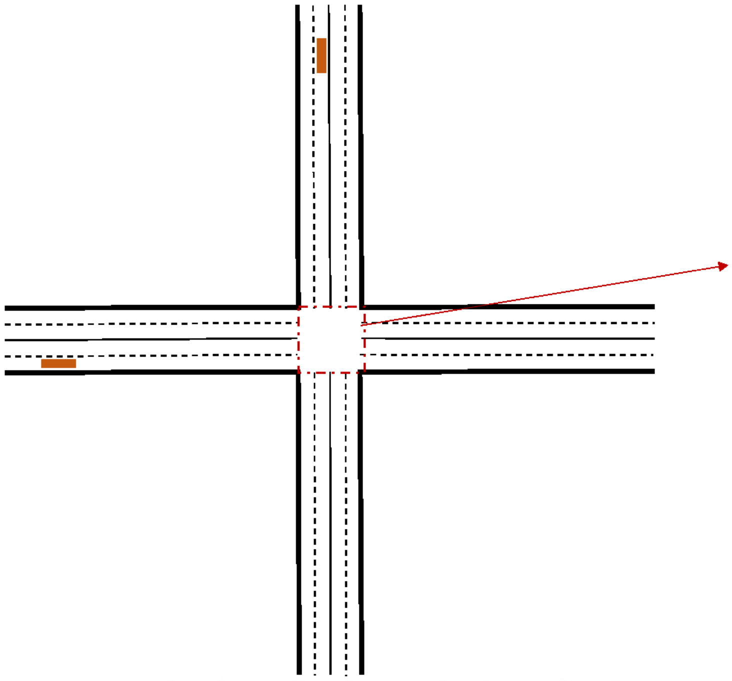
Figure 3.3 : Lengths of intersection parts.

3.1 Crash Detection

Crash detection can be considered as the first step of the intersection management, since possible collisions must be eliminated before concerning any other objectives. Intersection model is created in such way to ease crash detection. Center of the intersection is divided into grids as discussed in [28, 32]. Grid approach is used for roundabouts in [33].

The possible collisions depending on the estimated positions of the vehicles can be isolated with this approach. Processing exact location of a vehicle depending on time increases computational burden by adding an extra step to collision detection. Position information is not easy to be used directly in trajectory comparison. Even if the center of gravity position on X – Y Cartesian space for two vehicles are not same or close enough, vehicles might collide. Therefore, the border of the vehicles must be known, as well. Besides, this information must be transmitted to the other vehicles or a central intersection manager. In both cases, instead of transmitting too much data to indicate the projection area of the vehicle, transmitting numbers indicating predefined areas is simpler approach.

Intersection is divided into different number of grids and results are compared in [28]. It is stated that reduced number of grids lead worse results in terms of average delay, due to the inefficient space utilization. In this study, center of the intersection is divided into 8 × 8 grids as shown in Figure 3.4. Two grids are dedicated for each lane as width aiming to increase efficiency of space utilization during turns.



1	2	3	4	5	6	7	8
9	10	11	12	13	14	15	16
17	18	19	20	21	22	23	24
25	26	27	28	29	30	31	32
33	34	35	36	37	38	39	40
41	42	43	44	45	46	47	48
49	50	51	52	53	54	55	56
57	58	59	60	61	62	63	64

Figure 3.4 : 8 × 8 grids at the intersection.

Possible collisions at the intersection center are detected by using the grid structure. Vehicle paths are transformed into grid occupation. Only one vehicle must occupy a cell at a time. As it is seen in Figure 3.5, estimated time – space of the vehicles are compared and possible collision is detected. Instead of comparing whole trajectory of the vehicles, comparison for time – space occupation depending on grid structure eases the detection.

Trajectory of the vehicle approaching from north (blue path) overlaps the trajectory of the vehicle approaching from west (yellow path). However, this overlap is not important unless the cell occupation times conflict. In demonstrated case, vehicles occupy the cells 51 and 52 at the same time; thus, a collision is detected.

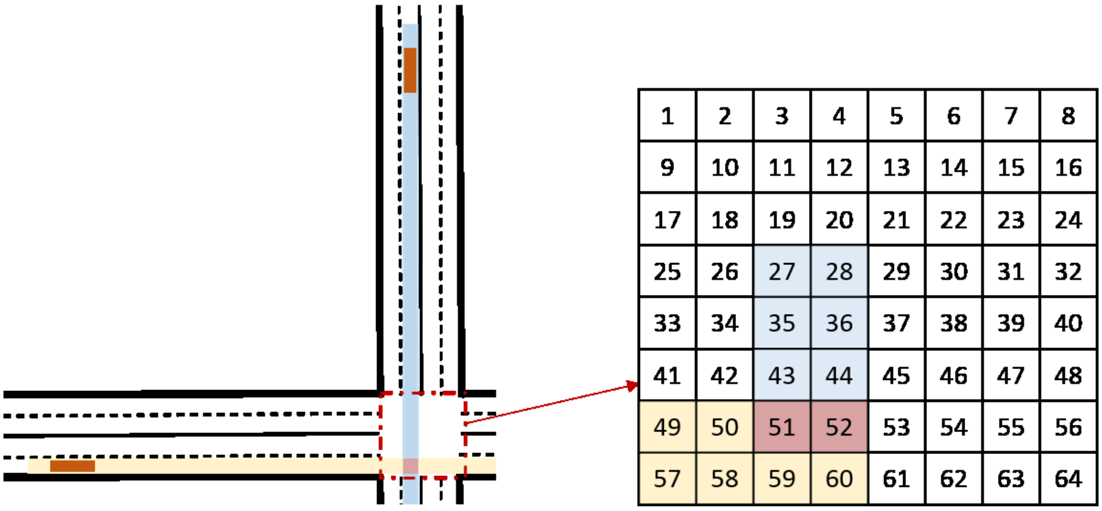


Figure 3.5 : Collision detection at the intersection.

Due to the necessity of information about time and location together, vehicle trajectories are stored in time – space matrices as discussed in [28]. Existence of the vehicles in the intersection in terms of cell numbers are indicated in the time columns. In Figure 3.6, combination of two time – space matrices is seen. Since there are two vehicles in cell 51 and 52, number of the vehicles are set to 2 at t.

Cell\Time	...	t-3T	t-2T	t-T	t	...
...	...	...	...	...	...	...
27	...	1	1	1	1	...
28	...	1	1	1	1	...
...	...	...	...	...	...	...
35	...	0	1	1	1	...
36	...	0	1	1	1	...
...	...	...	...	...	...	...
43	...	0	0	1	1	...
44	...	0	0	1	1	...
...	...	...	...	...	...	...
49	...	1	1	1	1	...
50	...	0	1	1	1	...
51	...	0	0	1	2	...
52	...	0	0	0	2	...
...	...	...	...	...	...	...
57	...	1	1	1	1	...
58	...	0	1	1	1	...
59	...	0	0	1	1	...
60	...	0	0	0	1	...
...	...	...	...	...	...	...

Figure 3.6 : Combined time – space matrix for two vehicles.

3.2 V2V Communication

Intersection management is executed as decentralized by the connected agents; hence, there is no central manager at the intersection. Communication between the agents is the key step for the management. Due to the range limitations on wireless communication, a field unit can be deployed to establish a communication area by enhancing signal transmission. However, these units are not expected to involve management process.

Communication of a vehicle with other vehicles starts when it enters Zone I, and it is terminated when the vehicle enters Zone II. Only the vehicles inside the Zone I are in interaction. In this area, vehicles simulate their velocity profile with their path, and generate an information about when they will be in the intersection. Intersection grid occupation of each vehicle is shared among them. Hence, all interacting vehicles have the same information about the occupation status of the intersection.

Flexibility of having the same information in multiple agents can be utilized to improve safety for failure in intersection. In case an agent is hacked to transmit false messages or malfunction, other agents can detect the failure. A different intersection management policy can be executed with the knowledge of a failure. K. Dresner and P. Stone introduced safety features for AIM [36]. They add safety information to the messages transmitted from intersection manager to the vehicles.

Each vehicle in Zone I, computes crash detection which is discussed previously. Possible collisions based on crash detection, are resolved by the intersection management algorithm which is run by each vehicle. Intersection management algorithm will be explained in the next section. Communication is done when a safe travel sequence is created as an outcome of intersection management algorithm. Communication starts again only if a new vehicle enters Zone I. In that case, intersection management algorithm is run again to consider the information of the new vehicle.

A vehicle is no longer part of the communication group if it leaves Zone I. Thus, an on – coming vehicle cannot know any information about the off – going vehicle. In that case, on – coming vehicle cannot calculate the same intersection management result with the other vehicle traveling in the communication zone. Hence, the time – space information of the exiting vehicle is considered as invariable. This situation is also evaluated by the intersection management and it is defined as globally set time – space. The vehicle entering Zone I is informed by the nearest vehicle about the global intersection cell occupation.

The information, which a vehicle will be get in case of entering Zone I, can be summarized as follows:

- Cell occupation by time from all vehicles in Zone I
- Global time – space information from the nearest vehicle in Zone I

An overall flow diagram for a vehicle entering intersection is given in Figure 3.7.

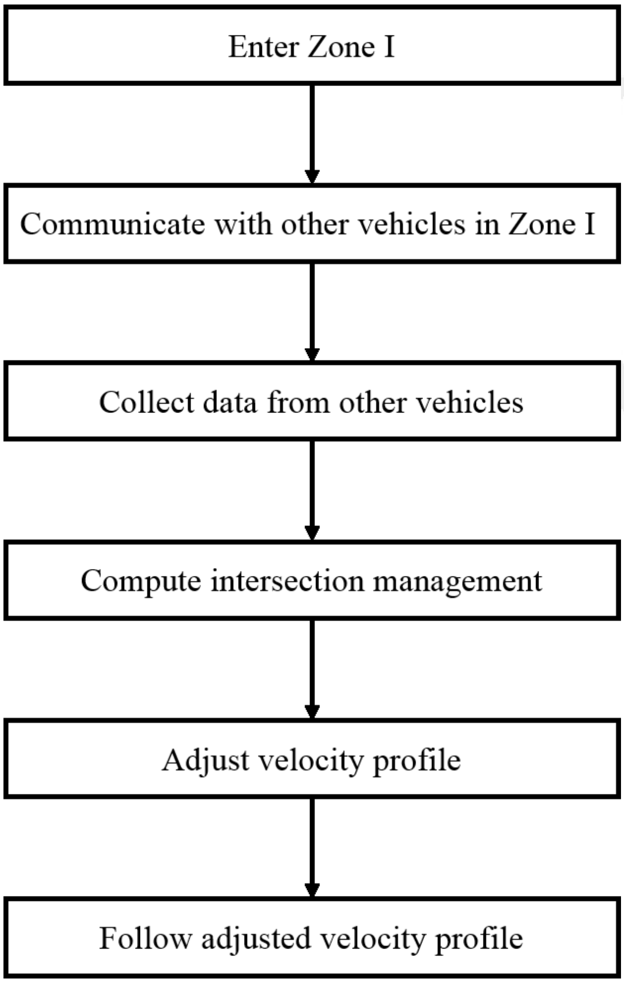


Figure 3.7 : Overall flow diagram for a vehicle approaching intersection.

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4. INTERSECTION MANAGEMENT

In this section, intersection management algorithms are explained. It is previously stated that the crash detection is the first step for the intersection management. In case of any estimated collisions, vehicles must be conditioned to avoid crash at the intersection. After the crash detection, an intersection management algorithm is executed. Output of the intersection management is delay on the vehicles' arrival time to the intersection. Basically, creating a window for a vehicle to pass the intersection is achieved by delaying other vehicles. The problem, which must be solved here, is to decide which vehicles are delayed. Order of priority must be constituted to make a decision. Simplest approach for intersection management decision problem is FCFS. First Come – First Served algorithm, gives the priority to the vehicle which requests to pass the intersection first, as its name suggests. However, this method may not provide the best decision all the time. In case a platoon approaches to the intersection and a single vehicle is estimated to reach the intersection before head vehicle of the platoon, delaying head vehicle results in delays on all vehicles in the convoy. On the other hand, waiting passage of all vehicles costs too much delay on one vehicle. Too much time delay may bring financial costs, as well. Delaying all vehicles in a convoy or waiting all of them to pass can converge to traditional traffic light solutions. Therefore, decisions can be made depending on a specified performance criterion. Look – ahead intersection control policy is a total time delay dependent intersection management algorithm.

4.1 LICP: Look – ahead Intersection Control Policy

As mentioned above, FCFS might be an insufficient solution in case existence of more than two vehicles. It is stated that Look – ahead intersection control policy increases efficiency of FCFS by 25% in terms of average intersection delay [28].

LICP searches for better passing sequences than the FCFS to reduce delay time. For example, if two vehicles approach to the intersection and a collision is detected depending on estimated paths, there are two solution for avoiding collision. Either arrival of vehicle 1 or arrival of vehicle 2 must be delayed. FCFS method delays the vehicle with latest reservation; however, the other passing sequence might be more efficient.

Potential collision of two vehicles and intersection occupation as time are seen in Figure 4.1. If Vehicle 1 has the reservation according to FCFS, scenario (a) is selected. Similarly, if the reservation is held by Vehicle 2, scenario (b) is selected. It is clearly seen that delay time in scenario (a) is less that the delay time in scenario (b). According to LCIP method, the scenario (a) is selected.

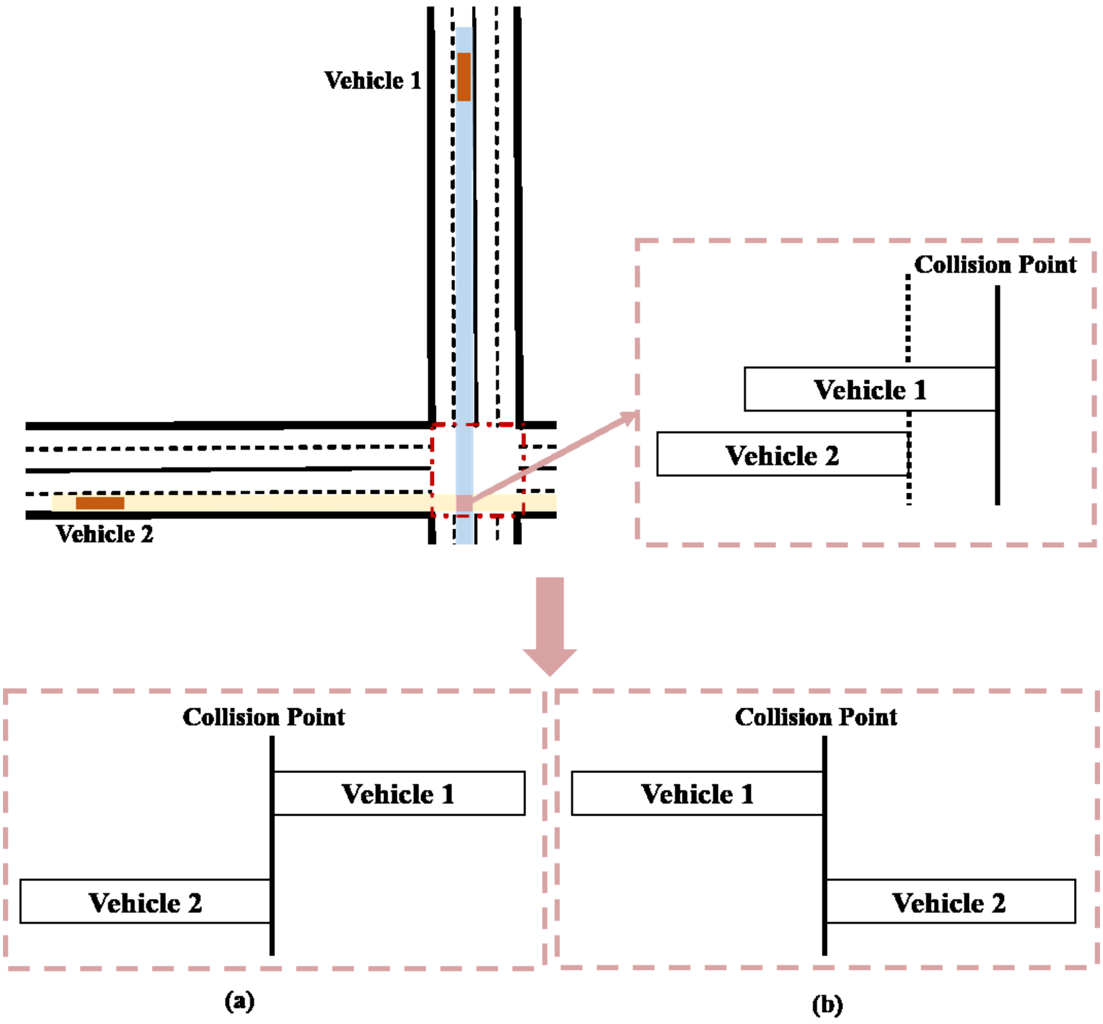

Figure 4.1 : Passing scenarios of two vehicle.

There might be a consecutive effect, if there are other vehicles following delayed vehicle and there is not enough distance between the vehicles to compensate deceleration of the head vehicle. In such cases, number of passing sequences increase.

There are two main criteria in LICP, which are the estimated delay time when the current reservation request postponed $\left(D_{postpone}\right)$ and the estimated delay time when the current reservation is approved (D_{allow}). If the estimated delay time for postponing the reservation is greater than the estimated delay time for approval, then the reservation request is postponed. Otherwise, the reservation request is approved.

Total time delay with the consecutive effect if the reservation request r is postponed, is given in equation 4.1 [28].

$$D_{postpone}(r) = (m + 1) \times D(r) + t \tag{4.1}$$

Here, m denotes the number of vehicles following vehicle i. $D(r)$ is the delay time assigned to the vehicle i. t denotes the starvation parameter.

t is calculated by a counter which increases when the reservation of vehicle i is rejected, and reset when it is accepted. If $D_{postpone}(r)$ is greater than $D_{allow}(r)$, the reservation is accepted. This prevents the starvation on passing sequence selection depending on delay time. Since, if there are too many vehicles behind the vehicle i, delay time due to consecutive effect might always be high enough to prevent passage.

$D_{allow}(r)$ calculation is given below. In order to calculate $D_{allow}(r)$, it is assumed that the reservation request r is allowed, and postponing delays are calculated for each conflicting reservartion requests.

$$L_i = sort(L_c, f_i), \quad f_i \in F, i \in [1, |F|] \tag{4.2}$$

$$D_{allow,i} = \sum_{j=1}^{n} D_{postpone}\left(r_j\right), \quad n = |L_i|, r_j \in L_i \tag{4.3}$$

$$D_{allow}(r) = \min\left\{D_{allow,i} \mid i \in [1, |F|]\right\} \tag{4.4}$$

Here, L_c denotes the reservation list which consists of approved reservations conflicted with reservation r. F represents a set of sorting function for L_c. f_i denotes the passing order for the vehicles. Each passing order postponing delays are calculated and summed. Minimum of the postponing delay summations is the approval delay for the reservation r.

To summarize, according to LICP, if there is a new reservation request and confliction on the requests, the delay time for postponing the new request and the delay time for allowing the reservation are calculated. If the cost of postponing the reservation in terms of time loss is greater than approving the reservation, the reservation is approved and other vehicles' reservations are rearranged.

4.2 Intersection Management Considering Energy Consumption

Proposed intersection management algorithm is run by each vehicle inside the communication zone (Zone I). If there is only one vehicle in the communication zone, execution of the algorithm is not required. Intersection management algorithm is developed under the assumption that the each vehicle is equipped with the required communication and GPS tools.

In case of a possible collision in the intersection, the vehicle with the lower priority is delayed as mentioned before. Delaying a vehicle could cause a consecutive effect on following vehicles. Proposed algorithm provides a solution for consecutive delay effect. Every time a new vehicle enters Zone I, intersection management algorithm is rerun. Instead of waiting request of a vehicle, conditions of all vehicles inside Zone I are evaluated. Considering all vehicles allows usage of time gaps between consecutive vehicles. Demonstration for an example case of possible collision of two vehicles with follower vehicles is given in Figure 4.2. All vehicles are assumed to be inside the communication zone.

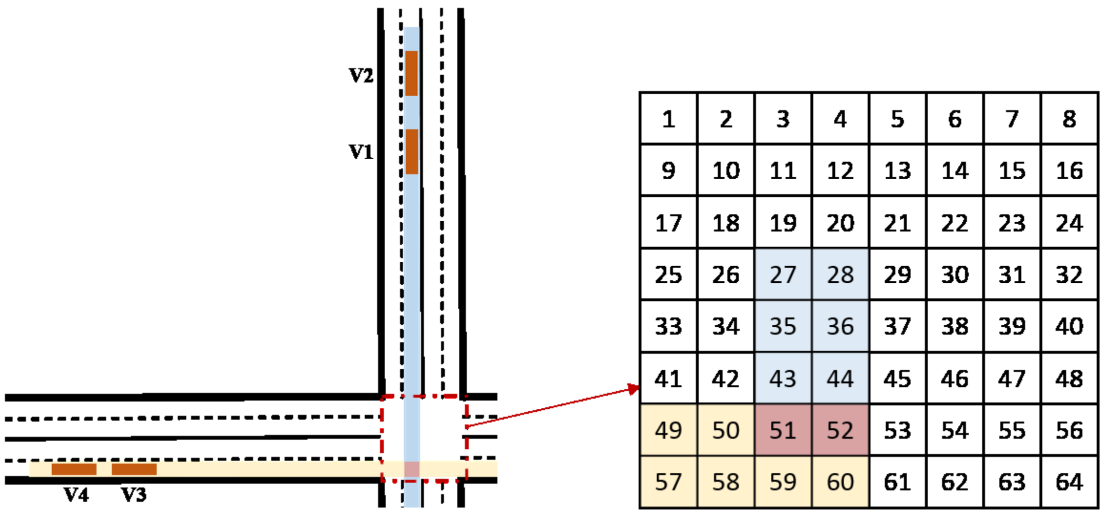

Figure 4.2 : Intersection management for 4 vehicles.

Vehicle 1 (V1) and vehicle 3 (V3) are expected to collide. Vehicle 2 (V2) and vehicle 4 (V4) follows V1 and V2, respectively. In such case, V1 or V3 must be delayed to prevent collision. However, if there is not enough gap between consecutive vehicles, delaying head vehicles could necessitate delaying V2 or V4, as well. On the other hand, if there is enough gap between consecutive vehicles, vehicles could interfere convoys. Possible passing sequence through the collision point is limited to $n!$, where n is the vehicle number. Since the following vehicles could not pass the collision point before their head vehicles, some sequences can be eliminated as described below.

$$\left.\begin{matrix} 1-2-3-4 \\ 1-2-4-3 \\ 1-3-2-4 \\ 1-3-4-2 \\ 1-4-2-3 \\ 1-4-3-2 \\ 2-1-3-4 \\ 2-1-4-3 \\ 2-3-1-4 \\ 2-3-4-1 \\ 2-4-1-3 \\ 2-4-3-1 \\ 3-1-2-4 \\ 3-1-4-2 \\ 3-2-1-4 \\ 3-2-4-1 \\ 3-4-1-2 \\ 3-4-2-1 \\ 4-1-2-3 \\ 4-1-3-2 \\ 4-2-1-3 \\ 4-2-3-1 \\ 4-3-1-2 \\ 4-3-2-1 \end{matrix}\right\} \rightarrow \begin{cases} 1-2-3-4 \\ 1-3-2-4 \\ 1-3-4-2 \\ 3-1-2-4 \\ 3-1-4-2 \\ 3-4-1-2 \end{cases}$$

After determination of all possible sequences, most efficient passing sequence is selected. Advantage of this approach is that each vehicle can be treated individually, compared to the LICP. In LICP, cost of delaying a convoy is evaluated in one function, and same amount of delay time is assigned for each consecutive vehicle. In the proposed method, flexibility of manipulating each vehicle separately allows us to utilized time gaps between consecutive vehicles. Advantages can be summarized as follows:

- Time gaps between consecutive vehicles can be utilized, so that a vehicle could pass between two vehicles
- Follower vehicles are not always required to be delayed with the same amount of delay time, which is assigned to the head vehicle.

Selection among the possible passing sequences is based on cost functions. Cost of each possible sequence is calculated, and a minimization strategy is maintained. Three cost functions are examined for this study:

- Total delay time based cost function
- Energy loss based cost function
- Combined cost function

4.2.1 Delay time calculation

Arrival time for the vehicles to the intersection is adjusted, in order to obtain safe passage according to each sequence. Visualization of two vehicles' arrival to an intersection is seen in Figure 4.3.

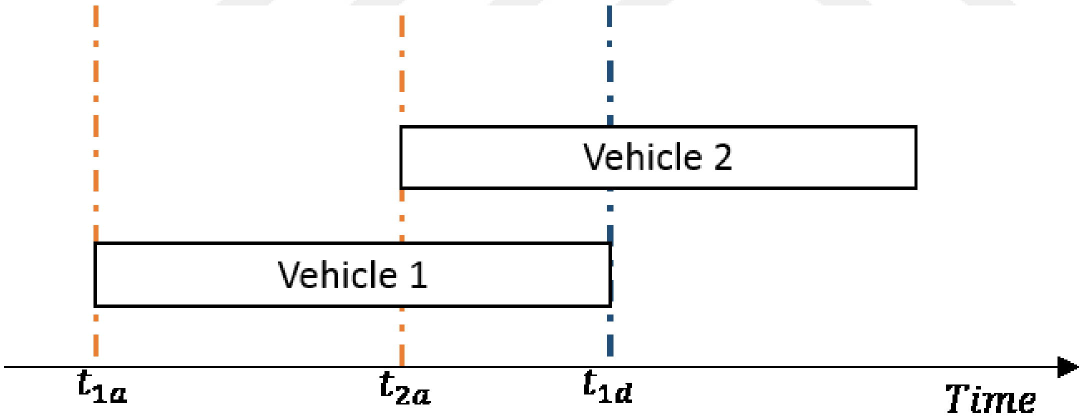

Figure 4.3 : Delay time calculation.

Here, t_{1a} is the arrival time for vehicle 1 to the collision point, and t_{1d} is the departure time. Similarly, t_{2a} is the arrival time of vehicle 2. Delay time is calculated as given below.

$$t_{delay} = t_{1d} - t_{2a} \tag{4.5}$$

4.2.2 Velocity adjustment

Delay time fulfillment is accomplished by deceleration and acceleration on the velocity profiles of the vehicles. The velocity profile is constructed based on delay time with the assumption that all vehicles travel with constant velocity once they enter the communication zone. Velocity profile adjustment is seen in Figure 4.4. A Similar approach for velocity profile generation is given in [29, 37].

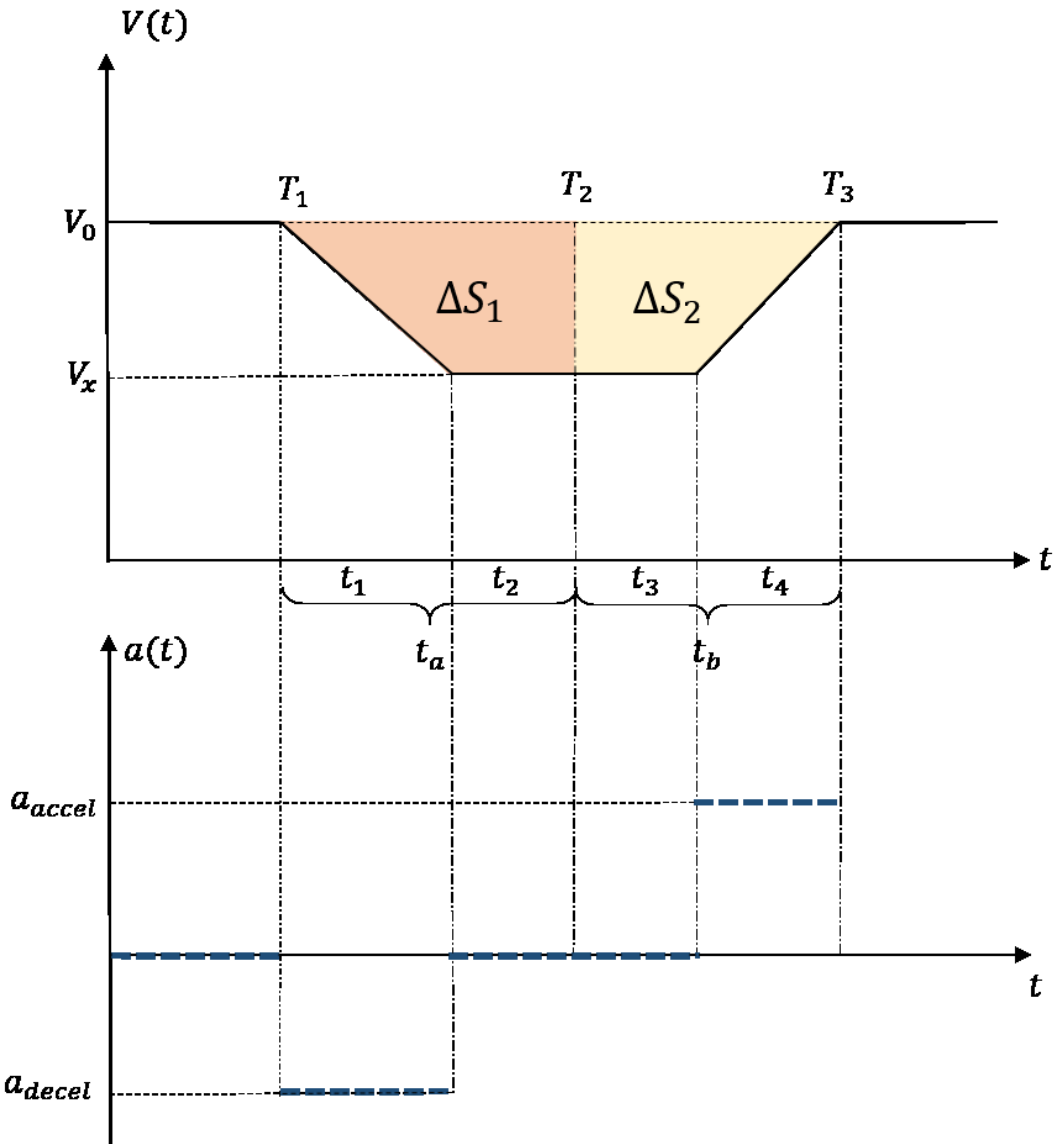

Figure 4.4 : Velocity profile adjustment.

Deceleration starts at T_1, when the vehicle enters Zone II. Acceleration starts at T_2, when the vehicle enters Zone III. Finally, vehicle arrives at the intersection at T_3. Travel time spent in deceleration area equal to difference between T_2 and T_1. Similarly, time spent in acceleration area is equal to the difference between T_3 and T_2.

Deceleration and acceleration area durations are represented as t_a and t_b, respectively. Deceleration depending on the delay time is calculated as below.

$$t_a = t_1 + t_2 \tag{4.6}$$

$$t_1 = t_a \cdot \gamma \tag{4.7}$$

$$t_a = \frac{S_1}{V_0} + T_d \cdot \alpha \tag{4.8}$$

$$\Delta S_1 = V_0 \cdot t_a - S_1 \tag{4.9}$$

$$V_x = V_0 - \frac{2\Delta S_1}{t_1 + t_a} \tag{4.10}$$

$$a_{decel} = \frac{V_x - V_0}{t_1} \tag{4.11}$$

Acceleration depending on the delay time is calculated as below.

$$t_b = t_3 + t_4 \tag{4.12}$$

$$t_b = \frac{S_2}{V_0} + T_d \cdot (1 - \alpha) \tag{4.13}$$

$$\Delta S_2 = V_0 \cdot t_b - S_2 \tag{4.14}$$

$$t_4 = 2\left(t_b - \frac{\Delta S_2}{V_0 - V_x}\right) \tag{4.15}$$

$$a_{accel} = \frac{V_0 - V_x}{t_4} \tag{4.16}$$

Here, T_d denotes the delay time, which is calculated by the intersection management algorithm. Distance between Zone III and Zone II is defined as S_1. Similarly, distance from Zone III to intersection is represented by S_2.

α parameter is used to divide delay time over two velocity adjustment areas. This parameter is selected depending on the intersection design and maximum/minimum acceleration. Since area lengths are the same, and the velocity rate is equal for both positive and negative values, α is selected as 0.5.

γ is a design parameter for deceleration part. It is used to specify deceleration and constant velocity sections. γ parameter is adjusted to change maximum allowed delay time for a vehicle. Since the vehicles are not desired to stop at any time, a minimum V_x value is determined. Delay time is derived from the equations 4.7, 4.8 and 4.11 for the predetermined minimum deceleration and minimum velocity values, as given in equations 4.17 and 4.18.

$$|a_{min}| = \frac{V_0 - V_{x_{min}}}{\gamma \cdot t_a} \tag{4.17}$$

$$\gamma \cdot \left(\frac{S_1}{V_0} + T_d \cdot \alpha\right) = \frac{V_0 - V_{x_{min}}}{|a_{min}|} \quad , 0 < \gamma \leq 1 \tag{4.18}$$

It is seen from the equation 4.19 that the delay time can be increased by decreasing γ.

4.2.3 Total delay time based cost function

Total delay time is the most common criterion for intersection management. Possible passing sequence deduction is previously explained for an example case in Figure 4.2. First vehicles of a sequence is not delayed. Other vehicles are delayed to avoid collision. It is possible that a member of a sequence may not be delayed if there is enough distance to the delayed front vehicle. Minimum delay for each vehicle is calculated as described in Delay time calculation section. Summation of the individual delays gives the delay time cost of the sequence. Total delay time is calculated for each possible sequence as shown below.

1. 1 – 2 – 3 – 4 → $\boldsymbol{Td_1}$
2. 1 – 3 – 2 – 4 → $\boldsymbol{Td_2}$
3. 1 – 3 – 4 – 2 → $\boldsymbol{Td_3}$
4. 3 – 1 – 2 – 4 → $\boldsymbol{Td_4}$
5. 3 – 1 – 4 – 2 → $\boldsymbol{Td_5}$
6. 3 – 4 – 1 – 2 → $\boldsymbol{Td_6}$

$$T_{d_j} = \sum_{i=2}^{n} t_{d_i} \quad , j \in [1, N] \tag{4.19}$$

$$N_{T_d} = \begin{bmatrix} T_{d_1} & \cdots & T_{d_j} & \cdots & T_{d_N} \end{bmatrix} \tag{4.20}$$

Here, n is the number of vehicles in the sequence j, and N represent the number of the possible sequences. t_{d_i} denotes the delay of an individual vehicle i in a sequence. The sequence with the minimum total delay is selected from the total delay time vector N_{T_d}. Cost of the selection is given below.

$$J_{T_d} = \min_{T_{d_j}} N_{T_d} \tag{4.21}$$

4.2.4 Energy loss based cost function

In this section we propose an energy loss based cost function for passing sequence selection. In order to obtain a safe travel through the intersection, arrival times of the vehicles with lower priority are delayed. Delay time is fulfilled by deceleration and acceleration as explained before. During acceleration, required traction force for the vehicle to follow a speed reference is increased as seen in equation 4.22, which is derived from equation 2.10. For constant speed the derivative term for the speed is equal to zero; however, during acceleration, it produces a counter force for movement.

$$F_T = M\frac{dv}{dt} + Mgf_r\cos(\alpha) + \frac{1}{2}\rho A_f c_d v^2 + Mgsin(\alpha) \tag{4.22}$$

Before the acceleration, a deceleration period must take place. Energy can be regenerated during deceleration by regenerative braking. This is called recuperation, and it is a sub-function of hybrid and electric vehicles. Recuperation is based on generation of energy from the kinetic energy of the vehicle. Regenerative braking requires existence of an electric motor. Energy regeneration is directly related to the capability of electric motor. In order to fully recover braking energy, electric motor must be capable enough to produce all braking force. However, mechanical braking systems are required in order to reduce braking distance. Braking force is mostly produced by both regenerative braking and mechanical braking for the hybrid and electric vehicles on the market. Percentage of available regenerative braking energy to total braking energy is given approximately 50% for typical urban driving cycles in [31]. Therefore, acceleration and deceleration are rated by a parameter η as given in equation 4.23. Regeneration torque of electric motor is derated for low speed, as well. This characteristic of electric motor is neglected.

$$F_T = \eta M \frac{dv}{dt} + Mgf_r\cos(\alpha) + \frac{1}{2}\rho A_f c_d v^2 + Mgsin(\alpha) \tag{4.23}$$

$$\eta = \begin{cases} 1, & \dfrac{dv}{dt} > 0 \\ 0.5, & \dfrac{dv}{dt} \leq 0 \end{cases} \tag{4.24}$$

Required traction power and energy is calculated as below.

$$P(t) = F_T(t) \cdot v(t) \tag{4.25}$$

$$E = \int_{t_0}^{t_f} P(t)dt \tag{4.26}$$

Vehicle longitudinal dynamics are modelled in MATLAB/Simulink, and a PID controller is used to accomplish velocity reference tracking. Velocity reference tracking results and required force for two identical vehicles are seen in Figure 4.5 and 4.6. Velocity profile of vehicle 1 includes acceleration and deceleration parts, while vehicle 2 follow a constant velocity profile.

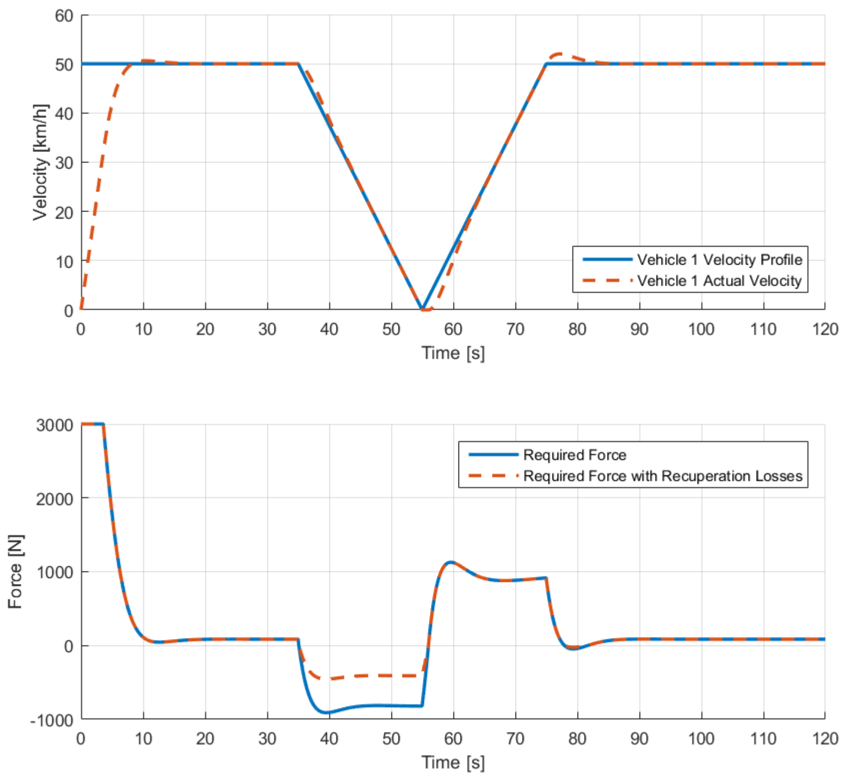

Figure 4.5 : Velocity and required force calculation for vehicle 1.

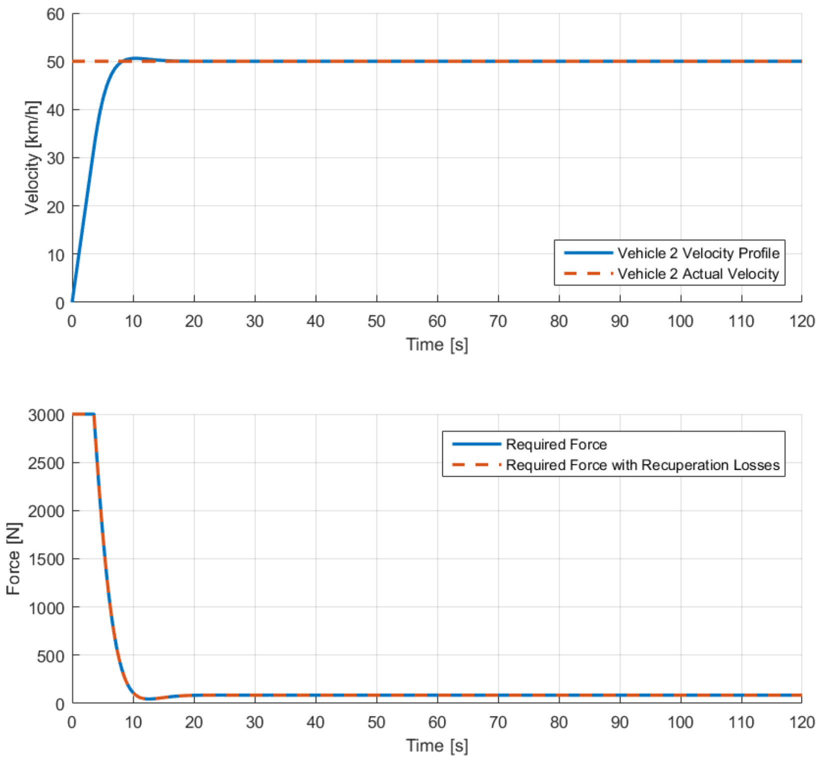

Figure 4.6 : Velocity and traction force calculation for vehicle 2.

Required force is used to calculate actual power request. As it is seen from Figure 4.5, braking force is reduced before power calculation, since the brake force is not fully used for energy recovery during deceleration. It is also seen that, the traction force is increased to follow velocity profile during acceleration. As it is seen from Figure 4.6, required force is constant since the vehicle follows a constant velocity profile. Actual power consumption of both vehicles are seen in Figure 4.7. Energy is recovered from braking between $35 - 60$ seconds for vehicle 1; however, more energy is consumed during the acceleration than the generated energy during the deceleration.

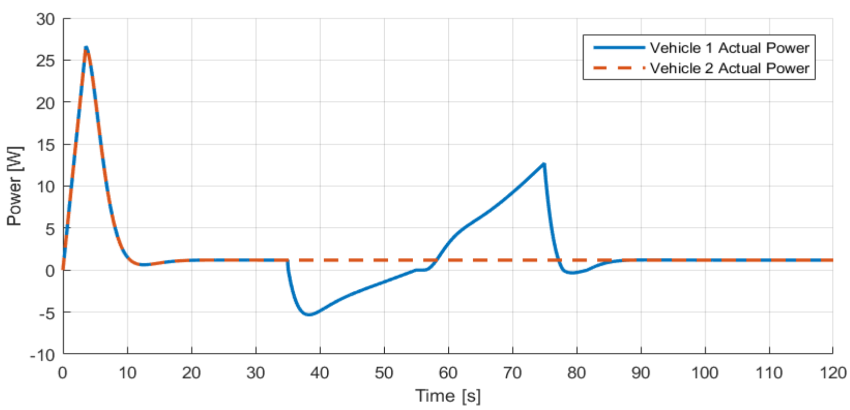

Figure 4.7 : Actual power comparison for two vehicles.

Assuming that both vehicles are equidistant from the collision point at the beginning of the simulation, total consumed energy is compared based on the positions of the vehicles. Vehicle 2 is considered to reach the collision point in the intersection at 80^{th} second, which corresponds to $1070m$. Vehicle 1 travels the same distance in 100 seconds. Total consumed energy when the vehicles arrive at the intersection is seen in Figure 4.8.

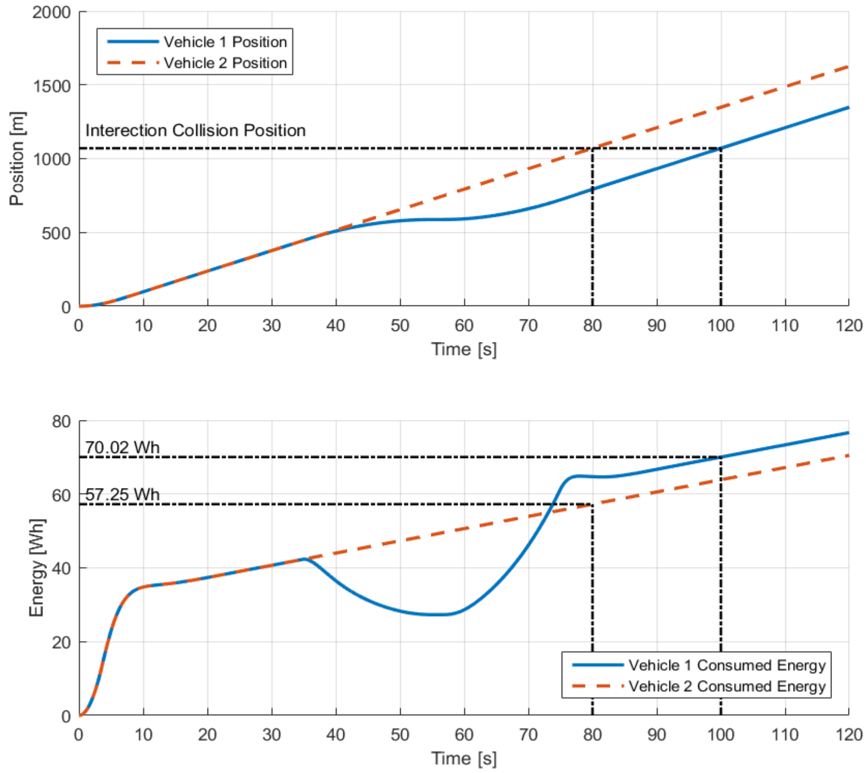

Figure 4.8 : Energy consumption of two vehicles.

As it is seen from Figure 4.8, vehicle 1 consumes $70.02\ Wh$ energy during its travel, while vehicle 2 consumes $57.25\ Wh$ energy for the demonstrated case. Energy consumption of the accelerating vehicle is greater than the energy consumption of the vehicle traveling with constant velocity.

Here, vehicle with the constant velocity represents the nominal behavior of a vehicle. In case of velocity adjustment due to delay time, vehicle wastes energy despite the energy regeneration during deceleration.

Energy loss can be used as an intersection management performance criteria. Since the vehicles are not identical, vehicle dynamic parameters are different. Therefore, energy loss is expected to be different for different vehicle, even if the velocity trajectories are the same.

Some vehicles are delayed to resolve estimated collision for each possible passing sequence as explained for total delay time calculation. Estimated required energy can be calculated by using adjusted velocity profiles based on delay time and vehicle longitudinal dynamic model. Estimated energy loss is equal to difference between required energy for tracking adjusted velocity profile and required energy for tracking nominal velocity profile. Summation of energy losses for individual vehicles in a sequence gives the total energy loss for a passing sequence. Corresponding total energy loss is calculated for each possible sequence as shown below for the example given in Figure 4.2.

$$\begin{array}{llllllllll}
\mathbf{1.} & 1 & - & 2 & - & 3 & - & 4 & \rightarrow & \boldsymbol{Ed_1} \\
\mathbf{2.} & 1 & - & 3 & - & 2 & - & 4 & \rightarrow & \boldsymbol{Ed_2} \\
\mathbf{3.} & 1 & - & 3 & - & 4 & - & 2 & \rightarrow & \boldsymbol{Ed_3} \\
\mathbf{4.} & 3 & - & 1 & - & 2 & - & 4 & \rightarrow & \boldsymbol{Ed_4} \\
\mathbf{5.} & 3 & - & 1 & - & 4 & - & 2 & \rightarrow & \boldsymbol{Ed_5} \\
\mathbf{6.} & 3 & - & 4 & - & 1 & - & 2 & \rightarrow & \boldsymbol{Ed_6}
\end{array}$$

$$E_{d_j} = \sum_{i=2}^{n} e_{d_i} \quad , j \in [1, N] \tag{4.27}$$

$$N_{E_d} = \begin{bmatrix} E_{d_1} & \cdots & E_{d_j} & \cdots & E_{d_N} \end{bmatrix} \tag{4.28}$$

Here, n is the number of vehicles in the sequence j, and N denotes the number of the possible sequences. e_{d_i} is the energy loss of an individual vehicle i in a sequence. The sequence with the minimum total energy loss is selected from the total energy loss vector N_{E_d}. Cost of the selection is given below.

$$J_{E_d} = \min_{E_{d_j}} N_{E_d} \tag{4.29}$$

4.2.5 Combined cost function

Combined cost function is constructed as summation of both total delay time and total energy loss with a ratio. As discussed before, same delay time and velocity profile may not result the same energy consumption for different vehicles to track the velocity profile. Total delay time based passing sequence selection is greedy in terms of energy consumption, since it tries to clear the intersection as soon as possible regardless of vehicle dynamics. However, vehicles may pass the intersection with less energy cost but slight increase on delay time. Similar scenario may occur with only energy loss dependent cost. Therefore, a trade off parameter is used to combine two cost. In order to combine two costs with different units, percentage loss is calculated as follows.

$$E_{pctg} = 100 \cdot \left(\frac{E_d - E_{d_n}}{E_{d_n}} \right) \tag{4.30}$$

$$T_{pctg} = 100 \cdot \left(\frac{T_d}{T_{d_n}} \right) \tag{4.31}$$

Here, E_d and T_d are total energy loss based on adjusted velocity profile and total delay time, respectively. E_{d_n} and $T_{d_n}$are total energy loss based on nominal velocity profile and estimated total nominal arrival time of the vehicles. Combine cost function is given in equation 4.32.

$$J = \alpha \cdot T_{pctg} + (1 - \alpha) \cdot E_{pctg} \quad , a \in [0,1] \tag{4.32}$$

Here, α is the trade off parameter between total delay time and total energy loss for a passing sequence. This parameter can be adjusted separately for each vehicle in the sequence as below.

$$J = [\alpha_1 \quad \dots \quad \alpha_N] \cdot \begin{bmatrix} t_{pctg_1} \\ \cdots \\ t_{pctg_N} \end{bmatrix} + [(1 - \alpha_1) \quad \dots \quad (1 - \alpha_N)] \cdot \begin{bmatrix} e_{pctg_1} \\ \cdots \\ e_{pctg_N} \end{bmatrix} \tag{4.33}$$

Here, N is the number of vehicle in a sequence. t_{pctg_i} and e_{pctg_i} represets the percentage delay time and energy loss for vehicle i in the sequence. The rating value is selected as equal and 0.5 for each vehicle in this study.

Overall intersection management algorithm flow chart is given in Figure 4.9.

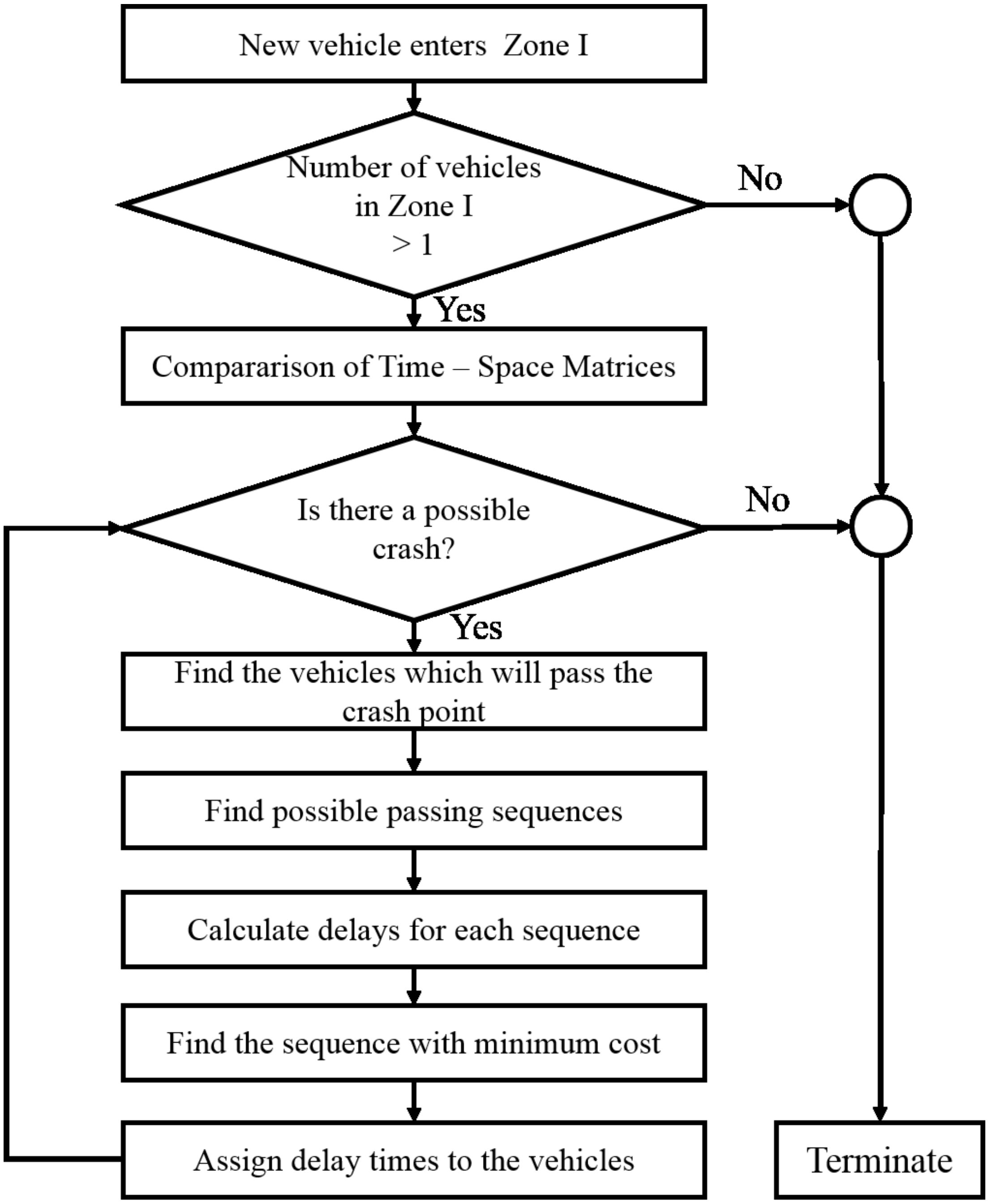

Figure 4.9 : Intersection management algorithm flow diagram**.**

5. SIMULATION ENVIRONMENT

A simulation framework is designed in MATLAB to simulate and test the intersection management algorithm. Cross road intersection model with two lane for each way is seen in Figure 5.1.

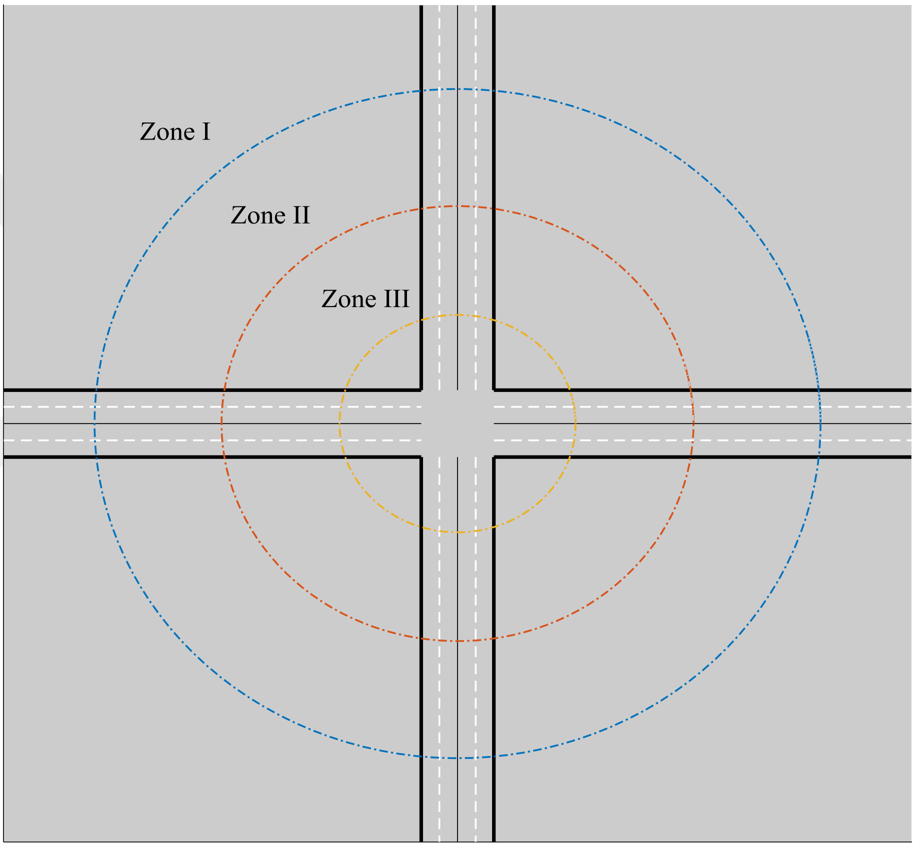

Figure 5.1 : Simulation framework.

Vehicles are defined with initial position, orientation, velocity, length, width, longitudinal dynamic parameter values, path and identification number (ID). Vehicle position is given as the center of the rear axle. Vehicle frame is constructed around the initial position (x_0, y_0) and rotated by orientation using rotation matrix.

$$R(\theta) = \begin{bmatrix} \cos(\theta) & -\sin(\theta) \\ \sin(\theta) & \cos(\theta) \end{bmatrix} \tag{5.1}$$

Vehicle representation in the framework is given in Figure 5.2

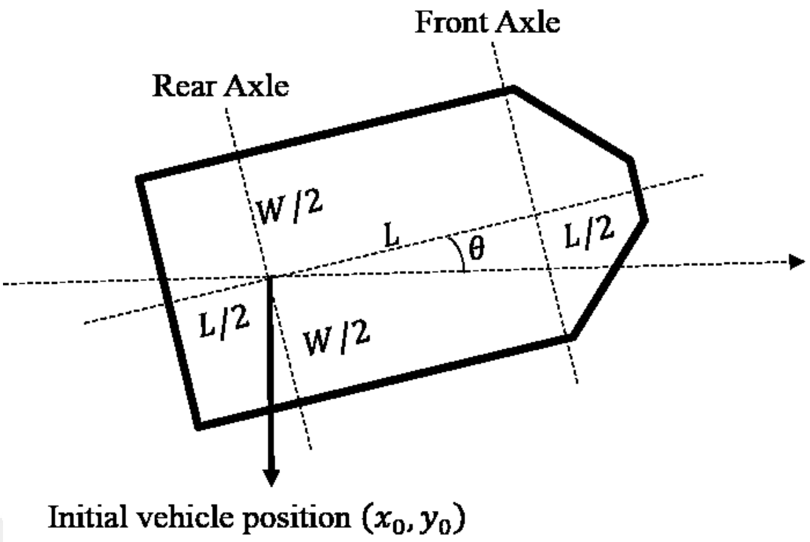

Figure 5.2 : Vehicle representation in framework.

Here, L and W denotes the length and width of the vehicle, repectively. θ is the orientation of the vehicle. θ variable is updated depending on the steering of the vehicle during the simulation. Steering is provided by pure pursuit path tracking algorithm. Pure pursuit algorithm is one of the most common path tracking algorithms due to the simplicity of its application. Geometrical representation of pure pursuit algorithm is given in Figure 5.3.

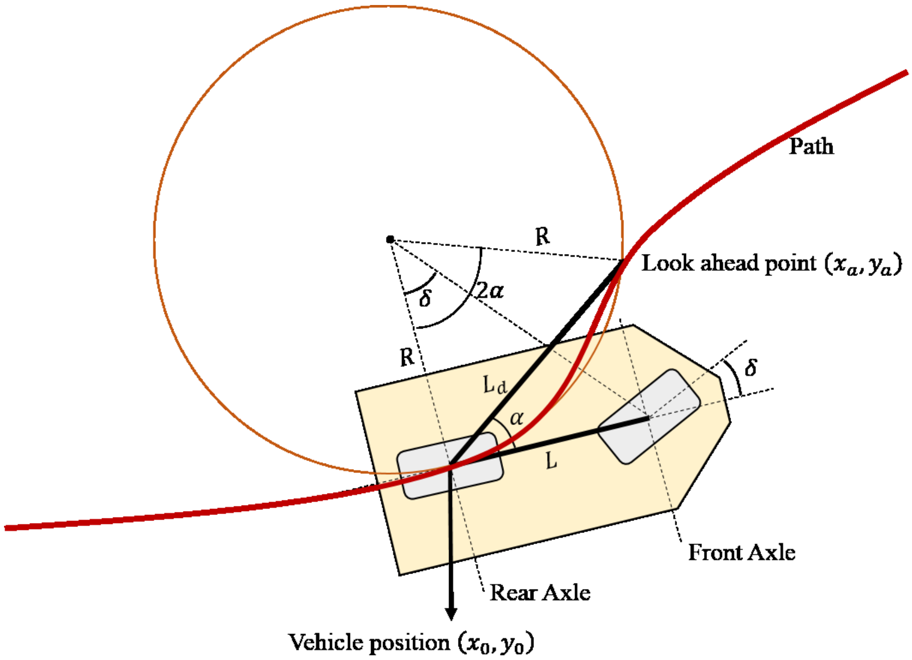

Figure 5.3 : Pure pursuit path tracking visualization.

Here, L_d is the distance between center of rear axle and look ahead point. Look ahead point is the target of the vehicle on the path. Algorithm is implemented for a bicycle model, which is explained in the vehicle model section. Geometric derivation of the steering angle to turn the vehicle towards the target is given below [38].

$$\delta = \tan^{-1}\left(\frac{L}{d}\right) \tag{5.1}$$

$$\delta(t) = \tan^{-1}\left(\frac{2L \cdot sin\left(\alpha(t)\right)}{L_d}\right) \tag{5.2}$$

Simulation result of the path tracking algorithm is seen in Figure 5.4.

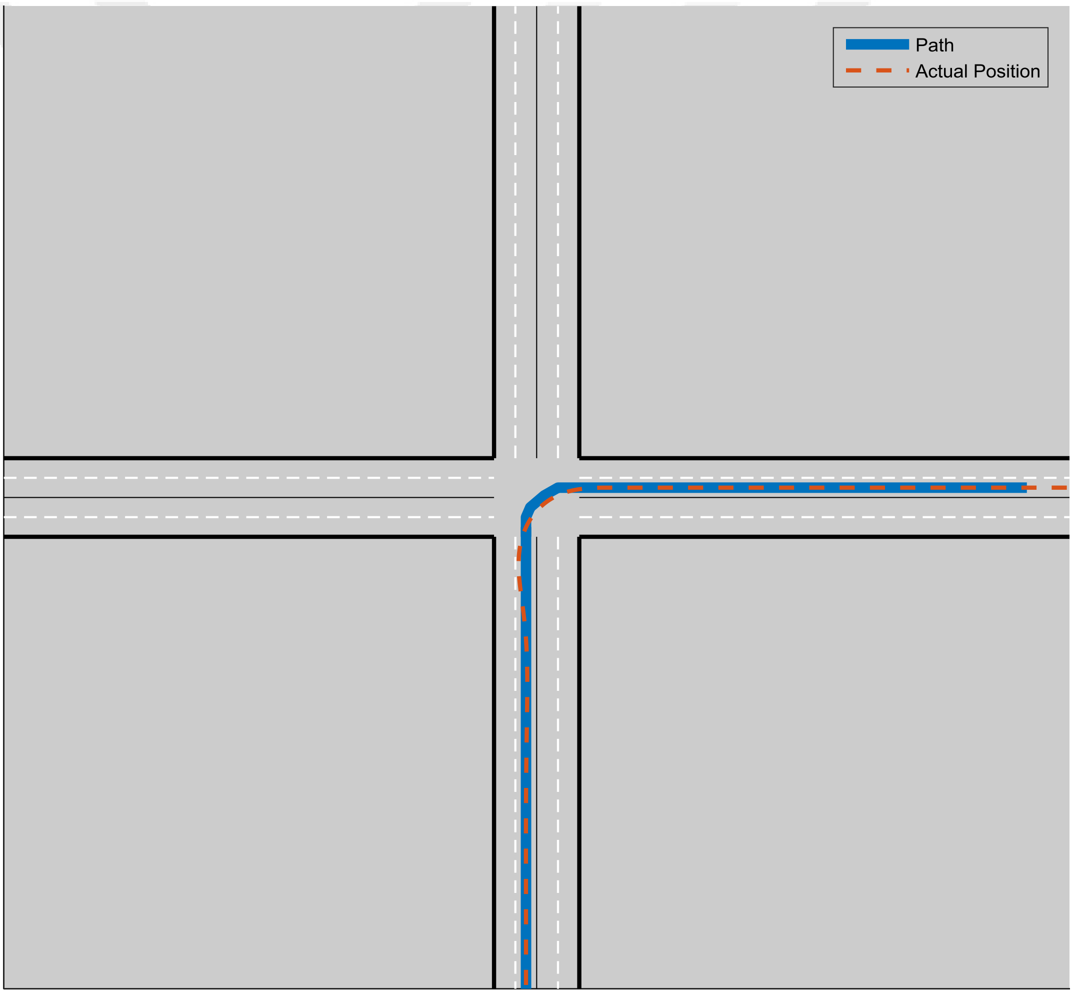

Figure 5.4 : Pure pursuit path tracking simulation result.

6. CASE STUDIES

In this section, proposed intersection management algorithm is simulated for different cases and results are discussed. Vehicles are assumed to travel with constant velocity when they enter Zone I if there is no assigned delay. Effective frontal area, drag coefficient and rolling resistance coefficient are set as the same by the given values in longitudinal dynamic model section. Additionally, recuperation is allowed for each vehicles. Simulation cases are constructed by different number of vehicles with different path, mass and initial velocity. All cases are simulated with total delay time, energy loss and combined cost function. Cost function dependent variations are named as Configuration 1, Configuration 2 and Configuration 3, respectively.

6.1 Case 1

10 vehicles are simulated for the case 1. Path of the vehicles, initial velocity and mass values are given in Table 6.1. A convoy with 5 vehicles approaches to the intersection from west to east. Two heavier vehicles travel from north to south with lower velocity. Two vehicles approach from west and turn to south. Vehicles are started at outside of the intersection.

Table 6.1 : Vehicle parameters for Case 1.

Vehicle ID	Path	Velocity (m/s)	Mass (kg)
Vehicle 1	West to East	10	1500
Vehicle 2	West to East	10	1500
Vehicle 3	West to East	10	1500
Vehicle 4	West to East	10	1500
Vehicle 5	West to East	10	1500
Vehicle 6	West to East	10	1500
Vehicle 7	North to South	9.2	4500

Table 6.2 : Vehicle parameters for Case 1 (cont'd).

Vehicle ID	Path	Velocity (m/s)	Mass (kg)
Vehicle 8	North to South	9.2	4500
Vehicle 9	East to South	11	1200
Vehicle 10	East to South	10	1200

Simulation results for different configurations are seen in Table 6.2. Results are given as delay time on each vehicle.

Table 6.3 : Case 1 simulation results.

Vehicle ID	Configuration 1 Delay (s)	Configuration 2 Delay (s)	Configuration 3 Delay (s)
Vehicle 1	0	0	0
Vehicle 2	0.3	3.75	0.3
Vehicle 3	1.2	3.2	2.75
Vehicle 4	0.65	2.65	2.2
Vehicle 5	0.1	2.1	1.65
Vehicle 6	1.05	1.55	1.1
Vehicle 7	1.1	0	1.1
Vehicle 8	5.3	0	1
Vehicle 9	0	0	0
Vehicle 10	0	0	0

Simulation results show that zero delay time are assigned to Vehicle 7 and Vehicle 8 in Configuration 2. Due to their high mass, energy loss is expected to be high compared to other vehicles. Therefore, total energy based sequence selection algorithm gives the priority to Vehicle 7 and Vehicle 8. Vehicle 1 to 6 have less delay in Configuration 1 than in Configuration 2; since delaying the head of a convoy result in delay on the following vehicles due to the consecutive effect. Therefore, total delay time based selection algorithm gives the priority to convoy for reducing total delay. Overall results is seen in Table 6.3.

Table 6.4 : Case 1 overall simulation results.

	Configuration 1	Configuration 2	Configuration 3
Total Delay (s)	9.7	13.25	10.10
Total Energy Loss (%)	4.7	3.06	4.04

As it is seen from Table 6.3, total delay in Configuration 1 is lower than the total delay in Configuration 2. Similarly, total energy loss in Configuration 2 is lower than the total energy loss in Configuration 1. It is seen that the total delay increases in Configuration 3, while energy loss decreases compared to Configuration 1. Similary, Total energy loss increases in Configuration 3, while total delay decreases compared to Configuration 2. It can be said that combined cost function based algorithm improves total delay based algorithm in terms of energy loss. Similary, it improves energy loss based algorithm in terms of total delay. Visualization of Case 1 for Configuration 1 is seen in Figure 6.1.

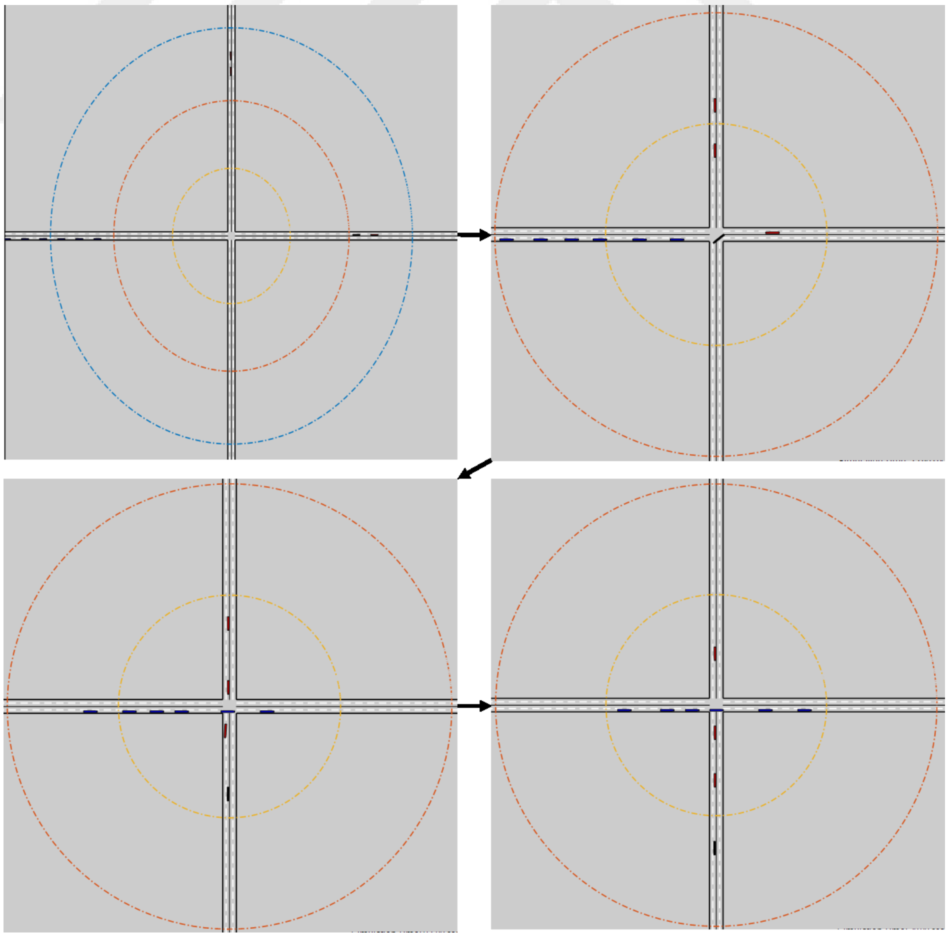

Figure 6.1 : Intersection management for Case 1.

6.2 Case 2

In case 2, 14 vehicles are simulated. Path of the vehicles, initial velocity and mass values are given in Table 6.4. Simulation consists of 4 convoys on each section. 4 vehicles approach from west, and 4 vehicles with higher mass approach from north. Three vehicles travel from east to west, while three vehicles travel from south to north with higher mass and lower speed.

Table 6.5 : Vehicle parameters for Case 2.

Vehicle ID	Path	Velocity (m/s)	Mass (kg)
Vehicle 1	West to East	10	1500
Vehicle 2	West to East	10	1500
Vehicle 3	West to East	10	1500
Vehicle 4	West to East	10	1500
Vehicle 5	North to South	9.2	4500
Vehicle 6	North to South	9.2	4500
Vehicle 7	North to South	9.2	4500
Vehicle 8	North to South	9.2	4500
Vehicle 9	East to West	10	1500
Vehicle 10	East to West	10	1500
Vehicle 11	East to West	9.2	1500
Vehicle 12	South to North	9.2	2000
Vehicle 13	South to North	9.2	2000
Vehicle 14	South to North	9	2000

Simulation results for three configurations are given in Table 6.5. In Configuration 2, it is seen that the more delay accumulated on the vehicles traveling from west due to their low mass. Delays on the heavy vehicles are reduced to reduce energy loss by comparison with Configuration 1. In Configuration 1, delays are distributed regardless of vehicle parameters. It is seen that the delays on the vehicles traveling form west are decreased, while the delays on the vehicles traveling from north increase.

Table 6.6 : Case 2 simulation results.

Vehicle ID	Configuration 1 Delay (s)	Configuration 2 Delay (s)	Configuration 3 Delay (s)
Vehicle 1	0	0	0
Vehicle 2	0.95	2.45	2.45
Vehicle 3	0.4	6	4.9
Vehicle 4	1.3	5.45	4.35
Vehicle 5	3.2	0	0
Vehicle 6	3.95	1.1	1.1
Vehicle 7	3.3	0.45	0.45
Vehicle 8	2.65	3.8	2.95
Vehicle 9	0	0	0
Vehicle 10	1.9	9	8.15
Vehicle 11	6.35	7.5	6.65
Vehicle 12	1.85	1.85	1.85
Vehicle 13	3.5	0.65	0.65
Vehicle 14	3.05	2.8	0.2

As it is seen from Table 6.6, total delay in Configuration 1 is lower than the total delay in Configuration 2; as, the total energy loss in Configuration 2 is lower than the total energy loss in Configuration 1. It is seen that the total delay increases in Configuration 3, while energy loss decreases compared to Configuration 1. Energy loss based algorithm is improved in terms of total delay by combined cost function. However it is observed that eenregy loss is aslo slightly reduced. This is an expected situation, since the intersection management algorithm is executed among the communicating vehicles in Zone I. Every new decision is made upon the previously made decision, since the decision for the vehicles, which leaves Zone I, is permanently set. Since the number of vehicles, which will travel through the intersection, is not known in advance, result of any configuration is not always global minimum in terms of corresponding cost functions.

Table 6.7 : Case 2 overall simulation results.

	Configuration 1	Configuration 2	Configuration 3
Total Delay (s)	32.4	41.05	33.7
Total Energy Loss (%)	8.35	5.75	5.2

Visualization of Case 2 for Configuration 1 is seen in Figure 6.2.

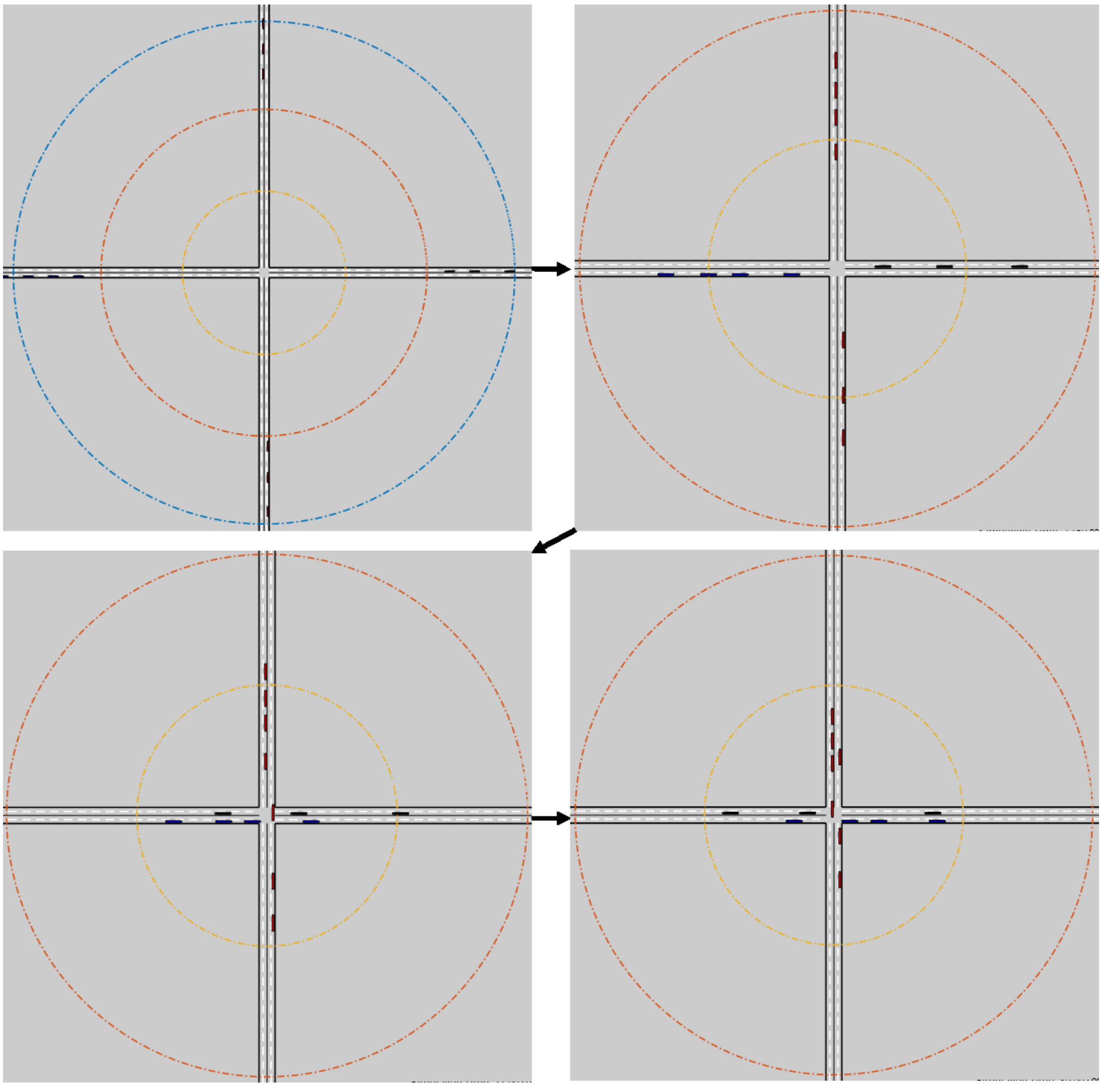

Figure 6.2 : Intersection management for Case 2.

6.3 Case 3

In Case 3, intersection management algorithm is simulated for 15 vehicles. Path of the vehicles, initial velocity and mass values are given in Table 6.7. There are two convoys approaching intersection from west and east. Mass of those vehicles are relatively less than the vehicles approaching from north. Additionally, one vehicle involves from south.

Table 6.8 : Vehicle parameters for Case 3.

Vehicle ID	Path	Velocity (m/s)	Mass (kg)
Vehicle 1	West to East	10	1500
Vehicle 2	West to East	10	1500
Vehicle 3	West to East	10	1500
Vehicle 4	West to East	10	1500
Vehicle 5	West to East	10	1500
Vehicle 6	West to East	10	1500
Vehicle 7	North to South	9.2	4500
Vehicle 8	North to South	9.2	4500
Vehicle 9	East to South	11	1500
Vehicle 10	East to South	10	1200
Vehicle 11	East to West	10	1200
Vehicle 12	East to West	10	1200
Vehicle 13	East to West	10	1200
Vehicle 14	North to South	9.2	4500
Vehicle 15	South to North	9.2	1200

As seen in Table 6.8, simulation results show that delay times assigned to the vehicles approaching from west and east in Configration 1 are lower than delays assigned in Configuration 2. Opposite distribution is seen on the vehicles approaching form north in Configuration 2 compared to Configuration 1. This trade off is the result of selection between time and energy based cost functions. Due to their heavy mass, vehicles 7, 8 and 14 are allowed to follow their initial velocity profiles in Configuration 2. Similary, less delay is distributed on the convoys in Configuration 1. In Configuration 3, delays on the heavier vehicles are increased compared to Configuration 2, in order to find a solution with less total delay.

Table 6.9 : Case 3 simulation results.

Vehicle ID	Configuration 1 Delay (s)	Configuration 2 Delay (s)	Configuration 3 Delay (s)
Vehicle 1	0	0	0
Vehicle 2	2.1	5.35	0.3
Vehicle 3	1.55	4.8	4.25
Vehicle 4	1	4.25	3.7
Vehicle 5	0.45	3.7	3.15
Vehicle 6	1.4	3.15	2.6
Vehicle 7	0	0	1.1
Vehicle 8	5.65	0	1
Vehicle 9	0	0	0
Vehicle 10	0	0	0
Vehicle 11	1.35	3.85	4.75
Vehicle 12	0.8	3.3	4.2
Vehicle 13	0.25	2.75	3.65
Vehicle 14	6.95	0	0.9
Vehicle 15	0.1	1.65	1.95

As it is seen from Table 6.9, total delay in Configuration 2 is higher than the total delay in Configuration 1; as, the total energy loss in Configuration 1 is higher than the total energy loss in Configuration 2. It is seen that the total delay slightly decreases in Configuration 3, while energy loss increases compared to Configuration 2. Besides, energy loss is reduced in Configuration 3 compared to Configuration 1.

Table 6.10 : Case 3 overall simulation results.

	Configuration 1	Configuration 2	Configuration 3
Total Delay (s)	21.6	32.8	31.55
Total Energy Loss (%)	5.53	3.84	5.27

Visualization of Case 3 for Configuration 3 is seen in Figure 6.3.

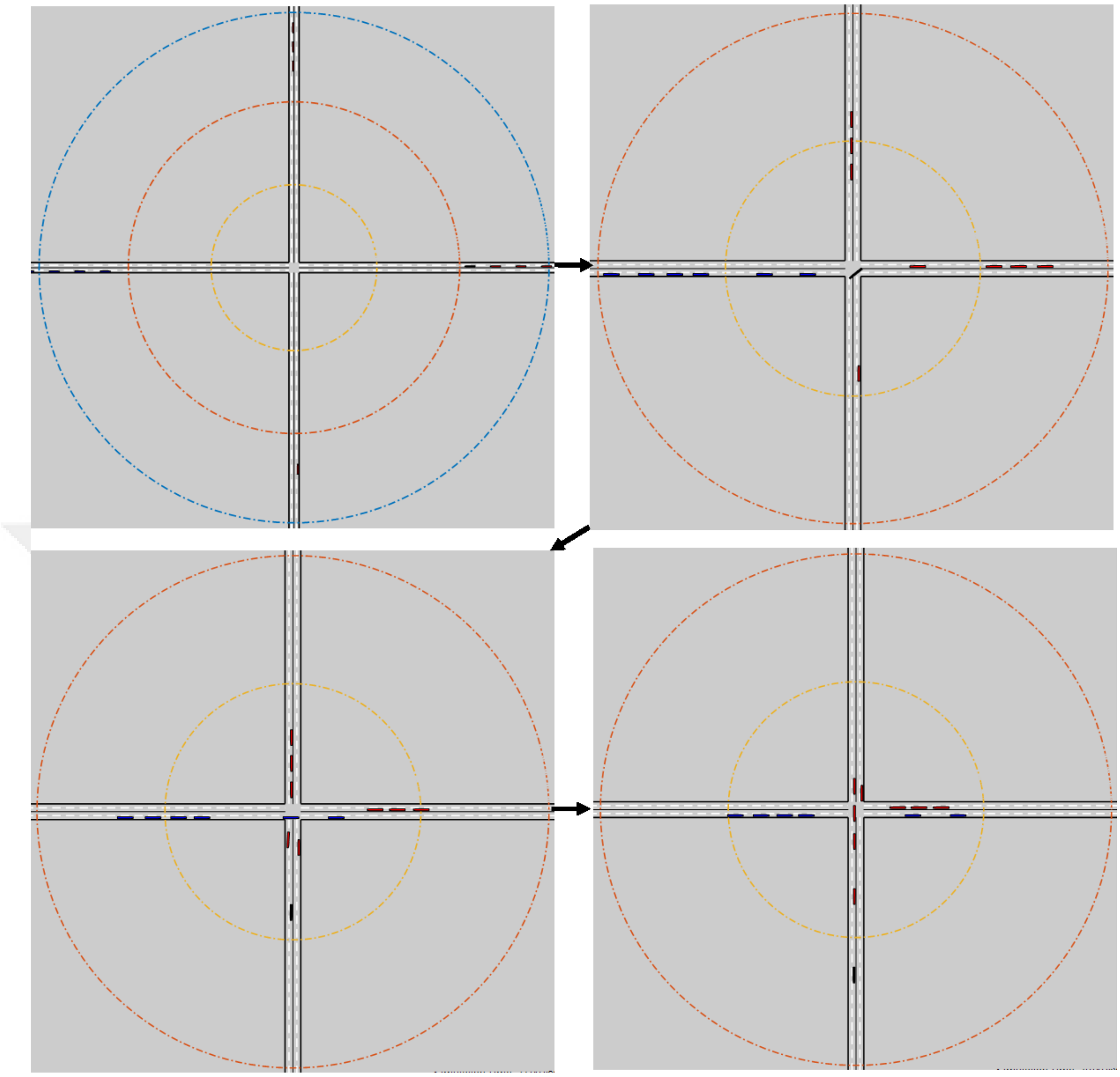

Figure 6.3 : Intersection management for Case 3.

6.4 Case 4

16 vehicles are simulated in Case 4. Path of the vehicles, initial velocity and mass values are given in Table 6.10. Mass of the vehicles are varied and one more vehicle is added to the path from south to north addition to Case 3.

Table 6.11 : Vehicle parameters for Case 4.

Vehicle ID	Path	Velocity (m/s)	Mass (kg)
Vehicle 1	West to East	10	1500
Vehicle 2	West to East	10	1500

Table 6.10 : Vehicle parameters for Case 4 (cont'd).

Vehicle ID	Path	Velocity (m/s)	Mass (kg)
Vehicle 3	West to East	10	1500
Vehicle 4	West to East	10	1800
Vehicle 5	West to East	10	1500
Vehicle 6	West to East	10	1800
Vehicle 7	North to South	9.2	4500
Vehicle 8	North to South	9.2	4500
Vehicle 9	East to South	11	1500
Vehicle 10	East to South	10	1200
Vehicle 11	East to West	10	1200
Vehicle 12	East to West	10	1200
Vehicle 13	East to West	10	1200
Vehicle 14	North to South	9.2	4500
Vehicle 15	South to North	9.2	1200
Vehicle 16	South to North	9.2	1600

Simulation results are given in Table 6.11. As it is seen, delays in Configuration 1are less than in Configuration 2 and 3; since any criteria other than reducing travel time is not concerned. Contrary, delays are distributed mostly on the relatively lighter vehicles to reduce energy loss.

Table 6.12 : Case 4 simulation results.

Vehicle ID	Configuration 1 Delay (s)	Configuration 2 Delay (s)	Configuration 3 Delay (s)
Vehicle 1	0	0	0
Vehicle 2	2.1	5.35	5.35
Vehicle 3	1.55	4.8	4.8
Vehicle 4	1	4.25	4.25

Table 6.11 : Case 4 simulation results (cont'd).

Vehicle ID	Configuration 1 Delay (s)	Configuration 2 Delay (s)	Configuration 3 Delay (s)
Vehicle 5	3.35	3.7	3.7
Vehicle 6	2.8	4.6	3.15
Vehicle 7	0	0	0
Vehicle 8	4.9	0	0
Vehicle 9	0	0	0
Vehicle 10	0	0	0
Vehicle 11	1.35	3.85	3.85
Vehicle 12	0.8	3.3	3.3
Vehicle 13	0.25	2.75	2.75
Vehicle 14	8.35	0	0
Vehicle 15	0.1	11.35	0.1
Vehicle 16	4.85	11	9.55

Overall simulation results are seen in Table 6.12. It is seen that the total delay time in Configuration is less than delay time in Configuration 2. Similarly, energy loss in Configuration 2 is less than energy loss in Configuration 1. It is seen from the comparison of Configuration 1 and 3 that the reduction in energy loss is dramatic compared to the increase in total delay. Additionally, energy loss reduction based configuration is improved in terms of total delay by Configuration 3.

Table 6.13 : Case 4 overall simulation results.

	Configuration 1	Configuration 2	Configuration 3
Total Delay (s)	31.4	54.95	40.8
Total Energy Loss (%)	5.97	3.73	3.68

It is also observed by comparing Configuration 2 and 3 that there is a slight improvement in energy loss. This situation is the result of cause and effect relation in the algorithm. Former decisions effect the later decision, since number of vehicles which will pass the intersection cannot be known. Intersection management is only executed by the vehicles in communication zone. Visualization of Case 4 for Configuration 1 is seen in Figure 6.4.

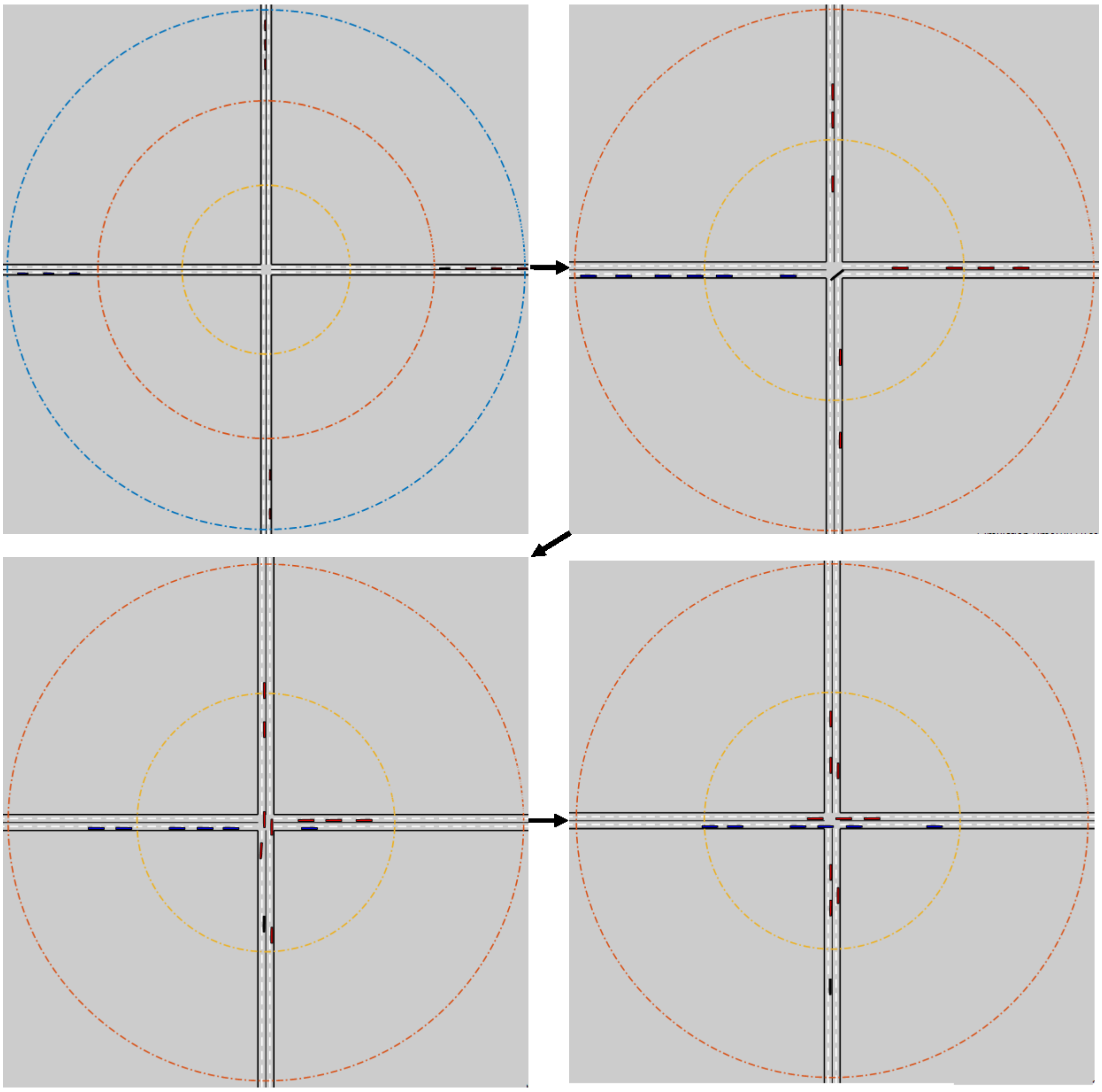

Figure 6.4 : Intersection management for Case 4.

7. CONCLUSION AND DISCUSSION

A multi agent intersection management algorithm for autonomous vehicles is proposed based on time delay and energy loss cost functions. Intersection model is explained with the communication protocols and crash detection. Passing sequence calculation for the vehicles, which are estimated to collide at the intersection, is explained after crash detection. Passing sequence selection is conducted based on cost functions. Total delay time, energy loss and combined cost functions are given. Vehicle longitudinal model is used for energy loss calculation. Performance of algorithm is tested in simulation framework, which is designed in MATLAB. Vehicle kinematic bicycle model is used for simulation of vehicle movements. Simulation results are explained in detail.

Intersection management includes communication, crash detection and vehicle conditioning processes. Vehicle to vehicle communication is established without existence of a field unit. Vehicles communicate with each other when they are inside the communication zone. Intersection is divided into three main parts, which are communication zone, deceleration zone and acceleration zone.

During communication, intersection management algorithm is executed. Vehicles simulate their planned trajectory, and determine the time – space to specify occupation of intersection. Vehicles' time – space occupations at the intersection are compared to detect any possible crash depending on estimated trajectories.

Output of the intersection management is delay on the vehicles' arrival time at the intersection. First Come – First Served algorithm is most common method to resolve estimated crash due to its simplicity. It basically gives the priority to the vehicle which request a reservation first. Look Ahead Intersection Control Policy, which is stated that it improves FCFS by 25% in terms of total delay time, is explained. Consecutive effect of delaying a vehicle, which is followed by other vehicles, is taken in consideration by LICP. Consecutive vehicles are considered as a group. Reservations of the vehicles are accepted depending on the total delay time, which they cause if the reservation is accepted.

Passing sequence selection is proposed in this study. Passing sequence is the permutation of the vehicles, which are estimated to pass the estimated collision point at the intersection. Each passing sequence results in total delay time. Selection between sequences is conducted based on minimization of delay time.

Another cost for sequence selection is total energy loss. Delay time on the vehicle trajectory is fulfilled by deceleration and acceleration. Acceleration requires additional traction force for a vehicle. In order to calculate required traction force, longitudinal vehicle dynamics are given. Increase in the required traction torque results in additional energy consumption, compared to the nominal trajectory even if there is energy regeneration from deceleration. Energy loss is calculated for each passing sequence. Even the delays are equal, energy loss may not be equal since the vehicle dynamic parameters are different. Sequence with minimum energy loss is selected.

After introducing total delay and energy loss dependent cost functions, a combined cost function is explained. Two costs are combined as percentage with a rating parameter. It is aimed to construct a selection criteria considering time and energy loss together.

Simulation results for different cases are given and explained. It is seen that the total delay time based selection method gives the passing priority to the convoys by assigning less delay time to reduce consecutive effect. Energy loss dependent method allows the heavier vehicles travel with their nominal velocity profiles as much as possible, since the required energy is high for acceleration of a heavy vehicle. It is observed that total delay based method is improved in terms of energy loss by the combined cost approach. Similarly, energy loss based method is improved in terms of total delay time by the combine cost method.

It is also observed for some cases that energy loss is also reduced with combined cost function compared to the energy loss based method. Reason of this situation is that there is a cause and effect relation in the proposed intersection management. Intersection management algorithm is executed by the vehicles inside the communication zone. A decision is made among the communicating vehicles. A new crash situation might be estimated over the decision. Another intersection management decision is made according to new situation. Therefore, a decision effects the next decisions. Besides, number of the vehicles, which will pass the intersection, is not known in advance. Thus, convergence to global minimum is not expected to be possible.

This thesis is summarized in a conference paper and will be presented at the 10th ELECO 10th International Conference on Electrical and Electronics Engineering in TURKEY which is technically sponsored by IEEE Turkey Section.

In this study, vehicles are assumed to travel with constant velocity once they enter the communication area. For the future work, delay time fulfillment with deceleration and acceleration can be improved to cover inconstant velocity profiles. Multi intersection structures can be established to reduce time and energy loss by using the information from other intersections.

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