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A Grid-based Framework for Managing Autonomous Vehicles' Movement at Intersections

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Abstract
With a full fleet of autonomous vehicles (AV) in the future, the concept of signal-free intersections has attracted transportation researchers. Multiple studies have investigated different methods and protocols to facilitate vehicle decision-making at intersections. Most of these methods have relied on strong centralized or inter-vehicle communications. This research aims to develop a new protocol for managing vehicle movement at four-leg intersections assuming a fully automated fleet. The main concept of the proposed protocol is to maintain a continuous movement of vehicles entering the intersection, without stopping in queues, by controlling their sequence of movements. In the methodology a dynamic occupancy grid (DOG) approach is applied by initially dividing the intersection into dynamic grids (i.e. cells). The cells are in a virtual movement, emanating away from each lane-group without overlapping, like a gear machine. Each vehicle sits on a specific cell to traverse the intersection safely at a predetermined time. In other words, vehicles approaching an intersection must register their speed and position by certain sensors, and in return receive the appropriate acceleration and speed to finally be allocated to the suitable moving grids. The efficiency of the applied protocol was demonstrated by a practical example that presented a higher intersection capacity value exceeding the ideal saturation flow rate in some cases. This reflects the efficiency of the implemented protocol and its applicability to different low to high traffic flows. Moreover, the protocol shows more flexibility in dealing with different weather, geometric and traffic conditions.

Keywords
intersection management, dynamic occupancy grid, autonomous vehicle, intersection capacity, equation of motions

1 Introduction

At a time when technology and artificial intelligence have invaded all fields (Muhammad, 2021; Omar, 2021), the rapid development in connected and fully autonomous vehicles (FAVs) technology has emerged. Researchers and traffic experts are counting on the expected role of FAV in improving traffic safety and efficiency. FAVs are considered to implement the highest level of automation (i.e. Level-5), according to the Society of Automotive Engineers classification (U.S. Department of Transportation, 2022). Currently, vehicles equipped with Level-2 automation systems are widely available for consumers, which often combine technologies such as the adaptive cruise control and lane centering. Some Level-3 autonomous vehicles (AVs) equipped with an automated driving system are currently in use in limited commercial fleets (e.g., commercial taxi, delivery) in restricted operating environments. However, the National Highway Transport Safety Administration (NHTSA), US agency (U.S. Department of Transportation, 2022) describes Level-3 as the highest level of automation currently being tested.

Multiple studies have investigated the potential of FAVs to reduce traffic congestion (Friedrich, 2016; Metz, 2018). When vehicles are enabled to travel closer together, communicate with each other, and anticipate the surrounding vehicles' movements, the capacity of roadways will increase. For instance, FAVs can sense and possibly anticipate the deceleration and acceleration of the leading vehicles, allowing for smoother adjustments of following vehicles' speed. Such technology contributes to reduce the traffic-destabilizing shockwave propagation. This could also increase congested traffic speeds by 8 to 13%, for all vehicles in the freeway travel stream, depending on

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the communication and how traffic smoothing algorithms are implemented (Ghadi et al., 2020; Tamimi et al., 2019; Xiong et al., 2018).

Intersection areas are deemed to be typical conflict points for road networks due to the intensive complexity induced by vehicles moving in different directions (Ganguly et al., 2022). The conflict points at intersections result in many risky black spots, and reduces the efficiency and level of service of the entire intersection (Ghadi et al., 2018; Ghadi and Török, 2021; Ghadi and Török, 2019). Foreign statistics show that traffic delays of intersections accounted for more than one-third of total delay of urban traffic and that accidents in the intersection areas represent more than 50% of the total traffic incidents.

As the problem of traffic congestion becomes more serious, more efficient traffic management approaches must be adopted. Currently, intersections are managed by the installed control tools and systems. The role of adaptive traffic control system (ATCS) has become increasingly prominent for intersection management (Gao et al., 2019). Traffic is detected at signalized intersections using the flow sensing approach by setting video cameras and induction loops. Video cameras and inductive loops have disadvantages of high installation and maintenance costs and have shown significant limitations under current road conditions.

Nowadays, several attempts have been made to develop management approaches for self-driving vehicles at intersections (Alkhatib and Sawalha, 2020; Dresner and Stone, 2004; Milanés et al., 2010). The emergence of Level-2 and 3 AVs in road networks was assessed in connection with the control of the intersection. The perception solutions for the AVs rely on on-board sensors, which are limited by line of sight and obstruction caused by any other elements on the road. Hence, Level-3 AVs are still in their preliminary stages that only enhance individual AVs to map their way across intersections but are insufficient to manage the entire intersection system (Cvietic, 2020; Tesla Inc., 2023).

Alternatively, telematics will enable vehicle-to-everything (V2X) communications, allowing vehicles to collaborate and enhance their cognitive capabilities. Telematics benefit from the application of vehicle communication networks and intelligent technologies, such as connected vehicles, video monitoring, automated vehicles and vehicle–environment collaboration, to observe traffic data in real-time (Gao et al., 2020). Through the sharing of information in real-time between vehicles and the infrastructure of roads, the transportation intelligence between them is realized; i.e. a collaboration to improve vehicle travel safety and reduce traffic congestion.

The Intelligent transportation system (ITS) is a comprehensive, efficient, and real-time, transportation and management system (Gao et al., 2020), thanks to the Cooperative Awareness Message, one of the successful ITS applications (Kitazato et al., 2016). This message standardizes the dissemination of the connected vehicle state, including information such as speed, position, heading or vehicle type. The emergence of the fifth-generation cellular network (5G) can significantly improve the dynamic behavior of ITS (Barros et al., 2020). Connected vehicles can also be used as sensors to collect high-precision status information, making a great contribution to intersection control (He et al., 2016).

With a full fleet of autonomous vehicles on the road in the future, the concept of signal-free intersections has attracted transportation researchers. The early proposal of signal-free intersections was based on reservation strategies. All approaching vehicles communicate with a central Intersection Manager (IM) (Dresner and Stone, 2004; Dresner and Stone, 2008). The IM receives reservation requests from vehicles and accepts a request if it has no collisions with the previous reservations. (Mladenovic and Abbas, 2014) developed a decentralized agent-based priority framework. Each individual user, in this framework, can traverse the intersection based on the approaching time and priority level. Lower priority vehicles have to either wait in queues or decelerate before reaching the intersection terminal, giving right for higher priority vehicles. Similarly, (Alonso et al., 2011) applied vehicle-to-vehicle (V2V) communication-based system. In his technique, each vehicle approaching the intersection must access a database and receive information about positions, speeds, and names of other approaching vehicles. Once the vehicle has examined these data, it will be able to decide whether to continue or wait and give way to others. Isele et al. (2018) developed a reinforcement learning method that allows a complete understanding of the scene at the intersection using Deep Q-Networks.

Another research applied the concept of the Dynamic Occupancy Grids (DOG) for intersection management. DOG divided the intersection area into living grids, like pixels. Every grid can estimate the kinematic attributes of each cell, such as velocity, turn-rate, and acceleration. The same concept has been applied by Yuan et al. (2017). In their work a low-latency inter-vehicle wireless communication accompanied with on-board vehicle sensors are applied to improve the vehicle decision making process. Godoy et al. (2021) incorporated messages received via V2X with on-board sensors to enhance data fusion. This will be reflected in better occupancy estimation and object tracking, and thus better intersection management, they claimed. Recently the DOG has been explored in a cloud-based realization (Lampe et al., 2020). The main drawback of these applications is the risk of network deficiency, where a critical mass of users is required to have a measurable advantage of using the technology, the so-called network effect (Cawley, 1995).

With the introduction of FAVs, new possibilities towards intersection management have been opened, and it is evident by the significant amount of publications in this regard. FAV is able to behave independently using its own rules without the need of IM centers. Every individual vehicle is modeled independently using agent-based approaches to finally form a more complex decentralized system for all FAVs. Dresner and Stone, (2004) applied a similar decentralized approach enhanced with a first-come, first-served (FCFS) protocol to manage traffic at intersections. In their work, intersection area was modeled into square grids (or blocks) in which vehicles need to call ahead for reservation of the blocks depending upon their arrival time and trajectory. In another work by Carlino et al. (2013), an auction-based scheme is proposed to manage the intersection. As vehicles approach the intersection they can bid for fast passage. The scheme has also deployed a benevolent system agent to regulate these auctions. Another intersection management scheme was presented by Parker and Nitschke, (2017). The scheme applies a decentralized neuro-evolution approach to automate the synthesis of collective driving behavior of vehicles through an intersection.

However, most of the previously mentioned literature assume either always-secure inter-vehicle communication networks or complex systems suitable for only low or medium traffic volumes. Moreover, part of previous works required high cost IM centers, which can be only established for important intersections.

The main contribution of this work is its simplicity and efficiency. The framework of this research is based on applying the DOG in a different mechanism. Grids at the intersection will be in a constant motion, like a gear machine, carrying vehicles at a predetermined time and speed through the intersection. Hence, communications between vehicles or IM will not be required. This will make it easy to apply for any important or unimportant intersection due to its simplicity and accepted cost. Moreover, the continuous movement of vehicles through the intersection will contribute much to the sustainability and intersection efficiency.

2 Proposed protocol: the conceptual assumptions

In order to achieve autonomous driving with high automation, self-driving vehicles should dispose of the unsignalized intersections appropriately. In the unsignalized intersection, the self-driving vehicles need to run through (left-turn, right-turn, or straight) the intersection with safety and efficiency objectives. Without the guidance of traffic lights, automated vehicles should adapt to the uncertain intentions of the surrounding vehicles.

In the proposed protocol, the right-of-way will be assigned to each lane group sequentially allowing one vehicle or platoon to traverse the intersection per cycle. This requires the vehicle from each lane group to approach the intersection at a predetermined time and continue its path at a specified speed. Technically, this can be implemented via installing a certain type of sensor at a sufficient distance before entering the intersection area. The sensor will act as a transceiver, which receives information about the speed and time of each passing vehicle, and sends it back with the appropriate acceleration or deceleration. This ensures the sequence of movements within the intersection area according to the proposed protocol, which will be addressed later in this paper. In practice, the proposed approach is somewhat similar to the transit system of ants (Chowdhury et al., 2002; Hoar et al., 2002), where each ant leaves a pheromone behind to show the way for the following ant. Similarly, the goal of the designed approach is to inform the following vehicle about the exact time and speed required to cross the intersection safely. Therefore, there is no need to set up expensive and complex control centers or any vulnerable systems and cameras. Moreover, no inter-vehicle communication neither IM is required. This makes it easy to apply for any important or unimportant intersection due to its simplicity and accepted costs.

The presented protocol focuses primarily on giving each direction of the intersection an exact sequence, time, and duration to cross the intersection. In other words, it focuses on assigning the right-of-way for a specific vehicle or platoon for one lane group at a time, according to a pre-established time sequence. Hence, the self-driving vehicle decides whether to accelerate or decelerate to take its position in this timeline.

3 Sampling method

In the given approach the intersection area will be divided into DOGs of small squares (i.e. small square cells), the side length of each cell is equal to the width of the lane. These cells are always in a constant and regular motion, just like the gears of a machine. The philosophy behind this approach is that each vehicle will just sit on two moving cells, which will finally carry it safely to the other side of the intersection at a constant speed. Fig. 1 shows the sequence of movement of the cells (or vehicles) according to the proposed protocol.

More precisely, as the vehicle agent approaches the intersection, there is a transceiver sensor at a predefined distance before the intersection area that collects data about the speed, time and direction of the vehicle, and in return sends back the appropriate acceleration or deceleration, based on a pre-defined time and speed in the protocol sequence. Consequently, the vehicle accelerates or decelerates to reach a terminal velocity for traversing the intersection, as shown in Fig. 1 Forward-moving vehicles will usually maintain the same speed, while left-turning vehicles are expected to slow down in order to accommodate the turning path safely.

In the protocol, each direction (forward or left) in every intersection-leg has a sequential role for the crossing. The protocol is divided into eight steps of equal time duration. At each step, vehicles move by one cell or more so that one vehicle or one platoon will traverse the intersection from all directions during a full cycle protocol (eight steps). The protocol cycle is repeated continuously to reach the largest possible traffic flow (per hour) from all directions. The process of calculating traffic speed and volumes will be done using the equation of motions in the following sections.

Referring back to Fig. 1, it can be noted that: at the first step (Fig. 1(a)), the opposite vehicles (1) and (5) will move forward to the middle of the intersection by 4 cells. If the time gap is sufficient (as will be discussed later) a platoon of the following vehicles will form for vehicles (1) and (5). In the second step (Fig. 1(b)), vehicles (2) and (6) will start moving in the left direction in a circular path at a lower speed until they cross the intersection, after six steps.

In the third and fourth step (Figs. 1(c) and (d)), vehicles (1) and (5) will clear the intersection allowing other movements without conflict. At the fifth and sixth steps (Figs. 1(e) and (f)) forward moving vehicles (3) and (7), and left-turning vehicles (4) and (8) will start moving, respectively, in a similar way. After the 8 steps (Figs. 1(a) to (h)) one cycle of movements from all directions will be completed. To this point, it can be noted that in the given protocol vehicles will never stop or wait in queues. Moreover, the protocol shows that forward moving vehicles have a higher speed compared to left-turning vehicles. In addition, left-turning vehicles need 6 out of 8 steps to cross the intersection. This is logical, since left-turning vehicles must slow down to accommodate the surface friction and ride comfort. The comparatively longer time duration for the left-turning allows forming platoons in the forward moving vehicles. The number of vehicles in each platoon is based on the available gap and safe time headway. This will finally increase the flow rate at the intersection.

4 Analysis and movement measurements

The main objective in designing the control system for any intersection is to reach the highest possible rate of traffic flow and level of service. This can be achieved by maximizing the travel speed within the intersection area considering safety and ride comfort. FAV technology will help largely fulfilling these goals if it is built up based on appropriate principles and rules. The aforementioned protocol rule has been designed to achieve these goals in addition to the factor of sustainability and social justice.

This rule is used to allow every vehicle at every lane group to enter the intersection area at a pre-determined specific time according to the movement sets in the protocol. Therefore, a specific length must be allocated before reaching the intersection terminal, allowing vehicles to accelerate or decelerate until they reach the intersection area at the appropriate time and speed. The maximum value of this length is found to be around 90 meters for the comfort deceleration value (3.4 m/s^2) (AASTHO, 2011). However, the proposed rule allows forward moving vehicles to maintain the same segment speed in and out of the intersection area, but different speeds (usually smaller) for left-turn movements.

The determined speed and time headway are affected by the physical parameters of the road, which consist of road difficulties (grade, pavement), environmental conditions (weather) and any other conditions that limit an unconstrained driver's maximum speed. The following subsections present the mathematical calculations for the left-turn and forward movement trajectories according to the proposed protocol.

4.1 Left-turn movement trajectory

The turning speed is affected by the turning radius and the friction coefficient. The lower the friction or the turning radius, the lower the speed and vice versa. The left-turn

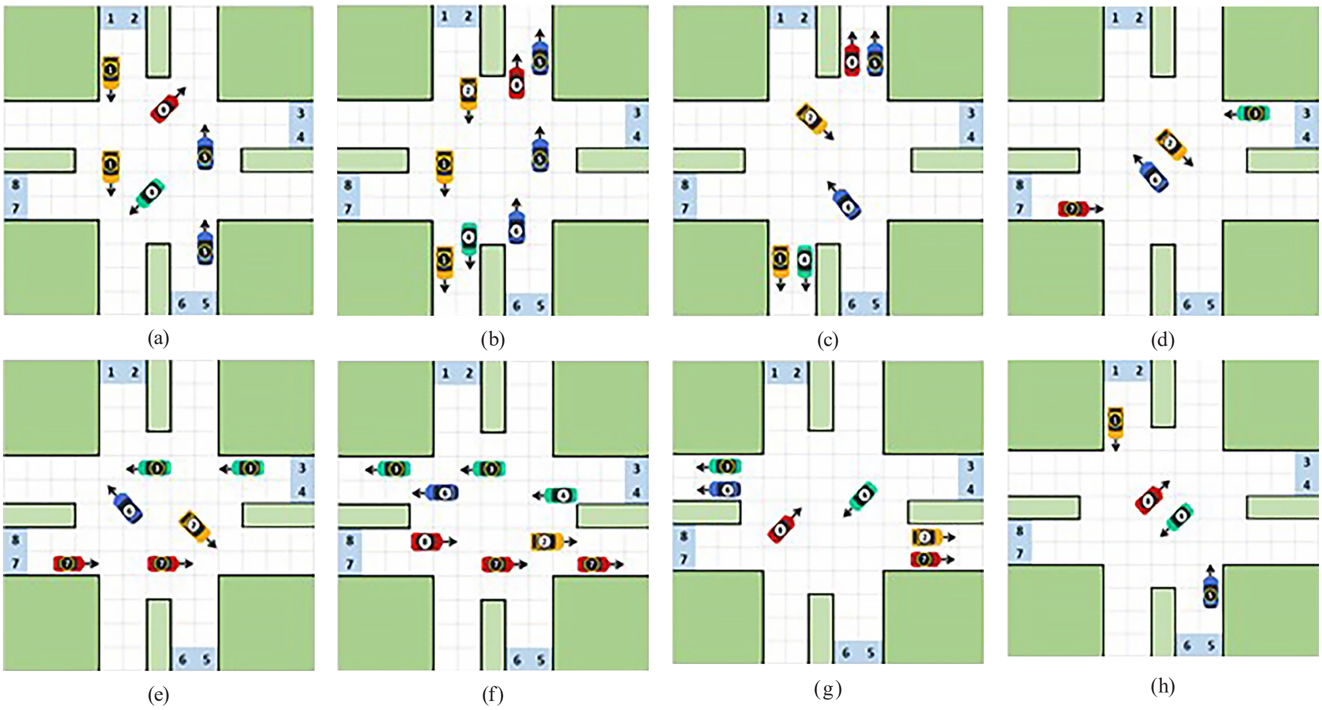


Fig. 1 Sequence of vehicle movements at the intersection by the proposed the protocol

speed is always lower than the forward movement speed, hence, it is considered as a reference speed in this proposal for safety considerations.

The length of the left-turn trajectory is assumed to follow the horizontal alignment design. Fig. 2 shows the trajectory of the left-turn movement of a 4-leg orthogonal intersection.

In the figure, the line of movement starts from the middle of the exclusive left-turn lane (No. 4) in a circular path towards the south. The length of turning arc (d_2) can be calculated using the basic circle Eq. (1), where the angle is assumed to be 90° (angle can be adjusted by the intersection design).

$$d_2 = R \times \Delta° \times \frac{\pi}{180} = \pi \frac{R}{2} \tag{1}$$

Where:

- $\Delta°$ = angle in degree
- $R(m)$ = Horizontal curve radius.

The horizontal alignment Eq. (2) can be used to calculate the turning speed based on the radius and the coefficient of friction which make it compatible with this case.

$$R = \frac{u_{\max}^2}{g\left(e + f_s\right) \times 12.96} \tag{2}$$

Where:

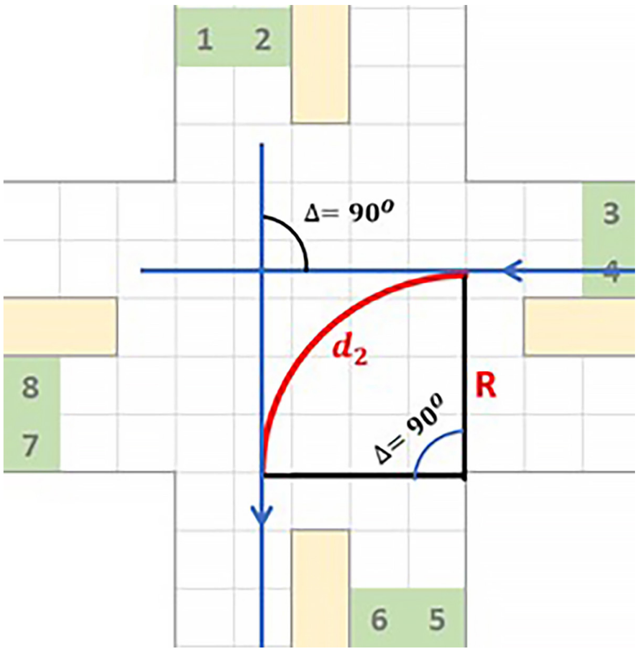


Fig. 2 Left turn trajectory

- $u_{\max}$ (km/h) maximum allowable left-turn speed
- g Acceleration of gravity (9.81 m/s^2)
- e = Superelevation (no superelevation at the intersection so $e = 0$)
- f_s Coefficient of side friction (usually between 0.10 and 0.30)
- 12.96 = to convert $u_{\max}^2$ $\left(km^2/h^2 \to m^2/\sec^2\right)$.

The left-turn speed (u^2) must stay within the accepted maximum speed u_{max} (i.e. $u_2 \leq u_{max}$), given by the horizontal alignment Eq. (2). However, it is found that, usually the value of u_{max} is small and safe enough to cross the intersection (Fitzpatrick et al., 2013). Due to the very short radius and side friction values at the intersection, it is assumed that $u^2 = u_{max}$. By re-writing the Eq. (2):

$$u_{max} = u_2 = \sqrt{\frac{254}{\pi} \times f_s \times d_2} \quad (3)$$

This speed (u_2) will increase with larger intersection area but decrease with lower side friction in snowy and rainy weathers. The coefficient of friction is left as a variable as its value can change with different weather and surface conditions. Using the equation of motion ($t_2 = d_2 / u_2$) for the left-turn movement and Eq. (3); the time required for the vehicle to cross the left-turn path is:

$$t_2 = \frac{2}{5}\sqrt{\frac{d_2}{f_s}} \quad (4)$$

Where:

- u_2 (km/h) = Left turn movement speed (km/h)
- d_2 (m) = length of the left-turn trajectory.
- t_2 (sec.) = time to cross the left turn trajectory within the intersection area.

However, the condition of a non-perfectly circular path has been taken into account in a geometric design and movement mechanism. In the geometric design, the start of a median has been moved back by one cell length from the intersection terminal. This allows gradual and comfortable entry to the circular path. Moreover, a safe space buffer equals to two cells has been given to each turning vehicle.

4.2 Forward movement trajectory

Referring back again to Fig. 1 and following the sequence of movements within the intersection area as described in the proposed protocol, the following can be noticed: left-turning vehicles start from the north and south (i.e. vehicles 2 and 6) need 6 out of 8 steps to cross the turning trajectory before the other opposite turning vehicles (8 and 4) start crossing from the east and west. This gives north and south forward moving vehicles (1 and 6) less than 6 steps to cross and clear the intersection area to avoid collisions.

This means that, the duration of each step in the protocol is equal to $t_2/6$. Moreover, the following vehicle or platoon, in the same lane and direction, must arrive the intersection terminal after 8 ($t_2/6$) seconds (i.e. a complete 8-steps protocol cycle). Therefore, for safety considerations, a forward moving vehicle must pass the intersection by less than or equal to 4 steps $\left(\text{must, } t_1 \leq 4\left(\frac{t_2}{6}\right)\right)$, as follows:

$$t_1 \leq \frac{2}{3} t_2 \quad (5)$$

Where, t_1, t_2: time in seconds to traverse the straight and left turn trajectory within the intersection area, respectively.

Substituting the equation of motion ($t_2 = d_2/u_2$) for the left-turn movement and Eq. (1), into Eq. (5) and rewriting the equation will give the acceptable range of speed for the forward movement.

$$u_1 \geq \frac{3}{\pi R} u_2 d_1 \quad (6)$$

Where:

- u_1, u_2 (km/h) = forward movement and left-turn speed (km/h), respectively.
- d_1 (m) = length of the forward trajectory.
- R (m) = Radius of the left-turn trajectory.

Eq. (6) proves that the forward movement speed is directly related to the characteristics of the left-turn path. Moreover, the equation does not allow the speed (u_1) to decrease below a certain value, to avoid the conflict of vehicle movements. On the other hand, increasing the speed over the accepted value will not affect the protocol or any safety controls, on the contrary this will increase the traffic flow at the intersection. In other words, high speed road segments can still pass the intersection forward at the same high speed.

4.3 Flow volume at the intersection

According to the proposed protocol of movements; only one unit of vehicles (or platoon) will traverse the intersection from each lane at every completed 8 steps' cycle ($8 \times t_2/6$, seconds). In other words, traffic flow at any lane will represent the number of repeated cycles per hour, and will increase with lower cycle length. Then, the traffic flow (F) per hour from each lane can be calculated as follows:

$$F(vehicle / hour) = 3600 / (4t_2 / 3) \quad (7)$$

Or (by substituting Eq. (4)),

$$F\left(vehicle/hour\right) = 6750\sqrt{\frac{f_s}{d_2}} \quad (8)$$

In some cases, the left-turn movement could be too slow, due to the small turning radius or low friction coefficient. This will increase the cycle length (i.e. reduce the traffic flow) but allow more time gap for vehicles moving forward at a higher speed.

To take advantage of this long gap and increase the traffic flow, a fleet of forward-moving vehicles (i.e. a platoon) may be allowed per course instead of a single vehicle. Therefore, the traffic volume for straight movements is multiplied by factor n.

$$F\left(vehicle/hour\right) = 6750\sqrt{\frac{f_s}{d_2}} \times n \quad (9)$$

The number of vehicles per a single platoon is represented by factor n (Eq. (10)). The process of finding this factor should be based on:

A minimum safe time headway between the following vehicles within the same platoon. A one second gap was taken.

The platoon must pass the intersection completely within a pre-defined period in Eq. (5).

$$n \leq \frac{2}{3}t_2 - t_1 + 1 \quad (10)$$

In Eq. (10), as the number of fleet increases by 1 vehicle, the available time gap (t_2) should have additional 1 second to satisfy Eq. (5). Moreover, n may increase if t_1 value decreases. In other words, more vehicles may join the platoon if the speed of the forward moving vehicles increases. For instance,

If $n = 1$, must $t_1 \leq \frac{2}{3}\ t_2$ (same as Eq. (5))

If $n = 2$, must $t_1 \leq \frac{2}{3}\ t_2 - 1$

If $n = 3$, must $t_1 \leq \frac{2}{3}\ t_2 - 2$, and so on.

Generally, left turn movements for autonomous vehicles at the intersection highly affects the traffic flow for the whole intersection.

5 Results

The main objective of the results is to test the applicability and performance of the proposed protocol. Table 1 presents the variation in traffic flow for different friction coefficients (first 3 rows) and different turning radii (last 3 rows).

Usually, the friction coefficient (f_s) for the turning movements has values between 0.1–0.3, and accordingly the variable values were selected in Table 1. In turn, different turning radii (R) were selected for different intersection areas according to different number of lanes; 2, 3, 4 lanes, per one direction.

It can be noted from Table 1 that the higher the value of f_s, the greater the traffic flow in the left-turn and forward directions (F_{LT} and F_{FM}, respectively), while the greater the intersection area, the lower the flow. This relationship is closely related to the turning speed (u_2) and traversing time (t_2). When the value of the friction increases, the turning speed increases and hence the traffic flow. Fixing the friction value, but increasing R will increase the time to pass the intersection and hence the traffic flow, despite the slightly raise in speed. However, the turning speed (u_2) resulted by Table 1, according to the established standards (Wendell, 2015), is considered safe and comfortable for drivers.

On the other hand, the volume of traffic heading forward (F_{FM}) is also affected by the turning characteristics, as well as, the selected speed (u_1) and the platoon size (n). The higher the value of f_s (i.e. the higher the value of u_2), the smaller the time gap that allows more vehicles to join the forward moving platoon (n) (as previously explained). Moreover, in Table 1 it was assumed that the forward movement speed is 90 km/h which is greater than the minimum allowable u_1. Hence, the forward movement speed satisfies the rule of Eq. (6). In other words, any safe speed can be selected for u_1 provided that it exceeds the computed u_2 for left-turn movements. In general, increasing a u_1 allows adding more vehicles in the platoon (n) and thus increasing the traffic flow in this direction.

The correlation between the characteristics of the turning lane and its effect on the forward-moving traffic can be observed graphically in Fig. 3.

According to Fig. 3(a), increasing f_s allows a faster speed for u_1 and consequently increase in the minimum value of u_2. Likewise, wider intersection areas required higher u_1 and u_2 to cope with the increased travel time and maintain a constant flow, as in Fig. 3(b).

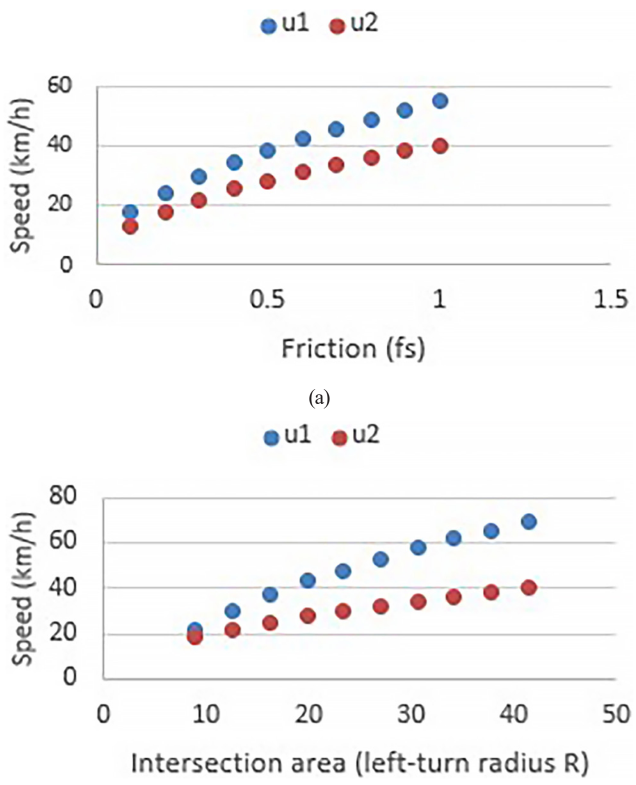
However, Table 1 and Fig. 3 show different ranges of the predicted traffic flow values for left and forward directional movements between 480–831, and 1219–2035 vehicle/hour/lane, respectively. These values are suitable for intersections with medium to high traffic volumes which makes the importance of this approach.

Table 1 the variation in traffic flow for different friction coefficients and different turning radii

f_s	Number of lanes	R	t_2	u_2	F_{LT}	Cycle length (Sec.)	Minimum u_1	Selected u_1	n Platoon	F_{FM}
0.1	2	12.6	5.6	12.7	480	7.5	17.2	90	4	1919
0.2	2	12.6	4	17.9	679	5.3	24.4	90	3	2035
0.3	2	12.6	3.2	21.93	831	4.3	29.9	90	2	1662
0.3	3	16.2	3.7	24.9	733	4.9	36.9	90	2	1465
0.3	4	19.8	4.1	27.5	663	5.4	43	90	2	1325
0.3	5	23.4	4.4	29.9	610	5.9	48.3	90	2	1219

6 Discussion

The previously presented results evaluate the performance of the proposed protocol for managing and controlling the efficiency of autonomous vehicles at a four-leg orthogonal intersection. The protocol applied a DOG concept that divides the intersection into grids. The grids are in a continuous virtual movement from different directions without conflict, like a gear machine, carrying vehicles across the intersection safely at predetermined time and speed. The movement mechanism is calculated with the assistance of equation of motions. Based on the prepared analysis and results, the following conclusions can be drawn:



(a)

(b)

Fig. 3 The relationship between the traversing speed with the (a) friction coefficient, and (b) area of the intersection

- The capacity of the intersection is significantly improved, depending on mainly the surface friction and the predetermined speed. Forward moving vehicles maintain their speed, no matter how fast they are, but the speed of turning vehicles must adhere to geometric and surface characteristics to avoid skidding and run-off-way. The precision required in the AV movement has also been assumed in most of the references (Ham et al., 2019; Yuan et al., 2017). In contrast, previous literature were only trying to develop theories and rules for AVs movement at intersections without any improvement or consideration of the intersection capacity (Dresner and Stone, 2004; Milanés et al., 2010). In fact Levin et al. (2016) found several instances for which FCFS had higher delay than traffic signals.
- The simplicity of the applied telematic system. The DOG is assumed in continuous motion, therefore no complex analysis or wide-range of communication is required. It is only required to place each coming vehicle on the appropriate moving grids. On the other hand, sometimes it is difficult to understand the developed systems and algorithms developed by some scholars that are even dedicated to certain traffic conditions (Carlino et al., 2013; Godoy et al., 2021).
- The applicability of the proposed protocol with medium and high traffic volume intersections. This is due to the ability to handle higher traffic speeds and hence larger traffic volumes, as explained in the results section. In contrast, traffic volumes did not improve similarly in many researches. (Lin et al., 2017) claimed that their proposed buffer-assignment based coordinated control method, can significantly reduce travel delays by 24.2%–77.1%. However, his method is limited to low AV penetration in a mixed traffic.
- The continuous movement of vehicles at the intersection can contribute much to the sustainability. This allows higher flow rate but lower environmental impacts (i.e. fuel consumption and pollution) that may occur

by the slowing down or stopping and waiting in long queues (Coelho et al., 2005). However, the concept of sustainability has not usually been the focus of interest for many researchers or was limited (Lin et al., 2017).

- The flexibility of the proposed protocol with different weather conditions (i.e. surface friction) and geometric features (i.e. number of lanes). This has been proved with the changed value of friction and number of lanes in the result section.
- Moreover, most of the current research didn't consider the situation of any system failure which could be catastrophic sometimes. On the other hand, the advantage of this method is that it does not depend on a centralized controlling system (i.e. IM). In case of any breakdown or accident, the other vehicles automatically act according to their own laws, as an agent-based entity. In the worst situation, only the defected lane is temporarily cancelled without significantly affecting traffic on the rest of the roadway (John et al., 2003)
- Considering the social justice perspective, this approach is based on the principle of equality in which the priority is based on the concept of first come first serve. However, the intersection shows very low delay with high speed, therefore the priority is not of much concern even in case of emergency and police vehicles.

7 Conclusion

The main purpose of this paper is to develop a new framework for managing autonomous vehicles' movement at intersections. The article assumes a 4-leg intersection with a full automation environment.

In the methodology, a dynamic occupancy grid (DOG) mechanism is applied. The intersection area is divided into virtual dynamic grids in constant motion, just like a gear machine. Every vehicle has to set, virtually, on suitable moving grids that will carry it safely through the intersection. In other words, vehicles from every lane group has to adhere to a predetermined speed and time to traverse the intersection sequentially according to a certain DOG protocol.

The main contribution of this paper is the developed protocol that governs the sequential movement of vehicles at the intersection from each lane group (refer to Fig. 1). Vehicles approaching an intersection must register their speed and position by certain sensors, and in return receive the appropriate acceleration and speed to finally be allocated to the suitable moving grids. Then, the right-of-way is assigned to each lane group sequentially (i.e. certain moving grids) allowing one vehicle or platoon to traverse the intersection per one cycle.

The mechanism of motion was developed mathematically to finally calculate the intersection capacity. Surface friction, number of lanes and speed limit were the main input variables. This allows more flexibility in applying the protocol for different weather, geometric and traffic conditions. Testing different input values shows different ranges in expected traffic flows for left-turning and forward movements (480–831, and 1,219–2,035 vehicles/hour/lane, respectively). These values show that the capacity may sometimes exceed the ideal saturation flow rate (i.e. 1,900 vehicles/hour/lane) at high speeds. This reflects the efficiency of the implemented protocol and its applicability to different low to high traffic flows.

Moreover, vehicles are not required to decide on priority, only to abide the prescribed speed and the sequential role of movement described by the proposed protocol. Hence, there is no need to set up expensive and complex management centers or inter-vehicle communication that may susceptible for failure or any malicious hacking.

However, the proposed framework is applied for 4-leg orthogonal intersections. Future work may consider the change in some geometric features of the intersection, such as, number of legs and grades. Moreover, scenarios of car-crash or any failure in the system should be explored in future studies. Finally, a simulation test of the proposed protocol can clearly demonstrate its effectiveness.

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