

REVIEW

Proposal of an integrated platoon-based Round-Robin algorithm with priorities for intersections with mixed traffic flows

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Abstract

The growth of vehicle ownership has necessitated the adoption of new approaches to cope with the arising problems. In this regard, while technological advancement in connected and automated vehicles (CAVs) leads to a new source of information upon which effective intersection control mechanisms can be built, it also necessitates considering the issue of mixed traffic, on the one hand, and enhancing current infrastructures, on the other. This paper first proposes a framework, which enhances pre-timed signals to incorporate CAVs and wireless communications. In this framework, Round-Robin has been selected as the main algorithm treating vehicles' platoons as the units. Dealing with mixed traffic conditions and embedding an algorithm for prioritization of special vehicles are also discussed in the context of this framework. The result is a proposal of the Platoon-based Round-Robin algorithm with Priorities (the *PRRP-framework*). This framework is further integrated into a speed advisory system to mutually augment each other's functions to provide for as much continuous movement of mixed traffic as possible. Performance indices obtained from the corresponding simulations show that while the *PRRP-framework* is promising even with a low proportion of the CAVs, it is possible to get out considerably more benefits in the case of the proposed integration.

1 | INTRODUCTION

The increasing number of vehicles in cities makes the mechanism of intersection control subject to different complexities, in many cases resulting in excessive queues, and consequently, economic, social, and environmental problems. The widespread occurrence of such consequences has led to a plethora of research studies on possible methods to attain better intersections' performance. Whereas the improvement of conventional intersection control methods is still being discussed among scholars, progress in wireless communications together with the presence of sensing technologies, and the advent of connected and automated vehicles (CAVs) have envisioned new opportunities for the effective control of intersections.

Opportunities resulting from the capability of the CAVs in sending and receiving information have led to the development of innovative intersection control mechanisms (see [1, 2]). As an example, in [3], the authors have used a reservation-based

strategy to describe a new mechanism for managing intersections. In this mechanism, an intersection is divided into a grid of tiles, which are supposed to be reserved by vehicles ahead of the intersection. However, according to the experimental results, this approach cannot make any tangible improvement to that of traditional traffic lights when a proportion of vehicles is still human-driven (even if that proportion is low). Considering this point, some frameworks have been proposed to address the challenge of managing mixed traffic¹ by using traffic sensors [4]. However, deploying traffic sensors (e.g. detectors) everywhere is practically neither cheap nor easy [5]. At the same time, given the general characteristics of technology diffusion [6], it is particularly not a promising approach (at least in the near future) to look at the issue of managing intersections from a fully connected environment standpoint. Accordingly, it is essential to look for an admissible way to use the information of CAVs for effectively managing intersections without resorting to the assumption of a fully connected environment.

¹ It is noteworthy to mention here that we assume, throughout the paper, CAVs communicate with the intersection controller while human-driven vehicles cannot.

To effectively manage intersections, we should address the issue of demand fluctuations. It is unrealistic to assume that traffic demand remains equal during any period [7]. Moreover, traffic demands in the approaching links of an intersection might be different. Therefore, an appropriate strategy should be adopted to (1) consider the congestion state of each approaching link and (2) determine the amount of service each link receives under its congestion state in order to prevent excessive congestion and backward propagation of traffic.

Furthermore, it would also be interesting to implement a priority scheme for emergency vehicles, on the one hand, and to reduce stop-and-go events of heavy vehicles (buses, trucks etc.) [8], on the other. In this regard, some studies have focused on emergency vehicle pre-emption [9], transit signal priority [10], or considering different priority treatments for different classes of vehicles [11]. It is important to note, however, the more comprehensive the priority algorithm, the more complex the intersection control mechanism becomes. Therefore, there should be a trade-off between comprehensiveness and complexity to reach a practical solution suitable for real-world applications.

Concerning the issue of complexity, caution should be taken to deal with the challenges resulting from the analysis of a high volume of data. As a case in point, in [12], a modified solution-tree-generation algorithm based on a permutation order has been applied to obviate the invalid orders of driving and eliminate the unsafe patterns of sequencing. Subsequently, the virtual vehicle mapping technique has also been used to guarantee safety in the merging lanes. In another case, in [13], the authors have looked into the issue of managing intersections from the machine scheduling perspective and present an objective function to minimize the total delay at an intersection by considering mixed traffic. In this regard, a new phase-time-traffic hyper network model has been developed to incorporate the interaction between the operation of traffic signals and heterogeneous traffic streams. While using such an optimization-based approach has led to remarkable results in terms of different measures of efficiency, the obtained models cannot usually be used for real-time intersection management due to the computation intensity.

Given the above explanations, while the problem of intersections' control with considering complexities including the issues of mixed traffic fleets, demand fluctuations, priorities, and computational complexity seems to be a promising research topic (due to the current traffic condition and also the future perspective), to the best of the authors' knowledge, there is a lack of studies looking at the full picture. Accordingly, the first contribution of this paper is to develop a framework that results from enhancing the current infrastructures (pre-timed signals, in particular, due to their extent in worldwide traffic networks) to efficiently manage mixed traffic at intersections while also considering the other mentioned complexities.

To this end, this study employs the *Round-Robin* algorithm (*RR*) as the main algorithm. This decision has been made by reviewing the properties of *Fair Queueing Schedulers* previously used in telecommunication networks (for detailed information, see [14, 15] and the corresponding references) and is driven by the comparative advantages of the *RR* algorithm over others in simplicity and alignment with the operation of current

signals. These key attributes make this algorithm suitable for managing mixed traffic. Within this algorithm, we also discuss how best to deal with the issue of demand fluctuations, on the one hand, and embed an algorithm for prioritization of special vehicles, on the other. This altogether results in the proposal of the *Platoon-based Round-Robin* algorithm with *Priorities* (the *PRRP-framework*). We evaluate the efficiency of the *PRRP-framework* (in terms of the average delay) by comparing it to that of a pre-timed signal setting and an actuated mechanism by means of simulations in VISSIM.

The second contribution of this study is to further integrate the proposed *PRRP-framework* into a speed advisory system to reach an *integrated framework* (by assuming bi-directional communication between the intersection controller and CAVs). Previous studies highlighted that improving any urban system entails strong integration among its elements [16]. An urban road network is no exception and, therefore, we have proposed a framework consisting of the *PRRP-framework* and a speed advisory system to (respectively) use the information of CAVs and the information of the intersection controller to (mutually) augment each other's function, resulting in continuous vehicular traffic movement. Finding an agreeable solution for these measures based on the emergent opportunities associated with wireless communication initiatives has remained an open topic for research projects [8], which is aimed at by this research.

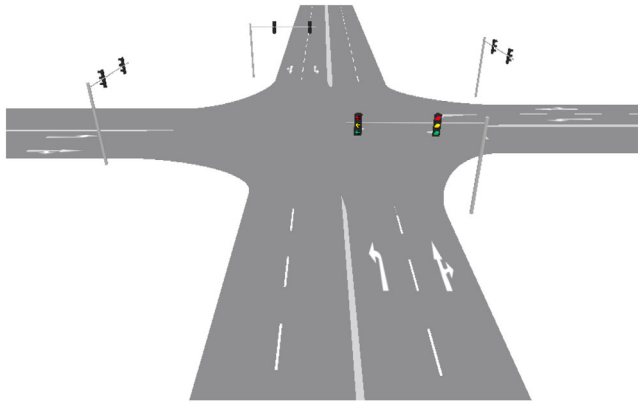
The efficiency of the integrated framework is also evaluated by using VISSIM as the simulation tool. While alternative simulation tools like SUMO [17] are also available, VISSIM has been selected here due to its comparative advantages in modelling multiple types of vehicles in different road network configurations managed by different methods [18].

The organization of the remainder of this paper is as follows. Section 2 develops the *PRRP-framework*. Section 3 provides the simulation results to show the operation and evaluate the efficiency of the *PRRP-framework*. Section 4 explains how the integration of the *PRRP-framework* with a speed advisory system can be undertaken to address the issues of average delay and emissions. Finally, Section 5 provides some conclusions and future research directions.

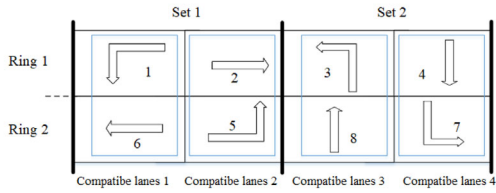
2 | THE PRRP-FRAMEWORK

This study considers a general type of intersection shown in Figure 1(a) that often appears in traffic networks. This intersection consists of four links, each of which has two approaching lanes whose trajectories are specified. In each lane, there can be different types of vehicles including CAVs and conventional vehicles, and different classes of vehicles including special vehicles (emergency and heavy vehicles) and ordinary vehicles.

In this intersection, we classify compatible lanes (whose signals can be simultaneously green) consistent with the standard NEMA (National Electrical Manufacturers Association) structure shown in Figure 1(b) [7]. Based on this structure, straight and left-turning lanes (which are labelled by even and odd numbers, respectively) form two sets, each of which consists of two rings. Using these sets and rings, groups of compatible lanes



(a) A general intersection layout



(b) Determination of the compatible lanes Based on the standard NEMA structure

FIGURE 1 An illustration of the studied intersection

could be identified (e.g. lanes 1 and 6). We have defined groups of compatible lanes as is marked in Figure 1(b).

Finally, as mentioned in Section 1, we apply RR to distribute the right-of-way among identified groups of compatible lanes. In a telecommunication context, this algorithm gives permission to the respective servers to transmit their corresponding *data packet* (if any). The next data packet of each server is transmitted in the next round. In the context of intersection control, by considering the defined groups of compatible lanes as the servers of RR, the operation of this algorithm translates into the determination of green times for respective groups of compatible lanes to serve their corresponding vehicles. The question then remains what corresponds with *one packet* mentioned in the telecommunication context, but we come back to this later. Note that RR (or its variants) has been previously applied in this domain [19, 20], owing to the following qualities:

- This scheduling algorithm follows the sequencing pattern similar to the current operation of signals. This analogy makes this algorithm (1) easy to comply with by human drivers in the case of mixed traffic and (2) executable by current infrastructures.
- The implementation of this framework at an individual intersection is computationally undemanding. Note that due to the need for analysing a high volume of data in the context of transportation, algorithms with heavy computation require high technological capacity that is lacking in many cases.
- While RR is in general handling all processes without priority, this algorithm can be easily modified to result in different treatments for different conditions.

Despite the above-mentioned properties of the RR algorithm, the literature reports only a few proposals of RR in the transportation domain, meaning that the benefit of this algorithm is not fully investigated in this sector. To narrow this gap, we first outline the *PRRP-framework* in Section 2.1, given RR as the scheduling algorithm. Then, we employ the potential of probability theory to derive the constitutive equations to implement an example of the *PRRP-framework* in Section 2.2.

2.1 | The outline of the PRRP-framework

As it is mentioned, RR distributes the right-of-way among groups of compatible lanes to admit their corresponding vehicles. In this regard, admitting vehicles individually is (1) not optimal in terms of effectiveness even if safety margins are small, (2) not easy for human drivers to comply with, especially when compatible lanes are served in parallel, and (3) not advantageous in required computations. Therefore, it is logical to choose a *platoon of vehicles* as the unit of RR.

A platoon is generally defined as a group of vehicles that move together with relatively short headways due to the presence of moving bottlenecks. The *PRRP-framework* treats platoons of vehicles as the units with the following objectives:

1. Managing varying demands: the number of vehicles in each platoon correlates with the traffic condition (there are more vehicles in a platoon at busy times or in busy lanes).
2. Reducing the number of stop-and-go events: serving platoons instead of individual vehicles results in the extension of green time until there is a big enough gap in a fleet.

It has been proved that with platooning there will also be potential for enhancing the overall throughput at intersections [21], reducing vehicle emissions [22], and improving computational efficiency [23]. Furthermore, treating platoons in the RR algorithm circumvents the limitations of the green extension, cycle extension, and early green strategies (see [24]) in terms of constant extension intervals by offering flexibility in both green time and cycle durations. However, before getting treatment, platoons should be identified while the intersection controller neither controls nor knows the complete traffic condition at the intersection nor the approaching platoons to the intersection. Accordingly, we use the information of CAVs to obtain an estimate of the platoon length PL_i in group i of compatible lanes. Note that the estimate PL_i will eventually allow us to determine the required green time G_i for group i under the *PRRP-framework* by

$$G_i = PL_i / S_i, \quad (1)$$

where S_i is the service rate that can be defined based on the geometric condition of the intended intersection. Now, to approximate PL_i , we more specifically propose to use

$$PL_i \approx E[N_i | I_i] + E[J(V_i, Z_i)]. \quad (2)$$

In Equation (2), the term $E[N_i|I_c]$ is the expected number of queued-up vehicles (in group i of compatible lanes) at the end of the associated red time given the information I_c of CAVs at that moment. The second term $E[J(V_i, Z_i)]$ in Equation (2) is the estimated number of vehicles that join the queued-up vehicles to cross the intersection within the same platoon. We have concentrated on these two terms, and we do so for the following reasons:

1. Queued-up vehicles (approximated by $E[N_i|I_c]$ in Equation 2) maintain short headways and, therefore, we have to incorporate them in the same platoon. It is important to take this issue into account, since overflow queues (i.e. vehicles that cannot cross the intersection in the same cycle in which they arrive) highly influence the issues of average delay and emissions.
2. Newly arriving vehicles (with relatively large headways) can still join the queued-up vehicles into one platoon due to the plausible difference between the speed of queue dissipation and newly arriving vehicles. Considering this issue plays an important role in reducing the number of stop-and-go events. Accordingly, given T_t^2 s as the maximum headway in a platoon, if we define V_i as the total number of arrivals in group i during the time g_i that is needed for the crossing of the queued-up vehicles ($E[N_i|I_c]$), we also need to take Z_i into account which is the number of vehicles (from V_i) that move with headways shorter than T_t and join the queued-up vehicles until a headway exceeds T_t for the first time. We have shown the expected number of vehicles that results from this interaction by $E[J(V_i, Z_i)]$ in Equation (2).

It should be noted here that in case of heavy traffic in a group of compatible lanes, the associated platoon length (PL_i) will become very large and, therefore, other groups cannot get enough services. For this reason, we assume a limitation of X_i^3 vehicles on the maximum platoon size to address fairness.

We shall further prepare the intersection controller for different treatments needed for effectively managing different types and classes of vehicles in each link by adding priorities for special vehicles to the picture. We can do this by switching to green time for a group of compatible lanes when such a vehicle approaches until it crosses the intersection or by extending green time for such a group of compatible lanes.

2.2 | An example implementation of the PRRP-framework

First note that for notational convenience, we eliminate the index i to refer to group i of compatible lanes. Also remark that throughout this example, the *Negative Exponential* distribution is adopted as the distribution of headways. We start with the

first term of Equation (2). We use the location L_p of the last CAV in the queues⁴ of compatible lanes, as the information of CAVs (i.e. I_c) received by the intersection controller. Now, to estimate $E[N|L_p = l_p]$, we have applied the model provided in [25], which estimates the number of queued-up vehicles in each lane at the end of the associated red time given the location of the last CAV in the queue. In this regard, by defining p as the (known) proportion of CAVs, the mentioned model results in the following expected value of the queue length:

$$E[N|L_p = l_p] = \sum_{n=l_p}^{\infty} n \cdot \frac{(1-p)^n P(N=n)}{\sum_{k=l_p}^{\infty} (1-p)^k P(N=k)}. \quad (3)$$

In Equation (3), $P(N=n)$ refers to the probability that the number of vehicles that have arrived during the corresponding red time equals n , without considering any information on the location of CAVs.⁵ Under the assumption of a *Negative Exponential* distribution for the distribution of headways, $P(N=n)$ is *Poisson* distributed⁶ and equal to

$$P(N=n) = \frac{e^{-(\lambda \cdot r)} (\lambda \cdot r)^n}{n!}. \quad (4)$$

In Equation (4), r is the red time and λ is the total arrival rate of vehicles (based on the arrival rate of CAVs and their proportion, data of neighbouring intersections, or recent history). We use a Kalman filter algorithm [26] to update the estimation of λ based on the information of CAVs at pre-defined time-steps. The authors of [27] have previously shown that such an algorithm can effectively capture the dynamic variations of arrival rates. Accordingly, we use

$$\lambda = \hat{\lambda} + \mathcal{K} \cdot \left(\frac{P}{p \cdot \tau} - \hat{\lambda} \right), \quad (5)$$

which is a simple form of the Kalman Filter algorithm. This equation updates the arrival rate at arbitrary time-steps by considering (1) the arrival rate at the previous time-step $\hat{\lambda}$, (2) the time interval between subsequent time-steps τ , (3) the total number of CAVs P that arrived at a group of compatible lanes during τ , and (4) a Kalman Filter gain $\mathcal{K}$ (which is a value between 0 and 1). Note here that as $\mathcal{K}$ gets values closer to 1(0), the result of the Kalman filter algorithm becomes more sensitive to the real-time observations of CAVs (more robust with respect to the low penetration rate of CAVs).

Regarding the second term in Equation (2), first, we formulate the probability that the number of vehicles that move with headways shorter than T_t joining the queued-up vehicles equals z (in other words, the probability that a headway exceeds T_t

² Here, we define T_t as a constant threshold to separate platoons. However, it is clear that in different traffic instances, the optimal value of T_t is different.

³ Similar to T_t , X_i can also be optimized in different traffic conditions. However, here we introduced this threshold to highlight the issue of fairness.

⁴ L_p is counted as the number of vehicles from the stop line by dividing the location of the last CAV by the average length of vehicles.

⁵ Notice that the case $l_p = 0$ (no CAV) is included in Equation (3).

⁶ In practice, other distributions could be used as well (for instance based on existing data).

between vehicle number z and $z + 1$ for the first time) by

$$P(Z = z) = P(T_{b_1} \leq T_t, T_{b_{1,2}} \leq T_t, \dots, T_{b_{z-1,z}} \leq T_t, T_{b_{z,z+1}} > T_t), \quad (6)$$

where T_{b_1} denotes the headway between the first newly arriving vehicle and the queued vehicles and $T_{b_{i,j}}$ is the headway between vehicles i and j . Based on a *Negative Exponential* distribution, the probability that a headway $T_{b_{i,j}}$ exceeds a defined threshold (T_t) is

$$P(T_{b_{i,j}} > T_t) = e^{-T_t \lambda}. \quad (7)$$

Accordingly, by using a *Geometric* distribution, the formulation presented in Equation (6) can be calculated by

$$P(Z = z) = e^{-T_t \lambda} \cdot (1 - e^{-T_t \lambda})^z. \quad (8)$$

Second, we use again a *Poisson* distribution as the probability distribution of the total number of vehicle arrivals during the crossing of the queued-up vehicles, as shown in Equation (9):

$$P(V = v) = \frac{e^{-(\lambda \cdot g)} (\lambda \cdot g)^v}{v!} \quad (9)$$

with $g = E[N|L_p = l_p]/S$. Taking Equations (8) and (9) into account, we can use

$$E[V(Z)] = \sum_{z=0}^{\infty} z \cdot [P(Z = z) \cdot \sum_{v=z}^{\infty} P(V = v|Z = z)] \quad (10)$$

to calculate the second term in Equation (2). Equation (10) represents the expected value of the number of vehicles joining the queued-up vehicles by considering the probability of two events: (1) the probability that a headway exceeds T_t after vehicle number z and (2) the probability that total $v (\geq z)$ vehicles arrive at the intersection during the crossing of the queued-up vehicles given that z vehicles are there with short headways.

According to Equations (8) and (9), Z and V are dependent. However, we use

$$P(V = v|Z = z) \approx P(V = v) \quad (11)$$

as the approximation in this example for simplicity.

Now, by defining X_t , it becomes possible to estimate the number of vehicles in the platoon (Equation 2) and, consequently, determine the required green time by Equation (1).

Next, we have implemented the strategy illustrated in Figure 2 to deal with the prioritization of special vehicles in this example. We assume here that all special vehicles have wireless communication on-board. In this apparatus, since the arrival rate of emergency vehicles is usually low (or even negligible) compared to the total arrival rate of vehicles and, more importantly, due to the nature of this class of vehicles, we give absolute priority to the group of compatible lanes that has an emergency vehicle.

Contrary to emergency vehicles, the arrival rate of heavy vehicles is usually considerably larger. Therefore, to decide whether or not to give priority to these vehicles, we consider the following possible scenarios:

1. Some heavy vehicles arrive at the intersection in conflicting groups of compatible lanes at the time that green time is extended for the crossing of a previously detected heavy vehicle.
2. The overall congestion at the intersection is that high that the adverse effect of queued-up vehicles is much more severe than that of the stop-and-go events of the detected heavy vehicle.

If either of these scenarios happens, the underlying reasons (in terms of sustainability and economic considerations) for giving priority to a heavy vehicle will be violated. Therefore, by considering the total arrival rate and also the arrival rate of heavy vehicles, we decide on whether to give priority to heavy vehicles or not (Function 4 in Figure 2).

3 | OPERATION REPRESENTATION AND EFFICIENCY EVALUATION OF THE PRRP-FRAMEWORK

To represent the operation of the *PRRP-framework*, first, we develop Python code⁷ to show the (effective) green time inferences of this framework for a group of compatible lanes in different conditions using our showcase equations. To do this, threshold T_t and threshold X_t are assumed 4 s and 20 vehicles, respectively. Moreover, we assume that the intersection controller gives priority to heavy vehicles. Furthermore, the average service rate of vehicles and the total arrival rate of CAVs are considered to be 2700 and 2400 (distributed evenly among all lanes) both in terms of vehs/h. Finally, we consider 25%, 1%, and 4%, as the proportion of CAVs, emergency vehicles, and heavy vehicles (respectively, without considering the overlaps) in the traffic composition.

Figure 3 presents the variations of the green time of a tagged group of compatible lanes in a 1-h simulation run. In this figure, the full green line represents the green time inferences resulting from Equation (1), relating green time duration with the current traffic condition. On the other hand, due to the presence of special vehicles in this group (other groups of compatible lanes), the *PRRP-framework* could increase (decrease) green time durations, as shown by the dotted red line in Figure 3, based on the apparatus presented in Figure 2.

To evaluate the effect of such green time inferences on the performance indices of an intersection, we have further simulated a general intersection (whose layout is shown in Figure 1a) in VISSIM. To this end, the following steps have been undertaken:

⁷ <https://github.com/HosseinMoradi/Project1>

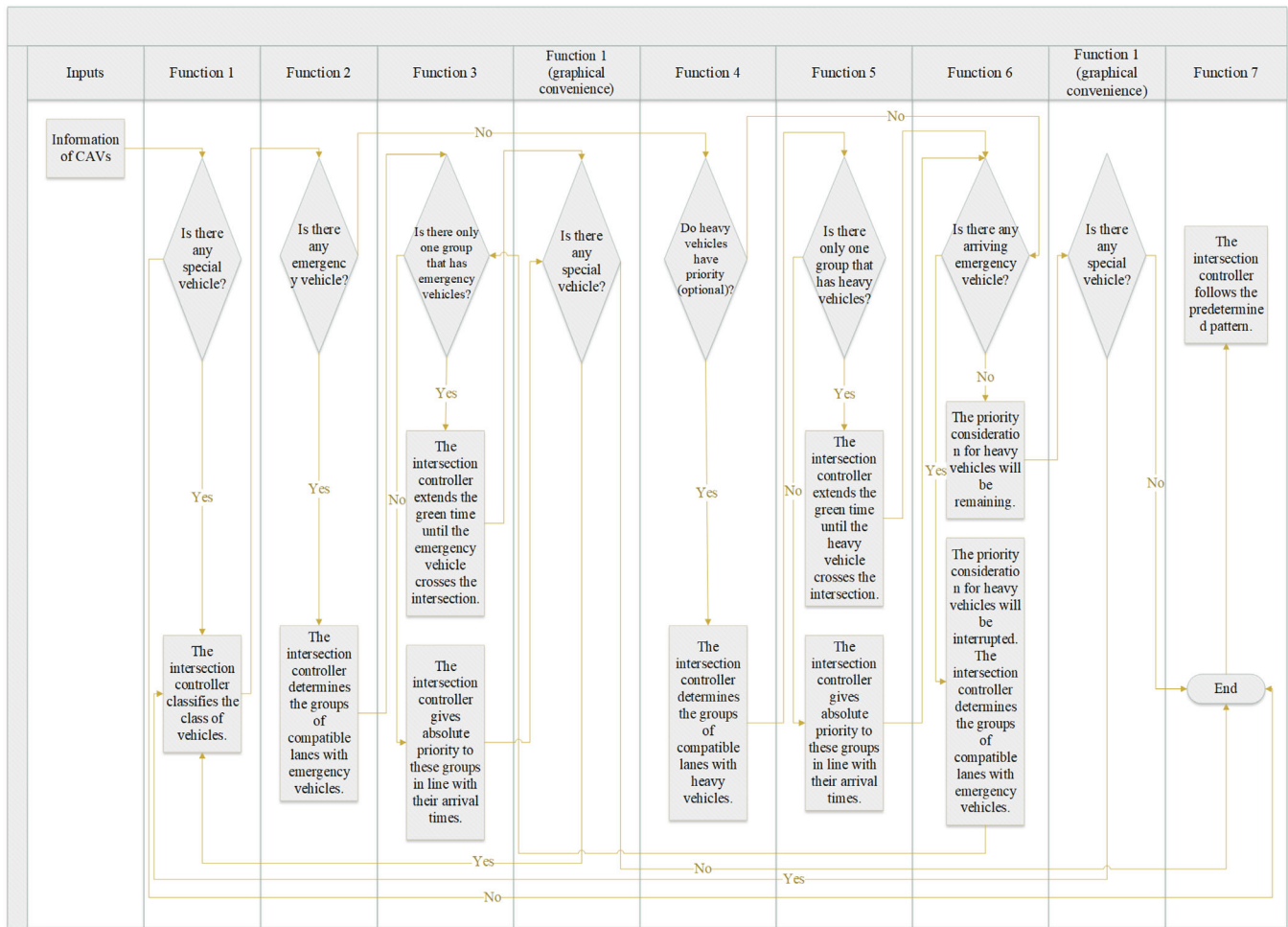


FIGURE 2 The algorithm for considering different priority treatments for different classes of vehicles

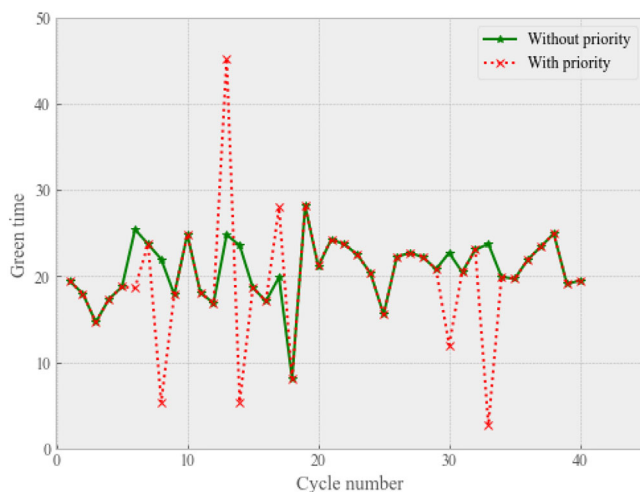


FIGURE 3 Green time inferences of the *PRRP-framework* for a tagged group of compatible lanes

1. Simulation of CAVs: It should be stated here that, compared to conventional vehicles, we suppose (1) CAVs' driving pattern is free of stochasticity, (2) they are attributed with differ-

ent (improved) parameters of car-following behaviour, and (3) they are featured with communication capability. Therefore,

- The issue of stochasticity in the driving pattern has been accounted for by calibrating the spread of speed and acceleration distributions, as is suggested by the literature [28];
 - The adaptation of CAVs into traffic fleets has been further carried out by changing the parameters of *Wiedemann 74 car-following model* that is available in VISSIM [29];
 - To deal with the communication capability of CAVs, we define and enable a Boolean attribute to discriminate between CAVs and conventional vehicles in terms of the ability to send and receive information.
2. Simulation of the *PRRP-framework*: We employ a signal control operating upon an internal script⁸ developed based on the *PRRP-framework*.

Using defined CAVs together with conventional vehicles already available in VISSIM, we apply the same traffic

⁸ <https://github.com/HosseinMoradi/Project2>

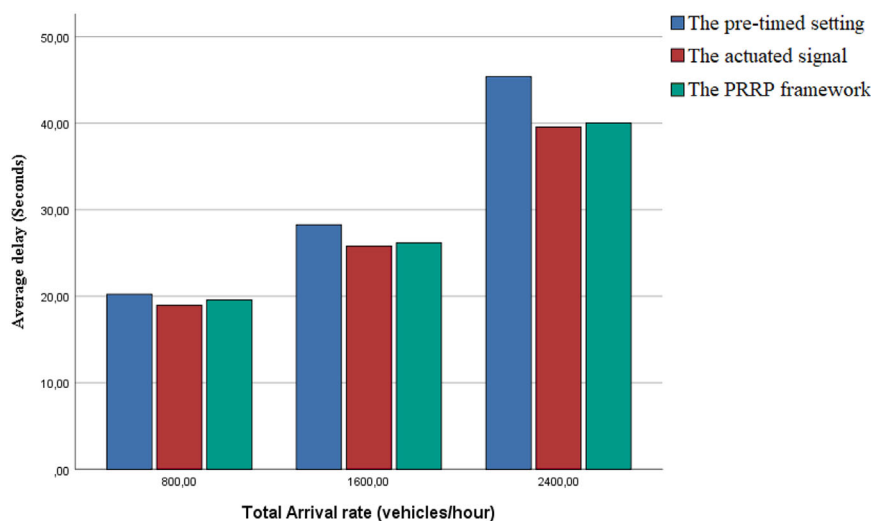


FIGURE 4 Comparing the average delay of the pre-timed setting, the actuated mechanism, and the *PRRP-framework* in different arrival rates

composition and consider similar parameters (e.g. the thresholds of the *PRRP-framework* and the average service rate) introduced earlier to compare the efficiency of the *PRRP-framework* and traditional approaches of managing intersections, namely, pre-timed and actuated signals, in terms of *average delay*. To carry out this comparison:

1. We define an actuated controller by considering 20-m extension loop detectors (to detect if there is a need for green time extensions) located at a few meters from the signal head in each individual lane of the intersection (Figure 1a).⁹ Accordingly, we first assign the minimum guaranteed green time (that is assumed 7 s in this mechanism) to a group of compatible lanes. During this minimum green time, if no vehicle occupies this detector, the associated signal switches to red. On the other hand, if a vehicle goes on this detector, an extension unit (assumed 2 s) is added to the minimum guaranteed green time, so that the vehicle can cross the intersection without stopping. This continues until a maximum of 25 s green time duration is reached.
2. we use the Webster method (see [30]) to determine the optimal cycle time for pre-timed signals. Note that we also distribute arrivals equally among approaching links, to help pre-timed signals to have their best performance.

We use different arrival rates to compare the above-mentioned mechanisms in different saturation degrees. In this regard, 10 series of (1 h) simulations have been carried out for each specific mechanism by considering total arrival rates, respectively, equal to 800, 1600, and 2400 (vehs/h) to represent under-saturated, moderate-saturated, and near-saturated conditions. The average results of simulation tests are shown in Figure 4.

As Figure 4 demonstrates, comparing with the optimal pre-timed signal setting, the *PRRP-framework* can help improve the performance of an intersection in terms of average delay. The

main reason behind this improvement is that the stochasticity of arrivals will be accounted for spontaneously by the *PRRP-framework*. It seems that the improvement is greater for higher arrival rates.

Indeed, at low arrival rates (arrival rate = 800 (vehs/h) in Figure 4), it is expected to have cycles without overflow queues. However, when signals operate close to the state of full saturation (arrival rate = 2400 (vehs/h) in Figure 4), the probability that some cycles have overflow queues (with consequently higher average delay) will also increase. Accordingly, the mechanism of the *PRRP-framework* in treating platoons of vehicles becomes more influential in the case of near-saturated conditions.

Compared to the defined actuated mechanism, we can see that our proposed framework is competitive to the actuated signals which require a considerable amount of detectors. Secondly, it must be stressed that the proposed algorithm for considering different priority treatments renders the *PRRP-framework* capable of prioritizing special vehicles over others while both the pre-timed and actuated signals treat all vehicles uniformly.

Regarding the priority setting, the green time duration in the *PRRP-framework* is adjusted to minimize the stopping time of special vehicles (in some cases) at the cost of the average delay of ordinary vehicles. To assess this further, we have repeated the VISSIM simulation for alternative proportions of special vehicles while considering a constant total arrival rate equal to 2400 (vehs/h). The results are shown in Figure 5.

According to Figure 5, if the proportion of *defined* special vehicles in the traffic composition is low (or, for example, only emergency vehicles get priority), we can see that the *PRRP-framework* outperforms not only the pre-timed setting but also the actuated mechanism. On the contrary, when the arrival rate of special vehicles grows, the average delay of the *PRRP-framework* becomes higher than that of the actuated mechanism. This increase in the average delay has its origin in the stochastic arrival of special vehicles which entails the variation of green (red) time irrespective of current demands. This

⁹ <https://github.com/HosseinMoradi/Project3>

FIGURE 5 Variations of average delay with considering different proportions (in percent) of special vehicles

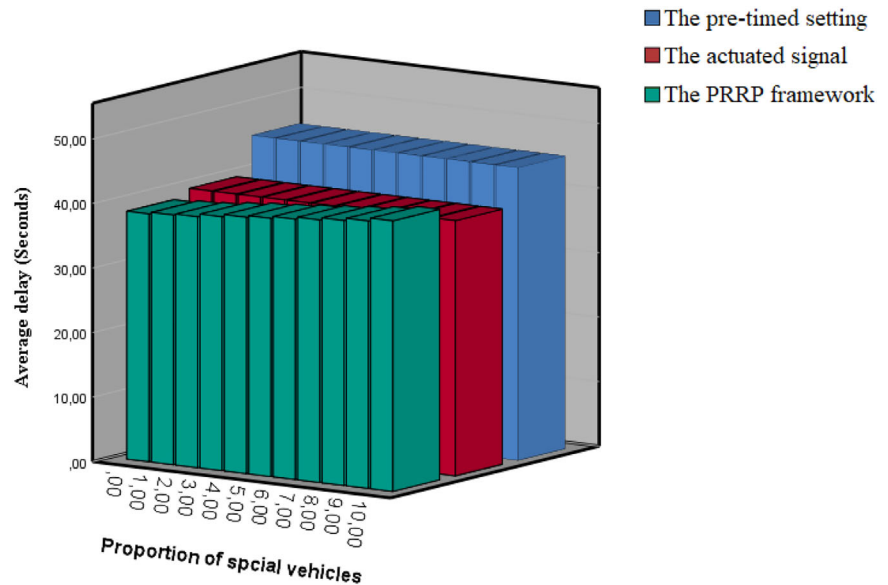
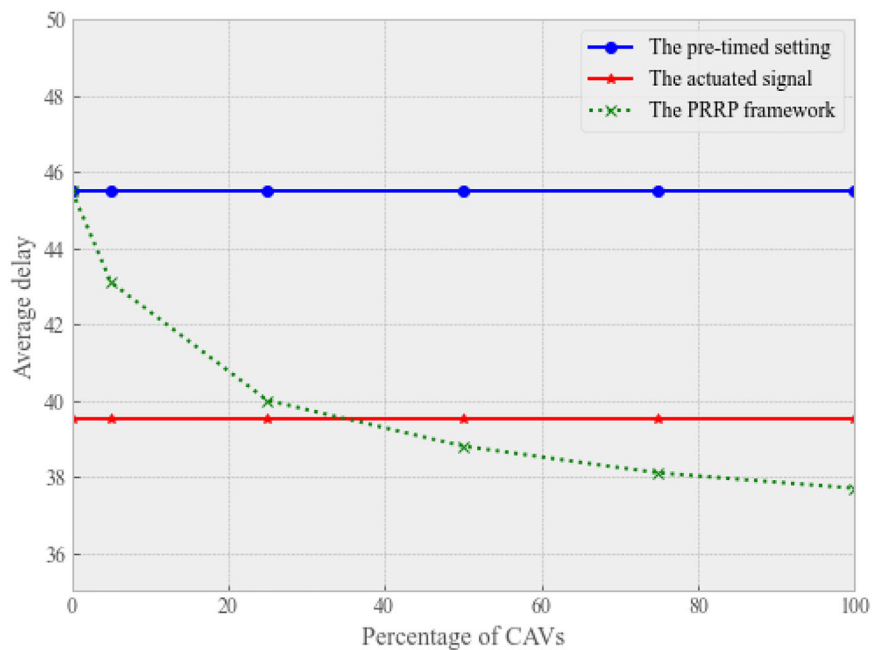


FIGURE 6 Evaluating the effect of the penetration rate of CAVs on the performance of the *PRRP-framework*



result clearly highlights the importance of flexibility in deciding whether or not to give priority to some special vehicles in different conditions (*Function 4* in Figure 2), which is left for future research.

We finally carry out a sensitivity analysis to assess the influence of the penetration rate of CAVs on the outcomes of the *PRRP-framework*. To this end, by assuming 2400 ((vehs/h) as the total arrival rate, we compare the obtained average delays, as shown in Figure 6. From this figure, we make the following observations:

- In the case of no CAVs, the operation of the *PRRP-framework* is similar to that of the pre-timed signal. In this case, l_p is always equal to 0 and, therefore, Equation (3) results in the same value for all groups of compatible lanes. Accordingly,

the *PRRP-framework* works as it is a controller with pre-timed green time and signal durations.

- The average delay decreases considerably by considering a low proportion of CAVs, as compared to the pre-timed signal. In this case, we see that if only 5% of the vehicles (e.g. only special vehicles) send their information, the *PRRP-framework* can, to some extent, incorporate the stochasticity of traffic in the determination of green times, resulting in a better performance.
- As the proportion of CAVs increases, the performance of the *PRRP-framework* gradually becomes better, as compared to both the pre-timed and actuated controllers. After 35% of CAVs, the *PRRP-framework* outperforms the actuated signal in terms of the average delay of all vehicles, while it also considers priority for special vehicles.

4 | INTEGRATION OF THE PRRP-FRAMEWORK INTO A SPEED ADVISORY SYSTEM

Speed advisory systems have been developed based on emission estimation models to determine the optimal *speed-trajectory* profile for (connected) vehicles to minimize energy consumption, and consequently, emissions [31]. In an individual intersection, this can be interpreted by the guidance of CAVs to arrive at the intersection (with the emission-optimal speed) when the associated signal is green. In this section, we study the integration effects of the proposed intersection control method and such a CAV-control strategy.

Regarding the advisory system, we customize the model employed in [32] with the following modifications:

1. The original model has been designed to determine the optimal speed of the leading vehicle in each platoon. However, delivering the optimal speed to a human driver (if the leading vehicle is not a connected one) does not seem to be feasible. At the same time, based on the results of previous studies, it is expected that using speed advisory systems for CAVs not only helps them reduce their own energy consumption, but also assists in improving the fuel economy of human-driven vehicles due to the car-following relationship [33]. Given this explanation, we choose to apply this speed advisory system for CAVs, whether or not they are platoon leaders.
2. The unknown condition of approaching conventional vehicles is another factor that might change the optimal solution. In other words, the obtained speed-trajectory profiles for CAVs are (probably) not the optimal ones if we process the information of both CAVs and conventional vehicles.¹⁰ Since we assume that conventional vehicles cannot communicate (whether with the intersection controller or CAVs), we allow CAVs to be driven with the desired speed (according to the defined speed limit) when the corresponding signal turns green. By doing so, CAVs will not be the traffic barriers for conventional vehicles (driving behind them) that can cross the intersection within the same cycle.

The following sections explain the applied speed advisory system, which is coupled to the *PRRP-framework* to form the integrated framework.

4.1 | Energy consumption of CAVs

In this section, we calculate the energy consumption of CAVs by considering the operational differences between gasoline and electric vehicles. First, regarding gasoline vehicles, we use

$$F(v(t), a(t)) = \max\{\alpha + \beta_1 \cdot v(t) \cdot R(t) + [\beta_2 \cdot M \cdot v(t) \cdot a^2(t)]_{a(t)>0}, \alpha\}, \quad (12)$$

¹⁰ As a case in point, it may cause conventional vehicles driving behind CAVs to get stuck behind a red light.

which is presented in [34] for estimating the gasoline consumption. In Equation (12), M , α , β_1 , and β_2 are the parameters that stand for vehicle weight (kg), idling gasoline consumption rate (mL/s), efficiency of engine (mL/kJ), and efficiency of engine in terms of making accelerations (mL/(kJm/s²)), respectively. Furthermore, $a(t)$ and $v(t)$ denote the acceleration (m/s²) and speed (m/s) of the vehicle at time t . Finally, $R(t)$ is the required tractive force (kN), which is given by

$$R(t) = b_1 + b_2 \cdot v^2(t) + M \cdot a(t) + M \cdot g \cdot \theta. \quad (13)$$

In Equation (13), b_1 and b_2 are drag forces (kN) resulting from the rolling and aerodynamic resistance (kg/m). Moreover, g is the gravitational acceleration (m/s²) and θ is the road gradient.

Second, regarding electric vehicles, the formulation presented in [35] has been adopted for the estimation of the power consumption, as shown in Equation (14):

$$P(v(t), a(t)) = \frac{r \cdot \gamma^2}{K^2} (M \cdot a(t) + k \cdot v^2(t) + f_{rl} \cdot M \cdot g + M \cdot g \cdot \theta)^2 + v(t) \cdot (k \cdot v^2(t) + f_{rl} \cdot M \cdot g + M \cdot g \cdot \theta) + \eta \cdot M \cdot a(t) \cdot v(t). \quad (14)$$

In Equation (14), r represents the motor resistance (Ω), γ is the radius of tires (m), and K is a defined factor ($\sqrt{\Omega \cdot \text{m} \cdot \text{s}}$) that is obtained by multiplying armature constant and magnetic flux. In addition, k and f_{rl} serve as the aerodynamic resistance (kg/m) and the rolling resistance coefficient, respectively. Finally, it should be considered that electric vehicles are capable of regenerating electricity during decelerating. The efficiency of this process is denoted by η .

Third, as a way to assimilate Equations (12) and (14), which result in different units (mL/s and W, respectively), we used 10 as the coefficient factor to convert the energy of gasoline into electricity.¹¹ As a result, we can represent the total energy consumption of CAVs by $E(v(t), a(t))$, whose value is a function of vehicle's speed and acceleration.

4.2 | The formulation and simulation of the speed advisory system

As indicated earlier, the speed advisory system is applied to advise each CAV upon coming into the area of the intersection on a speed profile that is optimized with respect to energy consumption. The corresponding optimization problem is formulated below. Equation (15) is the objective function, which seeks to minimize the total energy consumption ($\mathcal{E}$) for a given number of J CAVs (whose associated signals are red) by specifying their optimal speed profile $v_1^*(t), \dots, v_J^*(t)$:

$$\min \mathcal{E} = \sum_{j=1}^J \int_{t=0}^{t=t_{fj}} E_j(v_j(t), a_j(t)) dt. \quad (15)$$

¹¹ Based on [36], the energy of one gallon of gasoline is approximately equal to 33.7 kWh electricity. As a result, we consider 10 as the converting coefficient.

TABLE 1 Parameters used in the simulation

Parameters	Values
Light vehicle weight, M	1275
Heavy vehicle weight, M	15.431
Rolling resistance coefficient, f_R	0.006
Aerodynamic resistance coefficient, k	1.30
Product of armature constant and magnetic flux, K	10.08
Resistance of motor, r	0.11
Radius of tire (light vehicles), γ	0.34
Radius of tire (heavy vehicles), γ	0.58
Transmission efficiency, η	95
Idling fuel rate, α	0.444
Efficiency of engine, β_1	0.09
Efficiency of engine in terms of making acceleration, β_2	0.04
Drag force due to rolling resistance, b_1	0.333
Drag force due to aerodynamic resistance, b_2	0.00108

In Equation (15), $E_j(v_j(t), a_j(t))$ denotes the energy consumption of CAV j ($j = 1, \dots, J$), whether it is an electric or a gasoline vehicle. The time t_{fj} denotes the time instant vehicle j crosses the intersection. Given each CAV j , we have a decision variable $v_j(t)$, i.e. the speed profile of CAV j , with its corresponding acceleration profile $a_j(t)$. Furthermore, notice that by considering (1) the distance D_j of CAV j from the signal head at time $t = 0$, (2) different possible speed profiles, and (3) the start and end moments of the associated green time, different times $t = t_{fj}$ at which this CAV is supposed to cross the intersection could be calculated. All this taken into account, by also considering the total of J CAVs, we can conclude that this problem is very complex which cannot be dealt with in real time. Accordingly, to apply this system efficiently, we impose the following constraints:

- For each j , we limit our search space to three options: the current speed, the maximum speed, and the minimum speed. Accordingly, the final optimal speed v_j^* is in $\{v_j, v_{\max}, v_{\min}\}$.
- The change of speed is only done by the maximum positive or negative acceleration. Accordingly, we assume $a_j \in \{0, a_{\max}^+, a_{\max}^-\}$ to define speed profile $v_j(t)$.
- Possible t_{fj} are limited to those we can obtain with respect to D_j , the current speed, possible speed profiles, and the associated signal plan.
- Besides considering these simplifications, we still had to break the nested loop by selecting smaller sets of CAVs to solve Equation (15). Note that the complexity of this equation increases exponentially with respect to J .

By considering the same traffic composition introduced at the beginning of Section 3 (i.e. the proportion of CAVs is 25%), we further assign the values presented in [32] to the constant parameters used in Equations (12)–(14) in order to see the operation of the explained speed advisory system. Table 1 summa-

rizes the applied parameters. Figure 7 depicts the effect of applying this system on the trajectory of vehicles at a pre-timed intersection in a time-space diagram. Comparing Figure 7(a) with (b) confirms that the application of the speed advisory system leads to relatively fewer number of vehicles stopping at the intersection at a red light. Note that not only CAVs but also conventional vehicles in the same lane behind CAVs move at the optimal speed towards the intersection. Accordingly, while only 25% of the vehicles are CAVs, there are relatively more vehicles decreasing their speed as shown in Figure 7(b).

4.3 | Simulation and efficiency evaluation of the integrated framework

In this section, we incorporate the speed advisory system in the *PRRP-framework* explained in Section 2 to obtain the integrated framework.¹²

To evaluate the performance of the integrated framework, we utilize a general four-link intersection (with the same layout as we used before) and consider the total arrival rate to be equal to 2400 (vehs/h)¹³ to add the performance indices of:

- using a pre-timed signal setting as the signal control method along with applying the speed advisory system,
- and using both the *PRRP-framework* and the explained speed advisory system (the integrated framework).

to the picture. In this comparison, we also use the same traffic composition as in Section 3. Figure 8 compares the obtained average delays.

According to Figure 8, while applying only the speed advisory system can help improve the performance of an intersection in dealing with the issue of average delay by reducing shock wave propagation in the intersection (see Figure 7), the integration of the speed advisory system into the *PRRP-framework* (labelled as the integrated framework) outperforms all the mechanisms by resulting in a lower average delay. As a case in point, compared to the developed pre-timed signal setting (in its best scenario), using the integrated framework leads to a 19.5% reduction in the average delay, which is more than, respectively, 13%, 12%, and 10% reductions obtained from the actuated signal, the *PRRP-framework*, and the speed advisory system.

The most important reason for the observed improvement in the integrated framework is the complementary strengths brought by the *PRRP-framework* and by the speed advisory system. On the one hand, as shown in Section 3, the proposed *PRRP-framework* determines the proportional green time by aligning green time duration to the corresponding demands. On the other hand, the speed advisory system helps traffic fleets, in general, and CAVs, in particular, to better use that time. In this case, when the signal is red, CAVs drive with the optimal speed which helps them to arrive at the intersection during green time

¹² <https://github.com/HosseinMoradi/Project4>

¹³ Since this type of signals are meant to operate as closely as possible to the state of full saturation, the results of this arrival rate (in our showcase) are of the utmost importance.

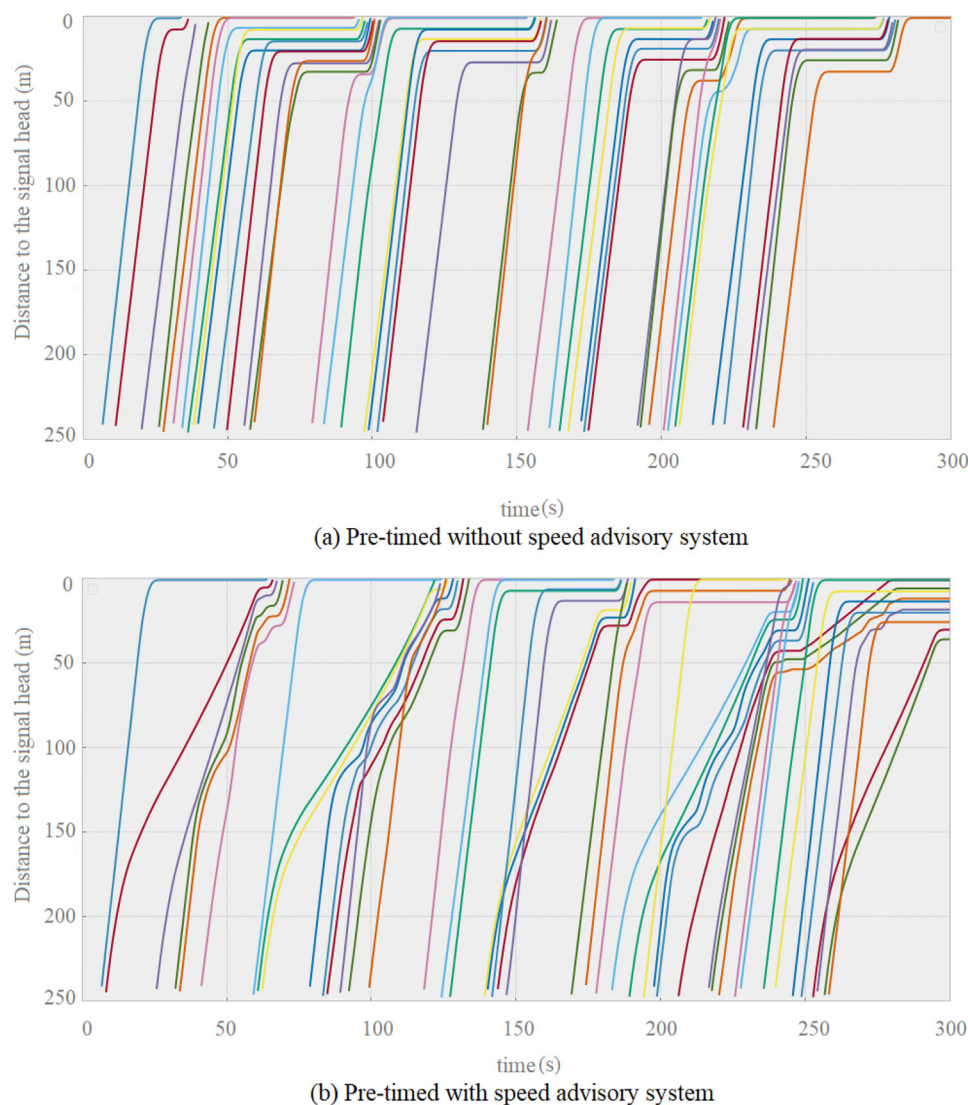


FIGURE 7 The result of the application of the speed advisory system on a time-space diagram

durations without the lost time needed for re-acceleration from a stop condition.

Finally, given the importance of the consideration of sustainability in any new proposal of traffic management systems [37], a series of simulations has also been carried out to compare the efficiency of the mentioned mechanisms in terms of emissions reduction. To this end, we also use VISSIM. Since, however, some research studies have raised concerns on the accuracy of VISSIM in evaluating emissions (see [38] as an example), this micro-simulator is employed here not for measuring emissions quantitatively, but for relatively comparing the framework in a general intersection with the standard control mechanism. Accordingly, Figure 9 presents the obtained results for the total CO emissions (g) at the intersection with considering a total arrival rate equal to 2400 (vehs/h).

According to Figure 9, the results show that by considering the optimal pre-timed setting as the benchmark:

- The actuated mechanism results in a 3.77% reduction in CO emissions mainly due to its ability in extending green time with respect to the current traffic condition;
- The *PRRP-framework* leads to a 4.77% reduction in CO emissions. In this case, we can see that while the average delay of the *PRRP-framework* is (slightly) higher than that of the actuated mechanism, it works better in terms of emissions reduction due to its capability for considering priority treatments for heavy vehicles;
- The speed advisory system reduces emissions by 5.16% through determining the optimal speed of approaching CAVs;
- The integrated framework brings a 9.9% reduction in CO emissions that results from (1) reducing the number of stop-and-go events, (2) reducing the average delay, (3) moving CAVs with the optimal speed, and (4) giving priority to heavy vehicles. In each specific condition, one of the

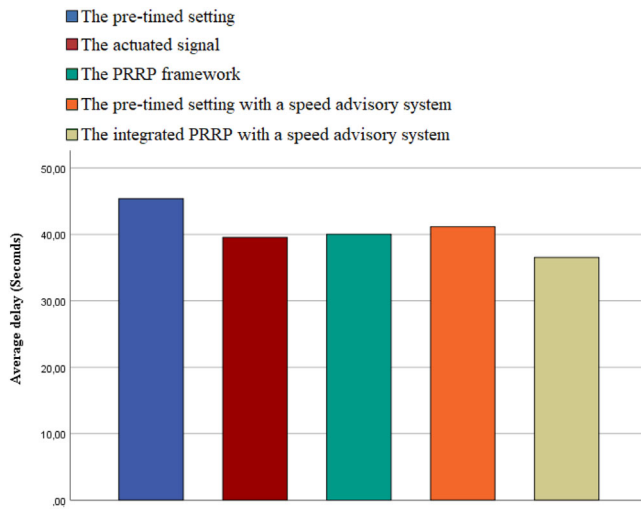


FIGURE 8 Comparing the average delay of the pre-timed setting, the actuated mechanism, the *PRRP-framework*, the speed advisory system, and the integrated framework in a near saturated condition

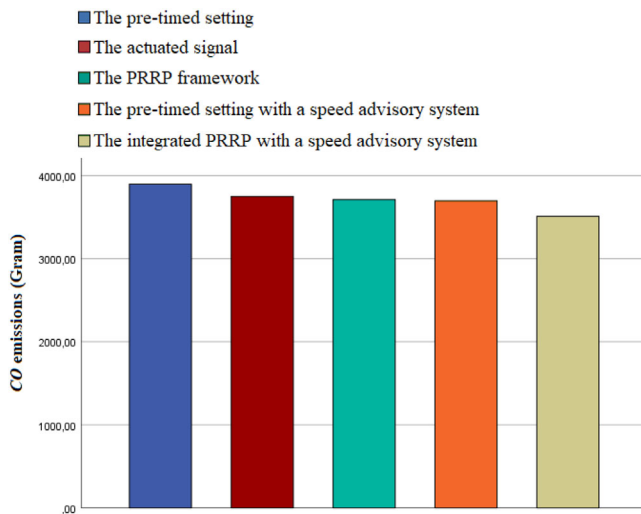


FIGURE 9 Comparing CO emissions resulting from the use of the pre-timed setting, the actuated mechanism, the *PRRP-framework*, the speed advisory system, and the integrated framework in a near-saturated condition

above-mentioned reasons becomes dominant and helps the integrated framework to have superior performance.

5 | CONCLUSION AND FUTURE RESEARCH DIRECTIONS

This paper has first proposed the *PRRP-framework* to address the need for a rule-based model capable of managing mixed traffic (with considering the concomitant complexities) and has secondly presented an integrated framework (built upon the *PRRP-framework* and a speed advisory system) with even better performance.

Regarding the *PRRP-framework*, our simulations first showed how this framework infers green time durations on the grounds

of the current demand and the presence of special vehicles. Then the relative efficiency of the *PRRP-framework* has been confirmed, compared to the traditional signals.

Regarding the integrated framework, the simulations showed that the proposed framework makes contributions with regard to the reduction of emissions whose amount is higher than that for (1) the optimal pre-timed signal, (2) the actuated mechanism, (3) the speed advisory system, and (4) the *PRRP-framework*. It was also shown that the integrated framework works better than the enumerated ones in terms of the average delay.

It should be noted that the implementation of the integrated framework is an illustration of a key rationale behind this work: integration among solutions is a pre-requisite to reach sustainable results. With this momentum, future research studies can be developed to integrate other solutions into this framework. As a case in point, a rigorous analysis of the effects of embedding signal synchronization systems into this framework is an interesting topic left for future work.

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