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Adaptive Traffic Signal Control Under Mixed Traffic Condition

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Abstract

The growing use of powered two wheelers (PTWs), coupled with their unique moving behaviors, has considerably influenced the overall traffic characteristics, requiring new approaches to traffic management and monitoring strategies. The present paper studies the effect of two-wheelers traffic on adaptive traffic signal control (ASC) and the methods to optimize the control plan for traffic flow consisting of PTWs and cars. For this reason, the queue build-up and dissipation processes are analyzed with a gradual increase of PTWs ratio. Besides, the effect of advanced stop lines, which are intended to give a head start for PTWs on the onset of the green period, on the queue build-up and dissipation processes is also studied. Based on queue clearance time analysis for different traffic compositions, the possible erroneous estimate of green time length resulted from the existing adaptive signal control approaches is presented. Furthermore, the flow rate of vehicles discharging from a queue is examined and a passenger car unit (PCU) value of PTW is computed. Finally, an effective green time allocation technique is devised to integrate PTWs in ASC signal plans. Simulation results show that the proposed technique leads to a promising improvement. For the study, a macroscopic model designed to capture the traffic dynamics of mixed traffic flow consisting of PTWs and cars is employed.

Keywords: Powered two wheelers; Adaptive traffic signal control; Heterogeneous traffic flow; green time optimization

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Nomenclature

i	Vehicle type, 1-PTW, 2- car
$\rho(x,t)$	traffic density
$q(x,t)$	flow rate
q^{max}	maximum flow rate or capacity
$v(x,t)$	average speed
(x,t)	(space, time)
Δt	simulation time step
Δx	simulation space step
CFL	Courant-Friedrichs-Lewy condition
CT	vehicle clearance time
ASC	Adaptive Signal Controller
PTW	Powered Two Wheelers
PCU	Passenger Car unit
SF	saturation flow rate

1. Introduction

An adaptive signal control (ASC) approach dynamically optimizes traffic signal plan according to the traffic condition in real time. Constantly gathered data are used to detect traffic demand variation, and to determine the appropriate offset, green split and cycle length. Due to its traffic responsive nature, ASC surpasses the limitation of the conventional pre-calculated signal control methods which rely on historical data. However, the efficiency of adaptive control scheme is limited by how the traffic control perceives the traffic flow characteristics. Traffic flow characteristics such as traffic arrival, queue formation, and dissipation patterns are the main factors that regulate ASC operations.

Most of the existing adaptive signal controllers are designed for lane-disciplined car traffic flows. Thus, the operation of ASC is adapted to the traffic characteristics of the lane disciplined flows. This assumption is challenged by the unique traffic flow behaviors appearing as a consequence of the growing use of Powered Two Wheelers (PTW). The queue formation and dissipation pattern of PTWs significantly differs from cars. For instance, during queue formations in mixed traffic conditions, PTWs tend to move to the head of the queue by filtering through the queue of other vehicles, giving them the opportunity to leave the queue before other vehicles. Besides, thanks to their high maneuverability, PTWs altogether depart from the queue in a very short time. Therefore, ASC operations based on the knowledge of car traffic flow will not anticipate this early departure and produce a suboptimal signal plan. This paper contributes to the improvement of ASC operations by analyzing the queue build-up and dissipation process in mixed traffic flows consisting of PTWs and car, and devises an effective adaptive signal control techniques to integrate PTWs in ASC signal plans.

In this paper, we consider adaptive traffic light controllers, which allocate green phase lengths according to the variation of traffic volumes (Zhou et al., 2010) (Faye et al., 2012). That is, the green time length is determined based on the volume (number) of vehicles in the queue. Adjusting the green phase length according to the traffic demand (i.e. traffic volume) allows to avoid over/under-allocation of green periods. As pointed earlier, the existing adaptive traffic controllers determine the green length on the knowledge of car traffic flow, thus the effectiveness of the control scheme is affected by the presence of vehicles with divergent moving behaviors, like PTWs. Thus, the objective of the present work is to show how ignoring the unique characteristics of PTWs traffic affects the effectiveness of ASC optimal operations, and how they would be improved when accommodating these unique properties.

In a previous work (Gashaw et al., 2017), we developed a macroscopic model designed to capture the dynamics of mixed traffic flow consisting of PTWs and cars. In this work, we apply this model to the study of the impact of a gradual increase of PTWs on specific traffic flow characteristics with substantial effect on ASC operation, such as queue formation, dissipation and maximum flow rate. Furthermore, the time required to clear the queued traffic is analyzed with respect to the traffic composition. By comparing the actual time needed to clear vehicles and the time that would be estimated according to existing control systems, we illustrate the performance enhancement achieved when ASC takes into account the presence of PTWs. The passenger car unit of PTWs is estimated by analyzing the queue discharge rate of each vehicle class. Moreover, using the estimated PCU value, we propose a method for optimal green time allocation. The presented study is yet limited to isolated intersections. However, the results can be extended for connected intersections. Our work shows how including PTWs properties in the prediction of green time duration improves the efficiency of traffic signals.

2. Literature review

Most of the research studies on traffic characteristics of mixed flow of PTWs and cars traffic at signalized intersections primary focus on analyzing the saturation flow, which is the maximum flow rate vehicles leave the intersection, and Passenger Car Equivalent/unit (PCU). Rongviriyapanich and Suppattrakul (2005) presented the effect of PTWs on saturation flow rate and start-up lost time of passenger car. Similar studies in (Shao et al., 2011) (Maini and Khan, 2000)(Branston and van Zuylen, 1978) showed the influence of traffic composition and vehicles characteristics on the saturation flow rate. The characteristics of the saturation flow rate in motorcycle-dominated traffic is illustrated by Nguyen (2016).

However, most research is limited to estimating PCU by studying the effect of PTWs on passenger car or flow characteristics at intersections by analyzing the saturation flow rate or the speed. For instance, based on field observation (Kumar and Dhinakaran, 2012) analyzed PCU values for different type of vehicles to determine saturation flow at signalized intersections. Another study (Lee et al., 2010) also examined the PCU value for motorcycle at two instants of green phase when traffic discharge from the queue. Yet, there is no common way of defining PCU and the proposed values are applicable only to a given traffic condition. To the best of our knowledge, integrating the PTWs properties on traffic signal plan optimizations has been given a little attention. A few studies addressed signal plan optimization based on the analysis on the queue formation and dissipation characteristics of motorcycle. For example, Lan and Chang (2016) propose an optimization plan for coordinated arterial intersections. Nuli and Mathew (2013) also presented the benefits of moving the vehicle detectors to the stop line could help to easily integrate traffic heterogeneity in traffic signal planning.

3. Traffic dynamics Modeling

The traffic flow dynamics is described by a macroscopic model capturing the traffic phenomena in a mixed flow of PTWs and cars. The flow equation is given by the conservation law of multi-class Lighthill-Whitham-Richards (LWR) model

$$\frac{\partial \rho_i(x,t)}{\partial t} + \frac{\partial q_i(x,t)}{\partial x} = 0, \qquad i = 1,2, \tag{1}$$

where ρ_i and q_i denote density and flow of class i, respectively. The fundamental relation for each class is given by $q_i(x,t) = \rho_i(x,t)v_i(x,t)$, with the average speed $v_i(x,t)$ satisfying the conditions $v_i = V_i(\rho_1,\rho_2)$, $\partial_1 V_i(\rho_1,\rho_2) \leq 0$, $\partial_2 V_i(\rho_1,\rho_2) \leq 0$. The average speed is expressed as a function of the density of each vehicle class. In this way, the model expresses the interaction among the vehicles class. The speed function is defined according to the porous flow approach which describes speed of vehicles as a function of free space between vehicles (Nair et al., 2011).

$$v_i = v_i^f \left(1 - \int_0^{r_i^c} f(l)\,\mathrm{d}l\right), \tag{2}$$

where v_i^f, r_i^c, $f(l)$ represent, respectively, the free flow speed, the minimum admissible gap and the probability density function of free space distribution. The distribution of free space (gap) between vehicles follows a left truncated normal distribution (Gashaw et al., 2017).

In order to simulate the traffic evolution, we apply multi-class cell transmission model as in (Fan and Work, 2015) to approximate the solutions of the traffic flow equations. The road segment is divided into equal sized sections (cells), and at each time step the traffic state in each cell j is updated according to the following supply-demand update rule:

$$\rho_j^{n+1} = \rho_j^n - \frac{\Delta t}{\Delta x}\left[F_{j+1/2} - F_{j-1/2}\right], \tag{3}$$

where the space and time steps Δx and Δt are selected to meet Courant-Friedrichs-Lewy (CFL) condition $\Delta t \leq \Delta x/\max\ (V_i)$. The flows at the cells boundaries ($F_{j+1/2}$ *and* $F_{j-1/2}$) are determined from the demand in upstream cell and the supply at the downstream cell. For example, the flow at the right boundary of a cell $F_{j+1/2}$ has the following formulation:

$$F_{j+1/2} = \min\left\{D_j(\rho_j^1, \rho_j^2),\ S_{j+1}(\rho_{j+1}^1, \rho_{j+1}^2)\right\}.$$

The supply S_{j+1} and the demand D_j for vehicle class 1 are defined as:

$$S_{j+1}^1 = \begin{cases} q_1(\rho_{j+1}^1, \rho_{j+1}^2) & \text{if } \rho_{j+1}^1 > \rho_c^1(\rho_{j+1}^2), \\ q_1^{max}(\rho_{j+1}^2) & \text{if } \rho_{j+1}^1 \leq \rho_c^1(\rho_{j+1}^2), \end{cases} \qquad D_j^1 = \begin{cases} q_1^{max}(\rho_j^2) & \text{if } \rho_{j+1}^1 > \rho_c^1(\rho_j^2), \\ q_1(\rho_j^1, \rho_j^2) & \text{if } \rho_j^1 \leq \rho_c^1(\rho_j^2), \end{cases} \tag{4}$$

where q^{max} and ρ_c denote the maximum flow rate and critical density, respectively. Likewise, the supply and the demand for vehicles class 2 can be defined correspondingly.
Traffic light operation is finally modeled by introducing a time-varying constraint at the traffic light location.

$$F_{k+1/2}(t) = \begin{cases} 0 & \text{for } t \in \text{Red phases}, \\ q_{max} & \text{for } t \in \text{Green phases}. \end{cases} \tag{5}$$

4. Analysis of traffic queue dynamics

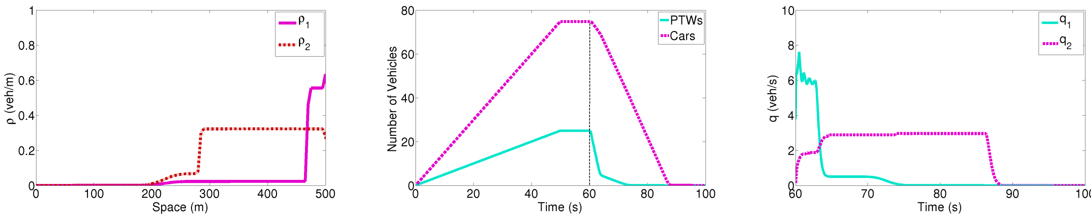
Understanding the queue dynamics is a basic procedure for the optimization of traffic signal plan in adaptive schemes. The queue dynamics describes the behavior of vehicles in the queuing process and their patterns to leave the queue. In the mixed flow of PTWs and cars, PTWs filtering and lane-sharing behaviors allow them to advance to the front of the queue at the red traffic light. This PTWs behavior in queue formations gives them an advantage during the queue dissipation process, changing the pattern cars would have under homogeneous traffic conditions. The queue dissipation pattern can be illustrated considering the maximum flow rate, called saturation flow rate, when vehicles leave the stop line. For the case of homogeneous traffic flow, the reached saturation flow rate is fairly constant. However, in a mixed flow situation the property is different.

To study the queue dynamics and identify the possible influences on the existing traffic signal operation, we perform simulation experiments. We consider the following simulation scenario: a single lane isolated intersection with road segment length of 510m and width of 3.5m, 80km/hr free flow speed for cars and PTWs. The road segment is divided into cells of size $\Delta x = 5m$, and the solution is updated at each time step Δt, which is chosen according to the CFL condition $\Delta t \leq \Delta x/\max\ (V_i)$. The traffic light is located at 500m, and red light is active between $t \in [0, 60s]$. Traffic demand (arrival flow rate) is imposed as inflow boundary condition and an open boundary is set downstream. A fixed total arrival rate of $2veh/sec$ is set for time $t \in [0, 50s]$ and the arrival rate is zero for the rest of the simulation times. The arrival rate for each vehicle class depending on their proportion. Accordingly, the queue dissipation behaviors will be studied with a gradual increase of PTWs ratio and the queue clearance time will be analyzed with respect to the traffic composition.

Table 1 shows the clearance time (CT), denoting the time needed to clear vehicles from the queue, considering each class obtained from the simulation. The influence of PTWs on intersection clearance time is illustrated by varying their penetration rate. According to the results, the intersection clearance time, which is the maximum of the clearance times of the two vehicle classes, decreases with the increase of the ratio of PTWs. This is further shown by examining the queue formation and discharging behaviors. Fig. 1 shows the queue dynamics for each class when the ratio of PTWs is 25%. The filtering and lane sharing capability of PTWs grants them to move close to the stop line (Fig. 1a) and dissipate from the queue at higher saturation flow rate (Fig. 1c).

Ration of PTWs(%)	CT of Cars	CT of PTWs	Relative Error
0	34.74	-	-
15	30.99	13.57	+10.8%
25	28.13	14.02	+19.01%
35	25.43	14.17	+26.79%
50	21.23	14.47	+38.89%
75	14.47	14.77	+57.47%
100	-	14.92	+57.04%

Table 1: change in clearance time with ration of PTWs



a b c

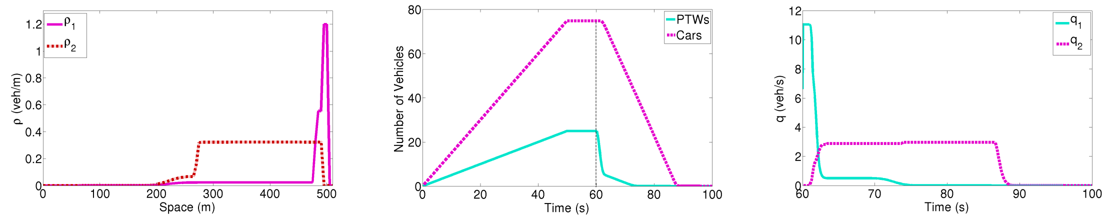
Fig. 1: (a) Density profile immediately before traffic light turns red, (b) Evolution of queue length, and (c) saturation flow rate, traffic proportion [25% PTWs, 75% Cars]

To explain this from the context of adaptive traffic light operation, let's consider an ASC that counts the number of vehicles in the queue and estimates the queue clearance time correspondingly. Accordingly, regardless of the proportion of PTWs, the clearance time would be estimated to $34.74s$ (see Table 1) on the assumption of car-only traffic, resulting in overestimation of clearance time. Moreover, the relative change of the actual CT and estimated CT, i.e. $\frac{EstimatedCT - ActualCT}{EstimatedCT}$, shown in Table 1 depicts that the estimation error increases with the increase of PTWs ratio. Due to CT overestimation, a longer green time is assigned than needed, which causes unnecessary delay on vehicles waiting in the queue of adjacent intersections.

The Introduction of an advanced stop line for PTWs has been proposed as a strategy to facilitate PTWs mobility at traffic signals, see (Allen et al., 2005). For traffic lights with advanced stops, we evaluate the clearance time and discharging behavior by performing similar experiments. In the simulation, the stop line for cars is located 10m upstream from the traffic light. The results in Fig. 2 and Table 2 illustrate that the measured relative CT error is higher than the case for the intersection without advanced stop line.

Ration of PTWs(%)	CT of Cars	CT of PTWs	Relative Error
0	35.34	-	-
15	31.14	13.57	+11.89%
25	28.43	14.02	+19.54%
35	25.73	14.17	+27.18%
50	21.53	14.47	+39.08%
75	14.62	14.77	+58.63%

Table 2: change in clearance time with ration of PTW, with advanced stop line for PTWs



a b c

Fig. 2: (a) Density profile immediately before traffic light turns red, (b) Evolution of queue length, and (c) saturation flow rate, traffic proportion [25% PTWs, 75% Cars] , with advanced stop line for PTWs

Given the queue formation and dissipation patterns of PTWs, another alternative for ASCs is to estimate the CT is by ignoring PTWs and counting only the number of cars in the queue to determine the clearance time. Obviously, the estimated CT is below the actual CT. Yet, the divergence from actual CT is lower than the case where all vehicles in the queue are counted (Table 3).

Both counting all the vehicles in the queue and counting only cars in the queue result in clearance time estimation errors. However, the estimation error for the latter case is smaller, particularly for low PTW penetration rates. Nevertheless, either way the performance of the ASC is affected as vehicles in adjacent intersection approach forced to wait for more time due to over estimation of the green time in the first case or some vehicles are forced to wait for more than one cycle to clear from the queue in the latter case.

Ration of PTws(%)	Estimated CT	Actual CT	Relative Error (%)
0	34.74	34.74	0%
15	29.63	30.99	-4.58%
25	26.33	28.13	-5.69%
35	22.88	25.43	-11.18%
50	17.77	21.23	-19.47%

Table 3: Estimated and actual clearance time, when number of PTWs is excluded from CT computation

5. Optimization approach

We consider an adaptive signal control in an isolated intersection that adjust the green time duration according to the upstream traffic demand. The ASC is assumed to measure queue length in number of vehicles queued at the intersection. The information of queue length can be gathered using connected vehicle technologies or detectors. The green time duration is set for a time sufficient to clear all queued vehicles. Accordingly, the queue clearance time or the green time is computed from the number of queued vehicles and the saturation flow rate (SF), ignoring the start-up loss time at the very beginning of the green time.

However, for the mixed flow of cars and PTWs, the individual vehicle class saturation flow rate is subjected to change depending on the traffic composition. The variation in the saturation flow rate can be seen in Fig. 1c. As can be seen, the saturation flow rate of car at the former green time period is lower than the latter period. The flow-density relation shown in 3 also explains the dependency of the maximum flow rate or saturation flow rate on the density of the other vehicle class. The figure shows the variation in maximum flow rate achieved by car traffic for different density values of PTWs. Therefore, the saturation flow rate for each class varies on the basis of the density of the other vehicles class. Due to this, the spatial distribution of each vehicle class in the queue is required since the number of queued vehicles in each class is not sufficient for clearance time computation.

In order to alleviate the complexity on the estimation of saturation flow rate, we develop a passenger car unit (PCU) for PTWs, and the total SF rate is expressed in PCU rather than taking the saturation flow rate of individual class. The

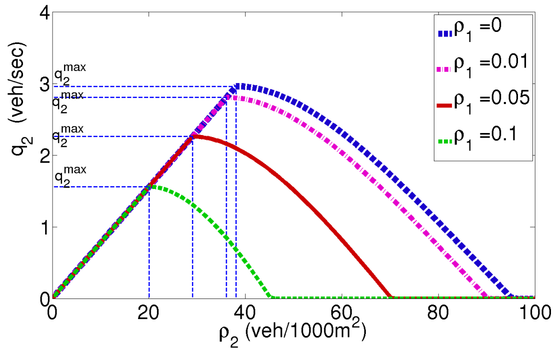


Fig. 3: Density-flow relationship and the maximum flow variation for different density (veh/m^2) of the other vehicle class, illustrate for car traffic flow

purpose here is to find PCU values for PTWs so that the total saturation flow rate can be expressed with a constant value regardless of the traffic composition and proportion. Hence, the PCU value of PTWs is expressed according to the following equation.

$$PCU_{PTW} = \frac{SF_b - SF_{car}}{SF_{PTW}}$$

where SF_b is the maximum flow rate for car only traffic, and SF_{car} and SF_{PTW} are the current saturation flow rate of car and PTW, respectively.

The results from the simulation runs of multiple ratio of PTWs is used to estimate $PPCU_{PTW}$ (hereafter referred as PCU) values. A result from one example scenario, where we have similar simulation setting as the previous experiments except here the red time is set to 80s, is shown in Fig. 4. As depicted by the figure, the PCU values for the first $1s$ of the green time decrease sharply and remain constant (≈ 0.19) until the saturation phase ends. The later sharp increases are related to the end of saturation phase, which is not important for our analysis. The result shows that when the ration of PTWs is less than 100%, the PCU value is more or less constant regardless of PTWs proportion, except the fluctuation for very short period at the very begging of the green time. Fig. 5b shows the flow of individual class (veh/s) and the total saturation flow rate in PCU/s. As illustrated, by using the PCU value the variation in the total saturation flow rate is hidden, making easier for queue clearance time prediction.

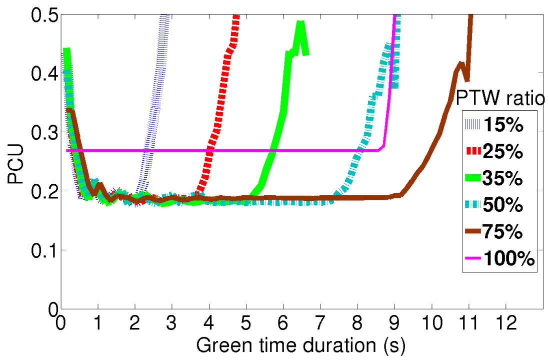
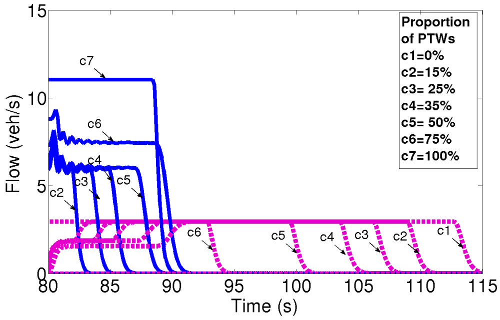
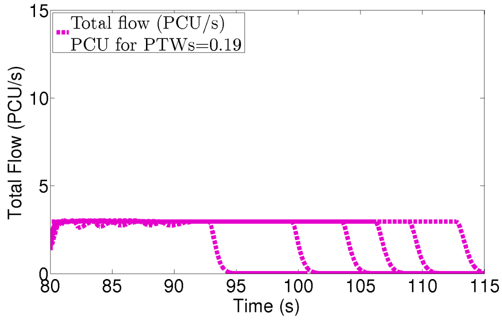


Fig. 4: The change passenger car unit (PCU) value of PTWs over the green time duration



a Flow of individual vehicle class in veh/s



b Total flow in PCU/s

Fig. 5: Flow in vehicle per second and PCU per second, when traffic discharge from the queue

Therefore, we can use the estimated saturation flow rate in PCU/s to determine green time duration. On the assumption of instantaneous transition to SF state, the green time need to clear the vehicles in the queue is formulated as follows:

$$T_{cl} = \frac{PCU * N_1 + N_2}{SF_b}$$

where N_1 and N_2 represent the number of PTWs and cars in the queue, respectively. With this formulation we integrate the flow behavior of PTWs and eliminate the over/under estimation of the green time.

The performance of the proposed green time optimization method is evaluated by comparing with the no-optimized approach. For the simulation, we use the scenario shown in Fig. 6. The length of each intersection approach is $505m$ and the stop lines are located at a distance of $5m$ upstream. Vehicles inflow rate of $1.3veh/s$ and $0.7veh/s$ is set for cars and PTWs, respectively. The evolution of the total number of vehicles at the two intersection approaches is assessed and the average delay is measured accordingly. The average delay is determined from the average number of vehicles unable to move to the next cell in one simulation step (Pohlmann and Friedrich, 2010). The green time duration for each approach is decided based on the traffic situation. However, for the first signal phase, intersection approach 1 (R_1) and intersection approach 2 (R_2) starts with green phase and red phase, respectively, where this state lasts for $60s$.

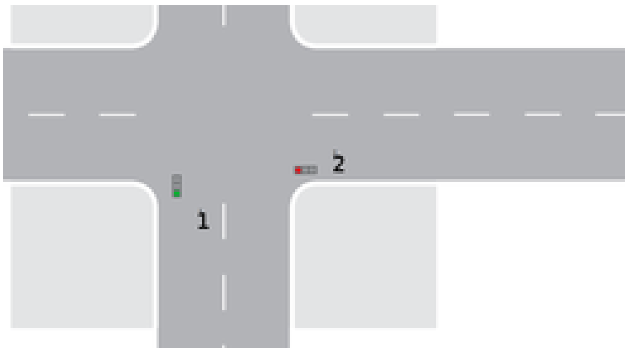


Fig. 6: Simulation experiment scenario

The evolution of number of vehicles at the first intersection approach is presented in Fig. 7. What can be observed from the result is that the queue length for the non-optimized approach is higher than the optimized approach at each red-to-green transitions, which is resulted from the long green time duration. The delay averaged over the simulation time is shown in Table 4. According to the results, our proposed green time computation method gives a better output in terms of the average delay.

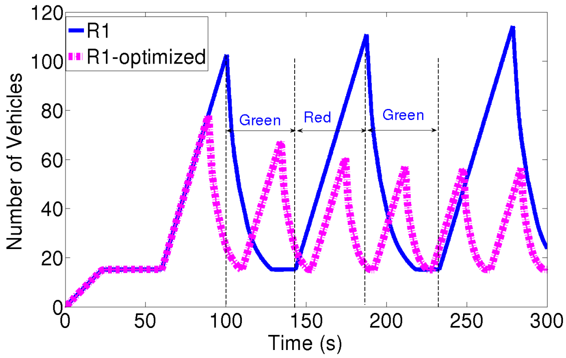


Fig. 7: The evolution of the total number of vehicles in the queue over the simulation time, at the 1st intersection approach

	non-optimized	optimized
R_1	42.59	29.36
R_2	46.34	34.8

Table 4

6. Concluding remarks

In an adaptive signal control scheme, the control parameters are adjusted with real time traffic. Therefore, understanding the traffic flow characteristic is imperative for effective control. In this work, we have evaluated the performance of the existing adaptive control methods under a traffic flow consisting of cars and PTW. The peculiar queue formation and dissipation behaviors, including the clearance time are analyzed. Due to the peculiar maneuvering behaviors of PTWs, the flow characteristics in such traffic is different from the follow-the-leader kind of flows. The main determinant factors of the control parameters of ASC, such as queue formation, dissipation, saturation flow rate and clearance time are investigated with a gradual increase of PTWs traffic. Based on the saturation flow analysis, we developed a PCU value of PTWs when vehicle discharge from the queue. Using this PCU value, we proposed a simple method for the integration of the unique behaviors, and the performance improvement gain with the introduction of the proposed model is presented.

This work can be seen as a first step toward the integration PTWs unique maneuvering behaviors in traffic managements, particular in traffic-responsive traffic signal controls. However, further research is required in multiple aspects of the study. The work here is done on a single lane and under saturation flow situation. Thus, the situation on multi-lane operation and over-saturation flow should also be studied. The impact of control parameters, such as the red time length, and arrival rates on the queue dynamics needs to be addressed. Furthermore, the different methods ASC uses to estimate the queue length should be considered for future work. Finally, additional research has to be done for further exploration of the practicality of the recommended approach.

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