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A platoon-based traffic signal timing algorithm for major–minor intersection types

Yi Jiang [a,*], Shuo Li [b,1], Daniel E. Shamo [c,2]

[a] *Department of Building Construction Management, Purdue University, 401 N. Grant Street, West Lafayette, IN 47907-1414, United States*
[b] *Indiana Department of Transportation, Division of Research, 1205 Montgomery Street, West Lafayette, IN 47906, United States*
[c] *URS Corporation, 47 South Meridian, Suite 312, Indianapolis, IN 46204, United States*

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Abstract

This paper presents a platoon-based traffic signal timing algorithm that reduces traffic delays at major–minor type of intersections. The algorithm reduces traffic delays at intersections by minimizing the interruptions to vehicle platoon movements on the major roads. In this paper, the characteristics of vehicle platoons are discussed, including the key platoon variables and their mathematical distributions. Then the platoon-based traffic signal timing algorithm is illustrated with proposed platoon detector placement and signal control logic. Further, through computer simulations it is shown that the platoon-based algorithm provides better performance at major–minor types of intersections than conventional signal timing algorithms.

Keywords: Vehicle platoons; Traffic simulation; Signal control; Traffic delay

* Corresponding author. Tel.: +1 765 494 5602; fax: +1 765 496 2246.
E-mail addresses: jiang2@purdue.edu (Y. Jiang), sli@indot.state.in.us (S. Li), dan_shamo@urscorp.com (D.E. Shamo).
[1] Tel.: +1 765 463 1521; fax: +1 765 497 1665.
[2] Tel.: +1 317 636 7469.

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1. Introduction

It was observed that about 70% of vehicles travel in platoons on Indiana highway corridors in the rural areas. Many vehicle platoons were halted at signalized intersections in order to give the right-of-way to vehicles on the intersecting minor road, even though there were only one or two vehicles on the minor road. This phenomenon indicated that a great portion of the traffic delay at an intersection was caused by stopped vehicle platoons. It also suggested that the total traffic delay at an intersection might be reduced if the approaching vehicle platoons on the major road were allowed to pass through the intersection at the expense of a reasonably prolonged delay of the few vehicles on the minor road.

A study was conducted to investigate vehicle platoon characteristics and to develop control logic for timing semi-actuated traffic signals at intersections, in light of the presence of platoons on the major road based on the real conditions of rural highway corridors in Indiana. Through this study, the mathematical distributions of key variables of platoon-based traffic flows were determined, a platoon-based adaptive signal timing algorithm was developed and tested through computer simulation. It was found that the platoon-based algorithm provides better performance at such intersections than the conventional signal timing algorithms. The remainder of this paper is organized as follows. First, we review the relevant literature. Then we study the traffic flow characteristics at major–minor type of intersections and develop the platoon-based signal control algorithm. Next we introduce the computer simulation program that was developed specifically for evaluating the performance of the proposed platoon-based signal timing algorithm. Finally we evaluate the proposed algorithm through computer simulation and conclude the paper with a few remarks.

2. Literature review

Traffic flows have been studied and modeled with mathematical and statistical theories since 1930s. For example, the Highway Research Board Special Report 79 "An Introduction to Traffic Flow Theory" was published in 1964 (Gerlough and Capelle, 1964). This report was updated and expanded in 1975 (Gerlough and Huber, 1975) and in 1999 (Gartner et al., 1999). There are three main types of intersection signal controls in the literature: pre-timed signal control, semi-actuated signal control, and fully actuated signal control (e.g., Garber and Hoel, 1999; McShane et al., 1998; TRB, 2000). The signal timings of the three types of signal controls are all determined according to traffic volumes in terms of individual vehicles.

Researchers have applied various theories and methods to improve the effectiveness of traffic signal timing. Michalopoulos et al. (1980) studied traffic flow between signalized intersections and illustrated shock waves caused by traffic signals. Based on shock wave theory, Michalopoulos et al. (1981) and Michalopoulos and Pisharody (1981) developed a traffic control algorithm to minimize total delay at isolated intersections. Genetic algorithms have also been utilized for traffic control and assignment (Lee and Machemehl, 1998; Yin, 2000; Ceylan and Bell, 2004), and Allsop and Charlesworth (1977), Gartner and Al-Malik (1996) and Smith and Ghali (1990) applied deterministic traffic assignment in traffic control and signal timing. Finally, Hall (1986), Miller-Hooks and Mahmassani (2000), Chang and Sun (2004) and Yang and Miller-Hooks (2004) employed adaptive methods to address the stochastic nature of traffic network.

Although vehicle platoons have not been used as a design parameter of traffic signal timing, their effects on traffic control at intersections have been studied for a long time. Car-following models were developed (Reuschel, 1950; Pipes, 1953; Kometani and Saski, 1958; Herman et al., 1959) to describe vehicle platoon movements. Pacey (1956) studied the process of vehicle platoons at intersections. Rouphail (1988) derived a mathematical model for estimating approach delays at pre-timed, coordinated signalized intersections. Platoon dispersion and secondary flows were considered via a simplified platoon-dispersion algorithm calibrated in the TRANSYT-7F model. Rouphail (1989) also developed a set of analytical models for estimating progression adjustment factors to delays at signalized, coordinated intersection approaches. His study showed that the progression adjustment factors were sensitive to the size and flow rate of platoons. A study by the Texas Transportation Institute (Chaudhary, 2003) used a platoon identification system to optimize traffic flow. Gaur and Mirchandani (2002) developed an algorithm to identify vehicle platoons from traffic density data on highway network links. In the Highway Capacity Manual (TRB, 2000), a platoon ratio, R_p, is used to take into account the presence of platoons in signal timing at pre-timed intersections. R_p is not a direct measurement of vehicle platoons. R_p is calculated using the values of proportion of all vehicles arriving intersection during the green phase, the cycle length, and the effective green time. It is used to represent the ‘‘progression quality’’ of intersection signal timing.

These studies analyzed vehicle platoons in various aspects and noted the significance of vehicle platoons in traffic flow. However, vehicle platoons have not been utilized as a major factor in signal timing. As shown in the following sections, in this study the characteristics of vehicle platoons are utilized in signal timing to minimize traffic delays at major–minor type of intersections. It is believed that this is the first signal timing algorithm based on vehicle platoons.

3. Characteristics of platoon-based traffic flow

A vehicle platoon is defined as a group of vehicles traveling together (Highway Capacity Manual 2000). The fundamental parameter, R_p, as discussed in the manual, is so simplified that the essential characteristics of vehicle platoons are omitted. It is desirable to identify the major variables of vehicle platoons and to represent their characteristics mathematically. Detailed discussions of the characteristics of platoon-based traffic flows at the selected intersections in Indiana can be found in Jiang et al. (2003). For the purpose of clarity of this paper, the major aspects of the platoon-based traffic measures are briefly discussed below.

3.1. Key variables and critical headway

In this study, the intersections for platoon data collection were specified as intersections of a major road and a minor road with significant platoon presence on the major road. Tube traffic counters were used to obtain vehicle platoon data. As traffic variables include traffic flow rate, speed and density in the conventional traffic signal timing, four fundamental variables were selected in this study to analyze the characteristics of platoon-based traffic flows. Fig. 1 shows a

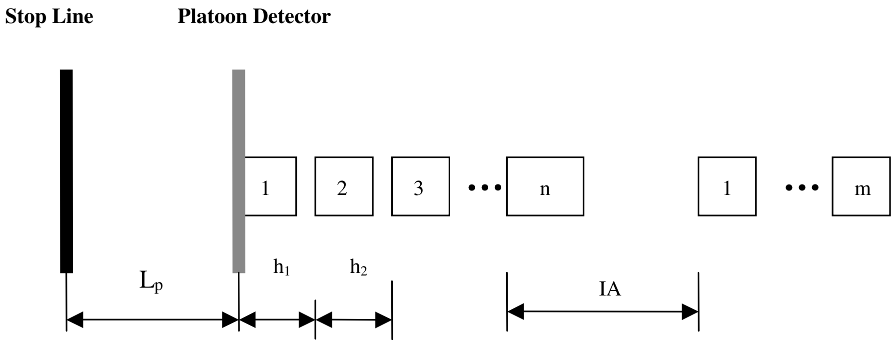

Fig. 1. Illustration of platoon variables.

graphical illustration of the four vehicle platoon variables: platoon size, platoon headway, platoon speed, and inter-arrival between consecutive platoons. The four vehicle platoon variables were chosen to identify and analyze the characteristics of vehicle platoons. Various values of platoon headway and inter-arrival between consecutive platoons can be used to determine appropriate critical headway for platoon identification and detection. Once the critical headway is determined, platoon size and platoon speed can be detected to calculate the signal timing adjustment to accommodate the approaching vehicle platoon.

L_p is the distance between the stop line and the platoon detector, the platoon size N_p is the number of vehicles in a platoon, h_p is the platoon headway (the average value of headways within a platoon), the platoon speed V_p is the average speed of the vehicles in a platoon, the inter-arrival between consecutive platoons IA is the headway between the last vehicle of the preceding platoon and the first vehicle of the following platoon. Apparently, the headway value is essential for determining whether a vehicle belongs to a platoon. That is, if a headway h_i is "small", then vehicle i and vehicle $i + 1$ belong to the same vehicle platoon. Otherwise, they are not in the same vehicle platoon. To quantify this "small" headway, a pre-determined headway value, or the critical headway as defined by Athol (1965), should be selected. May (1965) investigated individual headway distributions and concluded that vehicle headways were rarely less than 0.5 s or over 10 s at different traffic volumes. Athol (1965) investigated the effects of critical headways of 1.2, 1.5, 2.1 and 2.7 s on platoon behavior and selected a critical headway of 2.1 s corresponding to a traffic volume of 1500 vehicles per hour per lane (vphpl).

It is of great importance to select a proper critical headway since a small change in the critical headway may generate significant changes in the resultant platoon characteristics. In order to identify an appropriate critical headway, approximately 30,000 headway measurements at the selected Indiana intersections were examined with respect to critical headway values of 1.5, 2.0, 2.5, 3.0 and 3.5 s. As the critical headway increases, a greater portion of vehicles in the traffic flow will be included in platoons. Use of a large critical headway will result in too large platoon sizes and too large variances of platoon variables. In addition, detecting large vehicle platoons requires a large detection area, leading to a significant rise in the costs of detector installation and maintenance. The extreme end of a very large critical headway is that every vehicle belongs to a vehicle platoon. On the other hand, use of a small critical headway will result in small platoon sizes and insufficient platoon information. The extreme end of a very small critical headway is that no vehicle belongs to a vehicle platoon, or no platoons can be identified. Therefore, use of either a too large or a too small critical headway will not serve the purpose of an effective traffic control in terms of vehicle platoons.

To choose an appropriate value of the critical headway, the variance of platoon size should be kept at a reasonable level so that traffic data contains sufficient and accurate platoon information for signal timing. Therefore, the relationship between the platoon size and the coefficient of variation (COV) of the platoon size was examined to determine a proper value of critical headway. Approximately 30,000 traffic measurements were examined with respect to a critical headway of 1.5, 2.0, 2.5, 3.0 and 3.5 s, in order to identify the appropriate critical headway. The frequencies of platoon size are plotted in Fig. 2. It is shown that vehicle platoon observations were dominated by the two-vehicle platoons. The proportion of two-vehicle platoons increased as the critical headway decreased, accounting for about 45% of total traffic for the 3.5-s critical headway and 74% for the 1.5-s critical headway. As the critical headway increased, however, more vehicles were grouped into platoons. The proportion of large size platoons increased and that of small size platoons decreased as the critical headway increased.

Use of a large critical headway will result in a large average platoon size and require a large detection area in order to detect large vehicle platoons. Consequently, a large detection area leads to an increase of detector installation and maintenance costs. On the other hand, use of a small critical headway will result in a small average platoon size, but may not provide sufficient vehicle platoon information. Therefore, it is desired to find an appropriate critical headway so that sufficient platoon information can be obtained within a proper detection area. Fig. 3 shows the variations of the proportion of platooned vehicles with various critical headways. Also presented in Fig. 3 is the relationship between the dispersion of platoon sizes with the selected critical headways. The platooned vehicles were measured in terms of the percent of the total traffic volume, and the platoon size dispersion in terms of COV.

Fig. 3 demonstrates that as the critical headway increased, both the proportion of platooned vehicles and the platoon size dispersion increased. It appears that the 2.5-s critical headway is a turning point for both curves. When the critical headway exceeds this point, the two curves become much flatter. This implies that for the 2.5-s critical headway, the platoon characteristics may remain relatively stable. Consequently, 2.5 s was used as the critical headway for platoon

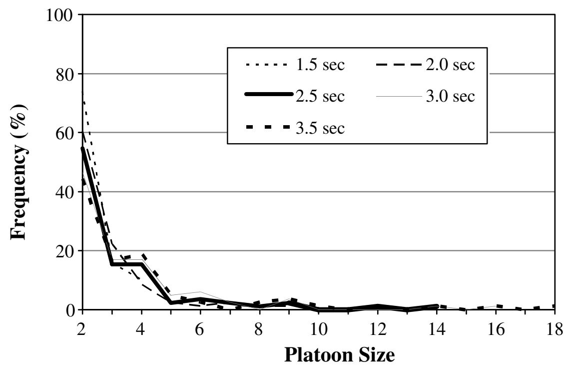

Fig. 2. Distributions of platoon size by critical headway.

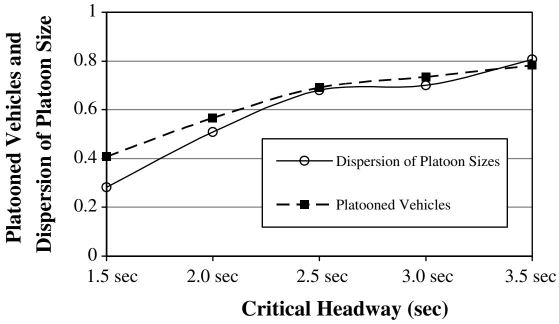

Fig. 3. Proportions of platooned vehicles and platoon size dispersion.

determination in the data analysis. This critical headway seems to be practically reasonable as it is right in the middle of the commonly assumed saturated headway (2.0 s) and the desired allowable gap (3.0 s).

3.2. Mathematical distributions of platoon variables

To study the characteristics of the platoon variables, intersections were selected for platoon data measurements on Indiana highway corridors based on a statewide traffic survey. For the purpose of this study, each of the selected intersections includes a major road with relatively high traffic volume and a minor road with very low traffic volume. A large amount of platoon-based traffic data was collected at the intersections with traffic counters placed at the calculated distances from the stop lines. Vehicle platoons were characterized using platoon size, platoon headway, platoon speed, and inter-arrival time between consecutive platoons as previously defined. Based on the frequency distributions of the four key platoon variables, three mathematical distributions were selected to fit the traffic data, including the negative exponential distribution, the normal distribution, and the lognormal distribution. The frequency distributions of the key variables were utilized in this study to develop a simulation program, so that the platoon-based signal timing could be evaluated under various traffic conditions. Detailed descriptions of various mathematical distributions can be found in many books on probability and statistics, such as Walpole and Myers (1972) and Neter et al. (1985). The Transportation Research Board (TRB) report on traffic flow theory (Gartner et al., 1999) is an excellent reference for traffic engineers on modeling traffic flows.

When analyzing vehicle platoons, a vehicle is usually classified either as a platooned vehicle or as a non-platooned vehicle. This would make it inconvenient for platoon analysis because of the random positions of the platooned vehicles and non-platooned vehicles within a traffic stream. It is therefore desired to analyze platoon-based traffic flows without separating platooned vehicles from non-platooned vehicles. This was achieved in this study by treating non-platooned vehicles as single-vehicle platoons. That is, each non-platooned vehicle is considered a special vehicle platoon with platoon size equal to one. Consequently, no vehicles are excluded from the platoon-based traffic flows and vehicle platoon sizes range from one to any number of consecutive vehicles with headways less than the critical headway of 2.5 s. By introducing single-vehicle platoons, it significantly simplifies the procedures for analyzing and simulating platoon behaviors because a

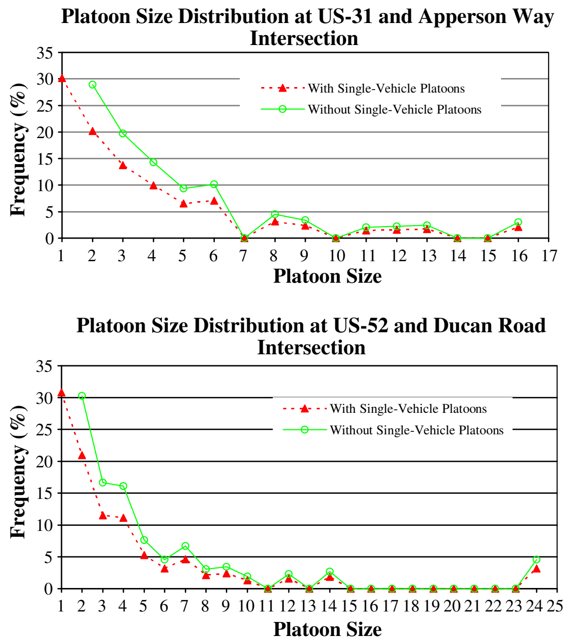

Fig. 4. Platoon size distributions at two intersections.

single mathematical distribution model can represent both platoon and non-platooned vehicles. Fig. 4 illustrates the observed platoon size distributions at two intersections during peak hours based on the critical headway of 2.5 s. One of the intersections is located at US-31 and Apperson Way in Kokomo, Indiana. At this intersection, US-31 is a divided four-lane highway with average daily traffic (ADT) of about 40,000 vehicles and Apperson Way is a two-lane minor road with low traffic volume. The other intersection is at US-52 and Duncan Road in Lafayette, Indiana. At this intersection, US-52 is a divided four-lane highway with ADT of about 30,000 vehicles and Duncan Road is a two-lane road with low traffic volume. Two distribution curves are shown for each intersection, one including and the other excluding single-vehicle platoons. The two curves for each intersection indicate that the platoon size distributions have a similar pattern either including or excluding single-vehicle platoons. This implies that treating non-platooned vehicles as single-vehicle platoons will not change the platoon variable's mathematical distribution. Fig. 4 also exhibits that approximately 70% of the vehicles traveled in groups (with platoon size of two or more).

To fit a mathematical distribution, the expected frequencies of a given platoon variable for the distribution model were calculated to compare with the observed frequencies. Several distribution models were utilized for fitting each of the platoon variables and χ^2 goodness-of-fit tests (Walpole and Myers, 1972) were conducted to determine which of the distributions could best represent the variable distribution. Through this model fitting process, it was determined that the negative exponential distribution was appropriate for platoon size distribution, the normal distribution for platoon headway distribution, the lognormal distribution for platoon inter-arrival time distribution, and the normal distribution for platoon speed distribution (Jiang et al., 2003).

4. The platoon-based signal timing algorithm

The purpose of the proposed platoon-based signal timing algorithm is to minimize the possible interruptions to platoon movements on the major road while the delays of the minor road vehicles are limited to a reasonable level. The platoon-based signal timing algorithm can be used where the traffic conditions satisfy signal warrant 2, i.e., the traffic volume on a major street is so heavy that traffic on a minor intersection street suffers excessive delay or hazard in entering or crossing the major street without a traffic signal (FHWA, 2003). In other words, the platoon-based signal control can be adopted in places where semi-actuated control would normally be utilized. A platoon detector must be installed at each approach on the major road in addition to the conventional vehicle detector as shown in Fig. 5. The platoon detector should be installed at an appropriate location that can be calculated based on the major road approach speed as discussed below.

Fig. 6 illustrates the placement of both conventional vehicle detector and the additional platoon detector. In the figure, L_p is the distance for the platoon detector, L is the distance for the conventional detector, and ΔL is the distance between the two detectors. ITE (1974) provided the following equation to determine the detector distance for detection of individual vehicles:

$$L = 0.28V(3 - UE) - 5.5 \tag{1}$$

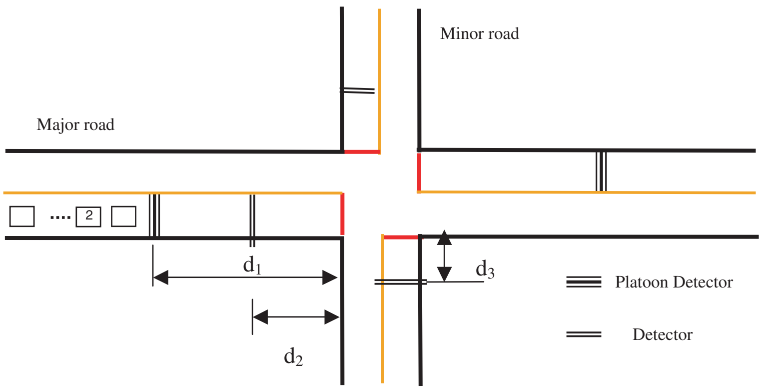

Fig. 5. Platoon detector layout at intersection.

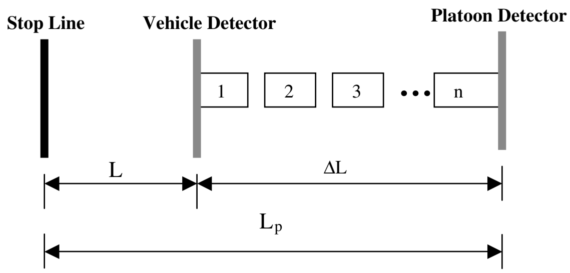

Fig. 6. Platoon detector placement.

where L = detector distance (m); V = vehicle speed (km/h); UE = vehicle interval (s); 5.5 = average vehicle length (m); 3 = desired allowable gap (s); and 0.28 = factor converting the vehicle speed from km/h to m/s.

To determine the appropriate location of the platoon detector, the distance between the conventional vehicle detector and the platoon detector ΔL, should be large enough to provide sufficient space for detecting a vehicle platoon. Based on similar concept as in Eq. (1), ΔL can be estimated in terms of platoon speed (V_{p}), platoon size (N_{p}), and platoon headway (h_{p}) as shown in Eq. (2):

$$\Delta L = 0.28 V_{\mathrm{p}}(N_{\mathrm{p}} - 1)h_{\mathrm{p}} + 5.5 \tag{2}$$

where the units for ΔL, V_{p} and h_{p} are m, km/h, and s, respectively.

L_{p} is the summation of Eqs. (1) and (2), which can be simplified as:

$$L_{\mathrm{p}} = 0.28 V_{\mathrm{p}} N_{\mathrm{p}} h_{\mathrm{p}} \tag{3}$$

where the units for L_{p}, V_{p} and h_{p} are m, km/h, and s, respectively.

To use Eq. (3), the values of L_{p}, V_{p} and h_{p} must be determined. However, the values of these variables are not constant and their representative values should be utilized to determine the detector location. With a given significant level, the platoon variables can be estimated with their statistical values, such as sample means and standard deviations. A random variable's mean, μ, can be estimated using the sample mean $\bar{x}$, the sample standard deviation S, and the sample size n with a $100(1-\alpha)\%$ confidence interval (Neter et al., 1985):

$$\bar{x} - t_{\alpha/2,n-1}\frac{S}{\sqrt{n}} \leqslant \mu \leqslant \bar{x} + t_{\alpha/2,n-1}\frac{S}{\sqrt{n}} \tag{4}$$

where $t_{\alpha/2,n-1}$ denotes the percentage point of the t distribution with $n-1$ degrees of freedom.

With Eqs. (3) and (4), the upper and lower bounds of L_{p} can be estimated in terms of the sample mean values of V_{p}, N_{p} and h_{p}. Set $\alpha = 0.05$ and $\lambda = t_{\alpha/2,n-1}$, then $\lambda = 1.96$ when sample size $n \geqslant 120$. Thus, the upper bound of the detector distance $\mathrm{UL_p}$ (in meters) can be estimated by substituting $V_{\mathrm{p}} = \bar{V}_{\mathrm{p}}(1+\lambda\frac{S_{V_{\mathrm{p}}}}{\sqrt{n}})$, $N_{\mathrm{p}} = \bar{N}_{\mathrm{p}}(1+\lambda\frac{S_{N_{\mathrm{p}}}}{\sqrt{n}})$, and $h_{\mathrm{p}} = \bar{h}_{\mathrm{p}}(1+\lambda\frac{S_{h_{\mathrm{p}}}}{\sqrt{n}})$ into Eq. (3):

$$\mathrm{UL_p} = 0.28\bar{V}_{\mathrm{p}}\bar{N}_{\mathrm{p}}\bar{h}_{\mathrm{p}}\left(1+\lambda\frac{S_{V_{\mathrm{p}}}}{\sqrt{n}}\right)\left(1+\lambda\frac{S_{N_{\mathrm{p}}}}{\sqrt{n}}\right)\left(1+\lambda\frac{S_{h_{\mathrm{p}}}}{\sqrt{n}}\right) \tag{5}$$

where $\bar{V}_{\mathrm{p}}$, $\bar{N}_{\mathrm{p}}$ and $\bar{h}_{\mathrm{p}}$ are the mean values of the platoon speed (km/h), size (number of vehicles), and headway (s) from n measured platoons, respectively; and $S_{V_{\mathrm{p}}}$, $S_{N_{\mathrm{p}}}$ and $S_{h_{\mathrm{p}}}$. are their corresponding standard deviations.

Similarly, the lower bound of the detector distance $\mathrm{LL_p}$ can be estimated as:

$$\mathrm{LL_p} = 0.28\bar{V}_{\mathrm{p}}\bar{N}_{\mathrm{p}}\bar{h}_{\mathrm{p}}\left(1-\lambda\frac{S_{V_{\mathrm{p}}}}{\sqrt{n}}\right)\left(1-\lambda\frac{S_{N_{\mathrm{p}}}}{\sqrt{n}}\right)\left(1-\lambda\frac{S_{h_{\mathrm{p}}}}{\sqrt{n}}\right) \tag{6}$$

With the installation of vehicle platoon detectors at the calculated locations, a platoon-based signal timing can be developed based on the conventional signal timing logics with some modifications. Using Eqs. (5) and (6), the Platoon Detector Distances were calculated with collected traffic platoon data at eight highway intersections. Each of the eight intersections consists of a major highway and a minor road (such as a county road with low traffic volume). The adjacent upstream

Table 1
Estimated platoon detector locations (m)

Intersection	US-52	US-31	SR-2	SR-332	SR-37	SR-66	US-27	US-30
LL_p (m)	799	817	402	412	396	396	408	597
UL_p (m)	1524	1661	869	665	857	890	835	1247

US: US highways; SR: state roads.

intersection of each selected intersection is at least 3 km away. Table 1 presents the UL_p and LL_p values at the intersections. In the table, each of the intersections is represented by the major highway at the intersection. It is demonstrated that the maximum platoon detector location is about 1.5 km, and the minimum platoon detector location is about 0.4 km. More detailed discussions on platoon detector locations can be found in Jiang et al. (2003).

In order to minimize possible interruptions to vehicle platoons, the green time on the major road should be extended to accommodate the approaching platoons. This would result in a longer waiting time for the vehicles on the minor road. To avoid unreasonable waiting time or possible large vehicle queues on the minor road, a maximum waiting time for the minor road vehicles should be established. Both the major and the minor roads should have a minimum green time to allow all vehicles potentially stored between the conventional vehicle detector and the stop line to enter the intersection. The minimum green time for the major road can be estimated by assuming a full queue between the conventional vehicle detector and the stop line (McShane et al., 1998):

$$G_{\min} = \left[4 + 2 \times \text{Integer}\left(\frac{d_2}{6.1}\right)\right] \tag{7}$$

where $G_{\min}$ = minimum green time (s); d_2 = distance between detector and stop line, respectively (m); 6.1 = assumed distance between consecutive vehicles in queue (m); 4 = assumed start-up time (s); 2 = assumed saturation headway (s).

Similarly, replacing d_2 with d_3, the minimum green time for the minor road can be calculated:

$$G_{\min} = \left[4 + 2 \times \text{Integer}\left(\frac{d_3}{6.1}\right)\right] \tag{8}$$

In a conventional actuated control system, the operation of the signal control system is based on the detections of individual vehicles (McShane et al., 1998). A green extension equal to the passage time of a single vehicle is added for each detector actuation subject to the minimum and maximum green time requirements. For the intersection shown in Fig. 5, the amount of the green time extension (Δg) is the passage time of a vehicle from the conventional detector to the stop line:

$$\Delta g = P_2 = \frac{d_2}{0.28 S_1} \tag{9}$$

This green time extension for individual vehicles can be modified to accommodate vehicle platoons:

$$\Delta g_p = P_1 + (N_p - 1) \times h_p \tag{10}$$

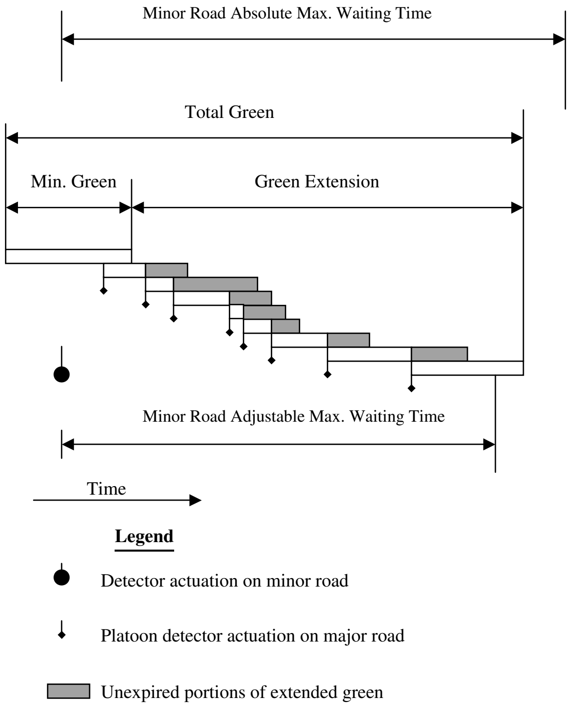

Fig. 7. Operation of platoon-based actuated major road green phase.

where Δg_p = green time extension for vehicle platoon (s); P_1 = platoon passage time (s), computed as $\frac{d_1}{0.28S_1}$; N_p = platoon size (number of vehicles in the platoon); h_p = platoon headway (s).

As can be seen in Eqs. (9) and (10), the green time extension for an individual vehicle (Δg) is a constant and the green time extension for a platoon (Δg_p) changes with platoon size and headway. In addition, when platoon size N_p is 1, Δg_p is equal to $\Delta g = P_1$. That is, non-platooned vehicles are also included in Eq. (10) as a special platoon, or a platoon with size 1. The operation of a platoon-based actuated phase on the major road is illustrated in Fig. 7. When a green indication is initiated on the major road, it will be retained for at least the specified minimum green time. When a vehicle platoon is detected during this minimum green period, if the unused portion of the minimum green time is larger than Δg_p calculated using Eq. (10), then no green time extension is needed. Otherwise, an amount of green time equal to Δg_p is added from the time of the actuation. If a subsequent actuation occurs within this green time extension, a new value of Δg_p is calculated and is added to the green from the time of the actuation. It should be noted that Δg_p is not a constant value and it must be calculated for each vehicle platoon detected. This process continues until the green is terminated under one of three conditions: (1) a green extension time elapses without additional actuation, or (2) an actuation occurs after the minor road adjustable maximum waiting time been reached, or (3) a new green time extension would make the minor road waiting time exceed the minor road absolute maximum waiting time.

Compared to the conventional actuated signal timing (JHK & Associates, 1991), this platoon-based actuated signal control is similar to the individual-vehicle-based actuated signal control in many aspects. However, the platoon-based actuated signal control algorithm possesses the following distinctive properties:

1. A platoon detector must be installed on the major road at an appropriate distance from the stop line.
2. A green time extension for the platoon-based control, Δg_p, varies with platoon size and headway, while that for the conventional control is a constant value.
3. The adjustable maximum waiting time for the minor road may be exceeded to allow the approaching platoon to pass the intersection under the condition that the platoon is detected before the adjustable maximum waiting time is reached and the new green time extension would not make the minor road waiting time exceed the absolute maximum waiting time. That is, green time may be added for the approaching platoon even if this added green time will extend beyond the adjustable maximum waiting time. The last green time extension in Fig. 7 illustrates a situation that the adjustable maximum waiting time is exceeded to allow a vehicle platoon to pass the intersection. This is different from the conventional control in which the current green phase is terminated as soon as the maximum waiting time on the conflicting phase is reached.
4. The absolute waiting time for the minor road is used to avoid unreasonably long waiting time for the vehicles on the minor road.

The purpose of this platoon-based actuated control algorithm is to minimize possible interruptions to the vehicle platoons and thus to reduce traffic delays at intersections. A platoon detector must be installed at a sufficient distance from the stop line so that pertinent information on vehicle platoons, such as platoon size and average headway, can be obtained. A green time extension is calculated for each approaching vehicle platoon subject to specified minimum green time for the major road and adjustable and absolute maximum waiting times for the minor road. It is unique that, in the platoon-based signal control, different vehicle platoons generally require different green time extensions because of their platoon characteristics. In order to avoid a vehicle queue being stopped when switching the green phase to the minor road, the last green time extension of a major road green phase might extend beyond the specified adjustable maximum waiting time as necessary.

5. A simulation program for platoon-based signal control

There exist many traffic simulation software packages, such as TRANSYT-7F (Wallace et al., 1991) and CORSIM (FHWA, 1998). The existing simulation programs can be employed to analyze traffic signals for both urban streets and rural highways. However, they simulate vehicle flows based on the distributions of individual arriving vehicle at the intersections. No studies or documents were found to address platoon-based signal control simulations. In order to efficiently evaluate the proposed platoon-based signal control algorithm, a computer simulation program was developed based on the characteristics of traffic flows at the selected intersections in Indiana in terms of vehicle platoons. This simulation program, named TraSin, can be used to evaluate traffic delays under platoon-based signal control at given intersections. The simulation program, written with Microsoft Visual Basic 6.0, consists of three major subprograms, including traffic flow generation, platoon detector location selection, and traffic delay evaluation.

As discussed above, the four key platoon variables, i.e. platoon size, platoon headway, platoon inter-arrival time, and platoon speed, follow the negative exponential distribution, the normal distribution, the lognormal distribution, and the normal distribution, respectively. To simulate platoon-based traffic conditions, random vehicle flows must be generated in terms of the four platoon variables with their corresponding mathematical distributions. This can be achieved by using computer generated random numbers with desired mathematical distributions. Similar to many other computer languages, Visual Basic contains built-in subroutines for generating uniformly distributed random numbers between 0 and 1. In order to realistically and accurately simulate a platoon variable, a uniformly distributed random number must be converted to a number following a desired distribution. In TraSin, generation of platoon-based traffic flows is achieved by generating uniform random numbers and then converting these random numbers to the numbers following appropriate distributions. Pooch and Wall (1993) present the procedures for conversions of random numbers from uniform distribution to other distributions.

By generating random numbers with desired distributions, traffic flow on the major road can be simulated in terms of vehicle platoons characterized by platoon size, platoon headway, platoon speed, and inter-arrival time. The simulation is based on a mesoscopic model. That is, it generates vehicle platoons with various values of platoon sizes, headways, speeds, and inter-arrival times. However, variations within each vehicle platoon, such as vehicle speeds and headways, are not captured. Instead, the average values of vehicle speed and headway within a platoon are used to represent the platoon speed and headway. Since this simplification does not change the relative temporal and spatial positions of the vehicle platoons in the traffic steam, it will not affect the characteristics of the platoon-based traffic flows. Traffic flow on the minor road can also be generated according to a series of randomly generated vehicle headways. As often used for low traffic volume flows (Rouphail et al., 1999), the negative exponential distribution is applied for minor road traffic flow in the simulation. As illustrated in Fig. 8, vehicles arriving at a specific intersection can be presented in a unique time sequence.

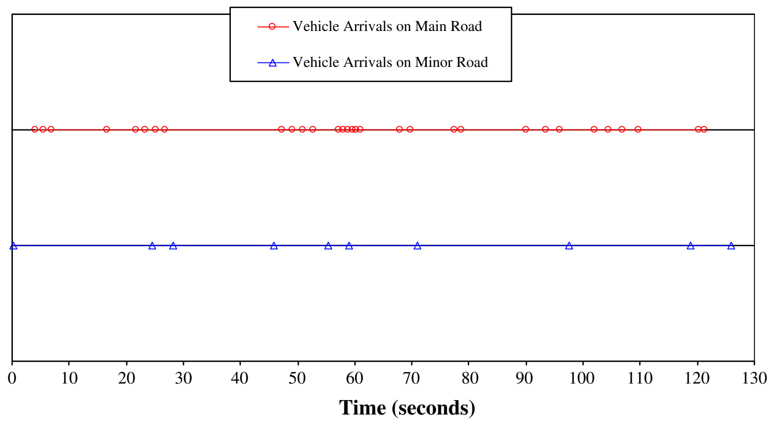

Fig. 8. Simulated vehicle arrivals at intersection.

6. Simulation analysis of the proposed platoon-based signal control algorithm

The computer simulation program, TraSin, was developed to address the specific issues associated with use of the platoon-based signal timing at intersections. With this simulation program, users can evaluate potential system performance under user specified traffic conditions. Sensitivity analysis can be conducted to examine the impact of design parameters on the performance of platoon-based signal control in terms of vehicle delays. As application examples, TraSin was utilized to simulate the performance of platoon-based traffic control with specified traffic volumes at an intersection. The effects of traffic flow rate and maximum waiting time on the traffic delays are discussed in the following based on the simulation results.

6.1. Effect of minor road traffic flow rate

To examine the effect of minor road traffic flow rates on traffic delays, computer simulations were conducted using TraSin and CORSIM with assumed intersection traffic conditions. In the simulation analysis, it was specified that the traffic flow rate on the major road was 1000 vehicles per hour (vph) and that the maximum waiting time for the minor road was 90 s. The traffic delays were calculated at different levels of minor road traffic flow rates with both platoon-based (TraSin) and individual-vehicle-based (CORSIM) simulations. Three types of individual-vehicle-based signal controls, i.e. pre-timed, semi-actuated, and actuated controls, were simulated with CORSIM. In pre-timed control, a preset sequence of signal phases is utilized in repetitive order. In semi-actuated control, vehicle detectors are located on the minor road only. The signal is set such as that the green is always on the major road unless a minor road actuation is received. Once actuated, the green remains on the minor road if additional actuations are received within a preset time interval, subject to a maximum green limitation. In actuated control, all approaches to the intersection have vehicle detectors. Each phase is subject to a minimum and maximum green time. A phase is terminated when there are no further actuations for the phase within the specified time interval, or the maximum green time has been reached (TRB, 2000; McShane et al., 1998).

Both TraSin and CORSIM were used with the same traffic data in order to compare the effectiveness of the different control strategies. Figs. 9 and 10 show the traffic delays on the major road and minor road at different levels of minor road traffic flow rates. Fig. 9 indicates that on the major road the pre-timed control would result in the highest delay and the platoon-based control would produce the lowest delay. As the minor road traffic flow rate increases, the simulated delay for pre-timed control remains stable, and the simulated delays for the other types of signal controls increase. Compared to the conventional signal control methods, the platoon-based signal control produced much lower traffic delay on the major road (Fig. 9) at the expense of higher traffic delay on the minor road (Fig. 10). Since the purpose of the platoon-based signal control is to reduce the total delay at an intersection, the performance of the signal control should be evaluated in terms of the total delay at the intersection. Fig. 11 displays the simulated total delays at the intersection for all signal control modes in terms of vehicle-seconds per hour. The figure shows that the total delay increases as the minor road traffic volume increases and that the platoon-based signal control yields the lowest total delay among the four control methods. The simulation results indicate that the proposed platoon-based signal control mode can indeed outperform the conventional signal control methods.

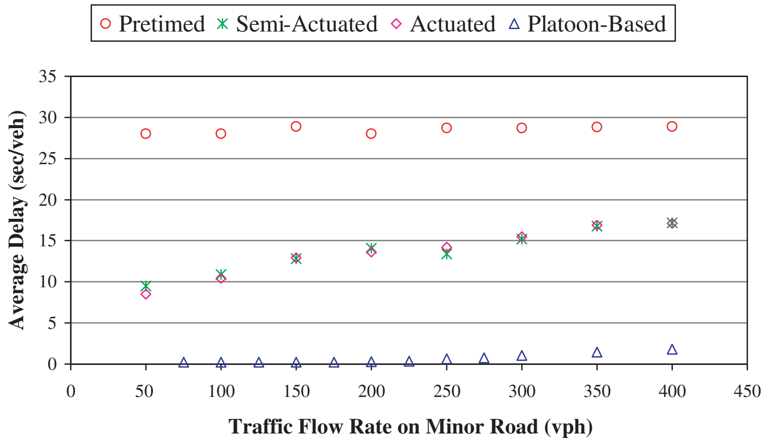

Fig. 9. Simulated average traffic delays on major road.

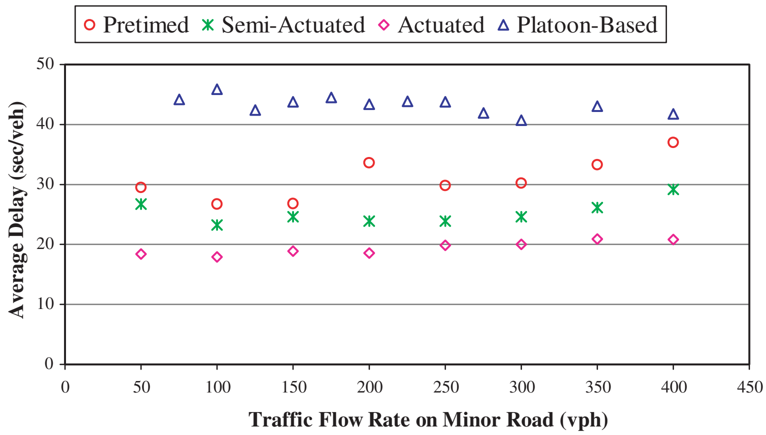

Fig. 10. Simulated average traffic delays on minor road.

6.2. *Effect of minor road maximum waiting time*

The adjustable maximum waiting time for the minor road in platoon-base control is used so that it may be prolonged under certain conditions to allow approaching vehicle platoons on the major road to pass the intersection. It is the allowed minor road red time between the first vehicle detector actuation on the minor road and the termination of the red phase on the minor road if there is no approaching vehicle platoon is detected on the major road. However, if a vehicle platoon is detected on the major road, the adjustable maximum waiting time can be prolonged to allow the approaching vehicle platoon to pass the intersection. The absolute maximum waiting time is specified to avoid unreasonable long waiting time on the minor road. The simulation program can be used to analyze the effect of maximum waiting time on traffic delays.

To examine the effect of maximum waiting time, simulations were conducted with TraSin to estimate traffic delays for different maximum waiting times. Two levels of minor road traffic

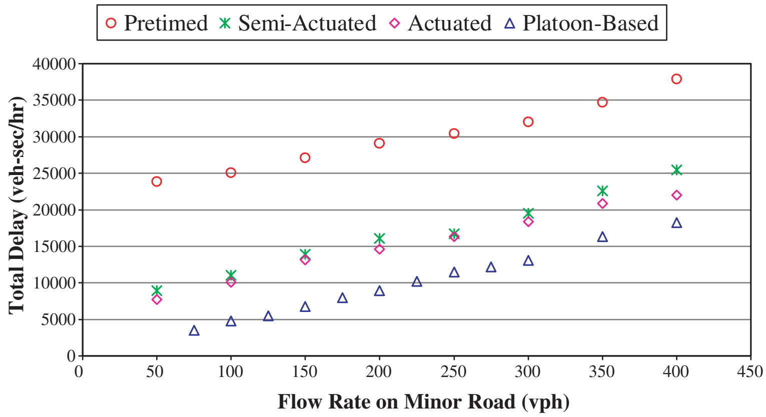

Fig. 11. Total delays at the intersection.

volumes, 30 vph and 100 vph, were utilized for the simulations while a major road traffic volume of 1000 vph was assumed. The simulated traffic delay values are plotted in Figs. 12–14 for minor road traffic volumes of 30 vph and 100 vph with adjustable maximum waiting time values between 30 and 180 s. Each point in the figures represent the average delay of 15 simulations. Each absolute maximum waiting time was specified as the adjustable maximum waiting time plus 20 s. For comparison purpose, the simulated delays are expressed as average delays in terms of seconds per vehicle (s/veh). Figs. 12 and 13 show how the average delays on the major and minor roads change with specified adjustable maximum waiting time on the minor road. The patterns of delay changes in Figs. 12 and 13 are as expected because more vehicle platoons on the major road are allowed to pass the intersection without stopping while the vehicles on the minor road would have to endure a longer waiting time. That is, the delay reduction of the major road is achieved at the expense of the delay increases of the minor road. The two figures also show that the average de-

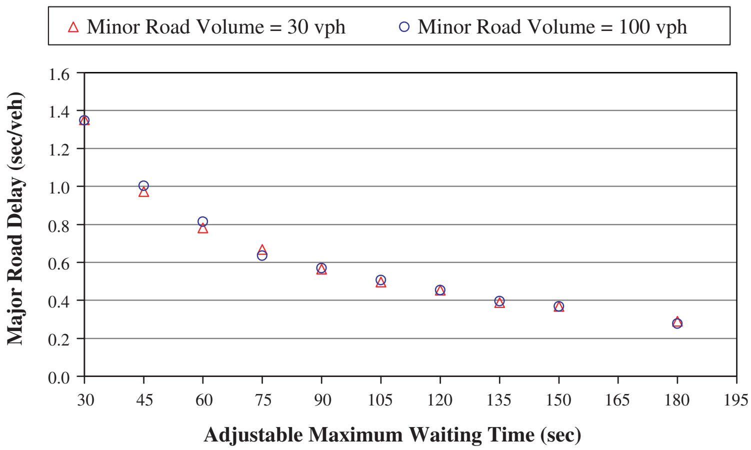

Fig. 12. Simulated average delay on major road.

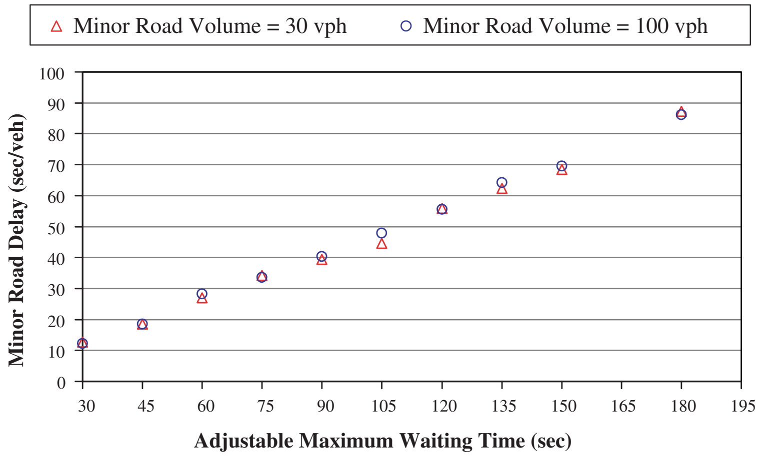

Fig. 13. Simulated average delay on minor road.

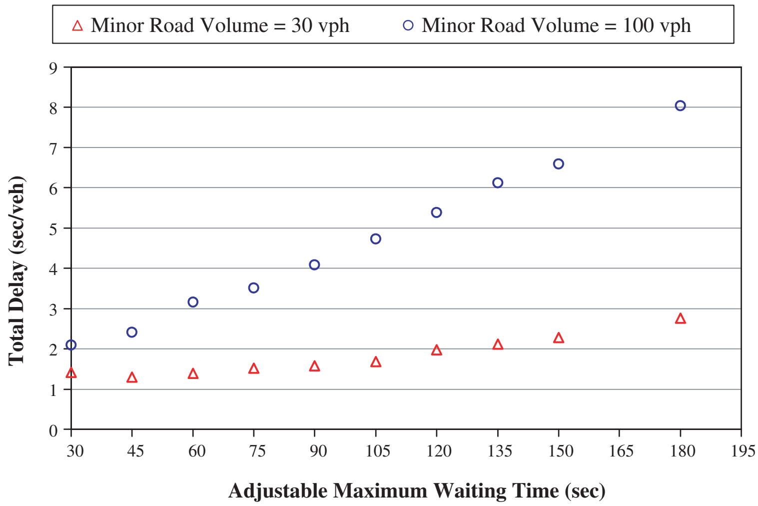

Fig. 14. Simulated total average delay.

lays for the two levels of minor road traffic volume are not significantly different and follow very similar patterns.

Fig. 14 illustrates the total average delay at the intersection. For the minor road traffic volume of 100 vph, as the adjustable maximum waiting time increases, the total average delay increases. However, for the minor road traffic volume of 30 vph, the total average delay decreases first and then increases when the adjustable maximum waiting time is greater than 45 s. This implies that 45-s adjustable maximum waiting time will result in a minimum total average delay for the minor road traffic volume of 30 vph. In addition, it can be seen in Fig. 14 that the curve for 100 vph has a greater slope than that for 30 vph. This means that the effect of maximum waiting time on traffic delay increases as traffic volume on the minor road increases.

It should be pointed out that choosing a maximum waiting time involves a great deal of engineering judgment and experience. Many factors, such as intersection location, traffic flow rates, and drivers' endurance of waiting time, must be considered and often compromised in determining an appropriate maximum waiting time. Currently, there is no an agreeable procedure for selecting an optimal value of waiting time. Nonetheless, as shown by the simulation results, simulation analysis should provide a basis for traffic engineers to make better engineering decisions on maximum waiting time.

7. Conclusions

Through this study, traffic flow on Indiana rural corridors was analyzed in terms of vehicle platoon movements. Traffic data was collected at selected locations to capture the characteristics of vehicle platoon movements. With the platoon data, the distributions of the vehicle platoon variables were determined. These distribution models were then utilized to formulize platoon generating patterns and to derive a platoon-based control algorithm. In addition, a platoon simulation program was developed as a tool to analyze platoon-based signal controls under different traffic conditions.

This paper introduced and defined the four key variables of platoon-based traffic flow—the platoon size, the average headway of vehicles within the platoon, the platoon speed, and the inter-arrival time between consecutive platoons. These four variables were utilized as a basis for the development of the platoon-based signal control algorithm and simulation program. The distributions of different vehicle platoon measurements were determined through statistical analysis and tests. It was found that the platoon sizes follow the negative exponential distribution, the average headways of vehicles within vehicle platoons have normal distributions, the inter-arrival times between consecutive platoons fit the lognormal distributions, and the platoon speeds suit the normal distributions. The distributions of these platoon measurements are essential for modeling traffic flow with platoons and for developing platoon simulation program. More importantly, they provide a foundation with a new point of view to analyze traffic flows in terms of vehicle platoons. The platoon-based signal timing is proposed to minimize traffic delays while the waiting time for vehicles on the minor road was limited to an endurable level. The computer simulation program, TraSin, was developed based on the platoon-based signal timing and the distributions of platoon measurements. With this simulation program, the potential system performance can be evaluated in terms of traffic delay. It provides an analytical tool to study various effects of platoon characteristics under user-specified traffic conditions.

It was shown with simulation results that the platoon-based signal control yielded the lowest traffic delay compared to the conventional signal control methods calculated by CORSIM under various traffic conditions. This indicates that the proposed signal control algorithm is effective in reducing traffic delays at intersections with low traffic volume on the minor road and relatively high traffic volume on the major road. It was found in this study that there exist many intersections with such traffic characteristics in rural or semi-urban areas through Indiana. At this type of intersections, it was observed that about 70% of vehicles travel in groups. Therefore, the opportunity for implementation of platoon-based signal control is tremendous and the potential benefit can be significant.

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