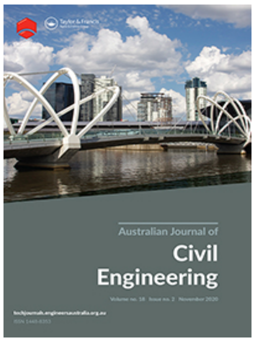

Australian Journal of Civil Engineering

ISSN: (Print) (Online) Journal homepage: https://engineersaustralia.tandfonline.com/loi/tcen20

Review and evaluation of methods for estimating delay at priority junctions

Mohammad Ali Sahraei & Elnaz Akbari

To cite this article: Mohammad Ali Sahraei & Elnaz Akbari (2020) Review and evaluation of methods for estimating delay at priority junctions, Australian Journal of Civil Engineering, 18:2, 126-139, DOI: 10.1080/14488353.2020.1743591

To link to this article: https://doi.org/10.1080/14488353.2020.1743591

AUSTRALIAN JOURNAL OF CIVIL ENGINEERING
2020, VOL. 18, NO. 2, 126–139
https://doi.org/10.1080/14488353.2020.1743591

Taylor & Francis
Taylor & Francis Group

Review and evaluation of methods for estimating delay at priority junctions

Mohammad Ali Sahraei [a] and Elnaz Akbari [b,c]

[a]Faculty of Civil Engineering, Department of Geotechnics & Transportation, Universiti Teknologi Malaysia (UTM), Johor, Malaysia; [b]Department for Management of Science and Technology Development, Ton Duc Thang University, Ho Chi Minh City, Vietnam; [c]Faculty of Electrical & Electronics Engineering, Ton Duc Thang University, Ho Chi Minh City, Vietnam

ABSTRACT

The Level of Service (LOS) for a priority junction is identified by the delay calculated for each movement. Because of the complexity of the traffic operations, various methods have been studied to evaluate more precise delay. This paper reviews benchmarks of these methods developed over past 55 years from Tanner's method, 1962, until now. The precision of these techniques is examined using real data from two priority junctions, i.e. three-legged formed, with multilane on the major and minor road. About 9-h data were gathered for each junction from morning until evening using video camera technique. This, in total, provided 18 hdata recording on normal working days. Then, observed delays incurred on minor road vehicles are compared with approximated delays from reviewed techniques. The study found that Brilon's and Troutbeck's methods that are the most popular methods provide consistent and closest calculated delay at priority junction. Additionally, Highway Capacity Manual (HCM) is an appropriate method only during low saturation where volume over capacity is less than 0.9.

ARTICLE HISTORY
Received 25 September 2018
Accepted 12 March 2020

KEYWORDS
Delay; priority junction; video camera; observed delays

1. Introduction

Generally, priority junctions can be divided into two forms, namely All Way Stop Controlled (AWSC) and Two-Way Stop Controlled (TWSC). According to the Highway Capacity Manual (HCM) 2000 (TRB 2000) and HCM 2010 (TRB 2010), TWSC is described as a form of traffic control at a junction where a motorist on a minor road or a motorist turning right from a main road waits for a gap at the main road traffic prior to carrying out a manoeuvre. On the other hand, AWSC refers to a junction with stop signs at the approaches. Regarding this matter, it should be understood that the driver's decision to proceed is dependent on the regulations on the road as well as the traffic situations of other approaches.

On another note, minor street approaches are generally known as driveways or side roads that provide entry to business or residential regions. The main street through traffic is in a free-flow state whereby the vehicles that turn left and right into the driveways or side roads are bound to cause a minor effect on the traffic speed. In most cases, it should be noted that there should be no delays for the main street through traffic considering that it passes through priority junctions. As suggested by Zhou et al. (2006) the delays of vehicles making left and right turn out of the side roads are the major elements that must be considered in identifying the operational performance and Level of Service (LOS) of the priority junctions.

The control of vehicles at junctions is regarded as a complicated and highly interactive process considering that each motorist tends to generate their own individual decisions in performing an important manoeuvre. Moreover, it is necessary to note that an individual's perceptions of speed, distance, and car performance play a significant role in this situation (Kaysi and Abbany 2007). In addition, each motorist must find a safe time for the movement by quickly observing existing traffic and traffic signs. Consequently, priority junctions generate a particular issue for potential accidents of vehicles which usually appear from the minor road considering that vehicles from the major road are the priority (Brilon, Troutbeck, and Tracz 1997).

The LOS for a priority junction is identified by the calculated or assessed delay for each movement. The LOS requirements for priority junctions are relatively distinct in accordance with the requirements utilised in signalised junctions, mainly because distinct transportation facilities generate distinct driver perceptions. The expectancy is that the purpose of the signalised junction is to handle greater traffic volumes as well as encounter higher delay compared to a priority junction. According to HCM 2000 (TRB 2000) and HCM 2010 (TRB 2010), the delay encountered by a driver is composed of a range of elements that is associated with geometrics, control, incidents, and traffic. In addition, it should be noted that control delay consists of preliminary deceleration delay, queue

CONTACT Elnaz Akbari elnaz.akbari@tdtu.edu.vn Department for Management of Science and Technology Development, Ton Duc Thang University, Ho Chi Minh City, Vietnam and Faculty of Electrical & Electronics Engineering, Ton Duc Thang University, Ho Chi Minh City, Vietnam

move-up time, stopped delay, and last acceleration delay. Furthermore, control delay with regard to field measurements is identified as an overall delay period at the time an automobile stops at the end of the queue to the time the automobile leaves the stop line. Regarding this matter, it is important to acknowledge the three essential factors related to the delay, namely capacity, follow-up time, and critical gap.

HCM 2010 (TRB 2010) describes a critical gap as the shortest period among successive main road automobiles that allows a minor road automobile to conduct a manoeuvre. Accordingly, this description clearly explains that the critical gap of a motorist is situated between the biggest approved gap and the declined gap. Furthermore, HCM 2010 (TRB 2010) likewise identified the follow-up time as the period among the departures of two successive automobiles at the minor road that utilise the identical gap under a situation of continuous queuing. Apart from the fact that follow-up time can easily be calculated through the site study; however, critical gap values can only be calculated depending on the gap time that was approved and declined by motorists. In addition, HCM 2010 (TRB 2010) refers capacity as the greatest sustainable traffic flow rate whereby automobiles are expected to traverse a place or consistent area of a roadway or lane throughout a particular period of time under a given geometric, roadway, environmental, traffic, and control situations.

Over the years, a considerable amount of studies have been established along with several methods for computation of delay at a priority junction. Nevertheless, a few of the methods require complicated computational processes that could only be obtained by utilising a laptop or computer although a number of those methods are really easy to utilise. The current paper aims to provide a comprehensive review of techniques for calculating delay at priority junctions. However, it is important to note that the following techniques consist of a set of advantages and limitations. Therefore, the precision of the outcomes of these techniques will be examined by utilising real data.

2. Theory of traffic delay

In a general sense, the delay is identified as the excess time taken in a transportation facility compared to a reference value. In this regard, it is described as the distinction between the times consumes to traverse a road section under ideal situations and the real travel time. Accordingly, a delay is considered as one of the most significant evaluations of the efficiency of priority junctions as recognised by road users.

HCM 2000 (TRB 2000) and HCM 2010 (TRB 2010) are utilised in the USA as well as a few other countries as a standard for assessing and analysing different transportation facilities such as priority junctions. Meanwhile, sign controlled junctions are also known as priority junctions with properly identified priority rules. For instance, a stop sign on the minor road indicates that it is compulsory for the vehicles on the minor road need to stop for a moment and wait until an acceptable gap is accessible.

Regarding this matter, it is important to note that different methods for calculating delay based on different theories can be found. One of the first delay models were established by Kimber and Hollis (1977) which suggested the relationships between traffic intensity and delay on the minor streets at priority junctions. Meanwhile, Troutbeck (1986) established a delay formula at priority junctions as a function of the subsequent variables: the degree saturation of the minor road, the average traffic delay when the minor road flow is low, and a form factor that quantifies the impact of queuing in the minor road. Khattak and Jovanis (1990) conducted a comparison between two principal methods which are deterministic and probabilistic for delay and capacity evaluation. Madanat, Cassidy, and Wang (1994) developed a probabilistic delay technique by highlighting the gap-acceptance behaviour of motorists at priority junctions which is appropriate for right-turning manoeuvre (right-hand driving system) at a T-junction. In addition, Heidemann and Wegmann (1997) provide an explanation on a standard queuing technique model for traffic flow at a priority junction.

Akcelik, Christensen, and Chung (1998) investigated three current delay techniques at priority junctions by further demonstrating the differences in the outcomes. Accordingly, they further suggested the improved styles for these techniques which are dependent on the simulation application. Kaysi and Alam (2000) investigated the impact of motorist behaviour on delay (experience, aggressiveness, and impatience) at priority junctions. Meanwhile, Tian et al. (2001), based on the simulation aspect, established a general form of the traffic delay technique which appears to provide significant outcomes compared to the basic exponential type of delay-total traffic volume at AWSC junctions. Apart from that, Luttinen (2004) established the relationships between traffic flow and delay on minor streets, while Chodur (2005) researched the capacity techniques and variables for urban priority junction. Next, Chandra, Agrawal, and Rajamma (2009) introduced a service delay method which is dependent on the microscopic evaluation of traffic delay under mixed traffic situations. In their study, it was discovered that the percentage of heavy composition in the conflicting traffic has a considerable effect on the service delay. In addition, the Transportation Research Board (TRB 2000, 2010) in several editions of the HCM have highlighted the process for calculating delay at priority junctions.

In the transportation and traffic field, micro-simulation technique developed by a number of researchers such as Fang and Elefteriadou (2005), Stevanovic and Martin (2008), Chevallier and Leclercq (2009), Chen et al. (2010), Caliendo and Guida (2012, 2014), Caliendo and De Guglielmo (2012), and Yousif, Alterawi, and Henson (2012) and has been frequently utilised for calculating not only delay at priority junctions but also for determining the performance of various forms of junctions. However, the utilisation of this particular application for more complicated geometric configurations that is comprised of one or more adjacent single-junction have not been thoroughly investigated by past studies.

Apart from that, the control delay definition described above further suggests several factors that may affect motorist behaviour. Consequently, this may influence the delay of minor movement including the storage length of such lanes, the traffic flow rate at a junction, geometric features on the driveways, and junction sight distance. In reference to these factors, different techniques have been established to calculate delay values at priority junctions which are further described in the following section.

3. Methods of calculating delay at priority junction

In the case of traffic delay estimation, scholars had successfully established a wide range of methods for obtaining the value of delay at priority junctions. Accordingly, this section will consider several existing techniques that will be discussed in detail as follows:

3.1. Tanner's method

Tanner (1962) was one of the initial founders who attempted to utilise a queuing theory and a steady-state situation for calculating delay on the minor street at priority junctions. The focus of the research was on the average delay of vehicles at a minor road of a junction whereby the traffic on the main movement has a definite priority. Specifically, this method is dependent on the 'gaps' and 'blocks' on the major street. In other words, it should be clearly understood that the delay to any specific minor movement vehicle might be altered. However, the delay remains the same since their arrivals are independent of the situations of blocks. Moreover, the influence on the minor street traffic is identical as if the bottleneck is expanded to a large length away from the junction even though the procedure assumes a bottleneck on the main street at the junction (Tanner 1962). In this regard, some limitations of this method are clearly presented in Table 1.

3.2. Hawkes's method

Hawkes (1965, 1966) developed a method that measures the delay to a minor street including mixed right- and left-turning manoeuvre from the minor road using the shared lane which seems to confront the main street. Accordingly, right-turning movement (right-hand driving system) commonly waits for gaps of enough length in the near side, whereas left-turning manoeuvre should wait for mixed gaps size in the far and near side. In the presumption of fixed critical gaps and move-up times, the right-turning manoeuvre was found to be lower than the fixed gap for left-turning movements. On the other hand, by presuming random arrivals for minor and main street Hawkes (1965, 1966) utilised a method known as Markov chain to consider the case of vehicles arriving at the minor road. In this regard, probabilities of delay for each minor street departure can be acquired in the following four probable activities: a left-turning vehicle followed by a left

Table 1. Summary of several methods for delay calculation.

Source	Method	Advantages (A)/Limitation (L)/Findings (F)
Tanner (1962)	Utilise queuing theory and a steady state situation for calculating the average delay.	• Complicated formula that is not valuable for user (L), • This method has limited use in practice (L), • It does not consider the situation of multiple lanes on the main street (L), • It does not take into account the turning movements (L).
Hawkes (1966)	Utilising a method known as markov chain.	• Well agreement between the observations and model were acquired (A).
Weiss (1969)	Probability Density Function (PDF) of delay was identified.	• Average delay for vehicles on the minor street could be raised substantially by the existence of heavy vehicle leading to the queuing on the main traffic stream (F).
Troutbeck (1986)	Improved Tanner's delay.	• Assumed that motorists were homogeneous and consistent and provides for the influence of bunching in the main road. Therefore, it is a little more realistic than Tanner's model (A), • Provide support to designers of priority junctions (A).
Kimber and Hollis (1978), and Kimber et al. (1986)	Using queuing models (M/G/1) based on the Pollaczek-Khintchine.	• This approach is not applicable for estimation total delays (L), • It is essentially practical for queue and geometry delay at priority junctions (A).
Kyte et al. 1991	A linear formula was recommended for minor road service time.	• Did not examine how this method can be utilised in calculating total delay (L).
Madanat, Cassidy, and Wang(1994)	Utilised in a stochastic queuing technique to create and demonstrate minor-street vehicle delay.	• This method is suitable for delay estimation in a very different manner from any queuing technique (A), • The model has only been created for a right turns at TWSC junction utilising data gathered from a single area (L).

turning arrival, (LL), a left-turning vehicle followed by a right-turning vehicle, (LR); and likewise, (RL) and (RR). In this case, for left-turning manoeuvre from a minor road, Hawkes assumed that the vehicles are encountered with a mixed total flow and random process of main flow arrivals. In reference to this method, Hothersall and Salter (1981) utilised Hawkes's model to a variety of priority junctions. Accordingly, they further provided a comparative analysis between the predicted result of delays and actual data set. The advantage of this method is described in Table 1.

3.3. Weiss's method

The method established by Weiss (1969) is concerned with the issue of an average delay from the minor street as a single arriving vehicle, while major street traffic is comprised of a mixture of vehicles and trucks. Under Weiss' presumptions, the existence of large trucks may create some specific queues length of vehicles on the major street. Based on this presumption, no crossing or merging can potentially occur throughout that period considering that the main road movements are recognised by blocks of vehicles driven by a heavy vehicle.

Presuming the negative exponential distribution for headways between non-queued main road vehicles and within the distance between a vehicle and heavy vehicle as well as the function of gap acceptance, Weiss (1969) found a way to determine average delay by utilising the passing of heavy vehicles throughout the major street. At the end, the values of average delay can be determined based on the value of the proportion of heavy vehicles on the major road, value of critical gap, the average range of vehicles inside a block, the average value of headway between non-queued vehicles and a vehicle followed by a heavy vehicle, and finally the average value of headway between consecutive vehicles inside a block.

3.4. Troutbeck's method

Troutbeck (1986) improved Tanner's delay formula by identifying the effect of bunching on the main road. Specifically, Troutbeck (1986) established several equations for the purpose of calculating average values of delay as a function of the minor street degree of saturation (minor road entrance flow/entrance capacity). Apart from that, he also developed a form factor which quantifies the impact of queuing in a single minor road as well as when the minor road headways are Poissonian. Regarding the above development, Troutbeck (1986) assumed that the headways in the main road share the same distribution provided by Cowan (1975). In this regard, the longer bunches results in a longer block on the main street, which consequently leads to longer delays on the minor street. Table 1 clearly explains a number of advantages of this method.

3.5. Kimber's method

Kimber and Hollis (1978), and Kimber et al. (1986) created a framework that estimates geometric delay and the queuing delay at a priority junction. In Kimber and Hollis (1978), and Kimber et al. (1986) believed that it is not feasible to assume that steady-state queuing technique offers sufficient ability to calculate the total delay at a priority junction. As a result, it was stated that queuing models (M/G/1) developed for predicting delays by the Pollaczek-Khintchine (Cox and Miller 1977) is able to provide a powerful set of approximate time-dependent relationships. Overall, the limitations and advantages of this method are further explained in Table 1.

3.6. Heidemann's method

Heidemann (1991) created a process for the estimation of delay on the minor street at priority junctions. In particular, this formula was established as a function of degree saturation by creating a queuing method as M/G2/1 system. Specifically, it should be noted that 'M' indicates the arrival process is Poisson (which has the Markovian property), followed by 'G2' that indicates the presence of two (2) general service time distributions, and '1′ postulates one (1) service facility backing of the stopping line. In particular, both the minor street and the main street vehicles are assumed to arrive at the junction based on a Poisson process. Heidemann (1991) assumed that a minor street vehicle starts to be served when it arrives at the first waiting position. Accordingly, the main street vehicles tend to operate based on the following rule: a minor street vehicle that is being served gets into the junction by traversing the stopping line, if and only if it identifies a time-headway in the mainstream that is not less than the 'critical time-headway'.

3.7. Kyte's method

Kyte et al. (1991) developed a set of preliminary empirical methods for the purpose of calculating delay at priority junctions. A linear formula was recommended for minor road service time which is dependent on the volume of the conflicting approaches. In addition, the total delay for priority junctions was divided into two elements, namely service delay and queue delay. Accordingly, queuing delays are identified to be generally influenced by the traffic volume on the subject approach, while service delays are influenced by the conflicting flow on the major road. Finally, Kyte et al. (1991) discovered that a few factors seem to have a significant effect on the minor road delays which include the length of the accepted gap, the directional movements of the subject vehicle, and conflicting traffic stream on the major road. The limitation of this method is provided in Table 1.

3.8. Madanat's method

Madanat, Cassidy, and Wang (1994) established a probabilistic delay technique at priority junctions which is dependent on the gap acceptance behaviour of motorists. Nevertheless, it should be noted that this is appropriate only to right-turning movements (right-hand driving system) performing an exclusive right-turn lane on the minor road of a priority junction.

On a specific note, this method utilises logit modelling to forecast the probability of randomly selected vehicles in accepting a specified gap in the conflicting traffic stream, particularly on the basis of the characteristics of the gap. Accordingly, the gap acceptance performance is utilised in a stochastic queuing technique for the purpose of creating and demonstrating minor-street vehicle delay. The reasonable agreement between the predicted and actual average delay signifies that the suggested analysis method offered in Madanat's research is more straightforward and has higher applicability than other earlier methods in the delay forecasts. Overall, the limitations and advantages of this method are described in Table 1.

3.9. Tian's method

Zongzhong et al. (1997) established a method associated with an average delay which is dependent on queuing theory. In addition, the method was dependent on an extensive database gathered throughout the research work. In this regard, the suggested technique was tested by Tian (1997) by utilising the data extracted from a priority junction which was videotaped for around 2 h.

Field observations confirmed that some minor road left-turn vehicles (right-hand driving system) would cross the nearest lane and stop in the median place in the wait of joining the main road traffic, thus producing in a two-stage gap acceptance procedure. However, this procedure is not considered in the TRB (1994) method. Consequently, the utilisation of the HCM method could result in impractical delay reports, while the above technique yielded more precise results. The advantages of this method are described in Table 2.

3.10. Al-Omari's method

Al-Omari and Benekohal (1999) developed a new technique to calculate the total delay (right-hand driving system) with random arrival patterns of undersaturated at TWSC junctions. For this statement, the total delay is divided into service delay and queue delay, while a different method was generated for each delay. In this regard, the empirical method was formulated to calculate service delay as the functions of conflicting traffic volumes. In addition, queuing delay is calculated by utilising the Markovian (random) arrivals/Generally distributed service times/One (M/G/1). Accordingly, the (M/G/1) method provides substantially better queue delay assessments compared to the Markovian (random) arrivals/Markovian service rate/One (M/M/1) method.

In addition, the suggested total delay method is very functional considering that it utilises only two input parameters, namely the arrival rate and

Table 2. Summary of several methods for delay calculation (continue).

Source	Method	Advantages (A)/Limitation (L)/Findings (F)
Tian (1997)	Using queuing theory.	• This technique produced more precise results than the TRB (1994) method (A), • This technique is easy to use and gives trustworthy results (A), • This technique can be utilised under any junction geometry conditions. This is particularly beneficial while current methods are not able to provide realistic solutions under different traffic flow and junction geometry conditions including medians (A).
Al-Omari and Benekohal (1999)	Using queuing theory (M/G/1)	• This method calculates delays that are nearer to the field study than the HCM's method (A), • These models are appropriate for low to moderate delays but definitely not of high delays. For congested (oversaturated and saturated) situations this model is not applicable (L).
Zhou et al. (2006)	A regression evaluation (the exponential form) was carried out to developed model.	• The delays from major to minor movements were not considered because these delays are relatively little in comparison with a delay from minor road (L), • Because of platoon flow, the methods may not reliably calculate delays in rural regions where through traffic arrival is more random (L).
Brilon (2007, 2015)	Using queuing theory.	• It is applicable during low saturation and over saturation condition (A), • This method can be used in situations with the effect of the initial queue (A). • It is not an appropriate method for practical utilise (L),
Chandra, Agrawal, and Rajamma (2009)	Exponential method to calculate service delay depending on microscopic evaluation of delay.	• This method is good for calculation of the service delay (A).
Ashalatha and Chandra (2011)	Using linear and multiple regressions.	• The results were identified to have a near match with field measurement (A).

conflicting traffic volumes. Al-Omari and Benekohal (1999) expressed that although the final results in their research are for two-lane two-way approaches using random arrivals, as suggested by them the method is recommended to be utilised for additional geometric and traffic conditions. In addition, Al-Omari and Benekohal (1999) recommend that the method should be examined for the cases of non-random arrivals, multiple lanes, heavy vehicles, the existence of pedestrians, various speeds on the main road, and several other situations. The advantages and limitations of this method are provided in Table 2.

3.11. Zhou's method

Zhou et al. (2006) stated that three existing methods including the HCM method, models that depend on queuing theory, and other empirical methods are highly dependent on either computer simulations or available field data in calculating minor traffic movement delays at priority junctions. However, none of them is able to sufficiently handle the situation whereby the main road is comprised of multi-lane approaches. Therefore, a regression evaluation (the exponential form) was carried out to develop the delay model dependent on the data collected. In this regard, average delays were calculated for left and right turn movements from a minor road at priority junctions into multilane arterials with wide medians, thus making it possible for one or more vehicles to stop and wait which clearly respect the field data obtained. The limitations of this method are described in Table2.

3.12. Brilon's method

Brilon (2007, 2008) established a set of equations that can be used to calculate average delays based on time-dependent flow at priority junctions based on the queuing theory. Accordingly, several equations can be used to explain time-dependent state possibilities within time-dependent queuing techniques including Morse (1958, 1976), Takács (1959), Newell (1982, 2013), Troutbeck and Blogg (1998), and Tarabia (2000). Specifically, they offer rather complex equations which are made up of trigonometric functions (sin, cos, ...). The critical point for the whole options is that input volumes (q) are not allowed to be beyond the capacity at any time. Hence, this prevents the temporary over-saturation situations from being covered. As a result, these analytical methods have limited performance for application in traffic engineering. Brilon (2007, 2008) utilised a case study including a basic case of one main road and one minor road where the vehicles from the minor road need to give priority to the main road vehicles. In this case, the first step of estimation is the presumption that the priority system can be created by an M/M/1 queue theory method, followed by the next step which is the so-called coordinate transformation method. Accordingly, a Markov-chain method has been created to generate numerically exact outcomes for validating these formulations. Particularly, Brilon (2007, 2008) expressed that it is only applicable during low saturation and over-saturation condition although the above method was created on the basis of the junction with one main road and one minor road.

Brilon (2015) asserted that the basic presumptions discussed in Brilon (2007, 2008) are not an appropriate method for practical utilisation section due to the large number of concurrent equations which may confuse the reader. Consequently, Brilon (2015) attempted to improve his methods. The circumstances of applicability are more oriented towards practical needs and future, especially for the purpose of finding the simplified solution. Brilon (2015) detailed that the description of the priority system by the M/M/1 queue method can create a bias, particularly for large main traffic volumes. Apart from this issue, it was described that the M/M/1 method is only appropriate for a particular process whereby the demand (q) and the capacity (c) are steady over time and where $q < c$ (under-saturated conditions). Hence, this demonstrates that both of these restrictions are not generally reasonable in real traffic situations. Consequently, solutions are needed for periods with $q > c$. In particular, Brilon (2015) asserted that a worthwhile solution for the average delay in the time-dependent system ought to be a transition between the steady-state delay (M/M/1) and the deterministic delay, thus the transition curve should be dependent on an approximation. In this case, Brilon (2015) compared the new method with HCM formula by asserting that HCM method can only be justified as a difficult approximation for intervals which are used in rather under-saturated situations. In addition, values from HCM formula are much lower than the new technique except for the basic situation of a clear initial queue and steady capacity. Therefore, the outcomes from the new technique and HCM formula become almost identical. The advantages and limitations of this technique are described in Table 2.

3.13. Chandra's method

Chandra, Agrawal, and Rajamma (2009) presented a preliminary exponential method to calculate the service delay dependent on the microscopic evaluation of delay under different groups of vehicles for several priority movements as well as various proportions of heavy and light vehicles in the conflicting traffic. In this case, the delays related to the right turn from the main road were excluded, while the delay model which is specific for the minor road was formulated.

The results revealed that the service delay to a vehicle is not significantly dependent on its type.

The delay relies mainly on the amount of conflicting traffic volume and its composition concerning the percentage of heavy vehicles. Chandra, Agrawal, and Rajamma (2009) described that the current methods were formulated under homogeneous and lane disciplined traffic situations; hence, they are not able to be utilised for mixed traffic at priority junctions. Overall, this is mostly due to the impatient behaviour of motorists as well as the distinction in the static and dynamic characteristics of vehicles in India and other developing countries. The advantages of this method is provided in Table 2.

3.14. Ashalatha's method

Ashalatha and Chandra (2011) developed a method to calculate the average service delay with mixed traffic conditions and conflict traffic volume for different priority movements (i.e. right, left, and through from minor, as well as right turn from the major road) using linear and multiple regression. Specifically, it consists of four types of subject vehicles, namely passenger car, two-wheelers, three-wheeler, and heavy vehicle confronting the conflicting stream of cars. The models show that the values of service delay for a vehicle turning left from the minor road are definitely close to those vehicles that are turning right from the main road. Similarly, the two curves corresponding to the through movement from the minor road and right turn from the minor road are also definitely close.

Regarding this matter, multiple linear regression was developed by Ashalatha and Chandra (2011) in order to convert all vehicles in the traffic stream into equivalent heavy vehicles for the purpose of calculating the average service delay under actual field measurement. Specifically, this method converts different traffic stream into the one having a passenger car and heavy vehicles only. Eventually, it was determined that service delay to a priority movement increased when conflicting traffic stream was of heterogeneous form with the addition of heavy vehicle in the conflicting traffic stream. Furthermore, Ashalatha and Chandra (2011) explained that it is worth to investigate the influence of composition and volume of conflicting traffic on queue delay, which is a substantial element of the total delay experienced by the vehicles at priority junctions. The advantage of this method can be found in Table 2.

3.15. Cvitanic's method

Cvitanić, Breški, and Vidak (2012) developed a method for evaluating total delay at priority junctions. Consequently, a practical equation for the delay assessments was extracted from the queuing theory method M/G/1. Specifically, M signifies random arrivals, followed by G which postulates some typical distribution function of service times (time used at the first place in the queue till merging or crossing the junction), and 1 signifies one approach lane. However, the above method can be utilised only in a steady-state situation. In this case, the average delay will reach infinity if the degree of saturation approaches one.

Furthermore, a mathematical alternative for time-dependent issue was created by Newell (2013) but it was too complex for practical use. Nevertheless, Cvitanic's method is still unrealistic for engineering use because it requires comprehensive data that are not generally gathered at junctions including queue lengths at the start of the study as well as the variations of flow during peak periods despite the fact that it is less complex than Newell's theoretical method. Overall, the limitations of this method are provided in Table 3.

Table 3. Summary of several methods for delay calculation (continue).

Source	Method	Advantages (A)/Limitation (L)/Findings (F)
Cvitanić (2012)	Using queuing theory method (M/G/1) during steady state situation.	• It is still unrealistic for engineering utilise (L), • This method can be used just for steady state situation (L).
Caliendo (2014)	Developed a micro-simulation method utilising AIMSUN software for calculation of average delays. A negative binomial regression method was used for predicted model.	• The values of the average delay on minor streets increased considerably as the conflicting volume on the major road also increased (F), • Appropriate for fast evaluations of junction performance mainly because of a diversification of traffic demand over time, as well as for the prediction of junction performances when modifications are proposed (A), • This method is suitable when the actual system is complicated to analyse (A), • Computations for the site need to be repeated to obtain better results (L).
HCM	An analytic method depending on queuing theory	• This method is fairly appropriate for practical purposes, particularly for low-saturated situations in which each approach has a volume over capacity ratio lower than 0.9. If this ratio higher than 0.9, the calculated delay is not stable (F), • For oversaturated situations, the HCM method is rather questionable (L), • at junctions where the complete approach traffic volume exceeds 2500 (veh/h), the HCM delay formula overestimates the actual control delay (Simpson and Matthias 2000) (L).
Sahraei et al. (2018)	Using Artificial Neural Network (ANN)	• Established a model based on the several input parameters and determined the effect of each ones (A), • Directly applicable to the evaluation of performance measures at priority junctions (A), • Did not consider upstream signal as well as junctions with ascending or descending gradient (L).

3.16. Caliendo's method

Caliendo (2014) developed a micro-simulation method using AIMSUN software for the purpose of calculating average delays (i.e. only for minor streets) at priority junctions throughout peak times. In doing so, a negative binomial regression method were used to create the model using traffic volume which gets into the junction from minor streets (VHPe) as well as conflicting volume on the major road (VHPc). Additionally, a variable known as the dummy (D) was presented to test the adequacy of the regression model through the range of hourly conflict traffic volumes.

The results clearly demonstrated that the values of average delays on minor streets are directly related with VHPe, VHPc, and D. Furthermore, a queuing technique was created by Caliendo (2014) and it was confirmed that the greatest queue size is directly connected to the conflicting volume on the major road. Overall, this method generated an appropriate level of conformity between the simulated performance and predicted values. Accordingly, several advantages and limitations of this method can be found in Table 3.

3.17. Highway capacity manual

The current version of HCM2010 (TRB 2010) provides a process for calculating delays at priority junctions which is an analytic method dependent on the queuing theory. Delay is simply calculated for each left- and right-turning manoeuvre from a minor road, as well as the left-turning movement from a major road (right-hand driving system). According to this manual, the total delay is comprised of several parts as follows: (1) deceleration to time stop at the end of the queue, (2) move-up time throughout the queue, (3) stopped delay behind the stop line, and (4) acceleration time. Basically, the total delay is actually identified when a vehicle stops at the end of the queue until the vehicle leaves the stop line which is given as second per vehicle (sec/veh). Overall, the HCM delay method in TRB (2000, 2010) is extensively used for the evaluation of control delay at priority junctions among other techniques. In this case, some limitations of this technique are described in Table 3.

3.18. Sahraei's method

Research by Sahraei and Puan (2018) was carried out to model the control delay using Multi-Linear Regression (MLR) for left- and right-turning manoeuvre from minor road at priority junctions in suburban areas in Malaysia. In this research, input variables including traffic flow rate on the minor road (left and right turn separately), capacity, follow-up time, and critical gap were employed to conduct further investigation. In both movements, it was found that control delays to minor street automobiles increase as the volume of main street traffic increases. The outcomes of this study revealed that the observed delays were in a good agreement with the values predicted using MLR's model for both movements from a minor road.

Meanwhile, another research by Sahraei et al. (2018) was conducted to model the traffic control delays at priority junctions incurred on minor road vehicles as well as right-turning manoeuvre from the major road using Artificial Neural Network (ANN) as part of the effort in improving the previous model. Accordingly, an ANN with two hidden layers and several sizes of neurons in the hidden layers were developed. Next, several mathematical formulas were developed for the estimation of control delay with reasonable accuracy that is dependent on the variety of geometry. In this research, the geometry was divided into three categories, namely four lanes major/four lanes minor road, four lanes major/two lanes minor road, and two lanes major/two lanes minor road. More importantly, it should be noted that the input variables include the movement traffic flow rate, follow-up time, critical gap, conflict traffic flow, the proportion of motorcycles, the proportion of heavy vehicles, and proportion of lorry. Finally, the advantages and limitations of this method can be found in Table 3.

4. Discussion

In the previous section, a number of aspects relevant to the delay investigation were assessed and discussed with the aim of being served as guides and equally provide comprehensive knowledge that is associated with traffic delay at priority junctions. In this case, the efficiency of a priority junction is considered to be highly affected through the delay induced by a low-priority traffic stream. Furthermore, it was found that the delay encountered by a vehicle is made up of a variety of elements that corresponds with geometrics, control, incidents, and traffic.

The significant analysis and discussion regarding the existing problems concerning traffic delay managed to be explored including their weaknesses and strengths that may help to advance research in this field. Accordingly, a few of the above methods have a number of important limitations in regard to delay investigation at priority junctions. For example, Tanner's method consists of complex equations that are not valuable for the user as well as the fact that it does not take into account the condition of multiple lanes on the main street. Meanwhile, Kimber's method cannot be applied for the estimation of total delay at priority junctions. On the other hand, Madanat's technique can only be used for the calculation of delay for right turns at a junction, while Zhou's method is not able to consider the values of a delay from major to minor movements. In addition, Cvitanic's formula is deemed unrealistic for delay estimation and can only be used for a steady state situation.

According to the methods described in section 3, several techniques have demonstrated significant advantages. In this case, Hawkes's method is perfectly capable of estimating delay at junctions based on the good agreement acquired between observed and theoretical results. Meanwhile, Troutbeck's formula is able to estimate the values of delay by taking into account the influence of bunching on the main road. Hence, it is considered to have a little more standard compared to Tanner's model. Tian developed a model by utilising queuing theory which describes its capability of calculating the delay with more precise results compared to the HCM's formula. Other than that, a method developed by Chandra can be used during mixed traffic conditions as well as deemed appropriate for the estimation of service delay.

In this regard, a few of the methods discussed previously have a mixture of advantages and limitations. For instance, Brilon's technique can be used during both low saturation and over-saturation conditions; however, it is not appropriate for the estimation of delay in practical utilisation. Caliendo's method is suitable for quick delay calculation due to the diversification of traffic demand over time. In addition, it is deemed to be useful when the actual system is complicated to be analysed. In spite of the advantages for Caliendo's method, the computations for the site need to be repeated in order to obtain better results. Nevertheless, HCM's method cannot be utilised for oversaturated situations considering the fact that it is a general procedure for practical purposes for evaluation of delay at priority junctions. Therefore, the HCM method is rather questionable. The development of Sahraei's formula is dependent on several parameters and geometries but it does not consider the effect of grade and upstream signal. Overall, the summary of the different methods of traffic delay at priority junction with their advantages and limitations are summarised in Table 1 until Table 3.

5. Assessment of methods in calculating delay

The accuracy of the delay estimation procedures is checked in this section using real data from two priority junctions with a multilane on the major and minor roads. In general, it has been acknowledged that data collection offers a wide range of data over the streams of intersecting traffic, especially during peak and off-peak time which considers the fact that traffic delay differs among time.

5.1. Data collection and site description

In the case of the current research, several TWSC junctions around Johor Bahru, Malaysia were visited for the purpose of data collection. According to the recording technique, the junctions were selected based on the following criteria:

- To have safety and appropriate access for the counting and equipment throughout the data gathering process.
- To have appropriate points with good height to instal the equipment.
- To have appropriate sight distance for the junctions in order to prevent any interaction between vehicles during counting.
- To have a suitable traffic volume on major and minor roads.

The site studies involved in the current research were chosen by compromising the above criteria. In this

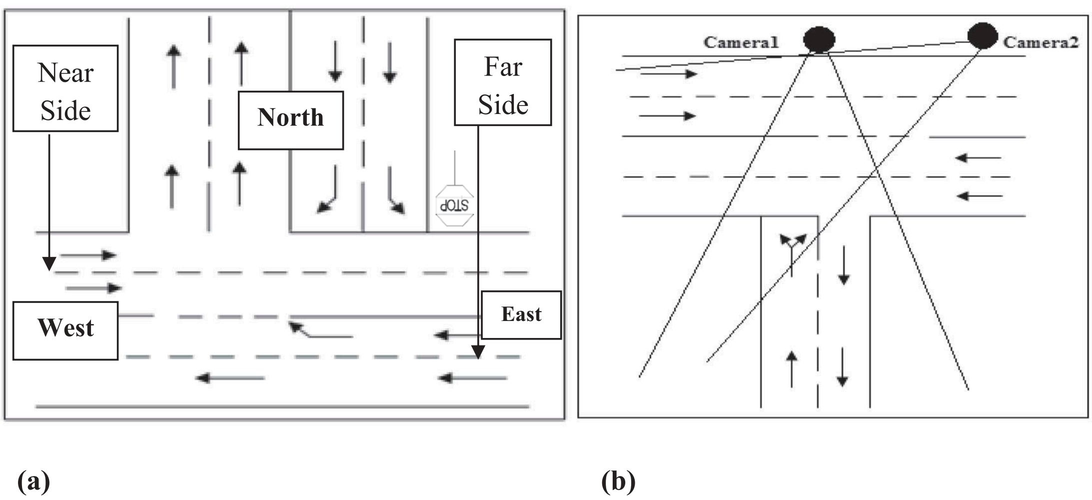

Figure 1. (a) Traffic lanes configuration at priority junctions (b) Location of cameras.

case, two TWSC junctions with multilane at the major and minor roads in the suburban area were selected. Figure 1(a) shows the traffic lanes configuration of junctions. In this case, it is important to note that these junctions were selected because the preliminary short traffic counts have confirmed reasonable volumes of turning movements which was appropriate for the assessment of mentioned methods in calculating delay.

In the current research, the process of data collection was performed by utilising a video camera recording technique. A number of researchers such as Ashworth (1976), Ke et al. (2017), Huang (2018) and Sahraei and Akbari (2019) have discussed the advantage of utilising this method for data gathering procedure. More importantly, this procedure of data collection was used in a considerable amount of research for the calculation of traffic delay at priority junctions including Lu and Lall (1995), Al-Omari and Benekohal (1999), Brilon (2007), Chandra, Agrawal, and Rajamma (2009), Shahpar, Aashtiani, and Faghri (2011), Ma et al. (2013), Caliendo (2014), and Sahraei et al. (2018).

Specifically, two video cameras were installed on a tripod at an appropriate place at about 1.70 m height and close to the junction for the purpose of recording an unblocked view of the whole approaches and turning movements. One video camera was located in the direction of the minor road (camera 1), while the other camera was located in the direction of the main road (camera 2). Consequently, all data including traffic flow, gap acceptance, and observed control delay for all approaches were successfully collected.

Figure 1(b) shows the location of the cameras during the data collection process. Data were gathered from morning until evening for a duration of 9 h for every junction, on normal working days. Consequently, the total recording times for both junctions were 18 h and the recording periods were considered appropriate to evaluate the required traffic parameters under a range of traffic flow. On a specific note, for the purpose of preventing the impact of adverse weather and environmental situations including darkness and rain, the total data gathering for the present study was carried out during daylight time period considering the fact that driving performance and behaviour tends to differ from day to night-time period (Ivey, Lehtipuu, and Button 1975) as well as without rainy weather condition (Rahman and Lownes 2012). Moreover, these conditions could influence the precision and reliability of the sampling and delay, thus it was excluded from the data collection process.

Next, the video camera recordings were played on the laptop several times to obtain suitable data, while both merging and crossing types of conflicts area were also evaluated. Finally, the following information managed to be extracted during the playback:

- The rates of traffic flow on minor and major roads – The data were collected by separately counting (i.e. manual counter) the number of vehicles in all directions at junctions. The video was played as fast forward in the laptop during this process.
- The values of accepted and rejected gaps for the minor road (i.e. right and left turn) – The data were collected using a stopwatch. Accordingly, the time distance (in second) recorded between vehicles on the major road by which a minor-street vehicle accepts to manoeuvre. The video was played back in real-time during this process.
- The value of observed delay for each vehicle movements on the minor road – The data were collected using a stopwatch.

5.2. Calculation of delay

In the case of the current research, the values of conflict traffic flow rate and the subject movement volume from the minor road were estimated in the process of data collection. The values of minor road critical gap (Equation (1)) and capacity (Equation (2)) during a variety of conflicting flow rate were computed using the formula proposed by HCM 2000 (TRB 2000) and HCM 2010 (TRB 2010).

$$t_{c,x} = t_{c,base} + t_{c,HV}P_{HV} + t_{c,G}G - t_{c,T} - t_{3,LT} \quad (1)$$

Where;
$t_{c,x}$ = critical gap for movement x (s), $t_{c,base}$ = base critical gap from Table 4, $t_{c,HV}$ = adjustment factor for heavy vehicles (1.0 for two-lane major streets and 2.0 for four-lane major streets) (s), P_{HV} = proportion of heavy vehicles for minor movement, $t_{c,G}$ = adjustment factor for the grade (s), G = percent grade divided by 100, $t_{c,T}$ = adjustment factor for each part of a two-stage gap acceptance process (1.0 for first or second stage; 0.0 if only one stage) (s), and $t_{3,LT}$ = adjustment factor for intersection geometry (0.7 for minor-street left-turn movement at three-leg intersection; 0.0 otherwise) (s).

$$C_{p,x} = V_{c,x} \frac{e^{-v_{c,x}t_{c,x}/3600}}{1 - e^{-v_{c,x}t_{f,x}/3600}} \quad (2)$$

Table 4. Base critical gaps for TWSC intersections.

	Base Critical Gap, $t_{c,base}$ (s)	
Vehicle Movement	Two-Lane Major Street	Four-Lane Major Street
Left turn from major	4.1	4.1
Right turn from minor	6.2	6.9
Through traffic on minor	6.5	6.5
Left turn from minor	7.1	7.5

Where;

$c_{p,x}$ = potential capacity of minor movement x (veh/h), $v_{c,x}$ = conflicting flow rate for movement x (veh/h), $t_{c,x}$ = critical gap for minor movement x (s), and $t_{f,x}$ = follow-up time for minor movement x (s).

In this regard, the values of critical gap at the multi-lane junction were, respectively, computed as 4.32 sec and 6.18 sec for a left turn and right turn from a minor road. Meanwhile, research by Mohan and Chandra (2016), estimated the critical gap values using several existing methods, particularly with the calculation from 2.63 sec using Probability Equilibrium Method (PEM) to 4.22 sec based on Probit's method. Next, the capacity was calculated depending on each 15–minute interval during various conflicting flow rates on the major road.

The value of follow-up time was measured from the site studies. Specifically, it was computed based on the time in second between the departure of one vehicle from the minor road and the departure of the next one that utilises the same gap under a condition of continuous queuing. In this case, the average follow-up time value was obtained from individual measurements.

The average magnitude of follow-up times from the site studies was identified to be around 1.75 sec and 1.28 sec for a right turn and left turn from a minor road, respectively. Regarding this matter, it is important to note that the direction of the vehicle in Malaysia is Left-hand Driving System (LDS).

5.3. Comparison of delay methods

A vast majority of methods that have been previously reviewed were utilised for the purpose of calculating delay at the priority junction, which is dependent on the data collected from various site studies. More importantly, it should be noted that the values of delay that is dependent on different methods were calculated based on the related input parameters including conflict traffic flow rate on the major road, traffic volume on the minor road for each subject movement, capacity, critical gap, and follow-up time. In this case, those parameters were extracted from junctions if additional input parameters for each specific method are needed. For example, Tanner's method requires two additional parameters including minimum time headway between major road vehicle and minimum time headway between minor road vehicles emerging from the minor road.

The observed data of the parameters were input into the existing methods as reviewed earlier in estimating the delay for the purpose of analysing the models' goodness of fit. The calculated delays which are dependent on its formulas were then compared with the observed data. Accordingly, a statistical analysis was carried out on the data to verify this procedure and presented in Table 5.

Table 5 summarises the values of Root-Mean-Square Error (RMSE), Mean-Square Error (MSE), and Residual Sum of Squares (RSS), R^2, and Q^2 for all movements. The RMSE is frequently used to calculate the distinctions between actual data set and the values calculated by a formula. In this case, the values closer to zero are deemed to be significant as justified in Table 5. The RSS also called the Sum of Squared Errors of prediction for the purpose of evaluating the discrepancy between the actual data set and results of the formula. A small RSS signifies a tight fit of the models to the observed data.

The comparative analysis presented in Table 5 clearly shows that some of the reviewed methods are appropriate to estimate delay at priority junction, while most of them did not provide appropriate magnitude for delay analysis. For example, the values of R^2 for Heidemann's, Kyte's, and Caliendo's methods for both left and right turns from the minor road are found to be less than 0.80.

Table 5. Statistical analysis on the data (i.e. observed and theoretical data).

		Left turna					Right turna				
Method	Movement direction	MSE	RSS	RMSE	R^2	Q^2	MSE	RSS	RMSE	R^2	Q^2
Tanner's Method	RDS	3.1E-02	0.08	1.7E-01	0.84	0.48	2.4E-02	0.13	1.5E-01	0.80	0.65
Hawkes's Method		3.8E-02	0.11	1.9E-02	0.81	0.37	1.4E-02	0.08	1.2E-02	0.84	0.75
Weiss's Method		5.1E-02	0.14	2.3E-01	0.75	0.16	1.8E-02	0.08	1.4E-01	0.88	0.74
Troutbeck's Method	RDS	1.4E-02	0.04	1.2E-01	0.95	0.80	8.8E-03	0.05	9.4E-02	0.94	0.90
Kimber's Method		1.2E-02	0.03	1.1E-01	0.93	0.81	6.9E-03	0.04	8.3E-02	0.94	0.89
Heidemann's Method		1.2E-01	0.22	3.5E-01	0.61	0.52	8.4E-02	0.45	2.9E-01	0.56	0.47
Kyte's Method	RDS	3.3E-02	0.18	1.8E-02	0.72	0.35	1.6E-02	0.09	1.3E-01	0.87	0.67
Madanat's Method	RDS	3.6E-02	0.16	1.9E-01	0.78	0.52	-	-	-	-	-
Tian's Method	RDS	1.5E-02	0.04	1.2E-02	0.89	0.74	1.5E-02	0.08	1.2E-01	0.87	0.80
Al-Omari's Method	RDS	2.4E-02	0.07	1.6E-02	0.87	0.57	2.9E-02	0.16	1.7E-01	0.75	0.57
Zhou's Method	RDS	1.9E-02	0.05	1.4E-01	0.89	0.66	5.1E-03	0.03	7.1E-02	0.96	0.92
Brilon's Method	RDS	1.1E-02	0.03	1.1E-01	0.94	0.81	2.5E-03	0.01	0.5E-01	0.95	0.95
Chandra's Method	LDS	3.2E-02	0.13	1.8E-01	0.82	0.59	2.1E-02	0.11	1.4E-01	0.88	0.80
Ashalatha's Method	LDS	2.4E-02	0.07	1.6E-01	0.87	0.57	1.9E-02	0.10	1.3E-01	0.84	0.71
Cvitanic's Method	RDS	4.1E-02	0.10	1.9E-01	0.81	0.37	1.2E-02	0.06	1.1E-01	0.88	0.82
Caliendo's Method	RDS	4.3E-02	0.12	2.1E-01	0.78	0.27	1.6E-02	0.08	1.3E-01	0.86	0.77
HCM	RDS	1.6E-02	0.04	1.3E-01	0.92	0.73	1.1E-02	0.06	1.1E-01	0.90	0.82
Sahraei's Method	LDS	1.3E-02	0.04	1.1E-01	0.92	0.78	7.9E-03	0.04	8.9E-02	0.94	0.88

Left turn and right turn from a minor road, RDS = Right-hand Driving System.

Overall, it can be concluded that there is no statistically significant difference between actual delays and resulted values of some methods such as Troutbeck's, Brilon's, and HCM's Methods. Furthermore, among the methods compared in this paper, Kimber (1986) was able to provide a powerful set of the approximate value of time-dependent delay. Apart from that, Sahraei's Method (2018) was able to predict control delays incurred on minor road vehicles at priority junctions.

6. Conclusion

One of the important variables in the analysis of priority junctions refers to the traffic delay for each movement. The current review paper evaluated various methods for the calculation of delay at priority junctions. The majority of the techniques provided the average delay values, while techniques such as Ashalatha and Kimber managed to provide the service delay and queuing delay, respectively. In addition, it should be noted that a number of these techniques are computationally easier even though some other techniques require complicated computational processes. More importantly, the conceptual distinctions among the techniques provided distinct magnitude for approximated delay at priority junctions. In this case, Brilon's, HCM's, and Troutbeck's methods were the most popular among the above reviewed techniques, and the method of Tanner that successfully underwent significant improvements over the years.

The accuracy of the delay estimation procedures was checked using real data with a total of 18-h data collection from two priority junctions, namely multi-lane on the major and minor road. The present study managed to identify that Troutbeck's and Brilon's Methods provided consistent outcomes, whereas the delay produced by Kyte's, Madanat's, and Tian's Methods was found to vary with the value of R^2 which was less than 0.80. In addition, HCM's method is one of the popular ones, particularly during low saturation. In this case, the formula is not stable because it does not meet the actual data if the volume over the capacity ratio is higher than 0.9 or traffic volume exceeds 2500 (veh/h). In future research, it is recommended to evaluate more junctions with different traffic volume and geometry even though some methods did not provide appropriate results or give a value of R^2 less than 0.90.

Acknowledgments

The authors declare that there is no conflict of interest regarding the publication of this article.

Disclosure statement

No potential conflict of interest was reported by the authors.

Notes on contributors

Mohammad Ali Sahraei received Master (2012) and Ph.D. degree (2018) in field of traffic ans transportation engineering at Universiti Teknologi Malaysia (UTM). He is postdoctoral researcher at Erzurum Technical University (ETU). His research interests include traffic and transportation modeling, simulation, traffic safety, traffic management and ITS.

Elnaz Akbari received Ph.D. degree in sensors based nanomaterials from the UTM in 2014. She was recently Postdoctoral Researcher at the University of California-Merced. Her research interests include machine learning and sensors.

ORCID

Mohammad Ali Sahraei http://orcid.org/0000-0002-9130-3685
Elnaz Akbari http://orcid.org/0000-0002-8238-3978

References

Akcelik, R., B. Christensen, and E. Chung. 1998. "A Comparison of Three Delay Models for Sign-controlled Intersections." Paper presented at the Third International Symposium on Highway Capacity.

Al-Omari, B., and R. F. Benekohal. 1999. "Hybrid Delay Models for Unsaturated Two-way Stop Controlled Intersections." *Journal of Transportation Engineering-ASCE* 125 (4): 291–296. doi:10.1061/(asce)0733-947x(1999)125:4(291).

Ashalatha, R., and S. Chandra. 2011. "Service Delay Analysis at TWSC Intersections through Simulation." *KSCE Journal of Civil Engineering* 15 (2): 413–425. doi:10.1007/s12205-011-1125-9.

Ashworth. 1976. "A Video Tape Recording System for Traffic Data Collection and Analysis." *Traffic Engineering & Control* 17 (Analytic): 468-470.

Brilon, W. 2007. "Time Dependent Delay at Unsignalized Intersections." Paper presented at the Transportation and Traffic Theory 2007. Papers Selected for Presentation at ISTTT17. London.

Brilon, W. 2008. "Delay at Unsignalized Intersections." *Transportation Research Record* 2071 (1): 98–108. doi:10.3141/2071-12.

Brilon, W. 2015. "Average Delay at Unsignalized Intersections for Periods with Variable Traffic Demand." *Transportation Research Record: Journal of the Transportation Research Board* 2483 (1): 57–65. doi:10.3141/2483-07.

Brilon, W., R. Troutbeck, and M. Tracz. 1997. "Review of International Practices Used to Evaluate Unsignalized Intersections." *Transportation Research Circular*, no. 468: 1-41.

Caliendo, C. 2014. "Delay Time Model at Unsignalized Intersections." *Journal of Transportation Engineering* 140 (9): 04014042. doi:10.1061/(ASCE)TE.1943-5436.0000696.

Caliendo, C., and M. L. De Guglielmo. 2012. "Road Transition Zones between the Rural and Urban Environment: Evaluation of Speed and Traffic Performance Using a Microsimulation Approach." *Journal of Transportation Engineering* 139 (3): 295–305. doi:10.1061/(ASCE)TE.1943-5436.0000495.

Caliendo, C., and M. Guida. 2012. "Microsimulation Approach for Predicting Crashes at Unsignalized

Intersections Using Traffic Conflicts." *Journal of Transportation Engineering* 138 (12): 1453–1467. doi:10.1061/(ASCE)TE.1943-5436.0000473.
Caliendo, C., and M. Guida. 2014. "A New Bivariate Regression Model for the Simultaneous Analysis of Total and Severe Crashes Occurrence." *Journal of Transportation Safety & Security* 6 (1): 78–92. doi:10.1080/19439962.2013.812169.
Chandra, S., A. Agrawal, and A. Rajamma. 2009. "Microscopic Analysis of Service Delay at Uncontrolled Intersections in Mixed Traffic Conditions." *Journal of Transportation Engineering* 135 (6): 323–329. doi:10.1061/(ASCE)0733-947X(2009)135:6(323).
Chen, X., L. Yu, L. Zhu, J. Guo, and M. Sun. 2010. "Microscopic Traffic Simulation Approach to the Capacity Impact Analysis of Weaving Sections for the Exclusive Bus Lanes on an Urban Expressway." *Journal of Transportation Engineering* 136 (10): 895–902. doi:10.1061/(ASCE)TE.1943-5436.0000155.
Chevallier, E., and L. Leclercq. 2009. "Microscopic Dual-regime Model for Single-lane Roundabouts." *Journal of Transportation Engineering* 135 (6): 386–394. doi:10.1061/(ASCE)0733-947X(2009)135:6(386).
Chodur, J. 2005. "Capacity Models and Parameters for Unsignalized Urban Intersections in Poland." *Journal of Transportation Engineering* 131 (12): 924–930. doi:10.1061/(ASCE)0733-947X(2005)131:12(924).
Cowan, R. J. 1975. "Useful Headway Models." *Transportation Research* 9 (6): 371–375. doi:10.1016/0041-1647(75)90008-8.
Cox, D. R., and H. D. Miller. 1977. *The Theory of Stochastic Processes*. Vol. 134. New York: CRC Press.
Cvitanić, D., D. Breški, and B. Vidak. 2012. "Review, Testing and Validation of Capacity and Delay Models at Unsignalized Intersections." *PROMET-Traffic&Transportation* 19 (2): 71–82.
Fang, F. C., and L. Elefteriadou. 2005. "Some Guidelines for Selecting Microsimulation Models for Interchange Traffic Operational Analysis." *Journal of Transportation Engineering* 131 (7): 535–543. doi:10.1061/(ASCE)0733-947X(2005)131:7(535).
Hawkes, A. 1965. "Queueing for Gaps in Traffic." *Biometrika* 52 (1/2): 79–85. doi:10.1093/biomet/52.1-2.79.
Hawkes, A. 1966. "Delay at Traffic Intersections." *Journal of the Royal Statistical Society. Series B (Methodological)* 28 (1): 202–212. doi:10.1111/rssb.1966.28.issue-1.
Heidemann, D. 1991. "Queue Length and Waiting-time Distributions at Priority Intersections." *Transportation Research Part B: Methodological* 25 (4): 163–174. doi:10.1016/0191-2615(91)90001-Y.
Heidemann, D., and H. Wegmann. 1997. "Queueing at Unsignalized Intersections." *Transportation Research Part B: Methodological* 31 (3): 239–263. doi:10.1016/S0191-2615(96)00021-5.
Hothersall, D., and R. Salter. 1981. "The Effect of Major Road Headway Distribution on Capacity and Vehicular Delays at Priority Junctions." Paper presented at the Institution of Civil Engineers, Proceedings, Pt2, 1149-1156. University of Bradford.
Huang, T. 2018. "Traffic Speed Estimation from Surveillance Video Data." Paper presented at the Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition Workshops
Ivey, D. L., E. K. Lehtipuu, and J. Button. 1975. "Rainfall Invisibility–the View from behind the Wheel." *Journal of Safety Research* 7 (4): 156–169.
Kaysi, I., and G. Alam. 2000. "Driver Behavior and Traffic Stream Interactions at Unsignalized Intersections." *Journal of Transportation Engineering* 126 (6): 498–505. doi:10.1061/(ASCE)0733-947X(2000)126:6(498).
Kaysi, I. A., and A. S. Abbany. 2007. "Modeling Aggressive Driver Behavior at Unsignalized Intersections." *Accident Analysis & Prevention* 39 (4): 671–678. doi:10.1016/j.aap.2006.10.013.
Ke, R., Z. Pan, Z. Pu, and Y. Wang. 2017. "Roadway Surveillance Video Camera Calibration Using Standard Shipping Container." Paper presented at the 2017 International Smart Cities Conference (ISC2), Wuxi, China.
Khattak, A., and P. Jovanis. 1990. "Capacity and Delay Estimation for Priority Unsignalized Intersections: Conceptual and Empirical Issues." *Transportation Research Record* 1287: 129–137.
Kimber, R., and E. Hollis. 1977. "Flow/delay Relationships for Major/minor Priority Junctions." *Traffic Engineering and Control* 18 (Analytic): 516-519.
Kimber, R., and E. Hollis. 1978. "Peak-period Traffic Delays at Road Junctions and Other Bottlenecks." *Traffic Engineering & Control* 19 (N10): 442-446.
Kimber, R., I. Summersgill, and I. Burrow. 1986. "Delay Processes at Unsignalised Junctions: The Interrelation between Geometric and Queueing Delay." *Transportation Research Part B: Methodological* 20 (6): 457–476. doi:10.1016/0191-2615(86)90025-1.
Kyte, M., C. Clemow, N. Mahfood, B. K. Lall, and C. J. Khisty. 1991. "*Capacity and Delay Characteristics of Two-way Stop-controlled Intersections.*" *Transportation Research Record 1320: 160-167.*
Lu, J. J., and B. K. Lall. 1995. "Empirical Analysis of Traffic Characteristics at Two-way Stop-controlled Intersections in Alaska." *Transportation Research Record*, no. 1495: 49–56.
Luttinen, R. T. 2004. *Capacity and Level of Service at Finnish Unsignalized Intersections: S12 Solutions to Improve Main Roads: S12 Pääteiden Parantamisratkaisut*. Finland: Tiehallinto.
Ma, D.-F., X.-L. Ma, S. Jin, F. Sun, and D.-H. Wang. 2013. "Estimation of Major Stream Delays with a Limited Priority Merge." *Canadian Journal of Civil Engineering* 40 (12): 1227–1233. doi:10.1139/cjce-2012-0532.
Madanat, S., M. Cassidy, and M. Wang. 1994. "Probabilistic Delay Model at Stop-Controlled Intersection." *Journal of Transportation Engineering* 120 (1): 21–36. doi:10.1061/(ASCE)0733-947X(1994)120:1(21).
Mohan, M., and S. Chandra. 2016. "Review and Assessment of Techniques for Estimating Critical Gap at Two-way Stop-controlled Intersections." *European Transport-trasporti Europei*, no. 61: 1-18.
Morse, P. M. 1958. *Queues, Inventories and Maintenance*. New York: Wiley.
Morse, P. M. 1976. *Queues-inventories and Maintenance*. 3 ed. Mineola, New York: John Wiley & Sons. (revised version (first edition 1958)).
Newell, C. 1982. *Applications of Queueing Theory*. London: Chapman & Hall.
Newell, C. 2013. *Applications of Queueing Theory*. Vol. 4. London: Springer Science & Business Media.
Rahman, A., and N. E. Lownes. 2012. "Analysis of Rainfall Impacts on Platooned Vehicle Spacing and Speed." *Transportation Research Part F: Traffic Psychology and Behaviour* 15 (4): 395–403. doi:10.1016/j.trf.2012.03.004.
Sahraei, M. A., and E. Akbari. 2019. "Implementing the Equilibrium of Probabilities to Measure Critical Gap at Priority Junctions." *Journal of Testing and Evaluation* 47 (2). doi:10.1520/JTE20180611.

Sahraei, M. A., and O. Puan. 2018. "Traffic Delay Estimation Using Artificial Neural Network (ANN) at Unsignalized Intersections." Paper presented at the the 3rd International Conference on Civil, Structural and Transportation Engineering (ICCSTE'18), Canada.

Sahraei, M. A., O. C. Puan, S. M. Hosseini, and M. H. Almasi. 2018. "Establishing a New Model for Estimation of the Control Delay at Priority Junctions in Malaysia." *Cogent Engineering* 5(1): 1424679.

Shahpar, A. H., H. Z. Aashtiani, and A. Faghri. 2011. "Development of a Delay Model for Unsignalized Intersections Applicable to Traffic Assignment." *Transportation Planning and Technology* 34 (5): 497–507. doi:10.1080/03081060.2011.586119.

Simpson, S., and J. Matthias. 2000. "Validation of Left-turn Delay at Two-way Stop-controlled Intersections." *Transportation Research Record: Journal of the Transportation Research Board* 1710 (1): 181–188. doi:10.3141/1710-21.

Stevanovic, A. Z., and P. T. Martin. 2008. "Assessment of the Suitability of Microsimulation as a Tool for the Evaluation of Macroscopically Optimized Traffic Signal Timings." *Journal of Transportation Engineering* 134 (2): 59–67. doi:10.1061/(ASCE)0733-947X(2008)134:2(59).

Takács, L. 1959. *Introduction to the Theory of Queues*.New York: Chapman & Hall.

Tanner, J. 1962. "A Theoretical Analysis of Delays at an Uncontrolled Intersection." *Biometrika* 49 (1/2): 163–170. doi:10.2307/2333477.

Tarabia, A. 2000. "Transient Analysis of M/m/1/n Queue-an Alternative Approach." *淡江理工學刊* 3 (4): 263–266.

Tian, Z., M. Kyte, M. Vandehey, W. Kittelson, and B. Robinson. 2001. "Simulation-based Study of Traffic Operational Characteristics at All-way-stop-controlled Intersections." *Transportation Research Record: Journal of the Transportation Research Board* 1776 (1): 75–81. doi:10.3141/1776-10.

TRB. 1994. *Highway Capacity Manual*. Washington, DC: National Research Council.

TRB. 2000. *Highway Capacity Manual*. Washington, DC: Transportation Research Board (TRB), National Research Council.

TRB. 2010. *Highway Capacity Manual*. Washington D.C.: Transportation Research Board (TRB), National Research Council.

Troutbeck, R., and M. Blogg. 1998. "Queueing at Congested Intersections." *Transportation Research Record: Journal of the Transportation Research Board* 1646 (1): 124–131. doi:10.3141/1646-15.

Troutbeck, R. J. 1986. "Average Delay at an Unsignalized Intersection with Two Major Streams Each Having a Dichotomized Headway Distribution." *Transportation Science* 20 (4): 272–286. doi:10.1287/trsc.20.4.272.

Weiss, G. H. 1969. "The Single Lane Merging Problem with Mixed Cars and Trucks." *Transportation Research* 3 (2): 195–199. doi:10.1016/0041-1647(69)90151-8.

Yousif, S., M. Alterawi, and R. R. Henson. 2012. "Effect of Road Narrowing on Junction Capacity Using Microsimulation." *Journal of Transportation Engineering* 139 (6): 574–584. doi:10.1061/(ASCE)TE.1943-5436.0000534.

Zhou, H., L. Hagen, J. J. Lu, and Z. Tian. 2006. "Empirical Delay Models for Multi-lane Two-way Stop-controlled Intersections." *Ite Journal-Institute of Transportation Engineers* 76 (9): 41–46.

Zongzhong, T., M. Kyte, and J. Colyar. 1997. "Field Measurements of Capacity and Delay at Unsignalized Intersections." *ITE Journal* 67(4): 22–26.