# Saturation Headway Variation at a Signalised Intersection Approaches with a Downstream Bus Stop and Bicycle Lane

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## Abstract

Signalised intersection operational analysis requires understanding of lane utilisation and saturation flow rate (SFR) of approach lanes. SFR represents the average queue discharge on a lane across the stop line measured during the middle interval, between 10s after the signal changes to green and whichever is earlier of the time when the queue clears or the signal changes to yellow. However, localised impacts may cause SFR to vary within and between middle intervals. Many studies have identified this characteristic and reviewed the factors that influence SFR under diverse traffic, geometric and environmental conditions. But, no empirical study found to analyse the influence of a highly used far-side, offline bus stop combined with an adjacent bicycle lane on SFR of the upstream through-lane.

Due to the increased demand for transit service and the increased allocation for arterial road space for bicycles, it is important to evaluate their impacts on signalised intersection operation. This study investigates this complex situation with a case study in inner Brisbane, Australia. The selected intersection is located on a constrained corridor with high volume of buses and bicycles especially during the inbound morning peak, coinciding with the localised congestion at the far-side offline bus stop. This study uses four scenarios and examines saturation headway (inverse of instantaneous SFR) between middle intervals when; no re-entering buses are present, re-entering buses are present, bicycles are present, and re-entering buses and bicycles are both present downstream of the intersection. It also examines the distributions of saturation headways and statistically tests whether they differ between scenarios. Statistical tests confirmed that buses significantly affect change mean saturation headway where bicycles do not. These findings can be used to improve both deterministic and microscopic simulation modelling of signalised intersections at these complex sites.

Key Words: Saturation Headway, Saturation Flow Rate, Bus Stops, Bicycles

## 1. Introduction

Signalised intersections are vital nodes on a road network and their operational efficiency greatly influences the entire network's performance. Saturation flow rate (SFR) occurs during the middle interval, which occurs between 10s and after the signal changes to green and when the queue clears or the signal changes to yellow. SFR is a fundamental factor of signalised intersection operation. Accurate estimation of SFR is important and using poorly estimated values of SFR can lead to incorrect results and inappropriate signal timing plans, which can increase delay and traffic congestion.

Various factors influence SFR, and the saturation headway being the inverse of instantaneous SFR. The Highway Capacity Manual, HCM (2010) procedure and related studies have incorporated various factors (traffic, geometric and environmental) in order to determine SFR. Stokes (1989) performed a comprehensive review of the influential factors of SFR at signalised intersections and prepared a summary which included a number of physical and operational features. With the increasing role of on-street buses (OSB) in the passenger carrying capacity of the overall transport system, it is critical to understand this modes' impact on signalised intersection operation. Stokes (1989) observed that among the operational and physical features, bus stops located near signalised intersections create a major impact upon SFR.

A bus stop may be located on the near-side, or on the far-side of its neighbouring intersection. In either case, a bus may occupy either a general traffic lane or a bus bay while dwelling at the stop to load and unload passengers. Where there is a bus bay, buses pulling out and exercising right-of-way can interrupt general traffic flow in the adjacent lane. In addition, geometric delay due to buses decelerating and accelerating into and out of the bus stop can interrupt general traffic flow in the adjacent lane.

This situation may be aggravated when a formal bicycle lane exists either immediately to the right of the bus stop pull-out bay (under Left Hand Travel conditions), or shared by the bus stop itself, and/or when bicycles are frequent in the left side travel lane. This may largely be due to drivers in the left side travel lane needing to change lanes either partially or fully, to avoid a cyclist, whether or not a bus is dwelling or re-entering. When a general traffic queue is discharged from the upstream signalised intersection on green, lane utilisation and SFR across the stop line may be impacted noticeably by the downstream state of the intersection.

To the best of our knowledge, there is no literature that quantifies the impact of aforementioned complex interactions of a far-side offline bus stop with bicycle lane. Addressing this need, this research aims to study and identify the influence of far-side offline bus stops with bicycle lanes and/or high bicycle activity on signalised intersection operation, as measured by SFR across the upstream stop line during the middle interval. A case study approach was developed for a complex signalised intersection of Old Cleveland Road/Cavendish Road in inner Brisbane, Australia. Traffic flow data were collected during the morning inbound peak period across six weekdays. Variation of operational characteristics of buses, general traffic and bicycles were analysed in four different scenarios. The distributions of saturation headways were statistically analysed using number of tests in each scenario. SFR was estimated for each scenario, and was then compared between scenarios.

The remainder of this paper is structured as follows: Section 2 summarises the relevant literature. Thereafter, research methodology is presented in Section 3, followed by data analysis and discussions in Section 4 and Section 5 respectively. Finally, Section 6 concludes the paper and provides insights for future research.

# 2. Literature Review

## 2.1. Saturation Headway and Saturation Flow Rate

The Highway Capacity Manual, HCM (2010) defines SFR as the maximum flow rate for a traffic lane measured at the stop line during the green phase of a signalised intersection approach. Webster (1958) used a model to define the SFR and the departure process. According to the assumptions of this basic model, when a traffic queue released by the green traffic signal, after a few seconds, the queue discharge rate becomes constant. This uniform departure rate is termed as the saturation flow rate. SFR is denoted as "$s$" and measured in vehicles per hour green per lane (vphgpl). When the green signal initiated at a signalized intersection, the vehicles waiting in the queue start to cross the stop line.

The time interval between consecutive vehicles crossing the stop line is referred as the headway. The first headway is the time interval between the initiation of the green light and the front wheels of the first vehicle crossing the stop line. The second headway is the time interval between the first and second vehicles crossing the stop line. After a few vehicles, the model presumes that the headway becomes constant. This constant headway is defined as the saturation headway, and denoted as *"h"*. In general, this constant headway occurs when the fourth or fifth vehicle crosses the stop line (Roess et al., 2011; Mathew, 2014).

When every vehicle requires "*h*" seconds of green time and if the traffic signal remains always green, then "*s*" vehicles per hour would be able to pass the intersection (Roess et al. (2011)). According to the traditional method, saturation flow rate is computed as *s = 3600/h.*

According to the results obtained by a study conducted in USA, Kenneth and Joeph (1982) concluded that the saturation flow starts with the fourth vehicle in a queue. However, according to the observations of recent studies (Prevedouros and Li (2002); Bonneson et al. (2005); Tang and Nakamura (2007)), queue discharge patterns at signalised intersections did not follow Webster's model or traditional theories. Different discharge patterns observed at intersections, and headway compression and elongation of vehicles were observed during queue discharge. Numerous factors associate with the environment of signalised intersections contribute to these variations and hence, as a result, SFR varies.

## 2.2. Influencing Factors of Saturation Flow Rate

Factors influence the SFR are diverse. Miller (1969) summarises the influencing factors of SFR as geometrics, operating conditions, environment and traffic characteristics. These factors are now discussed.

### 2.2.1. Influence of Traffic Variables on Saturation Flow Rate

Some studies examined the queue discharge patterns and saturation flow region at signalised intersections. Branston and van Zuylen (1978) performed their research in North London in order to estimate the saturation flow directly from vehicle departures. In this study, green and amber time were divided into three consecutive counting periods. The first counting period begins when the green light starts and ends at a time within the saturation flow period. Then from there, the middle counting period starts and ends at a time when the departure rate is still saturation flow. The last counting period normally ends with yellow light, but all the vehicles departed at the yellow and red light were included in the counting.

A similar approach, but some different counting periods were utilised by Akcelik (1998) in research report ARR No. 123, when counting the number of vehicles departed at signalized intersections. In this method, Akcelik (1998) used three intervals. First interval is first 10s of the green period. Middle interval is the rest of the green period while saturated. Last period is the period after the end of green, i. e. yellow and the following red period. Vehicles are counted when each vehicle cross the stop line. This method was incorporated in the present study to estimate the SFR, and described in detail in Section 3.

Prevedouros and Li (2002), Tang and Nakamura (2007), Chen et al. (2011) and Shao and Liu (2012) studied the variation of headways and SFR with queue discharge patterns at signalised intersections. They used different methods in their studies. In some studies, headway data were collected in different regions and variation of queue lengths, and queue discharge patterns could be observed. In addition, saturation flow region varied. Actual situation was different from the traditional scenario and headways compression

and elongation observed during queue discharge. In some cases, headway distribution followed log-normal distribution, while in other cases it followed normal distribution.

Some researchers have focused on the influence of speed on SFR. Nyantakyi et al. (2014) assessed the performance measures using a micro simulation model at Amacom intersection in Kumasi metropolis, Ghana. This analysis was performed to check the correlation of speed and headway with SFR. The results indicated, for both field and simulated conditions, the headway had a strong correlation with SFR compared to speed. Fornalchyk et al. (2013) developed a model at signalised intersections in Ukraine to analyse the speed and the saturation flow volume. The results indicated that the intersection passing speed influenced the saturation flow volume with all speed limits used for the study.

### 2.2.2. Influence of Geometric variables on Saturation Flow Rate

Miller (1969) found that the lane width affects the SFR. When the lane width increased up to 10ft (3.3m), SFR increased rapidly. After that, the lane width had very little effect upon SFR. Similar findings reported by other studies. Branston and van Zuylen (1978) measured the saturation flows at 16 intersections in three cities in Texas and found no significant difference of SFR for lane widths above 10ft (3.3m). Kimber and Semmens (1982) summarised the results of an experiment and observed SFR was increased with the increasing lane width. Miller (1969) observed that SFR is related to the number of lanes more than the lane width. Lane type was a significant influential factor of SFR. Contrast to this, Kimber and Semmens (1982) could not observe significant difference of SFR between the lanes. Arasan and Vedagiri (2006) and Alex and Issac (2014) developed simulation models to estimate the variation of SFR and observed significant increase in SFR with increasing road width.

Kenneth and Joseph (1982) studied SFR at intersections that had a considerable range in selected variables, and they found grade had a considerable effect on SFR. When grade increased, the value of SFR decreased. Resulting SFR was 5 percent lower for the steep grades than for flat grades. Also they prepared a summery for SFR in through-only lanes as a function of number of through lanes. The results showed that, providing additional through lanes increased the SFR of through-only lanes.

Fitzpatrick et al. (2014) studied the effects of geometric characteristics on double left-turn lane (DLTL) (LHT: double right-turn lane) operations. When lanes are wider, drivers may feel more comfortable and drive faster, which would be reflected in higher SFRs. This analysis found the opposite results.

Shang et al. (2014) studied the SFR under mixed traffic conditions, analysing a large number of experimental data collected at signalised intersections in Beijing. T intersections, cross intersections and more intersections that are complicated were selected for study. The results showed that the saturation headways approximately followed normal distributions. The results obtained were approximately equal to the base flow rates. This situation might be applicable to the particular sites studied. In other studies, different results observed, especially when the headway distributions did not fit with the normal distribution.

### 2.2.3. Influence of Environmental and other Factors on Saturation Flow rate

Stokes (1988) prepared a summary of reported SFR values from various studies. According to his summary, the range of the reported SFR values is 1600 – 1800 veh/h/ln. Here, the more recent estimates contain in the high end of the range. Stokes (1989) suggests that the most significant external factor requiring additional research is the influence of driving behaviour on the SFR.

Akcelik (1998) recommends that saturation flow values should be measured in the field whenever possible, and measured SFR values in local areas should be used for detailed design purposes. Rahman et al. (2005), Zhang and Chen (2009) and Majeed et al. (2014)

drew similar conclusions according to the observations made in their studies conducted in Yokohama in Japan, Dhaka in Bangladesh, Nanging city in China, and Alabama in USA. They suggest that the factors contribute to this difference of SFR are different traffic compositions, road geometries, congestion levels and socio-economic background of drivers.

Allen et al. (1998) conducted a study to analyse and quantify the effect of bicycles on capacity of signalised intersections. They developed a relationship between the bicycle volume and the percent of the green phase during which bicycles occupied a conflict zone between bicycles and right turning vehicles. Then they calculated the saturation flow adjustment factor ($f_{Rpb}$) and SFR. The estimated SFR and the capacities were lower than the values given by HCM (1994) procedure, which implies HCM (1994) procedure overestimates the capacity at signalised intersections when there is significant bicycle and pedestrian traffic.

## 2.2.4. Influence of Bus Stops on Saturation Flow Rate

A bus stop is a designated place where buses stop for passengers to board or leave a bus. The detrimental impacts to the traffic flow cause by the stopping buses cannot be avoided. Therefore, a realistic measure is needed to assess the effect of transit busses have on the capacity and SFR at signalised intersections.

Zegeer (1986) summarised the results of a saturation flow surveys conducted across the United States at signalised intersections. 262 buses stopping on intersection approaches were observed for analysis. The average length of time that these buses blocked the adjacent lane during a green phase was 9.1 seconds. (compared with 14.0 sec from the HCM (1985) surveys). Due to this bus blockage, Saturation flow rate was decreased about 2.5 percent for each of 10 buses per hour stopping on a one-lane approach.

Gibson (1996) focused on the influence of a downstream signalised intersection on the capacity of a multi-berth bus-stop. This experiment presented the results of simulation modelling on the impact of intersection/bus-stop interaction (upstream and/or downstream). He discussed the influence of signal timing, green time ratio for the bus-stop lane, Bus stop-intersection distance and Bus-stop exit discipline. It was found that bus-stop capacity reduction effect ties within a broad range, depending on all four factors. The most relevant one was the distance to the stop line.

Holt (2004) studied the effects of bus stops on SFR at signalised intersections developing analytical equations and simulation models. The average bus blockage time found in HCM (2000) is 14.4 seconds and the actual situation at field varied. Holt (2004) found a lack of any conclusive analysis in the literature for the impacts that an alternative bus stop design and treatment can have on an intersection's saturation flow rate.

Kwami et al. (2009) studied the effect of bus bays on the capacity of kerb lanes. He developed a model for determining the quantitative impact of bus bay on capacity of curb lanes. In this study, they observed that some aggressive drivers do not yield to buses when the buses were manoeuvring to pull into the bay as well as pull out of the bay to re-enter the traffic stream of the curb lanes. Further, the number of passengers boarding and/or alighting the bus will influence the dwell time on the bus bay and the entry time of the other buses into the bus bay. Ghasemlou et al. (2012) studied the effect of dwell time of busses on signalised intersection operation. They developed a model and found that the bus blockage factor influenced by the factors such as geometric shape of lanes, traffic, bus stop types and bus types (single unit bus or articulated bus). They observed that the variation of dwell time has a linear effect on SFR.

According to the literature review performed in Section 2, it was found that various studies have been conducted to analyse the influencing factors of SFR at signalised intersections as well as the influence of near-side and far-side bus stops on signalised intersection operation. But no study was found to address the complex situation of bus re-entry process of far-side offline bus stops with bicycle lanes.

# 3. Methodology

The case study was undertaken at a complex signalised intersection in inner Brisbane, Australia. The research methodology was planned and performed as per the steps given below.

(1) A pilot survey was carried out on Old Cleveland Road corridor in Brisbane's inner east. This road is a high-congested road corridor experiencing traffic congestion and high volumes of transit buses in peak periods. Meanwhile, high bicycle flow take place along the congested corridor. Inbound bus stop number 23 was selected as the study site. This express and local stop is an offline bus stop located downstream of the signalized intersection of Old Cleveland Road/Cavendish Road. During the morning peak hour, 50 buses are timetabled to stop here. This bus stop has three loading areas. It was observed cyclists pass the intersection, and the kerb lane is marked as a shared lane for the bus stop and cyclists. Study site shown in Figure 1.

**Figure 1: Lay Out - Old Cleveland Road/Cavendish Road Signalised Intersection**
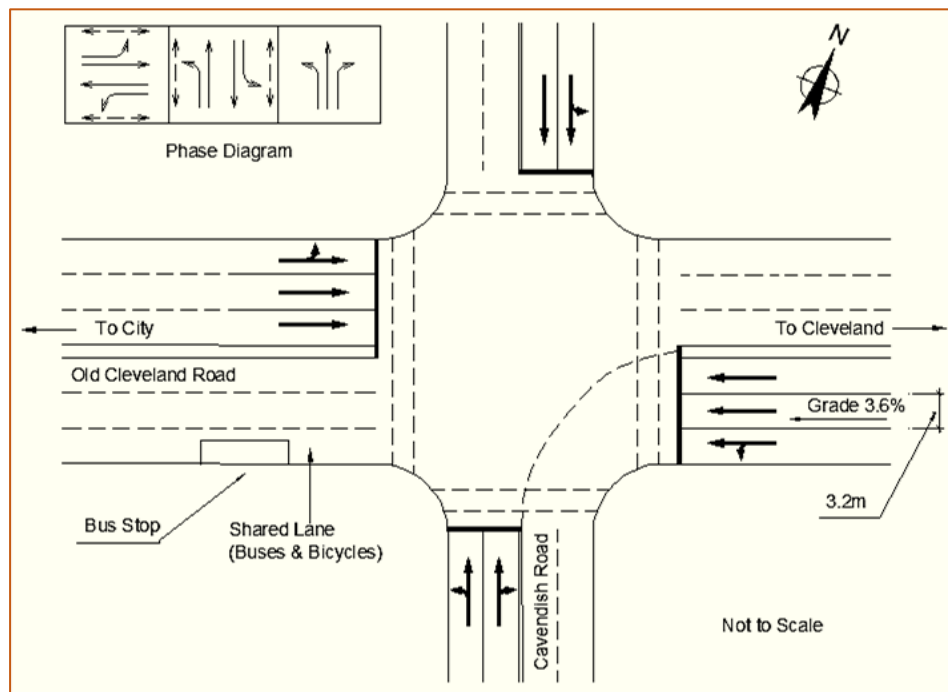


(2) Traffic flow data of middle lane were recorded manually at the stop line at signalized intersection in the morning peak time on six week days (working days). A macro program was prepared in an Excel spreadsheet that was developed for this purpose, and traffic flow data at stop line were collected using that program in laptop computer. Cars, buses, and heavy vehicles were marked in the spread sheet as they pass the intersection. Time stamp was recorded when each vehicle's front wheels crossed the stop line. It was also marked when bicycles pass the bus stop, and when buses departed the bus stop.

(3) Recorded traffic flow data at the stop line on six days were processed to obtain the headway data for each vehicle. First, the headway data for mixed traffic flow were estimated for all six days. Variation of departure headways was plotted for each signal cycle. A sample plot is given in Figure 3, which shows the different fluctuation patterns of headways. Considering these different fluctuation patterns, four scenarios were created in order to analyse the variation of saturation headway

(*h*) and SFR according to the operational characteristics of busses, general traffic and bicycles.

Four scenarios were identified as follows:
   a) "Cars only" scenario. Cars pass the stop line. No buses or bicycles at the bus stop.
   b) Bicycles pass the bus stop when there are no buses.
   c) Bus re-entry occurs when there are no bicycles.
   d) Bicycles pass the bus stop when there are buses / or when bus re-entry occurs.

(4) Using the Australian Research Report: ARR No. 123 method (Akcelik(1998)), SFR was calculated for mixed traffic flow for all six days. For this method, Akcelik (1998) used three intervals to record the vehicle departures at stop line, as described follows:
   i) First interval is the first 10 seconds of the green period.
   ii) Middle interval is the rest of the green period after 10 seconds. Only vehicles departing the stop line in saturation state are considered for middle interval counting.
   iii) Last interval: This is the period that include yellow and the following red period (after the end of green period).

Each vehicle is counted when it crosses the stop line. The counts were repeated for 30 cycles and tabulated in the table provided in ARR No. 123 report. The saturation flow in vehicles per second is given by Equation (1).

$$S = \frac{(X_2)}{(X_4 - 10n_4)} \qquad \textbf{Equation (1)}$$

$X_2$ = Total number of vehicles passed stop line during the middle interval, as described in above ii).

$X_4$ = Saturation time in seconds for $n_4$ cycles.

$n_4$ = Total number of samples included in the calculation of SFR.

Saturation time included first interval and the middle interval, but not the last interval. The maximum value of the saturation time is green period. If the saturation time is less than 10 seconds, the counts in that cycle are excluded. Finally, SFR is estimated as $3600s$.

In the present study, SFR was estimated for all six days using this method.

When estimating the design volumes, the passenger car equivalent (PCE) is used to convert a mixed traffic flow into an equivalent passenger car flow.
HCM (2000) and HCM (2010) do not give an explicit methodology to compute the PCE for heavy vehicles in a traffic stream. Therefore, researchers have conducted several studies in order to estimate the PCE factors for heavy vehicles using various methods in various contexts.
Cuddon and Ogden (1992) conducted a major study of lane saturation flows at signalised intersections in Melbourne, Australia. The influence of various vehicle types was examined in this study, taking lagging headways between vehicles. The formula derived by them is given by Equation (2) which was used to estimate PCE in present study. This formula was derived using headway ratio method as illustrated by Figure 2. Lennie (2006) used a similar method, for estimation of PCE.

**Figure 2: Time headway measurements between vehicles in a traffic stream for PCE calculation**
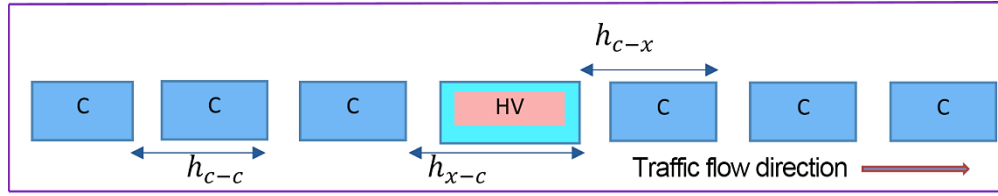


$$PCE = (h_{x-c} + h_{c-x} - h_{c-c})/h_{c-c} \qquad \textbf{Equation (2)}$$

$h_{c-c}$ = headway between cars

$h_{x-c}$ = headway between heavy vehicles and cars

$h_{c-x}$ = headway between cars and heavy vehicles

The present study used Equation (2) to estimate PCEs. Headways were measured between front bumpers of vehicles (leading headway method) which is stated in HCM (2000) and HCM (2010). SFR was estimated under each scenario, and variation was comparatively analysed.

(5) Finally, variation of saturation headways ($h$) in each scenario given in (3) were comparatively analysed using number of statistical tests described in Section 4.2.

# 4. Data Analysis and Results

In this section, data analysis is presented under two categories. Section 4.1 describes in step by step the procedure of estimating SFR. Section 4.2 gives the results of statistical analysis of saturation headway distributions.

## 4.1. Estimation of Saturation Headway and Saturation Flow Rates

For this analysis, first, the headway data ($h$) for each cycle were obtained and then, the SFR was estimated for all six days and different scenarios. This procedure is given by following steps.

1. Headway data for mixed traffic flow were estimated for all six days. Variation of departure headways was plotted for each cycle. Four samples of these graphs extracted from 02 November 2016 data depicted in Figure 3. These four samples represent the four different scenarios described in research methodology, and these cycles are randomly selected sample cycles from the recorded data. Headway distribution patterns show that "$h$" varies in different ways in each cycle according to the different circumstances prevailed at the intersection. Frequent fluctuations of headways could observe due to stopping buses and bicycles, heavy vehicles and re-entering buses. Headway data obtained from four cycles are given in Table1.

**Table 1: Variation of departure headways at stop line for four sample cycles reflecting each scenarios**

| Cycle | Headway minimum(S) | Headway maximum(S) | Mean Headway(S) | % increase in headway |
|-------|--------------------|--------------------|-----------------|----------------------|
| Cycle 1 | 1.7 | 5.1 | 2.5 | - |
| Cycle 2 | 1.9 | 4.3 | 2.6 | 4% |
| Cycle 3 | 1.1 | 6.4 | 2.7 | 8% |
| Cycle 4 | 1.5 | 6.6 | 3.0 | 20% |

The results indicate that mean headway increased by 20% from Cycle 1 to Cycle 4 (from "Cars only" scenario to "Bus re-entry and bicycles" scenario). Cycle 1, Cycle 2, Cycle 3 and cycle 4 represent the scenarios a, b, c, and d respectively, which described in Section 3 (Methodology).

**Figure 3**: **Variation of departure headways at stop line**
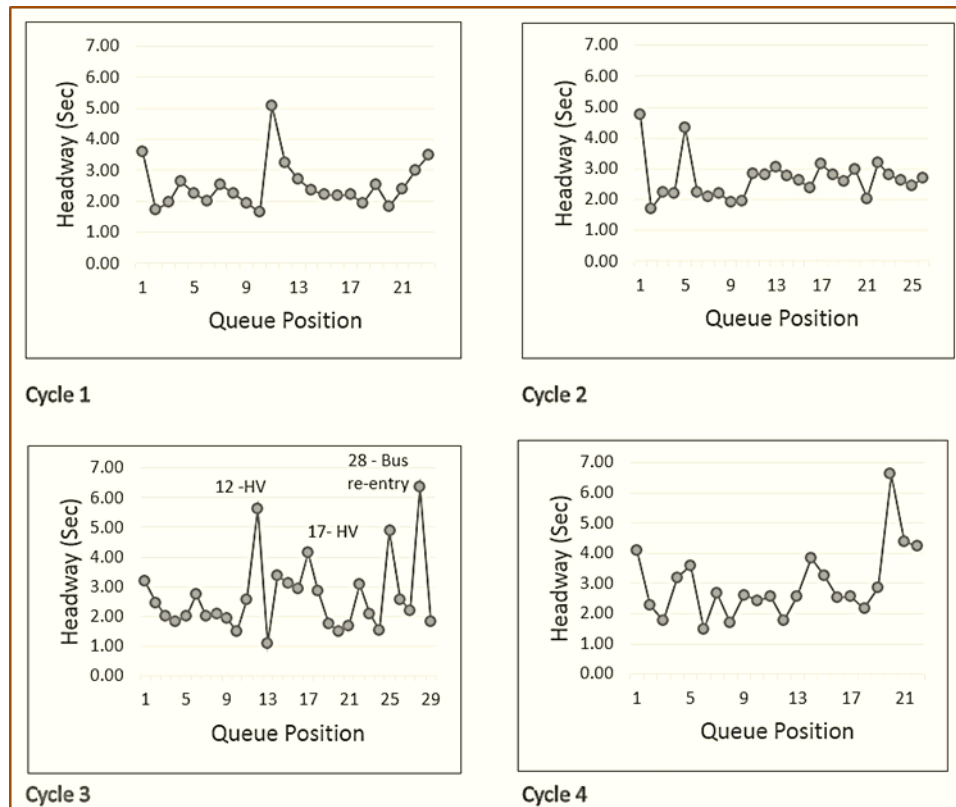


Variation of headway distribution patterns among four cycles, which belong to four scenarios described is evident in Figure 3. As an example, the reasons for frequent fluctuations of headways shown in Cycle 3. In Cycle 3, at queue positions 12 and 17, presence of heavy vehicles increased the headway. At queue position 28, bus re-entry increased the headway.

The headway data obtained in this step will be using in the statistical tests perform in Section 4.2.2.

2.  Using Australian Research Report: ARR No. 123 method (Akcelik (1998)), SFR was calculated for mixed traffic flow for all six days as described in Section 3. In this

method, traffic flow data from the middle interval departures for 30 cycles were processed to obtain the SFR. The estimated SFR values for mixed traffic flow are given in Table 2.

**Table 2**: **Estimated Saturation Flow Rates using ARR No. 123 Method for mixed traffic flow**

| Date | $X_2$ (Veh) Middle Interval | $X_4$(S) Saturation Time | $n_4$ (No. of Cycles) Middle Interval | SFR veh/h/ln | PCE Value | SFR pc/h/ln |
|---|---|---|---|---|---|---|
| 12/06/2016 | 647 | 1770 | 30 | 1584 | 1.56 | 1650 |
| 22/06/2016 | 680 | 1844 | 29 | 1575 | 1.54 | 1631 |
| 17/08/2016 | 736 | 2023 | 30 | 1537 | 1.60 | 1611 |
| 14/09/2016 | 644 | 1874 | 30 | 1475 | 1.32 | 1512 |
| 02/11/2016 | 574 | 1654 | 30 | 1526 | 1.55 | 1617 |
| 16/11/2016 | 670 | 1729 | 28 | 1664 | 1.24 | 1691 |

Estimated SFR varied from 1512 pc/h/ln to 1691 pc/h/ln.

3. In this step, traffic flow data for all six days were rearranged into four scenarios described in Methodology and, again SFR was estimated in pc/h/ln using ARR No. 123 method. Variation of SFR for different scenarios could be observed. The estimated SFR values for four scenarios are given in Table 3. The headway values given in Table 1 are only for four sample cycles. As given in Table 3, overall average headway for "Cars only" scenario was 1688 pc/h/ln, which is not unexpected for a 3.2 m lane adjacent to a bus and turning vehicle lane.

**Table 3: Variation of SFR for four Scenarios at the Bus Stop**

| Scenario | SFR pc/h/ln | % decrease of SFR |
|---|---|---|
| a) **Cars only** | 1688 | - |
| b) **Bicycles flow; no stopping buses or bus re-entry.** | 1642 | 2.73% |
| c) **Bus re-entry occurs; no bicycles.** | 1607 | 4.50% |
| d) **Bus re-entry occurs; bicycles flow.** | 1583 | 6.22% |

SFR decreased by 6.22% from "Cars only" scenario to "Bus re-entry occurs: bicycles flow" Scenario. These results indicate when movement of buses and bicycles increases, and when bus re-entry occurs, SFR decreases. However, further statistical analysis was warranted.

## 4.2. Statistical Analysis of distribution of Saturation headway

In this part of analysis, headway data obtained in Section 4.1 were re-arranged into four scenarios given in Table 3, excluding heavy vehicles from four samples in order to obtain the variation of car flow. Then using those four samples, six cases were developed in order to perform the statistical tests. These six pairs of samples selected as listed.

1. Cars Only vs Bicycles
2. Cars Only vs Buses and bicycles
3. Cars Only vs Buses
4. Buses vs Bicycles
5. Buses and bicycles vs Bicycles
6. Buses vs Buses and bicycles

Number of statistical tests were performed to study the variation of headway distribution in each case. The results of the data analysis for 02 Nov 2016 described systematically.

### 4.2.1. Normality tests

A normality test was performed and Q-Q plots were obtained for all four samples. This test was performed to check whether any of the samples follow the normal distribution. The Anderson – Darling test was used for this purpose.

### 4.2.2. Two-sample t- test

The typical comparison of two distributions is the comparison of means. For this study, even though the non-normality was observed in saturation headway distributions, the Student's t-test was used as a secondary test in order to compare for six pairs of samples of headways whether the means were different. Clear evidence for equal mean values was obtained only in combination 6 (Buses vs Buses and bicycles; $p=0.4$). These results indicate that departure headways fluctuated in different ways following different distribution patterns with variation of congestion level created due to the movement of cars, buses, and bicycles. Results are summarised in Table 4. Mean values of saturation headway are given in Table 5.

### 4.2.3. Two-sample Kolmogorov-Smirnov test / Two-tailed test

The two-sample Kolmogorov-Smirnov test (K-S test) was performed for six pairs of samples of headways. This is one of the most useful and general non-parametric methods of comparing two samples. These tests performed for each pair in order to check whether the two data samples come from the same distribution.

The test results are summarised in Table 4. Figure 4 gives a graphical representation. For all the tests, the significance level α was taken as 0.05. These results indicate that most of the pairs of samples did not come from the same distribution. Headways fluctuated in different ways in each case. Only in the case 6 (Buses vs Buses and bicycles), clear evidence could be found for equal distribution of samples ($p=0.634$). In case1 (Cars only vs Bicycles), some evidence found for equal distributions ($p=0.36$). In all other cases, results of K-S test confirmed each sample came from different distributions.

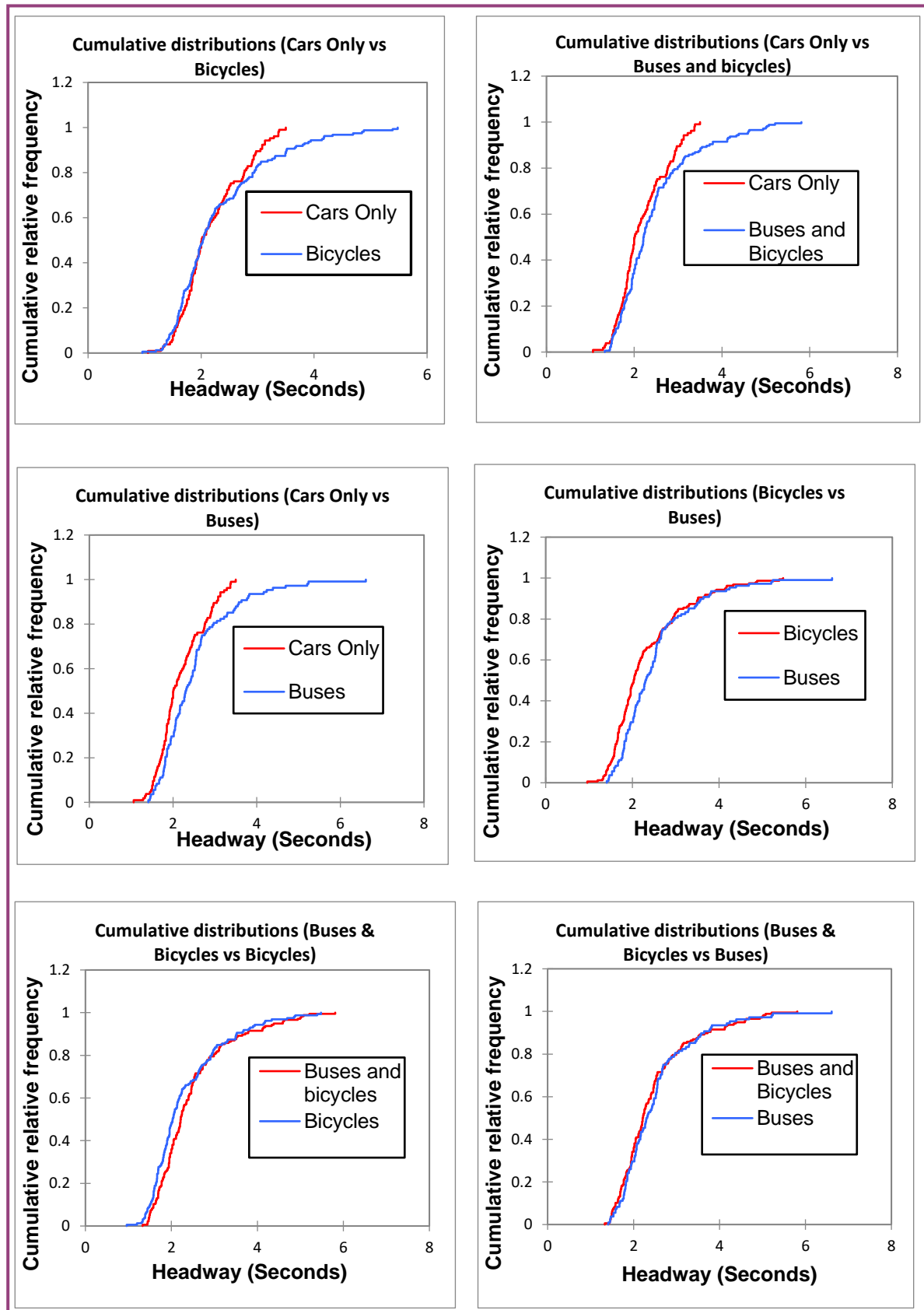**Figure 4**: **Results of Two-sample Kolmogorov-Smirnov test / Two-tailed test**

**Table 4: Results of Statistical tests on Saturation Headway Variation**

| Combination of Two Samples | Tests Performed and Results | |
|---|---|---|
| | **Two Sample K –S Test** | **Two Sample t-test** |
| 1. **Cars Only vs Bicycles** | Some evidence that two samples follow same distribution. p value=0.360 | Some evidence for equal mean values. Difference =0.13 p value=0.146 |
| 2. **Cars Only vs Buses and bicycles** | Distribution of two samples are different. p value=0.083 | Mean values are different. Difference =0.44 p value=0.0001 |
| 3. **Cars Only vs Buses** | Distribution of two samples are different. p value=0.02 | Mean values are different. Difference =0.33 p value=0.001 |
| 4. **Buses vs Bicycles** | Distribution of two samples are different. p value=0.021 | Very low evidence for equal mean values. Difference = 0.20 p value=0.07 |
| 5. **Bicycles vs Buses and bicycles** | Distribution of two samples are different. p value=0.019 | Mean values are different. Difference =0.30 p value=0.011 |
| 6. **Buses vs Buses and Bicycles** | High evidence that two samples follow same distribution. p value=0.634 | High evidence for equal mean values. Difference = 0.10 p value=0.40 |

**Table 5: Mean Values of Saturation Headway for different Scenarios**

| Scenario | Saturation Headway (Seconds) |
|---|---|
| **a) Cars only.** | 2.20 |
| **b) Bicycles flow; no stopping buses or bus re-entry.** | 2.30 |
| **c) Bus re-entry occurs; no bicycles.** | 2.50 |
| **d) Bus re-entry occurs; bicycles flow.** | 2.60 |

Table 5 indicates, in scenarios "a" and "b", mean headway is lesser and similar, but when the movement of buses increases, the mean headway increases as indicate in scenarios "c" and "d".

# 5. Discussion

The results of this study revealed that saturation headway fluctuated in a wide range at a busy signalized intersection with a far-side offline bus stop and bicycle lane, due to different circumstances prevailed at the intersection.

Steady traffic flow patterns could be observed in a very few number of cycles. In scenario "Cars Only", steady flow observed in some of the cycles, but it also varied in some other cycles. With the fluctuation of saturation headway in four scenarios defined in Table 3,

SFR decreased by 6.22%. This indicates the significance of variation of saturation headway and SFR between each scenario. These fluctuations create different congestion levels.

Saturation headway considerably fluctuated when re-entering buses were present as well as when re-entering buses and bicycles were present. When analyse some cycles, a steady – state queue discharge could not be observed at all. Traffic flow patterns varied in-between in the case when bicycles were present.

K-S test results revealed distribution of saturation headway differed for each case studied. Clear evidence for equal distributions could be observed only in case 6 (Buses vs Buses and bicycles).

T-tests confirms the mean values of headway distributions are different and mean value varied in a wide range (2.2 sec -2.6 sec). According to these results, percentage increase of saturation headway was 18.2%. These observations reflect the fact that saturation headway and SFR vary differently due to the surrounding traffic flow and congestion level at each time.  Table 4 shows the results of K-S test and t-test are similar and hence, K-S test results about distribution align with the t-test results about mean.

As per the observations made at this complex bus stop, the factors or reasons contribute to headway fluctuations can be listed as variation of dwell time, bus driver behaviour, variation of re-entry time (in red period or in green period) and interaction of buses and bicycles. When bus re-entry occurred during the green period of a cycle, the queue discharge from the stop line was severely affected.  When it occurred during the red interval, buses passed quickly without obstruction. When the door closed, some bus drivers passed quickly and re-entered the traffic stream while some other drivers waited and took some time to re – enter. Moreover, some buses stop at the bus stop for a while even after the boarding of passengers. When a following bus was waiting to enter the bus stop, this condition affected the traffic flow. Dwell time varied between six seconds and 67 seconds as per a sample data collected.

These observations and the results obtained from statistical tests confirm the existence of high-congested state on Old Cleveland Road corridor during peak periods due to the transit buses.

# 6. Conclusions

The main objectives of analysing and modelling traffic flow at signalised intersections are estimation of capacity and determination of level of service (LOS). Therefore, use of SFR for capacity analysis should be carefully examined for accuracy. This study revealed that obtaining true queue discharge patterns are significant in estimation of saturation headway and SFR.  Field data and Statistical tests proved that queue discharge patterns frequently fluctuate and deviate from the traditional theories with respect to a complex downstream offline bus stop with a bicycle lane.

As per the results indicate in Table 3, the decrease in SFR by 6.22% was significant when SFR varies from "Cars Only" scenario to "Bus re-entry occurred; Bicycle flow" scenario. SFR was decreased by re-entering buses.

The K-S tests revealed that the headway distributions were statistically significantly different in the cases when re-entering buses were present vs re-entering buses were not present. Likewise, t-tests confirmed that statistically significant difference of mean value of saturation headways could observe only between the cases when re-entering buses were present vs re-entering buses were not present. These results reveal that saturation headway and therefore SFR were impacted by re-entering buses, but not by the bicycles. Table 5 clearly reflects, when the movement of buses increases, the mean headway

increases. Even that, Table 5 indicates a marginal increase in saturation headway in the presence of bicycles.

With increasing travel demand, current transport infrastructure facilities and traffic control strategies have become inadequate. Development of public transport is the best solution to manage the growing mobility demands. Demand for transit service, as well as the allocation of arterial road space for bicycles have increased. More buses and bicycles are prevalent on roadways. Hence, the combined influence of these modes amongst localised traffic streams must be re-considered. The findings of this study can be utilised to improve both deterministic and microscopic simulation models develop at signalised intersections, in order to replicate the real situation of traffic flow adequately.

Frequent fluctuations of saturation headway and SFR indicate that models to estimate SFR should be calibrated and updated to represent the current field environments. It is recommended that SFR should be measured in the field wherever possible.

The impact of an intersection's location and the distance between stop line and the bus stop are factors affecting SFR. When the distance to downstream bus stop varies from 20m to 50m, SFR would vary significantly. These factors must be investigated in future research. When the buses enter to first through lane from the bus stop, the SFR of general traffic in that lane will be directly affected. The impact on traffic flow of second through lane will be fairly less and this is not analysed in this paper. It would be analysed in future research.

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