Abstract: The basic model of traffic operations at signalized intersections is based on the assumption that when a signal changes to green, the flow across the stop line increases rapidly to saturation flow rate, which remains constant until either the queue is exhausted or the green period ends. In recent years, this assumption has been challenged by some field observations in Taiwan and U.S.A. These observations showed marginal increase in queue discharge rate along the queued vehicles’ position. This paper investigates queue discharge behavior at signalized intersections based on video data collected from one of the busiest at-grade intersections. The methods proposed in the HCM (2000) and Australian Road Research Report 123 to estimate saturation flow rates were assessed against field observations. The results from field observations were similar to those observed in Taiwan and U.S.A., whereas the micro-simulation results went against some common perceptions that believed micro-simulation under represents queue discharge rate.

Key Words: saturation flow rate, queue discharge rate, signalized intersections, micro-simulation, HCM, ARR 123
1. INTRODUCTION

Capacity is the most widely used concept in traffic engineering practice. In the planning, design, and operation of signalized intersections an estimate of lane capacities is required under prevailing road geometric, traffic and signal control conditions. The U.S. “Highway Capacity Manual (2000)” published by Transportation Research Board and a research report ARR 123 on “Traffic Signals: Capacity and Timing Analysis” published by the Australian Road Research Board are two important references on this concept (HCM, 2000, Akcelik, 1981). Saturation flow rate represents the most important single parameter in the capacity and signal timing analysis of signalized intersection (Akcelik, 1981). It is defined as the steady maximum rate at which queued vehicles can be discharged into an intersection while the traffic signal is green.

The basic model of traffic operations at signalized intersections is based on an assumption that when the traffic signal changes to green, the flow across the stop line increases rapidly to saturation flow rate, which then remains constant until either the queue is exhausted or the green period ends (Akcelik, 1981). The model is shown in Figure 1. In recent years, this assumption has been challenged by some field observations conducted in Hawaii, Taiwan and U.S.A. (Li and Prevedouros, 2002, Lin et al., 2007, Lin and Thomas, 2005, Lin et al., 2004). The average headway between successive vehicles in these studies was measured to have a decreasing trend along the platoon through to the last queued vehicle discharged from the intersection, causing some marginal increase in saturation flow rate. Large variations observed in saturation flow measurements challenged the presumption that the base saturation flow rate of 1,900 passenger cars per hour of green time per lane (as specified in HCM (2000)) is either stable or a constant value.

While most of the analytical models are built on the capacity concept, micro-simulation models do not. Micro-simulation models are built based on a different modeling paradigm that is based upon car-following and lane-changing behavior of individual vehicles. Various studies have challenged the validity of micro-simulation models in their ability to replicate queue discharge behavior observed at signalized intersections (FHWA, 1981, Akcelik, 2008).

This paper reports on a study that investigates queue discharge characteristics at signalized intersections. The methods proposed in HCM (2000) and ARR 123 to estimate saturation flow rate were verified against field observations taken from a busy signalized intersection in Auckland, New Zealand during peak hours. A micro-simulation model of the same signalized intersection was developed in AIMSUN micro-simulation software to model queue discharge behavior at the signalized intersection and was assessed against the observed field data.

The specific objectives of this research are in three-folds:
1. Investigate queue discharge characteristics based on data collected from a signalized intersection in Auckland, New Zealand;
2. Measure saturation flow rate using methods proposed in HCM (2000) and ARR 123 and compare them with field observations; and
3. Evaluate the performance of the AIMSUN micro-simulation model in replicating queue discharge behavior at the signalized intersection.
2. SATURATION FLOW RATE

As discussed earlier, saturation flow rate is the most important parameter used in intersection design to determine the intersection capacity and level of service. Clayton (1941) suggested 1500 passenger cars per hour of green time per lane (pcphgpl) for saturation flow rate based on his field observations. The same value was proposed in the first edition of HCM published in 1950 (HCM, 1950), which was later revised in the second edition of HCM published in 1965 and increased to 1,800 pcphgpl (HCM, 1965). In a special report # 209 published by Transportation Research Board in 1997, the value was further increased to 1900 pcphgpl (HCM, 1998). This value has then remained the same for base saturation flow rate in the latest edition of HCM (2000). Saturation flow rate can be estimated from the base saturation flow rate after applying some adjustment factors to better represent prevailing roadway geometric, traffic and signal control conditions (HCM, 2000). There is no better substitute to accurately collected field data. When there is such data available, saturation flow rate can be directly measured from the average headway measurements between successive vehicles entering the intersection.

Since the research of Clayton (Clayton, 1941) a great deal of research has been conducted on the saturation flow rate, proposing values ranging from 1500 to 2500 pcphgpl (Lin et al., 2004, Teply, 1983). The base saturation flow rate has been assumed to be constant for traffic signalized intersections during the green time. The methodology proposed in HCM (2000) measures saturation flow rate by averaging the saturation headways, which is defined as the average headway after fourth vehicle in the queue till the queue dissipates. The saturation flow rate is then determined by the following equation;
Where $s$ is saturation flow rate and $h_s$ is the saturation headway in seconds. The following equation can then be used to calculate the subsequent capacity of the signalized intersection.

$$C_g = \frac{3600}{h_s}$$  \hspace{1cm} (1)

Where $c = \text{capacity of approach in vehicles per hour (vph)}$, $s = \text{saturation flow in vehicles per hour of green (vphg)}$, $g = \text{effective green time (s)}$, and $C = \text{cycle length (s)}$.

In recent years, the assumption that the saturation flow rate remains constant after the first three to five cars has passed through the stop line until either the queue is exhausted or the green period ends has been challenged by field observations conducted in Hawaii, Taiwan, and U.S.A. (Li and Prevedouros, 2002, Lin et al., 2007, Lin and Thomas, 2005, Lin et al., 2004). Li and Prevedouros (2002) observed fluctuations in the queue discharge rate for different queue positions in Hawaii. Lin et al. (2004) indicated, based on their study in Taiwan, that the queue discharge flow rate does not rise quickly to maximum level, instead, it rises gradually. This rising trend of maximum discharge flow rate is also observed in another study of three intersections at Long Island, New York (Lin and Thomas, 2005). Teply (1983) based on his field observations conducted in Canada also noted that saturation flow rate varies with the length of green time.

Long (2007) presented an analytical model to replicate queue discharge behavior at signalized intersections and verified his model against data collected in U.S.A.. The significance of this model is that, unlike others, it did not assume the saturation flow rate to be a constant rate. The gradual increase in saturation flow rates observed in the field data was well replicated by the model however, the author did not present complete mathematical expression of his model. It was mentioned that the analytical solution for the model is difficult to obtain and it must be solved by some root-search techniques.

3. CAPACITY ANALYSIS USING MICRO-SIMULATION

Microscopic simulation models are rapidly gaining acceptance as a promising tool to analyse and evaluate applications of ITS and other traffic control and management measures by traffic engineers and transportation professionals. Microscopic traffic simulation models describe the system entities and their interactions at high levels of detail. Its applications in solving complex traffic engineering problems have received popularity as well as criticism. These models can track and record the movements of individual vehicles, which help and allow the analyst to test a wide range of roadway configurations and operational conditions that far exceed the limits of typical analytical tools. Additionally, micro-simulation models include highly sophisticated graphical user interfaces (GUI) that allow visual displays and the demonstration of traffic operations on a computer screen, which was not possible previously.
in conventional computational tools. These significant characteristics help to enhance understanding both within the transportation professionals as well as those outside the profession. A better visualization of traffic operations thereby allows the graphical presentation (simulating real traffic behaviour) and a better understanding in public meetings; the effects of traffic improvements. However, micro-simulation models have been criticised for being time consuming requiring extensive resources and expense when compared with more traditional analytical tools.

A limited number of studies have been undertaken using micro-simulation approaches to investigate capacity and queue discharge estimations. A general perception is that micro-simulation under represents the capacity when compared with field observations (FHWA, 1981, Akcelik, 2008). Andjic and Nigel (2008) using a hypothetical model of a signalized intersection in Q-Paramics micro-simulation software (Q-Paramics, 2006); produced queue discharge flow rates close to what is suggested in ARR 123 (2). However the input parameters used in the model were unrealistic. For example, 0.5 second was used for reaction time which is much lower than the values observed in field (Ranjitkar et al., 2003). Chaudhry and Ranjitkar (2009) modeled a signalized intersection in Auckland, New Zealand (the same intersection modeled in this research) in AIMSUN micro-simulation software (AIMSUN, 2008). The results produced on queue discharge flow rates were quite comparable to those taken from loop detectors managed by SCATS; without compromising on input parameters values.

4. DATA COLLECTION

Balmoral Road -Dominion Road intersection was selected as a test bed for this research. This is one of the busiest signalized intersections in Auckland, New Zealand. It is a four legged urban intersection with a posted speed limit of 50km/h and roadway lane widths of 3.3 m. The intersection is located on flat terrain with a small proportion of heavy commercial vehicles (less than 3%) and quite low pedestrian movements. Dominion road is a major arterial road that connects several suburbs in Central Auckland with CBD. Balmoral Road is also a major arterial road connecting North-Western Motorway No. 16 with Auckland Hamilton Motorway No. 1. The layout of the intersection is shown in Figure 2. Most of the major urban intersections in the Auckland region operate under the Sydney Co-ordinated Adaptive Traffic System (SCATS). SCATS is a traffic management system that operates in real time, adjusting signal timings in response to variations in traffic and system capacity as they occur. The maximum intersection cycle time being employed by SCATS is 120 seconds. The composition of the traffic at this particular intersection mainly consists of cars commuting from home to work place and back.

The field verification data was collected by the use of video recording techniques. The original video data has a resolution of 30 frames per second, which was later reduced to 5 frames per second during the data reduction steps to simplify the calculations with an accuracy of 0.2 seconds. Signal green times, Start-up response time (SRT) and headways are calculated from the video data in the evening peak period. 34 cycles have been observed for the North and East approach, which carry the heavy tidal traffic load in evening peak hours. The weather at the time of data collection was clear and there were no special events which could cause any disturbance to normal daily traffic conditions. The screenshot of the video data is shown in Figure 3. The recorded data contains onscreen timer in a time format of 00:00:00 (hh:mm:ss).
In the evening peak hours, the East and North approaches were observed to have high traffic volume density as the traffic commuting from work places in the central city area to their homes predominates. The data is retrieved frame by frame by playing the video and noting the time of each vehicle crossing the stop line. After noting each vehicle the video is stopped to subsequently transfer the data to spreadsheets. Then the video is played again. Each frame corresponds to 0.2 seconds in the video and headways are calculated with reference to the stop line. The start-up response time (SRT) is calculated from the time the signal turns green to the time a vehicle starts moving. Additionally, signal timings are recorded for actual green, red and amber phases. Individual headways from the first vehicle through to the last vehicle are measured. These measured headways are then used for calculations of average headway for each vehicle position in the queue and subsequently saturation headways from the fourth to the last vehicle in a queue is determined.

The methodology in ARR 123 recommends saturation flow estimation by dividing the green time into three portions. The first 10 seconds are counted towards lost time and saturation flow rate is measured on the basis of the second portion of green time in which queuing vehicles passing the stop line is counted and divided by the second portion. Saturation flow rates based on the ARR 123 methodology was then calculated and compared with the HCM method.
The Micro-simulation approach is a good means of identifying the capacity and saturation flow of intersections. Observed field data is also compared with the micro-simulation approach in order to verify the applicability of the micro-simulation approach. Results of the micro-simulation model are also considered in the particular perspective of a general hypothesis regarding micro-simulation; that it generally under-represents the capacity. The micro-simulation model used for this study is AIMSUN (19).

![Figure 3 Screen shot from video data taken of Balmoral-Dominion Road Intersection](image)

5. DATA ANALYSIS AND RESULTS

The summary of three hours of traffic count data is presented in Table 1. The three hours data revealed that a total of 11539 vehicles entered the intersection. The traffic mainly consists of passenger cars with a volume of 11324 making a 98.1% of traffic composition. The share of buses is only 1% and the remaining composition is general purpose vehicles (GV). The volume of buses is concentrated on the North-South Corridor at Dominion road with 1.6% buses coming from the north approach and 1.7% buses coming from the south approach. This North-South corridor is one of the most important bus based public transportation routes in Auckland. The percentage of bus volumes on the remaining intersection approaches are less than 0.5%. A high percentage of passenger car composition with an ideal geometric layout makes this intersection an ideal study site for the calculation of queue discharge flow rates.
Table 1 Traffic counts at the intersection

<table>
<thead>
<tr>
<th></th>
<th>Buses</th>
<th>GV</th>
<th>Cars</th>
<th>Total</th>
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</thead>
<tbody>
<tr>
<td>TO BALMORAL RD WEST</td>
<td>0</td>
<td>3</td>
<td>7</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>30</td>
<td>3258</td>
<td>3303</td>
</tr>
<tr>
<td>TO DOMINION RD NORTH</td>
<td>38</td>
<td>12</td>
<td>2283</td>
<td>2333</td>
</tr>
<tr>
<td></td>
<td>0.6%</td>
<td>0.5%</td>
<td>97.9%</td>
<td>98.8%</td>
</tr>
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</table>

For all approaches

<table>
<thead>
<tr>
<th></th>
<th>Total</th>
<th>Cars</th>
<th>GV</th>
<th>Buses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td>11539</td>
<td>11324</td>
<td>99</td>
<td>117</td>
</tr>
<tr>
<td>Cars</td>
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<td>98.1%</td>
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<td>0.9%</td>
</tr>
<tr>
<td>GV</td>
<td></td>
<td></td>
<td>0.9%</td>
<td></td>
</tr>
<tr>
<td>Buses</td>
<td></td>
<td></td>
<td>1.0%</td>
<td></td>
</tr>
</tbody>
</table>

**Headway Characteristics**

Time headways data measured from the video data was processed to plot frequency distribution graph as presented in Figure 4. The headways observed in the particular intersection studied is broadly scattered in the range of 1.4 seconds to 2.8 seconds with the peak at 1.6 second headways. The observed mean headway was measured as 1.95 seconds. A chi-square test is performed on the headway distribution. The observed distribution is compared with normal and log normal functions as shown in the Figure 4.

**Queue Discharge Rate**

Figure 5 presents the cycle by cycle variation of maximum queue discharge flow rate based on the HCM and ARR 123 methodology. The saturation flow rate is measured with the HCM 2000 and ARR 123 methodology. The methodology in HCM describes saturation flow rate is achieved after the 4th vehicle enters the intersection. The ARR 123 divides the total green time in three parts and the saturation flow rate is measured after the first 10 seconds. Both methodologies recommend measurements for a number of cycles to determine the saturation flow rate. The average saturation flow rate calculated is 1876 pcphgpl by the HCM method and 1883 pcphgpl by ARR 123 method.
The results obtained in the study denotes that the maximum discharge flow rate can reach to a maximum of 2520 pcp/hgpl gleaned from the methodology from ARR123 and 2380 pcp/hgpl.
from the HCM 2000 methodology. This variation is because the ARR123 methodology recommends the recording of maximum discharge flow rate after the first 10 seconds till queue dissipates while HCM 2000 methodology takes into account the headway after 4th vehicle. This difference in methodology gives different queue discharge flow rate especially in the presence of short queue lengths.

FIGURE 6 presents a plot of the average queue discharge rate versus queue position in a group of three vehicles. A steady increase in the average discharge rate can be observed along the platoon. The increase from one group to another is statistically significant particularly between groups 4-6 and 7-9 and groups 10-12 and 13-15. The saturation flow rate obtained by the analytical methodologies is close to the groups average discharge rate of 7-9 and 9-12. The results are in the line with similar study conducted earlier by Lin and Thomas (2005) on three intersections on Long Island, New York.

![Saturation Flow Rate HCM/ARR 123](image)

Figure 6 Average queue discharge rate as a function of queue position group

Figure 7 presents the observed average headways and queue discharge rate with respect to queue position. A slightly decreasing tendency of headway is observed in this study causing a slightly increasing trend in queue discharge flow rate. The theoretical flow discharge curve becomes horizontal after the 4th vehicle when a constant saturation flow rate is assumed, however the observed field trend shows that towards the end of the green time, the discharge flow rate slightly increases. This increasing trend is not well represented by the theoretical curve.
In order to use these scenarios in a way that produces the best possible simulation results, it is important to validate these scenarios. The first step in any micro-simulation analysis is to calibrate the input parameters according to local conditions. The parameters used in this research are presented in Table 2.

The Micro simulation model was calibrated by adjusting the saturation flow rate. The saturation flow rate was derived in the micro-simulation model by maintaining a continuous queue and by allowing a warm up simulation time of 20 minutes. The average of the maximum flow rate is noted as 1948 pcphgpl over 20 simulations.

Figure 8 denotes that results from micro-simulation show a closer correlation with the reference analytical approaches including HCM and ARR123 methods. Increasing trend observed in the field data towards the end of the queue is not seen in the results from micro-simulation. However, the results obtained do not support the widely known belief in profession that micro-simulation under-represents the capacity.
Table 2 Input parameters after calibration

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detection Cycle</td>
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</tr>
<tr>
<td>Car following model</td>
<td>Deceleration estimation (avg. of follower &amp; leader)</td>
</tr>
<tr>
<td>Queuing up speed</td>
<td>1 m/sec</td>
</tr>
<tr>
<td>Queuing leaving speed</td>
<td>4 m/sec</td>
</tr>
<tr>
<td>Speed</td>
<td>50 km/h</td>
</tr>
<tr>
<td>Reaction time</td>
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</tr>
<tr>
<td>Reaction time at stop</td>
<td>1.35 seconds</td>
</tr>
<tr>
<td>Arrival distribution</td>
<td>Normal distribution</td>
</tr>
<tr>
<td>Acceleration rate</td>
<td></td>
</tr>
<tr>
<td>Max</td>
<td>2 m/sec2</td>
</tr>
<tr>
<td>Min</td>
<td>1.2 m/sec2</td>
</tr>
<tr>
<td>Normal deceleration rate</td>
<td></td>
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<tr>
<td>Max</td>
<td>4.5 m/sec2</td>
</tr>
<tr>
<td>Min</td>
<td>3.5 m/sec2</td>
</tr>
</tbody>
</table>

Figure 8 Forecasted queue discharge behaviour by micro-simulation

**Queue Discharge Time**

Figure 9 presents discharge times predicted by micro-simulation model and those taken from field observations. The discharge time is plotted in y-axis while distance to stop-line is on x-axis. The discharge time was computed from time headway measurements averaged for each queue position. It can be observed that micro-simulation model replicates the discharge time.
quite close to the field observations down to 80 meters from the stop-line, after which it started to diverge slightly from the observed values.

When traffic signal turns to green, the first vehicle in the queue starts moving. Apart from usual acceleration time, this vehicle also takes some fraction of time when driver perceives and reacts to the green light. The first vehicle’s discharge time is the elapsed time in seconds between the initiation of the green and crossing of the front wheels of the first vehicle over the stop line. This time also includes the first driver’s reaction time. The second vehicle’s movement is dependent on the first vehicle’s movement and it starts moving as soon as a safe distance between front vehicle is attained. The curve representing the trajectory of stopping car in the Figure 9 shows the elapsed time when a car starts moving from its position of queue. The vehicles at the back of queue have to wait longer to begin the movement. The time when a vehicle crosses the stop line is shown in two curves, representing micro-simulation and field observations. The comparison between these two curves shows that vehicles at the back of queue tends to take lesser time than predicted by the micro-simulation approach.

This state is representative of micro-simulation’s treatment of traffic flow under the car following model. The micro-simulation approach takes the static approach from start of green period to the end of green period with equal headways. In reality, the driver’s behavior in the back of queue could be influenced by the fear that the phase can be changed to red any time so he needs to hurry to cross the stop line. In this phenomenon, he pushes closer to the lead vehicle which can reduce the headway resulting in increase in saturation flow rate.

![Figure 9 Discharge time versus distance to stop-line plot for AIMSUN](image)

6. CONCLUSION

This paper has investigated the queue discharge behavior at a signalized intersection in Auckland, New Zealand, based on methods proposed in HCM (2000), ARR 123 and Aimsun micro-simulation. Video data collected in evening peak hours has been analyzed and assessment has been carried out to compare theoretical and field values of saturation flow rate.
and queue discharge flow rate of an urban intersection. This comparative assessment was carried out in three phases. Firstly, a comparison of headway characteristics was carried out. Secondly, after investigating the field queue discharge behavior it was compared with HCM and ARR123. In the last phase micro-simulation was computed for queue discharge time and was compared with respect to the position of vehicles in the queue.

The collected data depicts broad categories of drivers’ behavior and it is observed that the value of headway time scatters widely. The study reveals a decreasing trend in headway time for the vehicles which are at end of the queue. This trend is in line with the hypothesis presented in previous studies (3-6) and the possible reason of this decreasing trend could be due to behavior of drivers at the end of queue who try to push forward in order to cross the intersection before change of signal phase.

The study has observed slightly higher value of saturation flow rate for the vehicles at the end of queue. A comparison between average queue discharge rates as a function of queue position in a group of three vehicles has revealed an increase of about 6% queue discharge rate compared to theoretical saturation flow rate at queue positions 16 – 18. These results do not confirm the default constant saturation flow rate concept of HCM and ARR 123. This aspect has been further investigated by using AIMSUN micro-simulation model and the results indicate that they are closely aligned with the analytical approaches.

Queue discharge time analysis shows that field observations are closely aligned with micro-simulation results, for the vehicles in the queue up to a distance of 80m from the stop line. Comparison shows that micro-simulation behavior is flatter towards the end of queue, which indicates that headway time remains stable towards the end of queue. The observed field value curve deviates away from the micro-simulation trend line for the vehicles at the end of the queue reflecting an aggressive behavior of drivers to pass the stop line with lesser headway.

This paper validates the findings of the previous studies that reported increase in saturation flow rate with time in Taiwan and USA. It is found that the increase in saturation flow rate is not only recorded in these two countries, the same trend is also observed in New Zealand. Thus this paper reports that the increasing trend is not a local phenomenon and it should be looked in global perspective. This observation emphasizes the need to revise the conventional methods of capacity analysis in order to incorporate the variations within a single cycle due to increase in saturation flow rate. Another aspect of this study is on general perception of Micro-simulation models. It is generally perceived that micro-simulation models under represent queue discharge rate, however the results showed that the micro-simulation provides a reasonable replication of the queue discharge rate. On the other hand, Micro-simulation does not reflect variable headways towards the end of green period, though it is replicating well in the start of green time.

As the study is based on data collected from only one signalized intersection, the findings of the study have limited scope and the findings cannot be generalized. For better understanding of observed trends and verification of results, considerable amount of data is needed.
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REFERENCES


