SATURATION FLOW RATES

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ABSTRACT

For the calculation of delays and Level of Service at intersections it is important that the correct saturation flow rates for the specific circumstances be used. As a result of a lack of local data practitioners would often use default values from overseas software developers. This can lead to wrong results and inappropriate decisions based thereon.

In a recent study in the vicinity of Stellenbosch the saturation flow rates at a number of intersections were determined. The following situations were observed:

- Turning movement (through or right);
- Gradient (Up and down);
- Number of through lanes (1 and 2); and
- Speed limit (60 and 80 km/h)

From the results it is clear that there are significant differences between the saturation flow rates when the conditions of the movements are different in terms of the above characteristics.

In the paper the background to the study, references to earlier research and the results of this study are given. Recommendations are made as to the most appropriate values to be used under different conditions.

1. INTRODUCTION

Saturation flow is a very important road traffic performance measure of the maximum rate of flow of traffic. It is used extensively in signalized intersection control and design. Saturation flow describes the number of passenger car units (pcu) in a dense flow of traffic for a specific intersection lane group. In other words, if an intersection's approach signal were to stay green for an entire hour and the flow of traffic through this intersection were as dense as could be expected, the saturation flow rate would be the amount of passenger car units that passed through this intersection during that hour.

According to the Highway Capacity Manual (TRB, 2000) there are various factors that influence the value of saturation flow at an intersection. A few of these were investigated during this study and will be discussed later.

Very little information on South African research in this field could be obtained. In 1991 Allers and Stander did a study for the Department of Transport, but they did not include the effect of the speed limit or the number of through lanes. In a recent study in Stellenbosch in the Western Cape, saturation flow rates were determined at different intersections under different circumstances. The study focused firstly on determining saturation flow rates

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under ideal conditions and then compared the results with results obtained under different conditions. The study found significant differences in the results for the different conditions as well as similarities between different intersections, but under the same conditions. This report describes the theoretical background, data collection and results of the study done in Stellenbosch.

2. BACKGROUND

2.1 Start-up lost time and saturation headway

To determine accurate saturation flow rates, start-up lost time needs to be understood and taken into account. The principle of start-up lost time (Bester and Varndell, 2002) can be described as follows:

When the signal at an intersection turns green, the vehicles in the queue will start crossing the intersection. The vehicle headways can now be described as the time elapsed between successive vehicles crossing the stop line. The first headway will be the time taken until the first vehicle's rear wheels cross the stop line. The second headway will be the time taken between the crossing of the first vehicle's rear wheels until the crossing of the second vehicle's rear wheels over the stop line and so on.

The first driver in the queue needs to observe and react to the signal change at the start of green time. After the observation, the driver accelerates through the intersection from stand-still which results in a relatively long first headway. The second driver performs the same process with the exception that the driver could react and start accelerating whilst the first vehicle began moving. This results in a shorter headway than the first, because the driver had an extra vehicle length in which to accelerate. This process carries through with all following vehicles where each vehicle's headway will be slightly shorter than the preceding vehicle. This continues until a certain number of vehicles have crossed the intersection and start-up reaction and acceleration no longer have an effect on the headways. From this point headways will remain relatively constant until all vehicles in the queue have crossed the intersection or green time has ended. This constant headway is known as the saturation headway and can start to occur anywhere between the third and sixth vehicle in the queue. Figure 1 illustrates the situation described above.

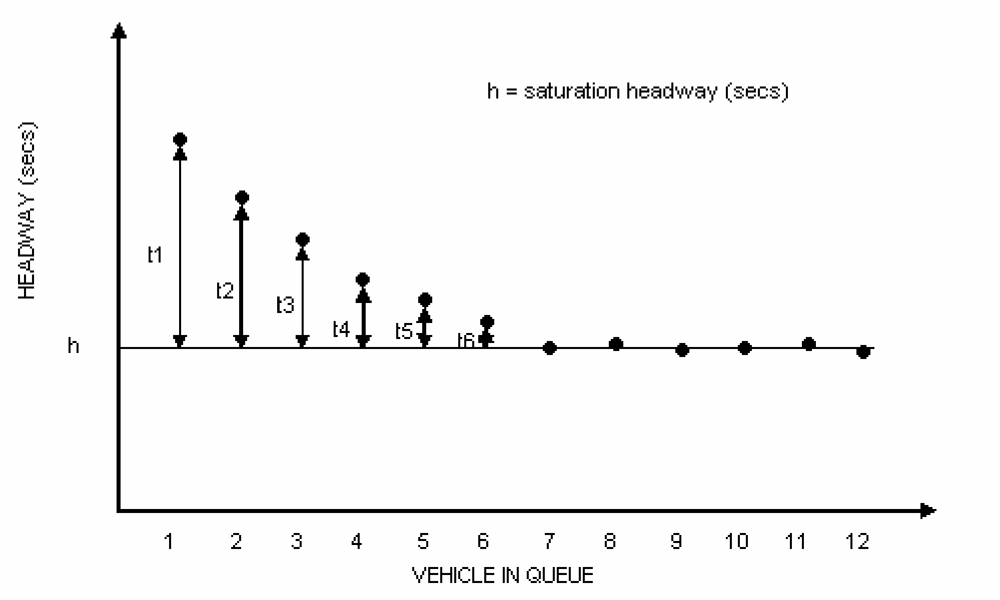

Figure 1 – Headways at a traffic interruption

To calculate the saturation headway from the above example in Figure 1 the following equation will be used:

$$h_s = \frac{\sum_{j=n}^{l} h_j}{(l+1-n)} = \frac{(h_7 + h_8 + h_9 + h_{10} + h_{11} + h_{12})}{(12+1-7)}$$

(Equation 1)

where:

h_s = saturation headway;
l = last queued vehicle position;
h_j = headway of jth queued vehicle;
n = position of queued vehicle from where saturation flow region started.

2.2 Saturation flow rate

Saturation flow is a macro performance measure of junction operation. It is an indication of the potential capacity of a junction when operating under ideal conditions. Ideal conditions (TRB, 2000) assume the following:

- 3,6 meter lane width;
- No heavy vehicles;
- Flat gradient;
- No parking or bus stops near the intersection;
- Uniform movement type, i.e only straight movement or only turning movement; and
- No pedestrians or cyclists.

The Highway Capacity Manual (TRB, 2000) prescribes an ideal saturation flow rate of one thousand nine hundred vehicles per hour per lane. An idealized view of saturation flow at a signalized junction is illustrated in Figure 2, the rectangular model of saturation flow rate (Turner and Harahap, 1993):

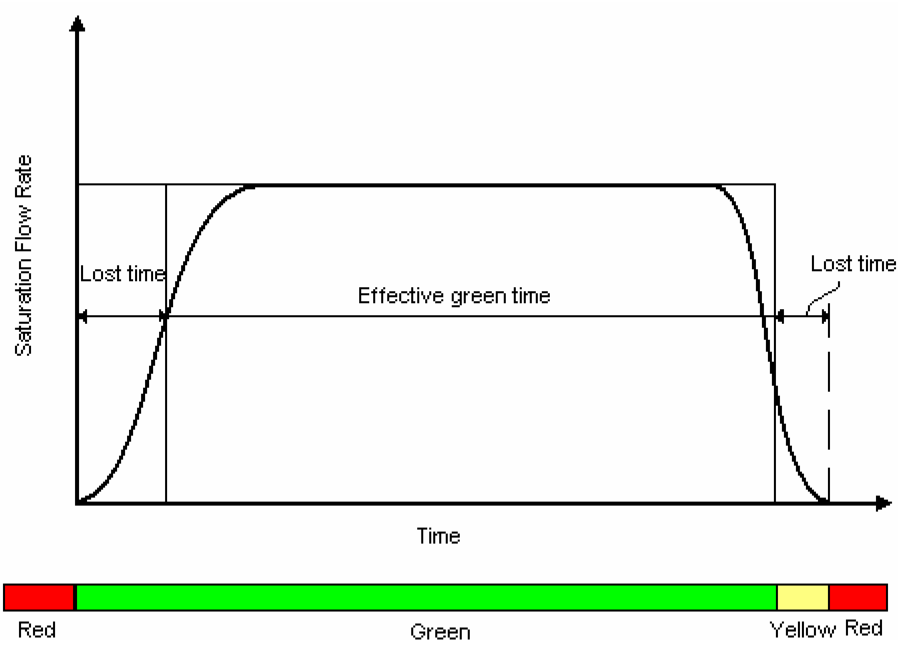

Figure 2 – The flow of traffic during the green period from a saturated approach

Note from the figure that as the traffic signal shows green, there is first a very short gap as the first driver reacts to the signal change. The rate of vehicles crossing the stop line increases as vehicles accelerate to the speed determined by the cars they are following. Vehicles soon reach a state where they are following one another at a constant headway. This constant rate is represented by the plateau of this flow profile. In a saturated junction, the queue formed in the red time will be too long to clear in the green period and so cars will follow each other at constant spacing during the green period. The flow rate will start dropping at an increasing rate when the signals are in yellow time and then stop when the signals turn red. The saturation flow is calculated by making the curved profile into a rectangle from which the dimensions can be measured. This is achieved by identifying lost time and effective green time. The lost time is the time from the start of green to a point where vehicles are flowing at half the maximum flow plus the time from where vehicles are flowing at half the maximum flow at the end of saturation to the beginning of red time.

However, to determine the saturation flow rate from time measurements taken in the field the following equation is used:

$$s = \frac{3600}{h_s} \qquad \text{(Equation 2)}$$

Where:

s = saturation flow rate;
3600 = number of seconds per hour;
h_s = saturation headway.

Various factors can influence traffic behaviour and in turn the saturation flow rates. The following factors (Turner and Harahap, 1993) play a role:

- Vehicle mix;
  A multitude of different types of vehicles, motorized and non-motorized, with different operating performances;
- Driver behaviour - poor lane discipline and observation of traffic signals;
- Public transport - varied mix of bus types, stopping places and driving styles
- Roadside activity - roadside land uses generate parking and non-transport activities that reduce effective lane width

The study done in Stellenbosch investigated the following possible influences on saturation flow:

- Speed limits - intersections with different speed limits namely 60 km/h and 80 km/h were observed;
- Gradient - intersections on different gradients were observed for traffic flow up hill and traffic flow down hill;
- Right-turn movements - intersections with a leading green-phase for right turning movements were observed;
- Number of through lanes.

2.3 Previous research

Several studies in various parts of the world on saturation flow rates have been conducted, but all under normal circumstances. Table 1 (Turner and Harahap, 1993) shows some of the earlier studies, where conducted, the mean saturation flow obtained and the sample size of each study.

A major study was recently completed by the Texas Transportation Institute (Bonneson et al, 2005). In this study they investigated the effect of heavy vehicles, the speed limit, traffic pressure; area population and the number of approach lanes on the saturation flow rate. They found that the saturation flow rate under ideal conditions (base rate) is 1905 pc/h/ln, that it will decrease by 9 pc/h/ln for a 1 mph decrease in the speed limit and that an approach with two through lanes will have a saturation flow rate of 130 pc/h/ln higher than that of an approach with one through lane.

Table 1: Previous studies' saturation flow rates

Study	Country	Mean (pc/h/ln)	Sample Size
Webster & Cobbe	UK	1800	100
Kimber et al.	UK	2080	64
Miller	Australia	1710	-
Branston	UK	1778	5
H.E.L.Athens	Greece	1972	35
Shoukry & Huizayyin	Egypt	1617	18
Hussain	Malaysia	1945	50
Coeyman & Meely	Chile	1603	4
Bhattacharya & Bhattacharya	India	1232	20
De Andrade	Brazil	1660	125

3. DATA COLLECTION

<u>3.1 Intersections surveyed</u>

For the purposes of this study it was important to identify and observe intersections that represented the various conditions described above. The following criteria were also taken into account for selecting intersections:

- The gradient for normal intersections should be as flat as possible;
- Standard lane widths of 3,7m should be available;
- The queues of through traffic should be long enough to facilitate the observation of saturation flow rates;
- No parking or bus stops should be in the immediate vicinity of the intersections;
- Low volumes of non-motorized vehicles and low volume of heavy vehicles should be present.

According to these criteria, the following intersections were selected for observation:
<u>60 km/h, flat gradient</u>:
Dorp Street/Strand Street, Molteno Street/Bird Street, Adam Tas/Bird Street intersections.
<u>60km/h, on gradient</u>:
Strand Road/Van Reede intersection.
<u>80 km/h, flat gradient</u>:
Paarl road/Welgevonden intersection.
<u>80 km/h, on gradient</u>:
Webersvallei road/R44 intersection.
<u>Right turn movements</u>:
Strand Road/Van Reede, Saffraan Road/Strand Road intersections.

3.2 Study periods
Collection of data was done during peak hours at the intersections with heavy traffic flow. All observations were done in good weather conditions and during weekdays when people familiar with the facilities were using them.

3.3 Study methodology
The method included the determining of start-up lost times, saturation headways and saturation flow rates of each observed vehicle queue at each intersection. This was done by recording the time from the start of green time to the time each vehicle's rear wheels crossed the stop line. This was done until green time or the queue ended.

Equation 1 was used to determine the saturation flow rates after the start-up lost time in the queue was identified. From this, equation 2 was used to determine the saturation flow for each observed queue. The total start-up lost time was not computed for this study's purposes, but simply identified in each queue to determine the saturation headways. A total of ten vehicle queues were observed at each intersection and for each direction or movement type.

In order to determine realistic comparisons between the different intersections, certain variables needed to be removed. This means that if the following conditions occurred, the recording was not considered:

- If heavy vehicles such as buses or trucks formed part of the observed queue;
- If non-passenger vehicles such as motorcycles formed part of the queue;
- If irregular flow occurred;
- If pedestrians interrupted traffic flow.

For time recording purposes a normal stopwatch with the 'split-timing' function was used. This however, left room for human error in the recordings, but the total number of recordings done minimized this effect.

4. RESULTS

The results of the study are given in Tables 2 and 3. The general statistics are shown in Table 2 and the results relative to the specific conditions are shown in Table 3.

Table 2: Saturation flow rates (Veh/h/lane)

Intersection	Sample size	Saturation flow rate	Standard deviation	Minimum	Maximum
Dorp/Strand	214	2026	133	1839	2254
Molteno/Bird	74	1711	133	1565	1946
Adam Tas/Bird	103	1820	151	1625	2071
Strand/ Van Reede (-G)	118	2197	204	1879	2471
Strand/ Van Reede (+G)	140	2044	123	1908	2314
Paarl/Welgevonden	84	2000	140	1835	2342
Webersvallei/R44 (-G)	102	2370	148	2062	2605
Webersvallei/R44 (+G)	105	2076	267	1553	2516
Strand/Van Reede (Right)	99	1840	180	1814	2069
Strand/Saffraan (Right)	95	1920	190	1603	2195

Table 3: Saturation flow rates relative to conditions (Veh/h/lane)

Intersection	Number of through lanes	Gradient (%)	Speed limit (km/h)	Movement	Saturation flow rate
Dorp/Strand	2	0	60	Through	2026
Molteno/Bird	1	0	60	Through	1711
Adam Tas/Bird	1	0	60	Through	1820
Strand/ Van Reede	2	-3,3	60	Through	2197
Strand/ Van Reede	2	+3,3	60	Through	2044
Paarl/Welgevonden	1	0	80	Through	2000
Webersvallei/R44	2	-5,2	80	Through	2370
Webersvallei/R44	2	+5,2	80	Through	2076
Strand/Van Reede	2	-3,3	60	Right	1840
Strand/Saffraan	2	0	60	Right	1920

5. DISCUSSION

An inspection of Table 3 shows that:

- an increase in the speed limit leads to an increase in the saturation flow rate;
- an increase (from 1 to 2) in the number of through lanes leads to an increase in the saturation flow rate;
- an increase in the gradient leads to a decrease in the saturation flow rate; and
- the saturation flow rate on exclusive single right turn lanes with their own phase can even be greater than that of a single through lane.

To quantify the different effects a multiple linear regression analysis was performed on the data of the through lanes in Table 3. The results were as follows:

$$S = 990 + 288TL + 8{,}5SL - 26{,}8G \qquad \text{(Equation 4)}$$

Where:

S = Saturation flow rate (veh/h/lane)
TL = Number of through lanes (1 or 2)
SL = Speed limit (60 or 80km/h)
G = Gradient (%)

Equation 4 explains 94,3% of the variation in the saturation flow rate ($R^2 = 0{,}943$) and all the coefficients are significant at the 97,5% confidence level.

When applying Equation 4 to ideal conditions (TL = 2, SL = 80 and G = 0), a base rate of 2246 is suggested. If, however, the general speed limit of urban areas of 60 km/h is used a value of 2076 will apply. This value compares well with a value found earlier in the UK (Table 1), but is clearly much higher than the 1 900 of the Highway Capacity Manual or the value (1905) found in the recent USA study (Bonneson et al, 2005) or the 1928 found in an earlier SA study (Allers and Stander, 1994). Equation 4 also suggests that an approach with two through lanes will have a rate of 288 pc/h/ln more than an approach with one through lane. This is more than double the increase found by Bonneson et al (2005). The effect of the speed limit is also higher in South Africa with an increase in the rate by 8,5 pc/h/ln for every one km/h increase in the speed limit as against the 5,6 pc/h/ln increase (9 pc/h/ln for each mph increase in the speed limit) as found by Bonneson et al (2005).

The Highway Capacity Manual (TRB, 2000) uses the following formula to adjust the ideal saturation flow rate for the effect of gradient:

$$f_g = 1 - \%G/200 \qquad \text{(Equation 5)}$$

Where:

fg = adjustment factor for gradient
%G = gradient in percentage

When applying the coefficient for gradient in Equation 4 to an ideal rate of 1 900 veh/h/lane, the following adjustment factor is determined:

$$f_g = 1 - \%G/71 \qquad \text{(Equation 6)}$$

From Equation 6 it can be seen that the effect of gradient found in this study is about three times the effect used in the Highway Capacity Manual.

6. CONCLUSIONS

In this study it was found that:

- saturation flow rates in South Africa (Stellenbosch at least) are much higher than in other countries. This could be an indication of the aggressiveness of local drivers;
- an increase in the speed limit leads to an increase in the saturation flow rate;
- an increase (from 1 to 2) in the number of through lanes leads to an increase in the saturation flow rate;
- an increase in the gradient leads to a decrease in the saturation flow rate; and
- the saturation flow rate on exclusive single right turn lanes with their own phase can even be greater than that of a single through lane. This could be ascribed to traffic pressure.
- the effects of speed limit, gradient and number of through lanes on the saturation flow rate are much greater locally than in the USA.

7. RECOMMENDATION

It is recommended that a more comprehensive study be performed over the whole of South Africa to validate Equation 4 for use as a basis for the determination of saturation flow rates in South Africa.

8. REFERENCES

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