THE EFFECT OF A LEADING GREEN PHASE ON THE START-UP LOST TIME OF OPPOSING VEHICLES

C J BESTER and P J VARNDELL

Department of Civil Engineering, University of Stellenbosch
Private Bag X1, Matieland 7602

1. INTRODUCTION

The main objective of phasing at a signalised intersection is to minimise potential hazards arising from the conflicts of vehicular and pedestrian movements, while maintaining the efficiency of flow through the intersection (1). The most basic operation is the two-phase cycle where the north-south and east-west traffic alternatively have the right-of-way and right-turning traffic in all directions must wait for an acceptable gap in the oncoming traffic. When a significant number of right-turning vehicles are present at one or more of the approaches, a third (and even a fourth) phase for these vehicles can be considered. When the right-turning traffic is from opposing approaches, both streams can be accommodated by the same phase while all through traffic will be stopped. However, if the need for a right-turning phase is for one approach only, that approach will be given the right-turn phase together with a part of the through phase. This right-turn phase can be in the beginning (leading green) or at the end (lagging green) of the through phase. During this phase the opposing through traffic is stopped.

There are a number of advantages and disadvantages in the use of a leading green phase for right-turning vehicles at a signalised intersection. The advantages include, amongst others, a safer operation for opposing right-turning vehicles, the reduced need for storage space for right-turning vehicles and fewer conflicts due to gap acceptance. One of the disadvantages that did not receive much attention in the past is the increase in the start-up lost time of opposing vehicles.

In a recent study (2) at two intersections with leading green phases for right-turning vehicles the start-up lost times and saturation flow rates were observed for both directions of travel. Significant differences were found for vehicles using the leading green phase and those from the opposing approach that have to wait until the end of the leading green phase.

In the paper the theoretical background, the data collection and the results of the study are described. Proposals are also made as to possible solutions to the problem of increased start-up lost time.

2. BACKGROUND

2.1 Start-up lost time

The principle of start-up lost time can be described as follows:

When the signal for a specific approach turns green, the queue of vehicles will begin to move into the intersection. The vehicle headways can then be defined as the time between successive vehicles crossing the stop line. The first headway will be the time elapsed between the changing of the signal and the moment when the rear wheels of the first vehicle cross the stop line. The second headway will be the time elapsed between the rear wheels of the first and the second vehicles crossing the stop line, and so on.

When the signal turns green, the driver of the first vehicle must first observe the signal before releasing the brake and accelerating through the intersection. This normally results in a comparatively long first headway. The second vehicle in the queue goes through a similar process, excepting that the driver has been able to react and begin accelerating whilst the first vehicle began to move. This second headway will then be slightly shorter than the first, because the driver has had an extra vehicle length in which to accelerate. The subsequent vehicle headways will follow the same process, but the headways will be slightly shorter than that of the preceding vehicle. This will continue until a number of vehicles have crossed the stop line and start-up reaction and acceleration no longer have an influence on the headways. From this point onwards, vehicle headways will remain constant until the last vehicle of the queue has passed over the stop line. This constant headway is known as the saturation headway and can occur anywhere between the third and sixth vehicle in the queue.

Figure 1 illustrates the situation explained above. Note how the headways of the first few vehicles are comparatively large as the drivers react to the signal change and accelerate. This effect diminishes until vehicles are fully accelerated when they enter the intersection, at which point approximately equal headways are observed.

The first few vehicles take t_i seconds longer than h, the saturation headway. To determine the total start-up lost time, the individual values of t_i should be added.

There are a number of factors that influence the start-up lost time, namely:

- Perception/reaction time which varies from driver to driver;
- Vehicle type and gradient that have an effect on the acceleration;
- Psychological factors. This includes aspects such as patience, confidence, experience and fatigue; and
- Pedestrians in the intersection.

The purpose of this paper is to show that a leading green right-turn phase for opposing traffic can also affect the start-up lost time.

The start-up lost time is used in the calculation of intersection capacity and level of service. It is assumed that vehicles can move through the intersection at the saturation headway for the duration of the effective green time. The latter is equal to the real green time minus the lost times at the beginning and end of a green phase. A typical value for the total lost time of an approach is two seconds, but can range anywhere between 0 and 8 seconds.

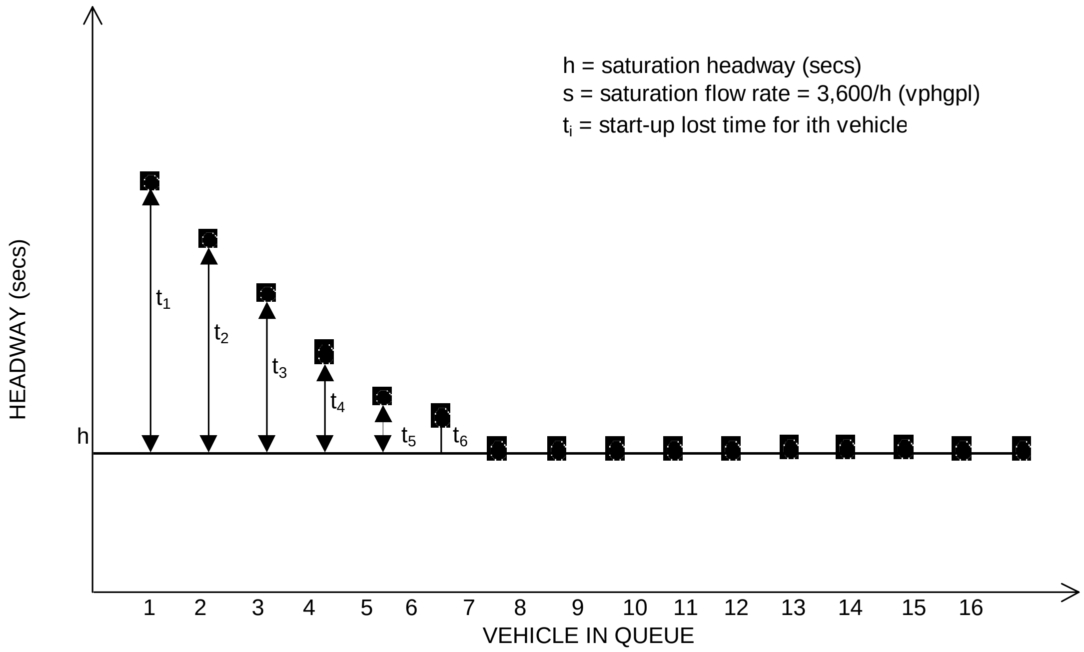

Figure 1 - Headways at a traffic interruption

2.2 Saturation flow rate

The ideal saturation flow rate is defined (3) as the maximum flow rate per lane at which vehicles can pass through a signalised intersection under ideal conditions. Ideal conditions assume the following:

- 3,6m lane width;
- No heavy vehicles;
- Flat gradient;
- No parking or bus stops near the intersection;
- No turning movements; and
- No pedestrians or cyclists.

The Highway Capacity Manual (3) prescribes an ideal saturation flow rate of 1900 vehicles/hour/lane.

The saturation flow rate can also be calculated from the saturation headway of a stable-moving queue:

$$s = 3600/h$$

where

s = saturation flow rate (vehicles/hour/lane)
h = saturation headway (seconds)

2.3 Leading versus lagging green phases

A leading green phase allows the right-turning traffic to complete the movement at the beginning of the green period. The advantages (4, 5) of the leading green phase are:

- Storage space for the right-turning traffic is not as important as in the case of the lagging green;
- Allows right-turners on single lane approaches to clear the intersection;
- There are fewer conflicts due to gap acceptance.

The disadvantages of the leading green phase are:

- Right-turners tend to think they have the right-of-way, even though the opposing traffic has been given a green signal;
- There is a tendency for the opposing traffic to false start, because they cannot anticipate the start-time of the green phase.

Both these disadvantages may lead to an increase in the start-up lost time.
A lagging green phase allows the right-turning traffic to complete the movement at the end of the green period. The advantages of the lagging green phase are:

- It approximates the normal traffic flow situation;
- The vehicles and pedestrians are better separated;
- It can be more readily controlled by vehicle actuated control.

The disadvantages of the lagging green phase are:

- A large area is required to store the right-turning traffic so that the through traffic is not held up unnecessarily;
- Opposing right-turners, whose green is terminated, are given no warning that the lagging green phase is still continuing. This results in the danger that vehicles can turn right in the face of opposing traffic;
- The right turning can occur in the face of fast moving traffic when opposing vehicles ignore the start of the red signal.

Because of these disadvantages, the leading green phase for right-turning traffic is usually preferred.

2.4 Previous research

A large number of studies on start-up lost time and saturation flow rate has been conducted in the United States of America. However, none of them has considered the effect of a leading green phase. Some of the results of the earlier studies (3, 6) are shown in Table 1.

It is interesting to note that saturation flow rates seem to have increased over the years. It should also be noted that the varying start-up lost times depend on the choice of screen line for measuring headways. This is because various combinations of stop lines, curb lines, front or rear bumpers and front or rear axles have been used to measure the vehicle headway. One must, therefore, be careful in comparing results from different tests.

Values of between four and six vehicles have been used as the position in the queue from where the headway is assumed to be constant.

Table 1: Observed lost times and saturation flow rates

Source	Date	Location	Sample size	Queue No	Start-up lost time (s)	s (veh/h/l)
Gerlough	1967	Los Angeles	5	5	2.05	1470
Carstens	1971	Ames, Iowa	4	4	0.75	1572
King	1976	USA	-	5	-	1682
Agent	1983	Lexington	-	4	1.40	1651
Lee	1986	Kansas	-	5	3.04	1827
Molina	1986	Texas	8	6	-	2000
Zegeer	1986	Various	7	5	1.31	1875
Fambro	1987	Houston	2	5	-	1896
Roess	1988	Various	7	5	-	1937
Short	1989	Texas	2	4	1.31	1905
Gaston	1991	Dallas	4	5	-	1910
Zegeer	1992	Florida	16	-	-	1840
Jacobs	1998	Stellenbosch	6	5	1.43	1988

3. DATA COLLECTION

3.1 Intersections surveyed

For the purposes of this study it was important to compare the start-up lost times and saturation flow rates of lanes opposing an approach with a leading green phase for right turners to those of lanes with no opposing right-turn phase. It was considered the best method to observe both types of lane at the same intersection. Intersections therefore had to be identified where these conditions exist. Additional criteria in the selection of the intersections were:

- The right-turning traffic must be of a reasonably large volume so that all the vehicles cannot always be accommodated in the right-turn phase;
- The queues of through traffic must be long enough to facilitate the observation of saturation flow rates (at least 12 vehicles);
- The gradient of the relevant approaches should be as flat as possible;
- Standard lane widths should be available;
- No parking or bus stops should be in the immediate vicinity of the intersections; and
- Relatively low volumes of non-passenger car traffic should be present.

With these criteria in mind, two intersections in Stellenbosch were selected. They are the Dorp Street/Strand Street and the Van Reede Street/Strand Street intersections. Both these intersections have a leading green right-turn phase for north bound traffic; and no right-turn phase for south bound traffic. The layouts of the two intersections are shown in Figures 2 and 3. For the purpose of this study the south and north bound through lanes were surveyed.

3.2 Study periods

The data collection was done during periods of peak traffic flow. The traffic at the Van Reede Street/Strand Street intersection was observed during the AM peak period between 07:15 and 08:00. The traffic at the Dorp Street/Strand Street intersection was done during the PM peak period from 16:45 to 18:00.

Recordings were taken only during good weather conditions and during normal weekdays when mostly people familiar with the facilities were using them.

3.3 Study methodology

The method involved the recording of the start-up lost time (l) and the saturation flow rate (s). This was done by recording the time from the instant the green signal showed until the sixth (t_6) and the twelfth (t_{12}) vehicles' rear axles crossed the intersection stop line.

From the above (and also see Figure 1) the start-up lost time and the saturation headway and flow rate can be determined as follows:

$$l = t_6 - (t_{12} - t_6)$$

$$h = (t_{12} - t_6)/6$$

$$s = 3600/h$$

This method assumes that the first six vehicles in the queue experience start-up lost time. This is a conservative assumption, but it ensures that the total start-up lost time is included.

A minimum of 100 recordings were taken for both the north and south bound approaches. The large number of recordings was decided upon to ensure that a normal distribution was approximated.

In order to produce a realistic comparison between the different start-up delays and saturation flow rates, a number of variables had to be eliminated. This meant that if any of the following situations occurred, the recording was not considered:

- Pedestrians delayed the vehicle start;
- A truck, bus , motorbike or any vehicle other than passenger cars or light delivery vehicles, was part of the vehicle queue; and
- The vehicle flow was not regular.

The recordings were taken by means of a stopwatch. This could result in inaccurate data due to human error. However, the effect of these errors was minimised by the large number of recordings that were done for the different situations.

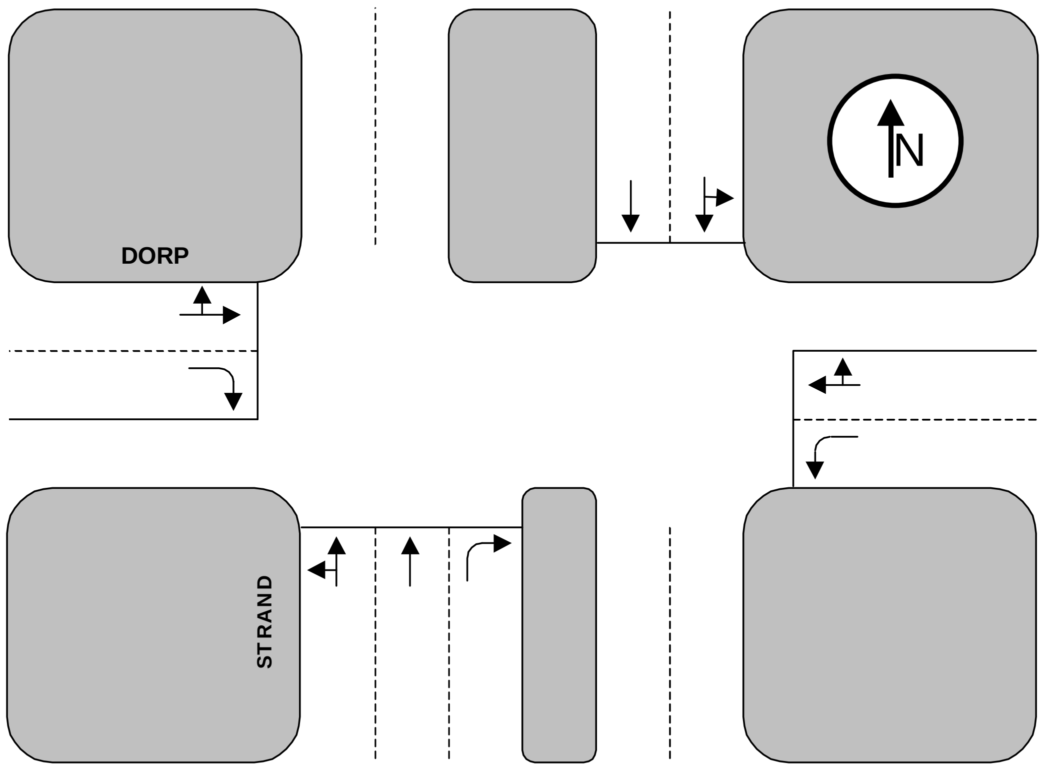

Figure 2: Dorp Street / Strand Street intersection

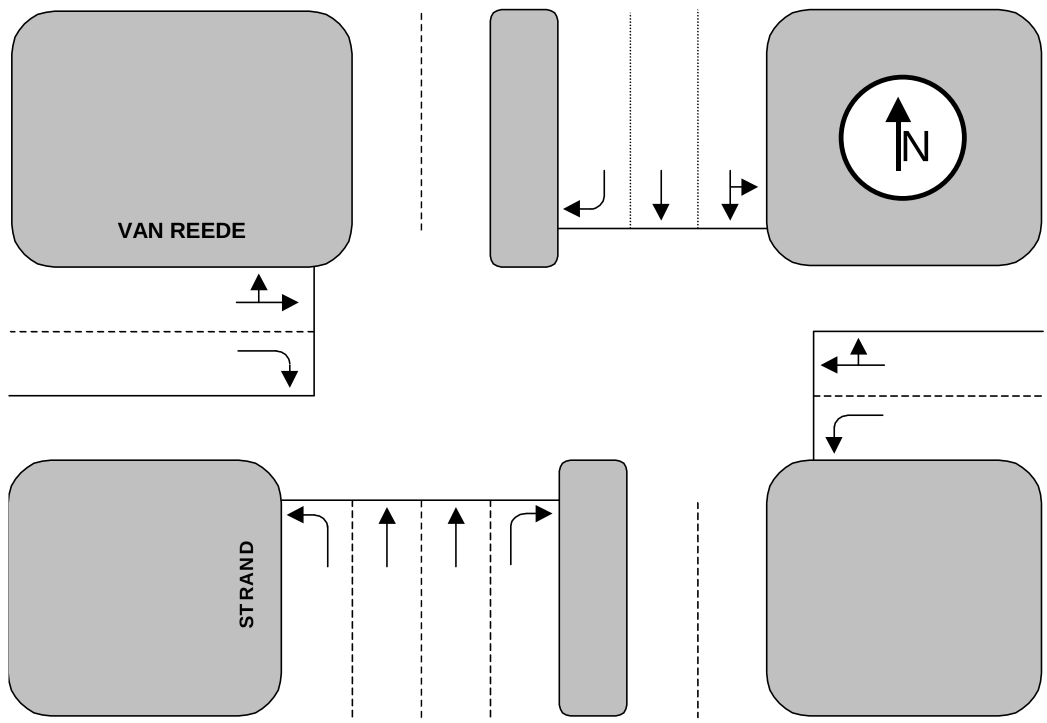

Figure 3: Van Reede Street / Strand Street intersection

4. RESULTS

4.1 Start-up lost time

The data collected were analysed to determine whether there was a significant effect of the leading green right-turn phase on the start-up lost time of opposing traffic. The results for the two intersections are given in Tables 2 and 3 respectively.

Table 2: Start-up lost time (s) (Dorp/Strand Street Intersection)

	Opposing Traffic	Subject Traffic
Sample size	110	100
Mean	3.2	2.1
Standard error	0.2	0.1
Median	3.0	1.7
Standard deviation	1.6	1.4
Variance	2.7	1.8
Minimum	0.4	0.1
Maximum	7.1	6.4

Table 3: Start-up lost time (s) (Van Reede/Strand Street Intersection)

	Opposing Traffic	Subject Traffic
Sample size	108	105
Mean	2.7	2.2
Standard error	0.1	0.1
Median	2.5	2.1
Standard deviation	1.6	1.3
Variance	2.4	1.8
Minimum	0.0	0.0
Maximum	7.8	5.0

It can be shown that for both intersections the difference in the start-up lost time for the two directions is statistically significant at a 95% confidence level.

4.2 Saturation flow rate

The saturation flow rate, that was determined from the difference in the arrival times of the 6th and the 12th vehicles, was derived for the same approaches and the same intersections for which the start-up lost times were calculated. The results for the two intersections are shown in Tables 4 and 5.

Table 4: Saturation flow rate (veh/h) (Dorp/Strand Street Intersection)

	Opposing Traffic	Subject Traffic
Sample size	110	100
Mean	2048	1946
Standard error	21	18
Median	2057	1964
Standard deviation	225	176
Variance	50705	30903
Minimum	1532	1421
Maximum	2602	2374

Table 5: Saturation flow rate (veh/h) (Van Reede/Strand Street Intersection)

	Opposing Traffic	Subject Traffic
Sample size	108	105
Mean	2097	2064
Standard error	22	23
Median	2057	2019
Standard deviation	233	231
Variance	54133	53287
Minimum	1612	1600
Maximum	2602	2700

For both intersections the through traffic in the opposing direction of the right-turn phase have a higher saturation flow rate than the through traffic in the same direction. The difference is, however, statistically significant for the DorpStreet/Strand Street intersection only.

The relatively high values of saturation flow compared to previous results (see Figure 1) must be ascribed to the fact that in this study only cycles with ideal flow conditions were considered.

5. DISCUSSION

5.1 Start-up lost time

The results of the study show that a leading green right-turn phase has a significant effect on the start-up lost time of opposing vehicles. It can, therefore, be said that an additional disadvantage of leading green phases is a significant increase in the start-up lost time of opposing vehicles. Over one full day the northern approach of the Dorp Street/Strand Street intersection can lose up to 13 minutes due to the leading green phase.

There are two possible reasons for the increase in the start-up delay:

- Many drivers of right-turning vehicles assume they have the right-of-way when the signal is already green for the opposing traffic. Because, after the end of the amber arrow, when a normal green signal is displayed, these drivers take additional gaps which are made easier by the fact that the opposing traffic is still stationary. And there is no legal prohibition to this movement.
- The drivers of the opposing through traffic have no idea when their green signal would start, especially because the right-turn signal can vary according to the demand.

5.2 Saturation flow rate

It is very interesting that the saturation flow rate for the opposing through traffic is higher than that of the through traffic in the same direction as the right-turning traffic. There are also two possible reasons:

- The drivers of the opposing through traffic are aware of the fact that they have less green time in which to clear the intersection and therefore try to reduce their headways.
- The drivers try to make up for the time lost by the first six drivers.

6. RECOMMENDATIONS

There are two possible ways in which the start-up lost time of opposing vehicles can be reduced:

- The introduction of a red arrow (just for a few seconds) after the amber arrow so that the drivers of right-turning vehicles can be prosecuted for taking the gap in front of the stationary vehicles. This is not acceptable according to the South African Road Traffic Signs Manual (5), but should at least be considered in the light of the findings of this study.
- The introduction of an amber phase before the green. This is done in some countries to reduce the start-up delays at all phases.

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Department of Civil Engineering, University of Stellenbosch
Private Bag X1, Matieland 7602

CV – CJ BESTER

Christo Bester has a BSc, BIng and MIng (1974) from the University of Stellenbosch and a DIng (1982) from the University of Pretoria. After four years with the firm Sennett & Wessels Inc in Pretoria, he joined the NITRR of the CSIR where, in 1986, he became the head of the Western Cape office. From 1988 to 1994 he was an associate in the Cape Town office of VKE Engineers. Since 1994 he has been a professor of Civil Engineering at the University of Stellenbosch. He is the author or co-author of 53 papers, 31 of which were presented at the South African Transport Conference.