INTERSECTION LEVEL OF SERVICE AND PERFORMANCE DISCREPANCIES

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ABSTRACT

The intersection level of service (LOS) method, especially as specified in the US Highway Capacity Manual (HCM), has been around for a long time. It continues to be discussed with various related issues raised by professionals. An example is the ITE eCommunity Group discussion on concerns about perceived discrepancy (or inconsistency) of low delay estimated at a high degree of saturation (volume / capacity, v/c ratio) leading to LOS F in HCM Edition 6. This condition happens in real-life traffic and it is relevant to intersection capacity and performance estimates from analytical models such as HCS, SYNCHRO and SIDRA, or various microsimulation models, although results from different models may differ. The purpose of this paper is to explain how this condition (as well as its opposite condition where high delay can occur at low degree of saturation) can occur and how these conditions relate to other performance variables such as queue length and the number of signal cycles to clear (cycle failures). Level of service methods based on degree of saturation only, delay only, and combined delay and degree of saturation are reviewed. Levels of service for different intersection types are also discussed.

Keywords: Intersection, Level of Service, HCM, HCS, SYNCHRO, SIDRA

INTRODUCTION

The intersection level of service (LOS) method, especially as specified in the US Highway Capacity Manual (HCM), has been around for a long time *(1-5)*. Various related issues continue to be raised by professionals frequently. An example is the ITE eCommunity Group discussion titled *Levels-of-Service and v/c Ratio (6)*. This discussion started with concerns raised about a perceived discrepancy (or inconsistency) of low delay estimated at a high degree of saturation (volume / capacity, v/c ratio) leading to LOS F in HCM Edition 6, and it attracted interesting comments.

The purpose of this paper is to discuss the questions raised and comments made in the ITE eCommunity Group discussion and offer detailed explanations regarding these.

In this paper, v/c (ratio of demand volume to capacity) will be referred to as *degree of saturation* and will be represented by symbol x. Traffic flow conditions will be referred to as *undersaturated* when $x < 1$ (demand below capacity) and *oversaturated* when $x > 1$ (demand exceeds capacity). The condition when average $x = 1$ (demand volume = capacity) can be referred to as *saturated*. However, it is important to understand that an *average* degree of saturation value is used for the analysis period in determining a LOS value. Cycle-by-cycle values of degree of saturation vary due to randomness in arrival flows, and average $x = 1.0$ (and some values of average $x < 1$) would mean that the analysis period has undersaturated and oversaturated cycles. The implications of this in relation to cycle failures (overflows) in undersaturated and oversaturated conditions will be discussed in detail.

The discussions in this paper are restricted to level of service methods and related performance measures for *intersections*. Route, segment and network level of service methods are not discussed.

The discussions will refer to *red time*, *green time* and *cycle time* in signalized intersection analysis, and the corresponding terms *blocked time*, *unblocked time* and g*ap acceptance cycle time* for roundabouts and two-way sign control analysis based on gap acceptance modelling *(7-8)*.

CONCERNS EXPRESSED ABOUT HCM LEVEL OF SERVICE METHOD

The questions raised and comments made in the ITE eCommunity Group discussion *(6)* can be summarized as follows:

- HCM 6, Chapter 5.4 *(1)* states that "The volume-to-capacity (v/c), or more correctly, demand volume-to-capacity (d/c) ratio, is a special-case service measure. It cannot easily be measured in the field, nor is it a measure of traveler perceptions. Until capacity is reached (i.e. when flow breaks down on uninterrupted-flow facilities and when queues build on interrupted- or uninterrupted-flow facilities), these ratios are not perceivable by travelers. Therefore, the HCM often uses a v/c (d/c) ratio of greater than 1.0 (i.e. capacity) as an additional test for defining when LOS F occurs, but it does not use these ratios to define other LOS ranges."

  "*Something does not seem to be consistent with this method. It has been suggested to me that because the v/c ratio is greater than 1.0, then flow conditions are unstable, and it is likely that vehicles cannot make it through the traffic signal in one cycle length period. But if that were the case, would not the delay calculations reflect that as well*?"

  "*To complicate matters, there are cases where a signalized intersection might be analyzed in which a turning movement / lane group is calculated to be a delay of 100+ seconds (LOS "F") while the v/c ratio is 0.80 (significantly less than 1.0)*".

- "*... a minor movement can be given enough time to clear (v/c < 1), but because the green time allotted is such a small percentage of the cycle ... , the average delay will calculate to be very high.*".

- "*If the calculated v/c is over 1.0 but everybody clears on each cycle, there is probably something wrong in the calculation assumptions.*".

- "*... both v/c ratio and delay should be considered in performance evaluation. In fact, v/c > 1 can be perceived by road users when they are waiting multiple cycles to pass through due to cycle failures ...*".
- "*... over the years there has been the general understanding the traffic flow breakdown typically begins to occur when demand exceeds capacity (i.e. v/c > 1.0), which logically has been associated with LOS F*".
- "*If there is disparity between the calculated delay and the v/c ratio, ... rather than rendering the level-of-service as "F", perhaps there could be a less abrupt transition*.".
- "*As I understand it, the model used to calculate delay was estimated and calibrated under stable flow conditions. ... a v/c > 1 would indicate unstable flow conditions are likely present, and thus the delay estimated by stable flow assumptions would be unreliable.*".
- "*... if the capacity of the project is of an issue, v/c is more important than delay*.".

These questions and comments will be addressed in the following sections.

AVERAGE DELAY AND DEGREE OF SATURATION

Firstly, it should be clarified that the analytical delay models, such as the one used in the HCM, are derived considering both undersaturated and oversaturated conditions with a smooth non-linear transition between these conditions. In the performance models developed by the author, the *unstable conditions* can be represented by steady increase of *overflows* (cycle failures). However, the overflows start at degrees of saturation below the capacity point ($x < 1$). These are caused by cycle-by-cycle variations in arrival flows. Overflows increase at a high rate as the average arrival flow approaches capacity and result in consistent cycle failures when $x > 1$, especially under highly oversaturated conditions *(9-10)*. Note that in most cases, the capacity will also have cycle-by-cycle variations (e.g. for actuated signals and all gap-acceptance situations).

Secondly, the "average delay" for the analysis period does not tell the whole story. As conditions approach capacity, the vehicles forming the overflow queues are delayed more significantly than the average delay implies. The non-linear nature of the delay - degree of saturation relationship, i.e. the high rate of increase in delay near capacity (near $x = 1$) is because of the overflow queues (cycle failures). In this sense, overflow queues are a good measure of congestion.

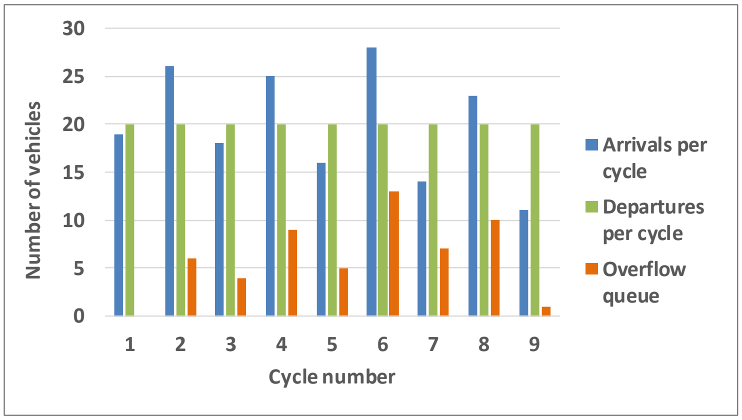
Vehicles subject to cycle failure (overflow) slow down or stop to join the back of queue, accelerate to depart (as queue moves up) but have to stop again at the start of the red signal (because of lack of enough capacity in the cycle) and as a result are subject to a long delay.

Figure 1 demonstrates that overflows (cycle failures) exist at capacity ($x = 1$) and below capacity ($x < 1$). This example has the following assumptions for a signalized intersection lane:

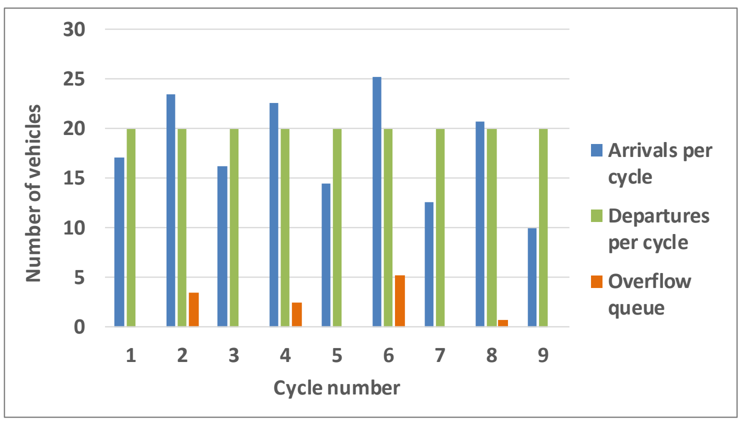
- cycle time = 100 s, green time = 40 s, saturation flow rate = 1800 veh/h, capacity = 720 veh/h, capacity per cycle, N_{Qi} = 20 veh (constant);
- analysis period = 15 mins, number of cycles = 9, arrival flow rate varies around the average value cycle by cycle;
- at capacity ($x = 1.0$): arrival flow rate = 720 veh/ h, average arrivals per cycle, N_a = 20 veh;
- undersaturated case ($x = 0.9$): arrival flow rate = 648 veh/ h, average arrivals per cycle, N_a = 18 veh;
- oversaturated case ($x = 1.1$): arrival flow rate = 792 veh/ h, average arrivals per cycle, N_a = 22 veh.

The overflow queue for the *ith* cycle is determined as $N_{oi} = max\ (0, N_{o(i-1)} + N_{ai} - N_{Qi})$ where $N_{o(i-1)}$ = overflow queue at the end of the previous cycle (or at the start of the ith cycle), N_{ai} = arrivals per cycle and N_{Qi} = capacity per cycle.

At capacity: x = 1.00 (Average arrivals per cycle, N_a = 20 veh):
Average overflow queue, No = 6.1 veh; Queue move-up rate, h_{qm} = 0.31



Undersaturated: x = 0.90 (Average arrivals per cycle, N_a = 18 veh):
Average overflow queue, No = 1.3 veh; Queue move-up rate, h_{qm} = 0.07



Oversaturated: x = 1.10 (Average arrivals per cycle, N_a = 22 veh):
Average overflow queue, No = 15.6 veh; Queue move-up rate, h_{qm} = 0.71

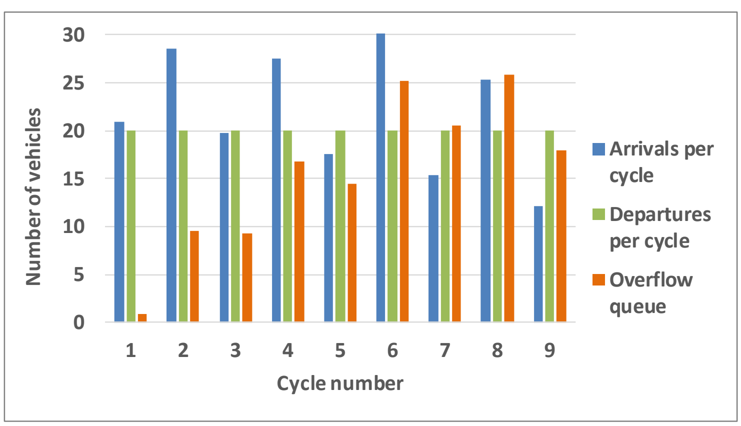


Figure 1 - Overflow examples for different degrees of saturation (capacity = 20 veh/cycle)

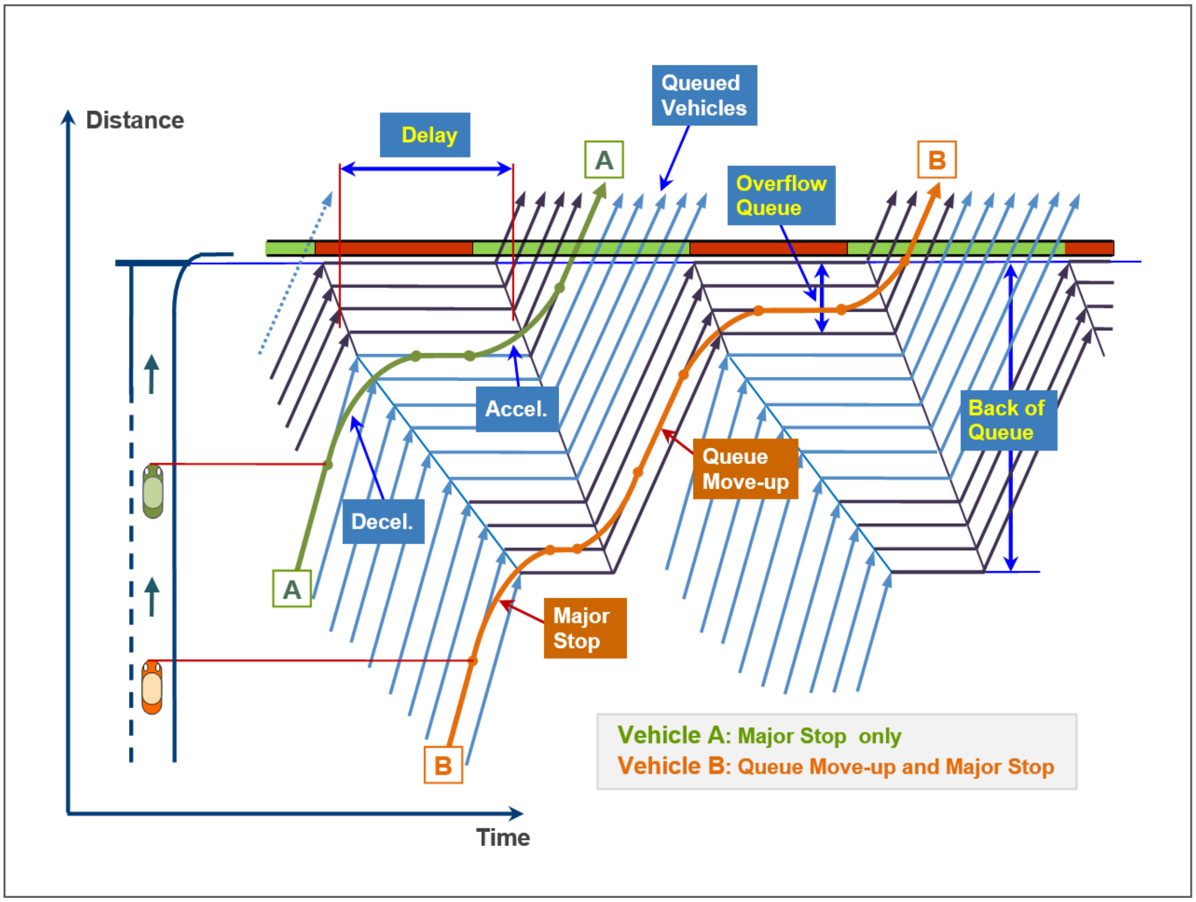


Figure 2 - Relationship between Queue Move-ups (Multiple Stops) and Back of Queue

The average *queue move-up rate* is a good indicator of how many cycles it takes to depart from the queue. It can be estimated from $h_{qm} = N_o / N_a$ where N_o = average overflow queue and N_a = average arrivals per cycle. *Figure 1* shows the average overflow queue and the average queue move-up rate for each case. For low degrees of saturation, these have zero values (all vehicles clear in all cycles).

Note that the HCM delay equation does not use the overflow concept *(1)*. The SIDRA delay, back of queue and stop rate equations for all types of intersection are based on the use of the overflow concept *(9-10)*. *Figure 2* shows the relationship between queue move-ups (multiple stops), overflow queues and back of queue with acceleration and deceleration paths of vehicles shown for a vehicle which clears in one cycle with one major stop (A) and a vehicle which is subject to a queue move up (B).

LOW DELAY - HIGH DEGREE OF SATURATION and HIGH DELAY - LOW DEGREE OF SATURATION

The delay and degree of saturation are not necessarily consistent in terms of magnitude. This also applies to the relationship between delay and back of queue. *Figure 3* shows the case of *long back of queue* associated with a *low average delay*, and *Figure 4* shows the opposite case of *short back of queue* associated with a *large average delay*. The delay values may also appear to be inconsistent when the case shown in *Figure 3* is associated with a *high degree of saturation* and the case shown in *Figure 4* is associated with a *low degree of saturation*.

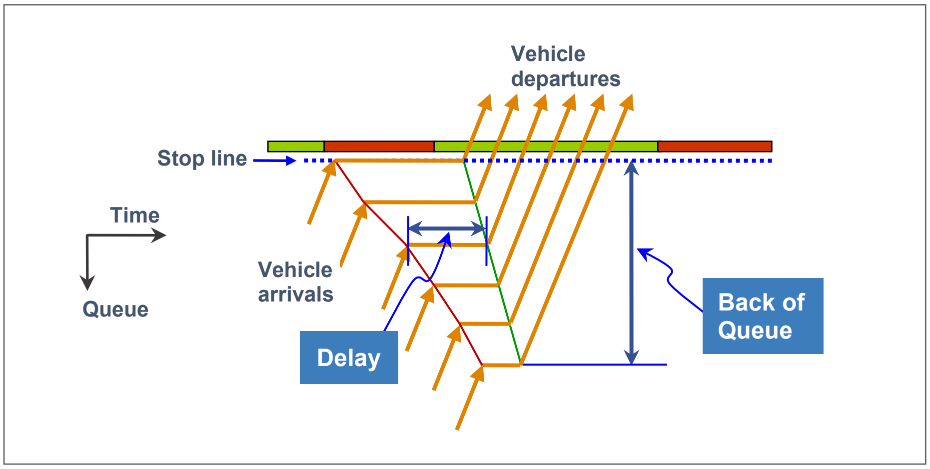


Figure 3 - *Long back of queue* associated with a *low average delay* at signals: this occurs with large green time ratio (short red time) and high arrival flow conditions

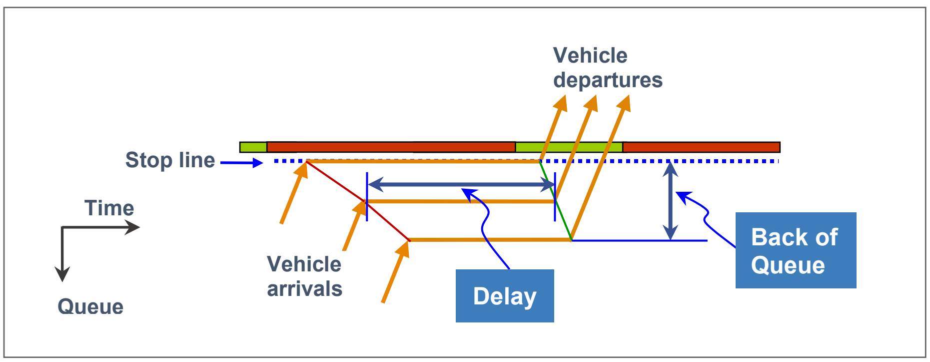


Figure 4 - The case of *short back of queue* associated with a *large average delay* at signals: this occurs with small green time ratio (long red time) and low arrival flow conditions

These cases can be explained in relation to the the two-terms of delay, back of queue and stop rate models: the first terms of these equations represent the *red / blocked time effect* and the second terms represent the *congestion effect*.

The first terms of these performance models depend on how long the red / blocked time is relative to the cycle time, i.e. on the *green / unblocked time ratio*. The second terms depend on overflows (cycle failures) and are strongly correlated with the degree of saturation (considering both undersaturated and oversaturated conditions).

The case in *Figure 3* occurs with short red (large green / unblocked time ratio) but high degree of saturation due to a large arrival flow rate while a large capacity is available as experienced by major movements. For roundabouts and two-way sign control, this case occurs under low circulating / opposing flow and high entry demand flow conditions. In such cases, many vehicles in the queue may experience acceleration and deceleration (slow down) delays only. The large back of queue represents a *moving queue* formed by a heavy arrival flow, and there may also be a large proportion of vehicles that are undelayed. These conditions also explain unbalanced roundabouts where the majority of departures with follow-up headway result in a uniform circulation road headway distribution at the next (downstream) entry which leads to low capacity for that approach.

This case also indicates the importance of *back of queue* as a performance measure in modelling approach short lanes in intersection analysis, and in modelling blockage of upstream intersection lanes (queue spillback) in network analysis.

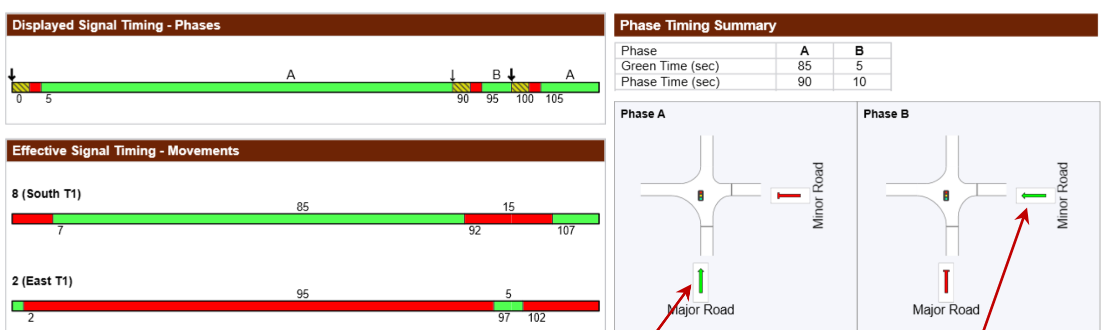
The case in *Figure 4* occurs with long red (small green / unblocked time ratio) but low degree of saturation due to low arrival flow rate while the capacity is low as experienced by minor movement. For roundabouts and two-way sign control, this case occurs under high circulating / opposing flow and low entry flow (minor movement) conditions. In such cases, short static queues will exist with most vehicles experiencing long stopped time (idling) delays.

Note that Figures 3 and 4 are intended to depict average conditions for the analysis period. They are shown as undersaturated cases (x < 1) with no overflows. However, as discussed in the previous section, there may be significant overflows (cycle failures) due to cycle-by-cycle variations in arrival flows for high degrees of saturation even if they are at or below capacity (x ≤ 1.0).

These conditions happen in real-life traffic and they are relevant to intersection capacity and performance estimates from analytical models such as HCS, SYNCHRO and SIDRA, or various microsimulation models, although results from different models may differ.

EXAMPLE

A basic example is given here to show both cases of *long back of queue* and *high v/c ratio* associated with a *low average delay*, and *short back of queue* and *low v/c ratio* associated with a *large average delay* (*Figure 5*).



Movement >>	Northbound		Westbound
Arrival flow rate	1665 veh/h	1600 veh/h	60 veh/h
v/c Ratio (Degree of Saturation)	1.03	0.99	0.63
Average delay	38.0 s	27.3 s	58.2 s
Level of Service			
HCM (Table 1)	F	C	E
Delay only	D	C	E
Combined Delay & v/c Ratio	F	E	E
Average back of queue	1714 ft (522 m)	1496 ft (456 m)	50 ft (15 m)
Average overflow queue	22.3 veh	17.6 veh	0.4 veh
Queue move-up rate	0.38	0.26	0.12

Figure 5 - A simple example to show both cases of *long back of queue* and *high v/c ratio* associated with a *low average delay*, and *short back of queue* and *low v/c ratio* associated with a l*arge average delay*

For simplified analysis, an intersection of two one-way single-lane roads with a very high Northbound flow and a very low Westbound flow is modeled. A simple two-phase signal sequence applies:

- Cycle Time: 100 sec.
- Green Times: 85 sec for the Northbound movement in Phase A and 5 sec (minimum) for the Westbound movement in Phase B.
- Intergreen Times: 5 sec.
- Saturation Flows: 1900 veh/h (no heavy vehicles).

Results obtained using the HCM delay and back of queue equations in SIDRA INTERSECTION are shown in *Figure 5*. The case of *long back of queue* and *high v/c ratio* associated with a *low average delay* for the Northbound movement is represented by two conditions, just above capacity (v/c ratio = 1.03) and just below capacity (v/c ratio = 0.99).

As seen in *Figure 5*, the Westbound movement has a low degree of saturation (0.63) but delay (58.2 s) is significantly higher than the Northbound movement delays. The delay for the Westbound movement is mainly due to a very long red time as indicated by a very low average overflow queue (0.4 veh). On the other hand, short delays for the Northbound movement are mainly due to a very favourable green time while large back of queue values are due to high arrival flow rates and high v/c ratios resulting in large overflow queues.

LEVEL OF SERVICE and INTERSECTION PERFORMACE MEASURES

The HCM level of service method for intersections uses the delay as the basis with the degree of saturation added for oversaturated (x > 1) conditions. The use of delay only in defining levels of service for capacity conditions (x = 1) and undersaturated conditions (x < 1) leads to the expectation that other performance parameters like degree of saturation, overflow queue or queue move-up rate representing cycle failures, stop rate and back of queue are well *correlated* with delay. An abrupt change to Level of Service F overriding any low delay values that may be associated appears to be inconsistent because of the lack of correlation between delay and degree of saturation in this case.

Good assessment of intersection performance should take into account at least *delay*, *back of queue* and *degree of saturation*. Overflow queue, queue move-up rate, stop rate and number of cycles to clear are useful measures as well. These parameters represent *different aspects* of traffic conditions, i.e. they do not always correlate well in implying "good" or "bad" traffic performance. Road users (car drivers, large truck drivers, pedestrians, cyclists) may or may not perceive all these performance measures as "good service" or "bad service" at all types of intersection and under all traffic conditions in the same way. However, they are useful for the analyst / modeler / engineer to assess the performance of the system. Specifically, it should be noted that:

- HCM does not model overflow queue, queue move-up rate, stop rate and number of cycles to clear.
- HCM does not model back of queue for roundabouts and sign-controlled intersections.

Drivers would perceive overflows (cycle failures), particularly because those who cannot make it in the first green will experience the longest delays. As the demand flow rate approaches capacity (x ≤ 1), more and more drivers will experience this at an increasing rate (performance deteriorating quickly). A long delay at a high degree of saturation includes the effect of this "congestion delay" element but a high delay at a low degree of saturation is a result of long red time (red time delay) with low likelihood of overflow delays (cycle failures). The *average delay for the analysis period* itself cannot explain these. Adding the degree of saturation to LOS evaluation is helpful with this in mind. A comparison of the following level of service definitions for vehicle movements would be useful:

- *Table 1* presents the level of service definitions based on HCM Edition 6 with the addition of a roundabout level of service recommended by the author and included in Australian guidelines *(1, 4, 5, 11)*.

- *Table 2* presents the Level of Service definitions based on the degree of saturation only including the ICU method used in USA *(2)*.
- *Table 3* shows level of service definitions based on *combined use of delay and degree of saturation* for undersaturated as well as oversaturated conditions with more smooth transitions between LOS grades. This is based on a method proposed by Berry about three decades ago *(3)*. The method is depicted in *Figure 6* using LOS thresholds for Signals. The blue curve in *Figure 6* indicates the non-linear characteristic of a general delay function. *Figure 6* also shows the LOS points corresponding to the results of the basic example given in *Figure 5*.

Table1 - Delay and Degree of Saturation method for Level of Service definitions (HCM Edition 6 method)

Level of Service for **v/c ≤ 1.0**	Average delay per vehicle in seconds (d)			Level of Service for **v/c > 1.0**
	Signals	"SIDRA Roundabout LOS" method *	Sign Control *	All Intersection Types
A	d ≤ 10	d ≤ 10	d ≤ 10	**F**
B	10 < d ≤ 20	10 < d ≤ 20	10 < d ≤ 15	**F**
C	20 < d ≤ 35	20 < d ≤ 35	15 < d ≤ 25	**F**
D	35 < d ≤ **55**	35 < d ≤ **50**	25 < d ≤ **35**	**F**
E	**55** < d ≤ 80	**50** < d ≤ 70	**35** < d ≤ 50	**F**
F	80 < d	70 < d	50 < d	**F**

Only the average delay value is considered in determining LOS for approaches and the intersection.

* The default *Roundabout LOS Method* is *Sign Control* in the HCM. The *SIDRA Roundabout LOS* method is is accepted in Australian guidelines *(1, 4, 5, 6, 11)*.

Table 2 - Degree of Saturation methods for Level of Service definitions (SIDRA Method and ICU Method)

Level of Service	Degree of Saturation (x) ***SIDRA Method***			Degree of Saturation (x) ***ICU Method***
	Signals	Roundabouts	Sign Control	All intersection types
A	x ≤ 0.60	x ≤ 0.60	x ≤ 0.60	x ≤ 0.60
B	0.60 < x ≤ 0.70	0.60 < x ≤ 0.70	0.60 < x ≤ 0.70	0.60 < x ≤ 0.70
C	0.70 < x ≤ **0.90**	0.70 < x ≤ **0.85**	0.70 < x ≤ **0.80**	0.70 < x ≤ 0.80
D	**0.90** < x ≤ **0.95**	**0.85** < x ≤ **0.95**	**0.80** < x ≤ **0.90**	0.80 < x ≤ **0.90**
E	**0.95** < x ≤ 1.00	**0.95** < x ≤ 1.00	**0.90** < x ≤ 1.00	**0.90** < x ≤ 1.00
F	1.00 < x	1.00 < x	1.00 < x	1.00 < x

Table 3 - Delay and Degree of Saturation method for Level of Service (SIDRA Method based on a proposal by Berry *(2)*)

Level of Service	Control delay per vehicle in seconds (d)			Degree of saturation (v/c ratio) (x)
	Signals	Roundabouts	Sign Control	
A	d ≤ 10	d ≤ 10	d ≤ 10	0 < x ≤ 0.85
B	10 < d ≤ 20	10 < d ≤ 20	10 < d ≤ 15	0 < x ≤ 0.85
C	20 < d ≤ 35	20 < d ≤ 35	15 < d ≤ 25	0 < x ≤ 0.85
D	35 < d ≤ 55	30 < d ≤ 50	25 < d ≤ 35	0 < x ≤ 0.85
	0 < d ≤ **55**	0 < d ≤ **50**	0 < d ≤ **35**	0.85 < x ≤ **0.95**
E	**55** < d ≤ 80	**50** < d ≤ 70	**35** < d ≤ 50	0 < x ≤ 0.95
	0 < d ≤ 80	0 < d ≤ 70	0 < d ≤ 50	0.95 < x ≤ 1.00
F	80 < d	70 < d	50 < d	**1.00 < x**

Only the average delay value is considered in determining LOS for *approaches* and the intersection.

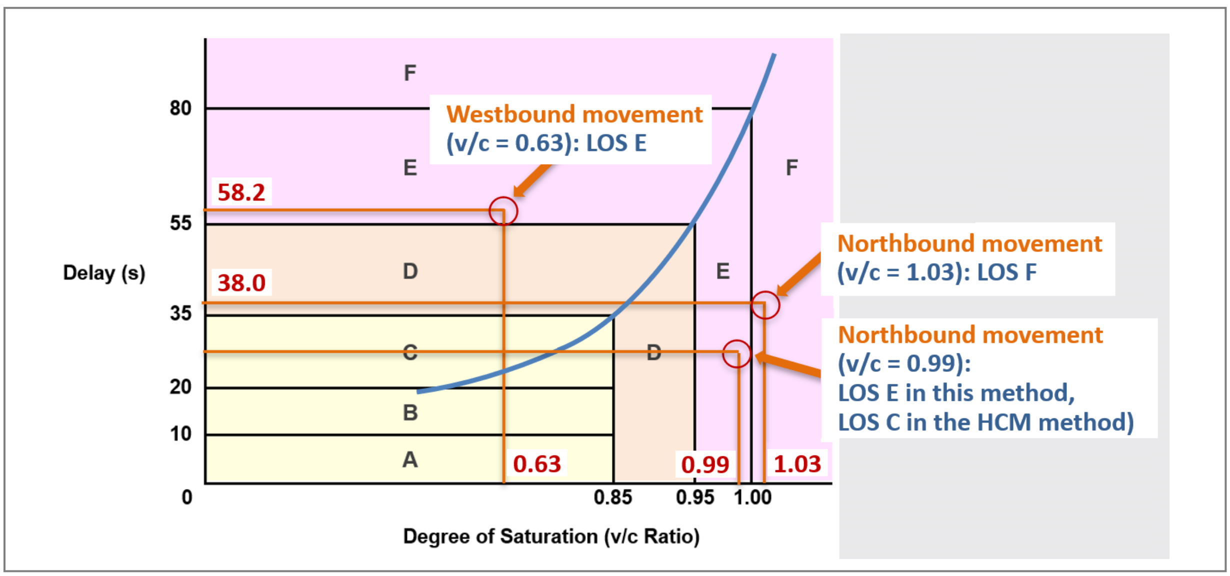


Figure 6 - SIDRA combined Delay and Degree of Saturation Level of Service Method (threshold values shown for Signals)

CONCLUDING REMARKS

Conditions of long back of queue associated with a low average delay, and the opposite case of short back of queue associated with a large average delay have been explained and simple examples to demonstrate these cases have been given. These cases appear to give inconsistent results in terms of magnitude when the former case associates a low delay with a high degree of saturation and the latter case associates a long delay with a low degree of saturation. It has been emphasised that the "average delay" for the analysis period is not a sufficient measure to explain the reasons for existence of such conditions. As conditions approach capacity, the vehicles forming the overflow queues are delayed more significantly than the average delay implies. The non-linear nature of the delay - degree of saturation relationship, i.e the high rate of increase in delay, queue length and number of stops near capacity ($x \le 1$) is because of the overflow queues (cycle failures). Existence of overflows due to cycle-by-cycle variations in arrival flow rates has been demonstrated with a simple example for oversaturated, at-capacity and undersaturated flow conditions.

Overflow queues representing cycle failures are easy to observe. They are recorded as part of the back of queue survey *(12)*. In the ITE eCommunity discussion referred to in this paper *(6)*, there seemed to be a consensus about driver perception of overflows. However, it was not recognized that overflows do not happen suddenly when demand flow exceeds capacity, but they occur at demand flows below capacity, and they increase at a high rate when demand flows approach and exceed capacity.

It is recommended that modelers should pay attention to *delay*, *back of queue* and *degree of saturation* rather than just the level of service. Overflow queue, queue move-up rate, stop rate and number of cycles to clear are useful measures as well. Road users (car drivers, large truck drivers, pedestrians, cyclists) may or may not perceive all these performance measures as "good service" or "bad service" at all types of intersection and under all traffic conditions in the same way. However, they are useful for the analyst / modeler / engineer to assess the performance of the system.

Modeling of stop-starts is essential for environmental assessments using energy and emission estimates. It is recommended that this and the level of service method which combines delay and degree of saturation (v/c ratio) are considered for inclusion in future HCM editions.

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