The Relationship between Capacity and Driver Behaviour

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Paper presented at the TRB National Roundabout Conference, Kansas City, MO, USA, 18-21 May 2008

ABSTRACT

Analytical models use traffic stream capacity as a basic parameter in traffic performance estimation. Traffic characteristics that affect capacity are not often clearly explained or understood. This causes difficulties in practice when professional judgement has to be used in interpreting output and calibrating models for specific applications. There is also a need to establish relationships between traffic parameters used in analytical models and microsimulation models. This paper presents a general analytical model that provides a common formulation relating key variables in intersection analysis to various driver behaviour (driver-vehicle) characteristics. These key variables are follow-up headway for gap-acceptance situations (roundabouts, sign control, and filter turns at signals) and saturation flow rate for signalised intersections. This provides a direct relationship between capacity and parameters representing driver behaviour, namely driver response time during queue discharge, spacing between vehicles in the queue (jam spacing) and saturation (queue discharge) speed. Research is recommended both on conceptual aspects of the relationships presented in this paper and their calibration using field studies of many different traffic situations, as well as the investigation of driver and vehicle parameters used in various microsimulation software packages in relation to the analytical relationships presented in this paper.

INTRODUCTION

It is often overlooked that driver behaviour (characteristics of driver - vehicle units in traffic) is the main determinant of capacity. This paper gives the basic expressions for capacity and related traffic movement parameters, and then presents expressions for various queue discharge parameters. This provides a direct relationship between capacity and driver behaviour parameters, namely driver response time, jam spacing, and saturation speed, as well as the proportion of time when the vehicles can depart from the queue, i.e. when signals are green or gaps are available in the opposing stream.

Various issues related to capacity modelling are discussed. Relationships are also given to enable estimation of queue discharge parameters such as queue clearance wave speed, average acceleration delay, acceleration time, acceleration distance, and average acceleration rate. These help to assess the reasonableness and realism of the basic models and their implications.

The results for signalised intersections based on previous research are summarised. Then the relationships are applied to roundabouts with an example given. A brief description of the use of the queue discharge relationships for deriving a heavy vehicle equivalent (pcu factor) for capacity estimation is given. Relevance of the relationships given in this paper as a link between analytical and microsimulation models is discussed.

An equation for estimating capacity directly using driver behaviour parameters (driver response time, jam spacing and saturation speed) is given in the conclusion section, and examples of various factors that affect capacity are given to explain the sensitivities in relation to the driver behavior parameters used in the capacity equation.

CAPACITY

Capacity is the maximum sustainable flow rate that can be achieved during a specified time period under given (prevailing) road, traffic and control conditions. The Highway Capacity Manual defines it as "the maximum sustainable flow rate at which vehicles or persons reasonably can be expected to traverse a point or uniform segment of a lane or roadway during a specified time period under given roadway, geometric, traffic, environmental, and control conditions; usually expressed as vehicles per hour, passenger cars per hour, or persons per hour" *(1)*.

Capacity is the main parameter used in formulating performance measures such as delay, queue length and stop rate since it represents the service rate (queue clearance rate) in these performance functions. Such relationships are often expressed in terms of degree of saturation, i.e. the demand volume / capacity ratio. Lane utilization is an important issue in this context since unequal lane utilization means higher degrees of saturation for critical lanes.

Due to the lack of a direct analytical formulation of the relationship between capacity and driver behaviour, it is often overlooked that driver behaviour is the main determinant of capacity. In this paper, the term driver behaviour is used to refer to the characteristics of driver - vehicle units in traffic.

Capacity models for signalised intersections use the saturation flow and lost time parameters which reflect driver behaviour. Capacity models for roundabouts and two-way sign controlled intersections based on gap-acceptance modelling use follow-up headway and critical gap parameters for entering traffic, and headway distribution parameters for opposing (circulating, or major road) traffic reflecting driver behaviour.

When parameters such as *environment class (area type)* and *environment factor* *(1,2)* are considered as affecting saturation flow and gap-acceptance parameters, the relationship to driver behaviour becomes more apparent. These parameters are used indirectly to allow for the effects of such factors as driver aggressiveness and alertness (driver response times), standard of road (intersection) geometry, visibility, significant grades, operating speeds, sizes of light and heavy vehicles, interference by pedestrians, standing vehicles, parking manoeuvres, buses stopping, and so on.

More aggressive and alert driver attitudes (smaller response times), good intersection geometry, good visibility, smaller vehicle sizes and minimal interference from pedestrians and other vehicles would result in higher capacities whereas less aggressive and relaxed driver attitudes (slower response times), poor intersection geometry, poor visibility, large vehicle sizes and significant interference by pedestrians and other vehicles would lead to lower capacities.

An analytical formulation of queue discharge headways in terms of some key driver behaviour parameters is presented in the following section after expressions for capacity and related traffic movement parameters are given below.

The basic equation for the calculation of *capacity* for interrupted traffic movements (signalised and unsignalised intersections) is:

$$Q = u\,s \tag{1}$$

where Q = capacity (veh/h), u = proportion of time when the vehicles can depart from the queue (signals are green or gaps are available in the opposing stream) and s = saturation (queue discharge) flow rate (veh/h).

For signalised intersections, u is the *green time ratio,* u = g / c, where g = effective green time (s) and c = cycle time (s). For gap-acceptance processes at roundabouts and sign-controlled intersections, u is the *unblocked time ratio* related to average durations of block and unblock periods in the opposing stream *(3)*.

For uninterrupted traffic movements (e.g. on freeways), the parameter u = 1.0 by definition, and the saturation flow rate is the capacity, Q = s.

Saturation flow rate (s) is the maximum flow rate that can be sustained when there is a queue and the vehicles can depart from the queue, i.e. signals are not red or the gaps in the opposing stream are not too short. For signalised intersections, the saturation flow rate is measured as the maximum departure flow rate during the saturated (queued) portion of the green period achieved after about four or five vehicles depart from the queue, or about 10 seconds after the start of green period *(1,2,4,5)*.

Saturation flow rate as a queue discharge flow rate corresponds to a *queue discharge headway* which represents the minimum headway between vehicles that is achieved while they are departing from the queue:

$$h_s = 3600 / s \quad (2)$$

where h_s = queue discharge (saturation) headway (seconds) and s = saturation flow rate (veh/h).

For example, a saturation flow rate of s = 2000 veh/h corresponds to a saturation headway of h_s = 1.8 seconds.

For uninterrupted traffic movements, the maximum flow rate (capacity) is relevant to *bunching* or *moving queues (6)*, and the saturation headway corresponds to the minimum headway at capacity, h_s = 3600 / Q. This corresponds to the intra-bunch headway in the bunched exponential distribution of headways in a traffic stream *(2,3,6)*.

The gap-acceptance method uses the *follow-up headway* (t_f) as the queue discharge (saturation) headway ($t_f = h_s$). The follow-up headway corresponds to a saturation flow rate which is the maximum gap-acceptance capacity that can be achieved when the opposing flow is close to zero:

$$s = 3600 / t_f \quad (3)$$

where s = saturation flow rate (veh/h) and t_f = follow-up headway as a queue discharge (saturation) headway (seconds).

For example, a follow-up headway of t_f = 3.0 seconds implies a saturation flow rate of s = 1200 veh/h.

The saturation flow rate for a gap-acceptance process is the maximum capacity that can be achieved when the opposing flow is close to zero. The capacity is reduced from this value with increased opposing flow rates, due to the decreased value of unblocked time ratio as seen from *Equation (1)* and depicted in *Figure 1*.

While the follow-up headway determines the capacity value at low opposing flow rates directly, the critical gap parameter affects the u parameter (the proportion of time when the vehicles can depart from the queue) in *Equation (1)* with lower values of u resulting from larger values of critical gap (hence lower capacity) for a given opposing flow rate. This is also depicted in *Figure 1*.

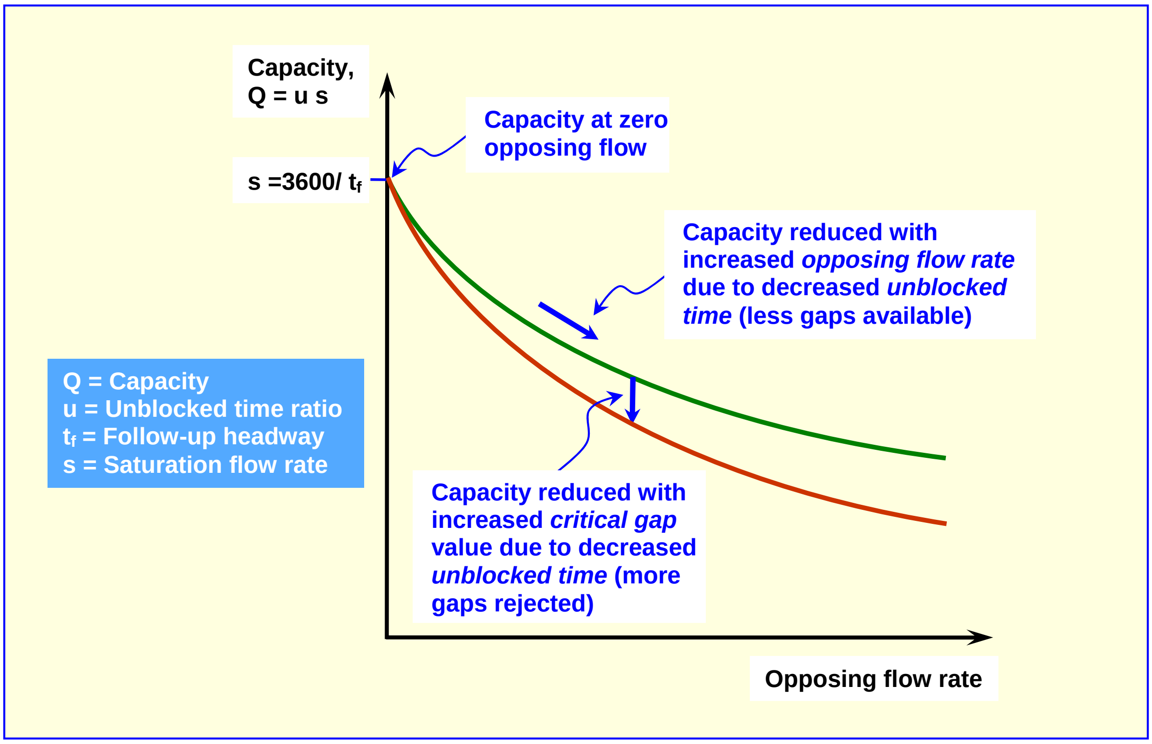

Figure 1 - Gap-acceptance capacity

Issues in Capacity Modelling

Important issues in modelling capacity, relevant to all types of intersection, are the level of aggregation in terms of individual lanes, lane groups and approaches, and the method of measuring capacity.

Different methods have been used to measure and model capacities in terms of level of aggregation:

- *lane-by-lane* analysis as in the SIDRA INTERSECTION software *(1)*,
- analysis by *lane groups* (movements combined according to shared lanes) as in the Highway Capacity Manual *(2)*, and
- analysis by total *approach flows*, i.e. all movements in all approach lanes combined, as in the TRL (UK) method for roundabout capacity analysis *(7-14)*.

The lane-by-lane method simplifies the analysis method and introduces improved accuracy levels in capacity and performance prediction by allowing improved spatial (geometric) modelling of all types of intersection. This method allows modelling of unequal lane utilization which is an important factor that affects the capacity and performance of roundabouts, including the effect of circulating lane use at multilane roundabouts.

Two methods are possible for measuring capacity at intersections:

- measure departure flow rates (volume counts) during saturated (queued) portions of individual stop-go cycles (green periods, or gaps used for queue discharge) and extrapolate using the associated proportion of time available for queue discharge as implied by *Equation (1)*.
- measure departure flow rates at the stop or give-way (yield) line during saturated (continuous queuing) conditions over sufficiently long observation periods, and

The first method is used commonly for signalised intersections *(1,4,5)*. This method is more difficult to implement for unsignalised intersections due to the short duration of gap-acceptance cycles. A method to determine the follow-up headway (and critical gap) is available for unsignalised intersections *(3)*.

The latter method provides an easy method of measuring capacity that prevails in oversaturated conditions, i.e. when the arrival (demand) flow rate exceeds the departure flow rate, as it is obtained from a simple volume count. In oversaturated conditions, the demand flow rate can be measured by counting the number of vehicles arriving at the back of queue, not at the stop or give-way (yield) line. The use of turning movement volumes counted at the stop or give-way (yield) lines for performance estimation will result in underestimation of benefits from intersection improvements, and may result in inadequate design *(14)*.

The method of increasing the demand flow rate on an approach road to create oversaturated conditions in order to measure capacity has been suggested in the literature as a way of obtaining capacity estimates from microscopic simulation models. It should be noted that this method introduces some bias to the analysis since, for example, signal timings would be affected at signalised intersections, and modelling problems would arise when the method is applied to a *closed (interactive) system* such as paired intersections or roundabouts. For example, the amount and queuing characteristics of the approach flow at a roundabout will affect each leg in turn, eventually affecting the circulating stream characteristics for the subject approach.

It should also be noted that the capacity for prevailing conditions should not be confused with the level of demand volume a facility can handle. The capacity estimated using *current* traffic demand levels may be misleading since the capacity will be less under future (increased) demand scenarios as relevant to design life analyses. This is because the capacity depends on opposing flow levels, especially for roundabouts and sign-controlled intersections. Short lane and blocked lane capacities also tend to drop with increased flow levels.

QUEUE DISCHARGE HEADWAY

The discussion on capacity and its formulation shows that the queue discharge headway is a key parameter that determines capacity. The queue discharge headway can be expressed as a function of the driver response time during queue discharge, spacing between vehicles in the queue (jam spacing) and saturation (queue discharge) speed *(5,16)*:

$$h_s = t_r + L_{hj} / v_s \qquad (4)$$

where h_s = the saturation (queue discharge) headway (seconds), t_r= driver response time during queue discharge (seconds), L_{hj} = queue space per vehicle (jam spacing) including the vehicle length and the gap distance between vehicles in the queue (metres or feet), and v_s = saturation speed (m/s or ft/s).

Equation (4) shows the importance of vehicle length and driver alertness which affect not only the driver response time but also the queue discharge speed and the gap distance left between vehicles in the entry lane queue (e.g. less gap under pressure of high traffic demand levels). These factors affect saturation flow rates, and therefore capacity through *Equations (1) to (3)*.

Thus, where the saturation headway, queue space per vehicle and saturation speed are known, the driver response time can be determined from:

$$t_r = h_s - L_{hj} / v \qquad (5)$$

This relationship assumes that the response time is the same for all drivers in the queue, i.e. an average value is used for all drivers.

Other useful parameters related to the queue discharge behaviour of traffic are the queue clearance wave speed and average acceleration delay. These can be determined from:

$$v_x = L_{hj} / t_r = L_{hj} / (h_s - L_{hj} / v_s) \qquad (6)$$

$$d_a = t_s + h_s - t_r = t_s + L_{hj} / v_s \qquad (7)$$

where v_x = queue clearance wave speed (m/s or ft/s), d_a = acceleration delay (seconds), t_s = start loss (seconds), and t_r, L_{hj} and v_s are as in *Equation (4)*.

The method for determining the start loss (t_s) parameter for signalised intersections is discussed in detail in Akçelik et al *(5)*.

In a major study of departure flow characteristics of traffic at signalised intersections, Akçelik, Besley and Roper *(5)* identified a maximum queue discharge (saturation) speed (v_s) that corresponds to the maximum queue discharge flow rate (s) observed at the signal stop line. This saturation speed was found to be around 0.4 of the approach speed limit for arrow-controlled (protected) right-turn movements (left-turn movements for driving on the right-hand side of the road), and in the range 0.4 to 0.8 of the approach speed limit for through movements.

As an example, the queue discharge speeds and headways observed at an isolated signalised intersection site with a very long green period during morning peak traffic period are shown in *Figure 2 (5)*. For this site, the saturation flow rate was s = 2278 veh/h (saturation headway, h_s = 1.58 s) and the saturation speed was v_s = 52.8 km/h where speed limit was 70 km/h, and the jam spacing was L_{hj} = 6.6 m. The full set of parameters, including the driver response times, determined for this site as well as "average" through and arrow-controlled (protected) right-turn traffic sites are given in *Table 1*.

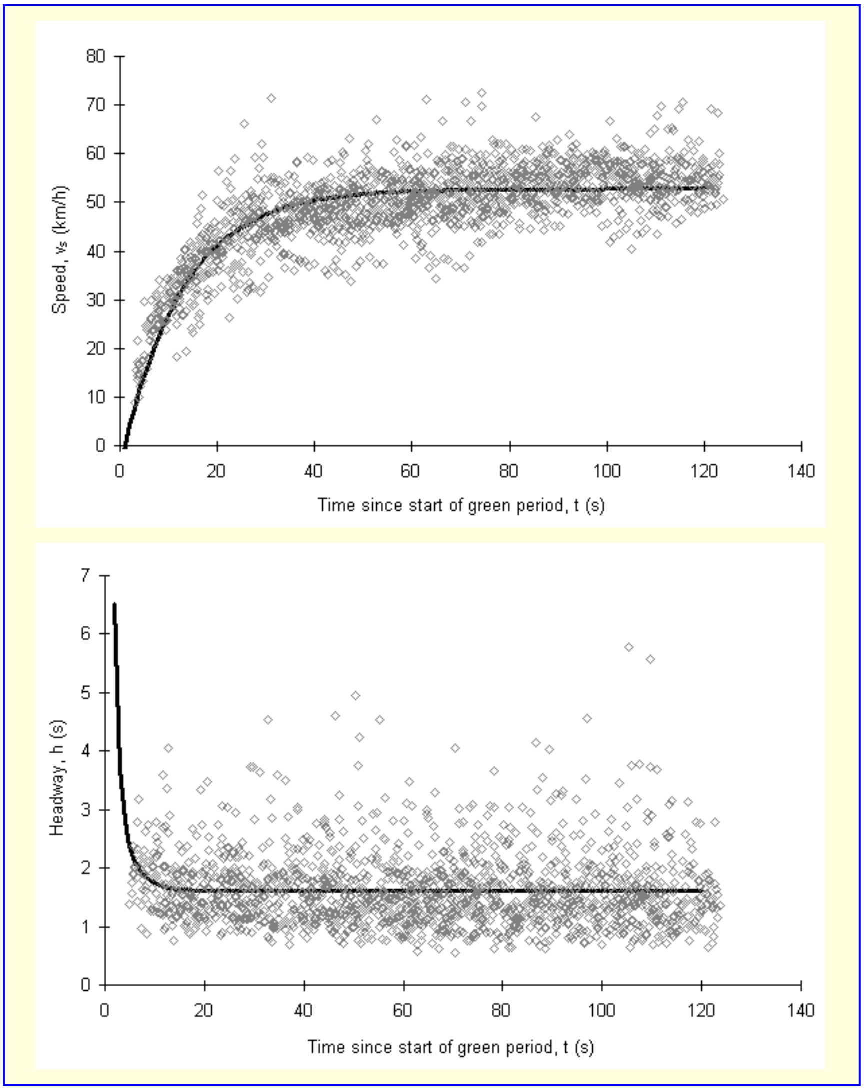

Figure 2 - Queue discharge speeds and headways observed at the intersection of General Holmes Drive and Bestic Street in Sydney, Australia

Table 1 Queue discharge model parameters observed at signalised intersections in Australia

Site	s (veh/h)	h_s (s)	v_s (km/h) (mph)	L_{hj} (m) (ft)	t_r (s)	v_x (km/h) (mph)	t_s (s)	d_a (s)	t_a (s)	L_a (m) (ft)	a_a (m/s^2) (ft/s^2)	a_m (m/s^2) (ft/s^2)
Site represented by *Figure 2*	2278	1.58	52.8 (32.8)	6.6 (22)	1.13	21.0 (13.0)	3.4	3.86	9.04	76 (249)	1.62 (5.3)	2.83 (9.3)
Through (isolated) sites	2083	1.73	45.1 (28.0)	6.9 (23)	1.17	21.3 (13.2)	2.6	3.19	7.20	50 (164)	1.74 (5.7)	3.01 (9.9)
Through (paired intersection) sites	1958	1.84	30.9 (19.2)	7.0 (23)	1.02	24.6 (15.3)	1.8	2.63	5.57	25 (82)	1.54 (5.1)	2.63 (8.6)
Average right-turn traffic site *	2032	1.77	24.5 (15.2)	6.4 (21)	0.84	27.3 (16.7)	1.7	2.64	5.45	19 (62)	1.25 (4.1)	2.13 (7.0)

* Isolated arrow-controlled (protected) movement (Left-turn for driving on the right-hand side of the road)

Information about the acceleration delay can be used for determining parameters for relevant acceleration manoeuvres. Acceleration time (t_a in seconds), acceleration distance (L_a in metres or feet) and the average and maximum acceleration rates (a_a and a_m in m/s^2 or ft/s^2) given in *Table 1* were calculated using the polynomial acceleration model described by Akçelik and Biggs *(17)* in the form adopted in the SIDRA INTERSECTION software *(2)*. For vehicles accelerating from zero initial speed to the queue discharge speed (v_s):

$$d_a = t_a - L_a / v_s \tag{8}$$

$$t_a = v_s / a_a \tag{9}$$

$$L_a = m_a\, v_s\, t_a = m_a\, v_s^2 / a_a \tag{10}$$

$$d_a = (1 - m_a)\, v_s / a_a \tag{11}$$

where m_a is an acceleration model parameter, $m_a = v_a / v_s$, i.e. the ratio of the average speed during acceleration ($v_a = L_a / t_a$) to the final speed (v_s in m/s or ft/s), and can be estimated from:

$$m_a = 0.467 + 0.0072\, v_s \qquad \textit{subject to } m_a \leq 0.70 \tag{12}$$

From *Equations (7) and (11)*, the average acceleration rate can be estimated from:

$$a_a = (1 - m_a)\, v_s / d_a = (1 - m_a)\, v_s / (t_s + 3.6\, L_{hj} / v_s) \tag{13}$$

Application to Roundabouts

The relationships given above for the queue discharge headway and related parameters (*Equations 4 to 11*) were explained by means of various diagrams for signalised intersections in previous publications *(5,16)*. The application of the concept to roundabout entry movements is discussed in this section and explained by means of *Figure 3*. The concept is also applicable to other gap-acceptance situations as observed at sign-controlled intersections (two-way stop and give-way / yield) and signalised intersections (filter / permitted turns and slip lanes).

Figure 3 uses the signal analogy concept described by the author *(3)* to depict a gap-acceptance process where an opposed (entry) stream gives way (yields) to an opposing stream (circulating traffic at roundabouts). It shows the arrival times of the circulating (opposing) stream vehicles at the top of the figure, and the entry (opposed) stream vehicles arriving at the bottom of the figure. All arriving vehicles decelerate from the approach cruise speed (v_{ac}) to a safe negotiation speed (v_{an}). At this speed, they make a decision about accepting or rejecting the gap in the opposing stream. The first entry stream vehicle in *Figure 3* stops due to an unacceptable gap. Subsequent entry stream vehicles join the back of queue at jam spacing (L_{hj}) measured as the distance between the front ends of two successive vehicles. The jam spacing consists of the vehicle length and the gap distance between vehicles.

The entry stream vehicles depart from the queue with follow-up headways (t_f) when a headway greater than the critical gap ($h > t_c$) occurs in the opposing stream. In *Figure 3*, the last vehicle at the back of queue stops again since the headway is not long enough. This vehicle is referred to as an *overflow* at the end of the gap-acceptance cycle. Thus, *Figure 3* depicts a fully-saturated gap-acceptance cycle.

The gap-acceptance capacity and queue discharge parameters used in *Equations (4) to (11)* are shown in *Figure 3*. In applying these equations to a roundabout, the exit negotiation speed can be used as the saturation speed, $v_s = v_{en}$, the lost time value, $t_s = 0.5\ t_f$ can be used as the start loss, and a jam spacing value of L_{hj} = 10 m (33 ft) can be used for light vehicles *(15)*.

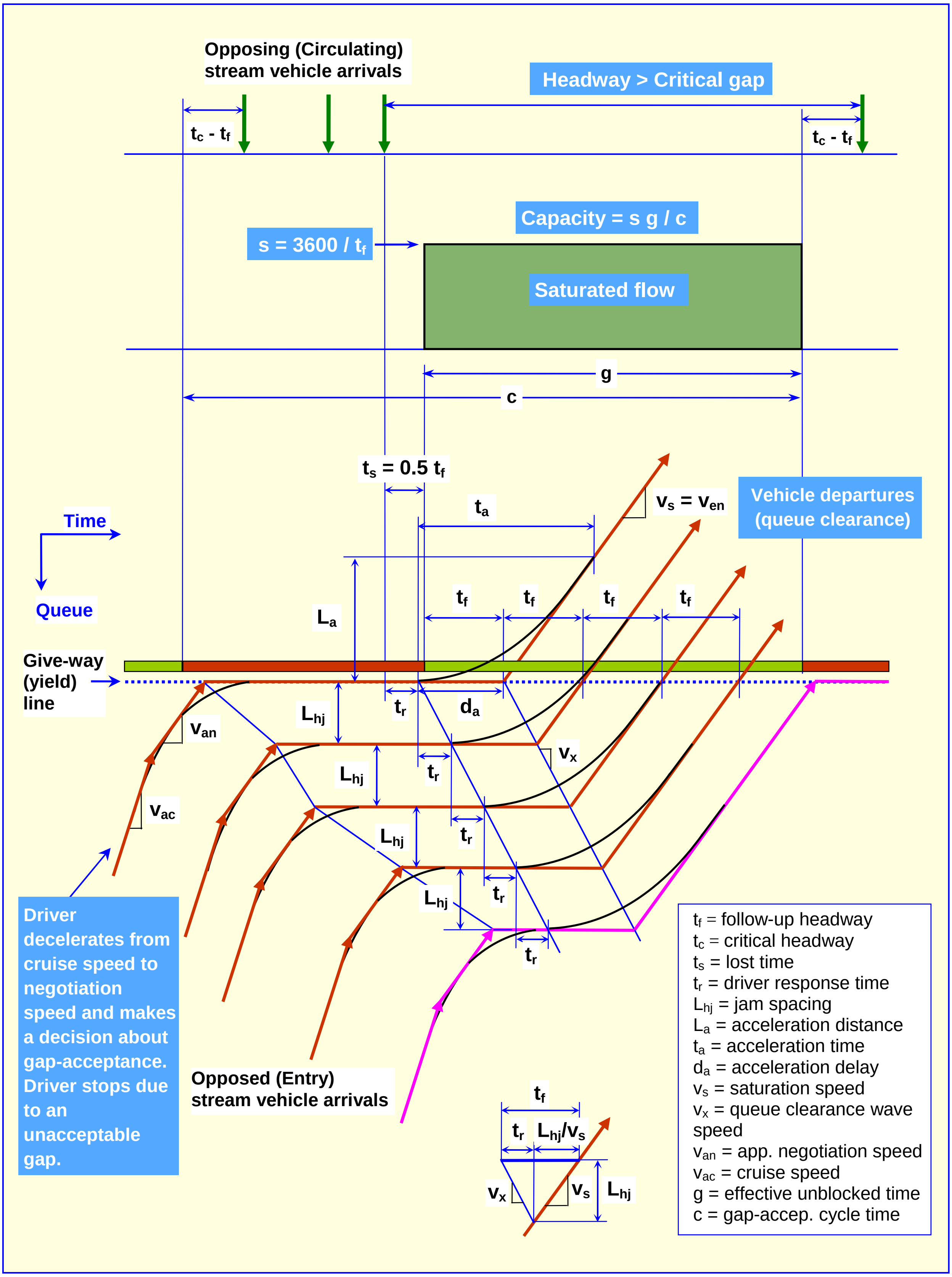

Figure 3 - Gap-acceptance capacity and queue discharge parameters

Example:

A one-lane roundabout with a central island diameter of 20 m (66 ft), circulating road width of 8 m (26 ft), and flow rates of 200 veh/h with no heavy vehicles for all movements (hence all circulating flow rates = 600 veh/h) was analysed using SIDRA INTERSECTION. The software estimated a negotiation speed of v_{en} = 26.2 km/h (16.3 mph), hence v_s = 7.278 m/s (23.9 ft/s), follow-up headway of t_f = 2.34 s (= h_s), and critical gap of t_c = 4.15 s. Using a jam spacing of L_{hj} = 10 m (33 ft), the following queue discharge parameters were determined:

t_r = 0.97 s, v_x = 10.3 m/s (33.8 ft/s) , t_s = 0.5 t_f = 1.17 s, d_a = 2.54 s, m_a = 0.52, a_a = 1.377 m/s^2 (4.5 ft/s^2) , L_a = 20.0 m (66 ft) , t_a =5.3 s.

It is seen that the driver response time and other queue discharge parameters for this roundabout example are not too different from those observed at signalised intersections, especially turning movements which have low saturation speeds due to turn radius effect (see *Table 1*). On the other hand, very large follow-up (saturation) headway values at two-way sign-control situations imply significantly longer driver response times due to the difficulty of the gap-acceptance process where several high-speed opposing movements from different directions are involved in the driver decision making process to accept or reject a gap.

When an Environment Factor value of 1.2 (default in the HCM version of SIDRA INTERSECTION) is used for the above example, the software estimated t_f = 2.86 s (= h_s) and t_c = 5.05 s. Using a jam spacing of L_{hj} = 10 m (33 ft), a driver response time of t_r = 1.49 s is found. Thus, about 0.5 s increase in the follow-up headway value is attributed to the longer driver response time. If a longer vehicle length is assumed resulting in a longer jam spacing, e.g. L_{hj} = 11 m (36 ft), a driver response time of t_r = 1.35 s is found. In this case, about 0.4 s of the 0.5 s increase in the follow-up headway is attributed to the driver response time and about 0.1 s is attributed to the longer vehicle length.

Determining a Heavy Vehicle Equivalent

The queue discharge model given in this paper can be used to determine heavy vehicle equivalents (*pcu factors*) for signalised intersection saturation flow rates as well as heavy vehicle equivalents for gap-acceptance purposes *(2)*.

For this purpose, the heavy vehicle equivalent is calculated as the ratio of the heavy vehicle queue discharge headway to the light vehicle queue discharge headway. Selecting a larger value of jam spacing reflecting longer vehicle size and slower saturation speed reflecting slower acceleration rate, the heavy vehicle saturation headway can be determined from *Equation (4)*.

For the above example, let us assume that the jam spacing for a heavy vehicle at a roundabout is 20 m (66 ft) rather than 10 m (33 ft) and the saturation speed is 30 per cent less than the light vehicle value, i.e. v_s = 7.278 x 0.70 = 5.1 m/s (17 ft/s). Assuming the same driver response time, the heavy vehicle queue discharge headway is calculated as 4.89 s, and the heavy vehicle equivalent is calculated as 4.89 / 2.34 = 2.09. This implies an average acceleration rate of 0.40 m/s^2 (1.3 ft/ s^2) compared with 1.377 m/s^2 (4.5 ft/s^2) estimated for light vehicles above.

This can be used as an easy way of determining the heavy vehicle equivalents for very large vehicles.

Critical Gap Parameter

The equations given above establish a direct relationship between the follow-headway parameter in gap-acceptance situations and queue discharge parameters. This is also relevant to the critical gap parameter which includes the driver response time. The critical gap will be affected by the same factors (adversely or favourably) affecting the driver response time which is also part of the follow-headway parameter.

Research shows that the follow-up headway and critical gap parameters are correlated, i.e. if drivers accept larger gaps, they also indicate a shorter queue discharge headway. Usually, the ratio of follow-up headway to critical gap is in the range 0.5 to 0.7, and as a rough rule of thumb, a value of 0.6 could be used:

$$t_f = 0.6\ t_c \tag{14}$$

Thus if the follow-up headway is estimated from *Equation (4)*, then the corresponding critical gap could be estimated as $t_c = t_f / 0.6$. Keeping the t_f / t_c ratio constant helps with the capacity calibration process for roundabouts and sign control cases.

ABOUT MICROSIMULATION MODELS

The relationships given in this paper provide a link between analytical and microsimulation models. This could help to improve compatibility between microsimulation methods and established analytical techniques used in traffic engineering practice, and to improve the practical usefulness of microsimulation tools through better model calibration and verification *(18)*.

Capacity is the most widely used concept in traffic engineering practice. Analytical models are built on the use of this basic traffic parameter whereas microsimulation models tend to ignore it. The reason is the difficulty of measuring capacity in simulation (see the CAPACITY section of this paper).

While saturation flow and lost time for signalised intersections are the most widely used parameters in traffic engineering practice, and are employed by analytical models extensively, microsimulation models generally ignore them, as in the case of the capacity parameter. The reason in this case is the use of a different modelling paradigm, i.e. one based on queuing, acceleration and car-following behaviour of individual vehicles rather than one based on the use of saturation headways between vehicles observed at the stop line. It is interesting to note the comment "The simulated behaviour of queue formation and discharge at traffic signals was reviewed. Values for queue discharge lost times were questioned as to their validity. Concern was similarly expressed regarding the acceleration versus speed relationships …" made in a workshop on simulation models in early 1980s (FHWA, page 72) *(19)*.

For roundabouts and sign controlled intersections, the compatibility between analytical and microsimulation methods that use gap-acceptance methods is expected to be better in principle. However, capacities at unsignalised intersections are very sensitive to the values of gap-acceptance parameters (follow-up headway and critical gap). Dependence of these values on driver behaviour through the effect of intersection geometry, traffic conditions, and many environmental factors is an important consideration in this context.

It is therefore recommended that saturation headway (or saturation flow rate), saturation speed, jam spacing, driver response time and other queue discharge parameters described by *Equations (4) to (13)* are observed in simulation as a function of the queuing, acceleration and car-following model parameters used in simulation. This would be useful to assess reasonableness and accuracy of parameters used in simulation.

It is also recommended that queue discharge flow rate (headway) and speed patterns for signalised intersections generated by microsimulation models (in a form similar to *Figure 2*) are compared with the exponential models proposed by Akçelik, et al *(5,16)*. These models imply constant saturation speed, headway (time) and spacing (distance) between vehicles as they pass the stop line, which means that queued vehicles do not start accelerating to the cruise speed until after they clear the intersection. It appears that microsimulation models do not conform to this behaviour.

The relationships given in this paper show that the driver response time parameter should have different values for specific situations, and therefore the use of global parameters would have serious implications on the accuracy of results. For example, a global driver response parameter calibrated for gap acceptance process during freeway merge would not be correct if used as a driver response time for roundabout or sign control cases.

While microsimulation software packages use several vehicle and driver types, it would be interesting to investigate whether different default values of queue discharge parameters are used for individual vehicles and drivers, and if so, the basis of the values used.

CONCLUDING REMARKS

From *Equations (1) to (4)*, the capacity can be expressed directly in terms of driver behaviour parameters driver response time (t_r in seconds), jam spacing (L_{hj} in metres or feet), and saturation speed (and v_s in m/s or ft/s) as well as the proportion of time when the vehicles can depart from the queue, i.e. when signals are green or gaps are available in the opposing stream (u):

$$Q = 3600\ u\ /\ (t_r + L_{hj}\ /\ v_s) \tag{15}$$

where the queue discharge headway is $h_s = t_r + L_{hj} / v_s$, and the saturation flow rate is $s = 3600 / h_s$.

This equation can be used to explain the sensitivity of queue discharge headway, saturation flow and capacity to driver behavior (driver-vehicle characteristics) as affected by intersection geometry and various environmental factors. For example:

- larger jam spacing reflecting longer vehicle size and slower saturation speed reflecting slower acceleration rate for heavy vehicles indicate longer queue discharge headway, therefore lower capacity;
- on a rainy day, drivers may leave longer gap distances in the queue (larger jam spacing), may be more cautious in starting up (longer response times) and could use lower saturation speeds which would explain lower saturation flows resulting in reduced capacities;
- higher traffic pressure levels (high demand flows, high degrees of saturation, long delays and queues) could cause drivers to leave shorter gap distances in the queue (smaller jam spacing), to be more aggressive in starting up (shorter response times) and to use higher saturation speeds which would explain higher saturation flows resulting in increased capacities; SIDRA INTERSECTION estimates lower follow-up headway values as circulating flow rate increases reflecting the effect of higher traffic pressure levels at roundabouts;
- small-town drivers may be more relaxed resulting in larger jam spacing, longer response times and possibly lower saturation speeds leading to lower saturation flows and capacities;
- drivers using turn bays (short lanes) leave shorter gap distances in the queue, thus reducing their jam spacing which leads to high saturation flows (see T*able 1* for turning vehicle parameters);
- in special traffic situations such as the effect of platooned traffic generated by upstream signals on side road traffic waiting for gaps, or very high entry flow rate interrupted by very low circulating flow at roundabouts, driver aggressiveness may increase resulting in shorter response times and therefore shorter follow-up headways;
- in two-way sign-control situations, drivers give-way (yield) to high-speed opposing movements from many different directions which makes the driver decision making process (to accept or reject gaps) a difficult one, explaining longer driver response times and therefore longer follow-up headways used for two-way sign control; compared with this, drivers in roundabout entry streams look for gaps in a single low-speed circulating stream, which explains shorter driver response times and therefore shorter follow-up headways and higher capacities at roundabouts;
- lower capacities observed at US roundabouts as indicated by NCHRP 3-65 research *(20)* relative to the roundabout capacities observed in Australia could be explained by larger vehicle sizes in the USA (hence larger jam spacing), and larger driver response times which may be due to driver hesitation resulting from lack of familiarity with roundabouts coupled with the all-way stop control culture of US drivers (this control form is very rare in Australia).

Due to the correlation between the follow-headway and critical gap parameters in gap-acceptance situations (follow-up headway = 60 per cent of the critical gap as a rough rule of thumb, the above sensitivities would also apply to the critical gap parameter, especially because this parameter includes a driver response component. The critical gap parameter affects the u parameter (the proportion of time when the vehicles can depart from the queue) in *Equation (15)* with lower values of u resulting from larger values of critical gap for a given opposing flow rate.

Comparison with other analytical models is also possible. For example, an implied saturation headway can be calculated for the TRL (UK) linear regression model for roundabout capacity *(7-14)* using the value of capacity at zero circulating flow as a saturation flow rate as in *Equations (2) and (3)*. The TRL roundabout capacity model generally implies larger driver response times compared with those estimated using the SIDRA INTERSECTION software.

Similar relationships that enable estimation of driver response parameter from speed-flow relationships for uninterrupted traffic streams have been described by the author in a previous publication *(6)*.

Further research is recommended both on conceptual aspects of the relationships presented in this paper and their calibration using field studies of many different traffic situations. Investigation of driver and vehicle parameters used in various microsimulation software packages in relation to the analytical relationships presented in this paper is also recommended.

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