

## REPRINT

# Opposed turns at signalised intersections: The Australian method

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### NOTE:

This paper is related to the intersection analysis methodology used in the SIDRA INTERSECTION software. Since the publication of this paper, many related aspects of the traffic model have been further developed in later versions of SIDRA INTERSECTION. Though some aspects of this paper may be outdated, this reprint is provided as a record of important aspects of the SIDRA INTERSECTION software, and in order to promote software assessment and further research.

# Opposed Turns at Signalized Intersections: The Australian Method

BY RAHMI AKÇELIK

The 1985 *Highway Capacity Manual* (HCM)<sup>1</sup> brought the U.S. and Australian methodologies<sup>2-6</sup> for signalized intersections closer together. An important element in this methodology is the techniques used for the estimation of opposed (permissive) turn saturation flows. Although the basic modeling philosophies of the HCM and Australian methods are similar, there are significant differences in the procedures used and therefore in the results from the two methods. In particular, the latest methodology employed in the SIDRA software<sup>3,7</sup> has eliminated the use of opposed turn adjustment factors for lane groups and adopted an explicit and direct method of modeling individual lanes. The purpose of this paper is to bring these new methods to the attention of the U.S. researchers since it is understood that efforts are being made to improve the 1985 HCM method. The intention is also to dispel any misunderstanding about the Australian opposed turn models that may have resulted from statements in some U.S. papers.

A 1987 paper by Roess explaining the development of procedures for the analysis of signalized intersections in the HCM includes the following statement:

The most dramatic change from source materials involved permitted or opposed left turns. Previous materials developed in Australia, England and the United States have always assumed that permitted left turns filter through the opposing flow at a calibrated rate for the entire period of the green phase.<sup>8</sup>

After explaining the HCM model, the

paper goes on to state that this model was adopted

after it was clear that no simpler methodology would eliminate the overprediction of left-turn capacity, which results from assuming filtration for the entire green phase.

The only Australian reference in the paper is the ARRB Research Report ARR No. 123.<sup>2</sup> However, the statement also relates to the early Australian model<sup>9,10,11</sup> since it forms the basis of the opposed turn model in ARR No. 123. In both cases, the statement is not valid: the Australian methods have never assumed that permitted (opposed) turns filter through the opposing flow for the entire length of the green period.

It is hoped that this article will explain the similarities and differences between the HCM and the Australian opposed turn models and dispel any misunderstanding that may have resulted from earlier statements by others. The discussion is relevant to opposed turn modeling in general and will be useful towards explaining the HCM option in the SIDRA program.<sup>3,6</sup> In this discussion, various limitations of the HCM model will also be pointed out.

The discussion in this article is limited to the case of a single opposed (permitted) green period only. The treatment of the more complicated case of "protected plus permitted phasing" (two green periods per cycle) in the HCM has further limitations, as pointed out in earlier papers using an example from the HCM.<sup>5,6</sup> A recent U.S. paper analyzed the same example and recommended some revi-

sion of HCM.<sup>12</sup> The modeling of opposed turns with protected and permitted phasing is fully implemented in the SIDRA program in a general way that applies to both exclusive and shared lanes. [For an example of the shared lane case, see Figure 6 in cited reference 7.]

## The Basic Model

The basic opposed turn model used in Australia is shown in Figure 1. Strictly speaking, the model applies to the case of opposed turns in an exclusive lane, but it is also useful to explain the basis of the model for opposed turns in a shared lane. The following model assumptions are seen in Figure 1:

- Opposed turns cannot filter during interval 1 (blocked—no gap acceptance), which corresponds to the saturated part of the opposing movement green period,
- Opposed turns can only filter during interval 2 (departures by gap acceptance), which is the unsaturated part of the opposing movement green period, and
- The departures after the green period are included in interval 3.

The notation in Figure 1 is as follows:

- $c$  = cycle time,
- $r, g$  = opposing movement effective red and green times,
- $q, s$  = opposing movement arrival and saturation flow rates,
- $g_s, g_u$  = saturated and unsaturated portions of the opposing move-

ment green period ( $g_s + g_u = g$ ).

$s_u$  = opposed turn saturation flow during  $g_u$ , and

$n_f$  = number of vehicles that depart after the end of green period.

All traditional capacity models employ the simplifying assumption shown in Figure 1 as "Approximate Model 1" in order to be able to derive opposed turn equivalents (or adjustment factors) for use in the prediction of capacities of *shared lanes* and *lane groups* with opposed turns. The basis of this approximation is the use of an average saturation flow,  $s_o$ , which applies for the whole of the opposed turn green period (with no change in the capacity estimate):

$$s_o = (s_u g_u + n_f) / g \quad (1)$$

This assumption was used in the early Australian model<sup>9,11</sup> and retained in ARR No. 123<sup>2</sup> for shared lanes only. For opposed turns in exclusive lanes, "Approximate Model 2" shown in Figure 1 was introduced in ARR No. 123 as a more accurate model, which treats interval 1 as part of the lost time—i.e., as effectively red. Essentially, the same opposed-turn capacity is obtained from the two approximate models shown in Figure 1. However, Model 2 predicts queue lengths and delays better, which has advantages for predicting short lane capacities also. This model was subsequently extended to shared lanes in the SIDRA program.<sup>7</sup>

The reason for the earlier reported statement<sup>8</sup> that in the Australian method "permitted left turns filter through the opposing flow . . . for the entire period of green phase" may be related to the assumption of the "Approximate Model 1" shown in Figure 1. However, this assumption is also used in the derivation of the HCM opposed-turn adjustment factors, as will be explained below. It should be noted that an even earlier U.S. paper incorrectly presented the early Australian model as if the model predicted the "left-turn" capacity as  $s_u g / c$  (1200  $f$  in that paper's Equation 2 is equivalent to  $s_u$  in the original model).<sup>13</sup> It may be that this is the basis of the statement that permitted left turns filter through the opposing flow for the entire period of green phase in the Australian Method.<sup>8</sup> On the other hand, another U.S. paper had stated the early Australian model correctly, and found very favorable results in a field evaluation of the model.<sup>14</sup>

### Opposed Turns in a Shared Lane

For shared lanes, the capacity characteristics of opposed turns and other traffic need to be mixed. The term "opposed turn" usually applies to left turns in the United States (driving on the right) and right turns in Australia (driving on the left). Generally, the term "opposed turn" also applies to left turns in Australia, or to right turns in the United States (turning from a slip lane or turning on red), or giving way to opposing right turns according to the Victoria and New Zealand rule. Again, generally speaking, opposed turns in shared lanes may mix with through, left-, or right-turning traffic, as the case may be. Although the following discussion applies generally, it will be presented in terms of "opposed left turns" and "through" traffic in shared lanes since the HCM model is expressed specifically in these terms.

The assumptions involved in deriving the HCM equations for shared lanes with opposed left turns and through traffic can be seen in Figure 2. Importantly, the model divides interval 1 (when opposing traffic is at saturation) into two parts:

- During the first part of interval 1, a number of through vehicles can depart

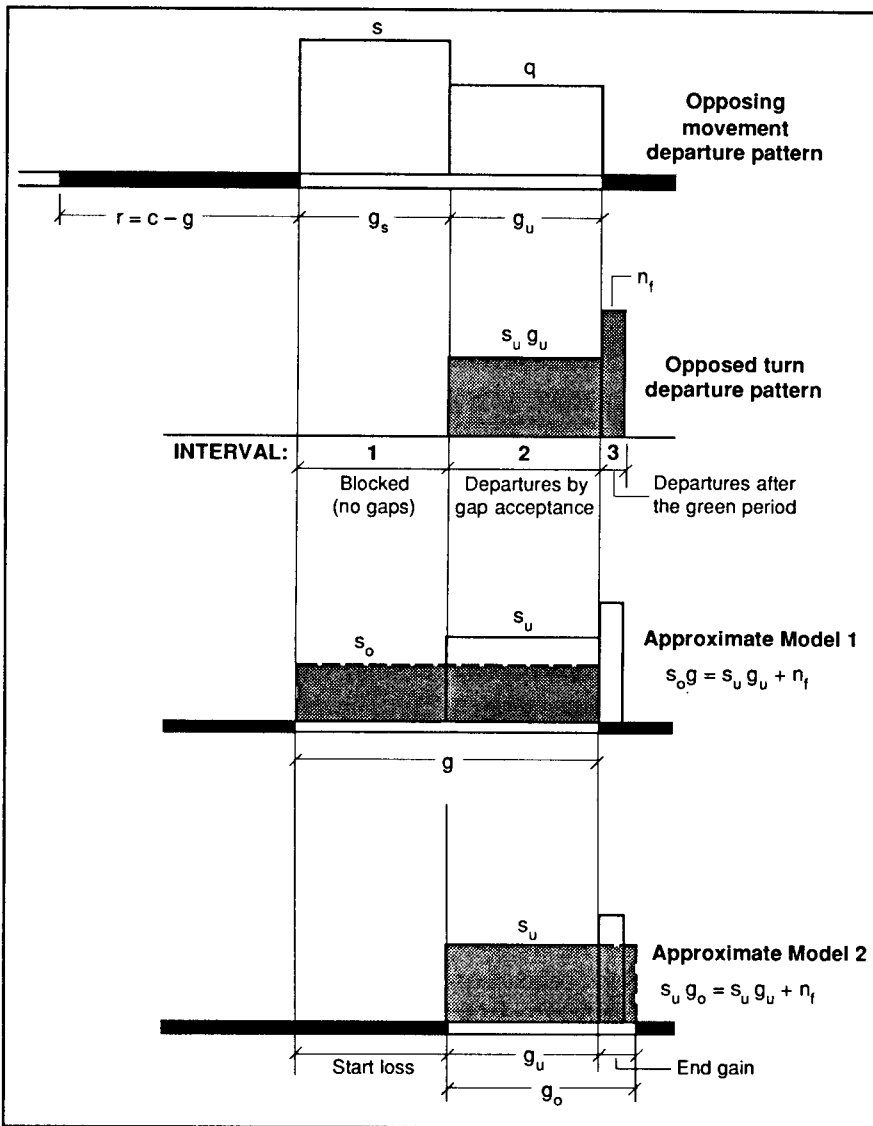


Figure 1. Basic opposed turn model. SOURCE: Appendix F in cited reference 2.

before the first left-turning vehicle arrives at the stop line and blocks the lane. The length of this period is  $g_f$  and the number of through vehicles that can depart is  $S_f = s_f g_f$ , where  $s_f$  is through traffic saturation flow.

- During the rest of interval 1 ( $g_s - g_f$ ), no through or left-turning traffic can depart (the HCM notation for  $g_s$  is  $g_u$ ).

In interval 2, opposed left turns and through traffic depart at a mixed saturation flow rate of  $s_a$ . The total number of departures is  $S_a = s_a g_u$ . In interval 3,  $S_e$  vehicles depart, which is equivalent to  $n_i$  in Figure 1 for the number of departures after the end of the green period.

The HCM gives the following left-turn factor,  $f_m$ , for a single *exclusive or shared lane* (HCM Equation 9-16):

$$f_m = \frac{g_f}{g} + \frac{g_u}{g} \left[ \frac{1}{1 + p_L (E_L - 1)} \right] + \frac{2}{g} (1 + p_L) \quad (2)$$

where  $g_f$ ,  $g_u$ , and  $g$  are as explained above,  $p_L$  is the proportion of left turners in the lane ( $p_L = q_L/q$  where  $q_L$  and  $q$  are the left-turn and total flow rates), and  $E_L$  is a through-car equivalent for left turns (which applies during  $g_u$  period only). The HCM formulas for  $g_f$  and  $E_L$  are

$$g_f = 2 \frac{p_L}{p_L} (1 - p_L^{0.5k_s}) \quad (3)$$

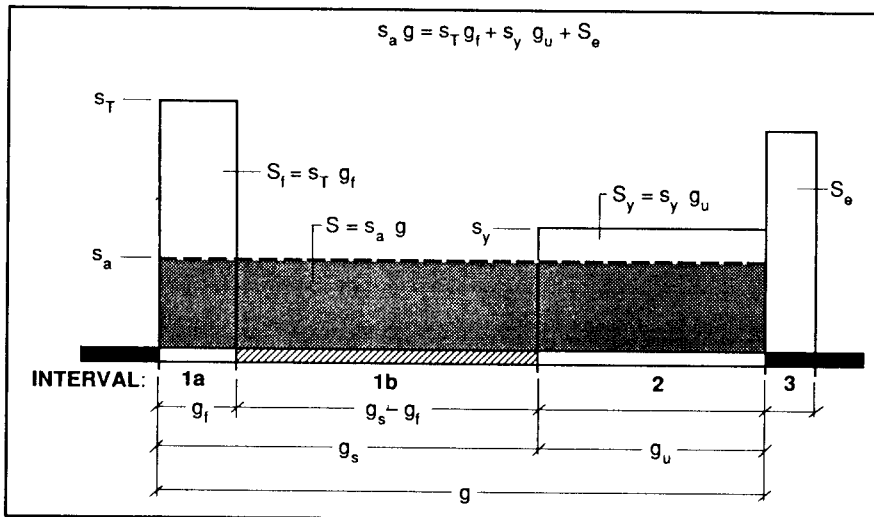


Figure 2. The opposed turn model for shared lanes (the HCM model approximation is indicated by the shaded area).

$$E_L = \frac{1800}{1400 - v_o} \quad (4)$$

where  $p_L$  is the proportion of through vehicles in the shared lane ( $p_L = 1 - p_L$ ), and  $v_o$  is the opposing flow rate (veh/h).

For an exclusive left-turn lane,  $p_L = 1.0$  and  $g_f = 0$ . Therefore, Equation 2 can be rewritten as

$$f_m = \frac{1}{g} \left( \frac{g_u}{E_L} + 4 \right) \quad (5)$$

An analysis of Equations 2 to 5 shows that the HCM opposed-turn model employs the basic assumption of the traditional "Approximate Model 1" shown in Figure 1—that is, it uses an average saturation flow rate throughout the opposed green period. This is explained below (refer to Figure 2). For the purpose of this discussion, the HCM saturation flow equation (HCM Equation 9-8) can be written as

$$s = s_i N f_L f_{L,T} \quad (6)$$

where

$s_i$  = ideal saturation flow per lane ( $s_i$  in the HCM notation), usually 1800 through car units per hour (tcu/h),

$f_L$  = the product of adjustment factors used to allow for the effects of lane width, grade, area type, buses, adjacent parking, heavy vehicles, and right turns ( $= f_w f_G f_{BB} f_P f_{UV} f_{RT}$ ).

$N$  = number of lanes in the lane group, and

$f_{L,T}$  = adjustment factor for left turns in the lane group.

For a single lane,  $N = 1$  and  $f_{L,T} = f_m$ , where  $f_m$  is given by Equation 2 or 5. Putting  $f_L = 1.0$  for ideal conditions, the saturation flow for a single lane case is

$$s = s_i f_m \quad (7)$$

An important aspect of the derivation of left-turn factors given in the HCM is that all through-traffic flows are assumed to have ideal saturation flows:  $s_T = s_i = 1800$  tcu/h = 0.5 tcu/s ( $f_L = 1.0$ ). Thus,  $s = 0.5 f_m$  is obtained from Equation 7 as a basis for single-lane opposed-turn saturation flow.

## Derivation of the HCM Equations

The derivation of the HCM adjustment factor for opposed left turns in a single lane,  $f_m$  (Equation 2), and its extension to the case of opposed turns in a lane group,  $f_{L,T}$  (HCM Equation 9-17), are discussed here in reference to capacities in various intervals shown in Figure 2.

### Interval 1a

The average number of through vehicles per cycle that can depart before being blocked by the first left turner to queue in the lane is  $S_f = s_f g_f$ . Putting  $s_f = s_i = 0.5$  veh/s and using  $g_f$  from Equation 3,

$$S_f = \frac{p_L}{p_L} (1 - p_L^{0.5k_s}) \quad (8)$$

The general form of Equation 8 uses  $s_f g_f$ , instead of  $0.5 g_f$ , which is the *maximum* number of through vehicles that can depart during  $g_f$  ( $s_f = s_i = 0.5$  veh/s in Equation 8), as discussed in more detail later in this article.

### Interval 2

The shared lane saturation flow,  $s_a$ , during interval 2 (of length  $g_u$ ) can be found by mixing the through and opposed left-turn saturation flows ( $s_T$  and  $s_L$ ). Using the method described in Akçelik<sup>7</sup>, this can be expressed as

$$q/s_a = q_L/s_L + q_T/s_T \quad (9)$$

or

$$1/s_a = p_L/s_L + p_T/s_T \quad (9a)$$

where  $q$ ,  $q_L$ , and  $q_T$  are the flow rates

for total, left-turn, and through traffic, and  $p_l$  and  $p_r$  are the proportions of left-turn and through traffic in the lane.

The left-turn saturation flow can be expressed in terms of through traffic saturation flow,  $s_r$ , and through car equivalent for left turns,  $E_l$ , as

$$s_l = s_r/E_l \quad (10)$$

In interval 2,  $s_l = s_u$  where  $s_u$  is the filter (opposed) turn saturation flow. Using the ideal saturation flow for through traffic ( $s_r = s_i$ ),

$$E_l = s_i/s_u \quad (11)$$

is found. Comparing Equations 4 and 11, it is seen that the HCM method uses  $s_i = 1800$  veh/h and

$$s_u = 1400 - v_o \quad (12)$$

where  $v_o$  is the opposing flow in veh/h.

Putting  $s_l = s_i/E_l$  and  $s_r = s_i$  in Equation 9 and substituting  $p_r = 1 - p_l$ , the average saturation flow during interval 2 is found as

$$s_v = \frac{s_i}{1 + p_l(E_l - 1)} \quad (13)$$

Therefore, the number of vehicles that can depart during  $g_u$  is found as

$$S_v = s_v g_u = \frac{s_i g_u}{1 + p_l(E_l - 1)} \quad (14)$$

### Interval 3

Equation 2 implies that the number of departures after the end of the green pe-



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riod is a function of the proportion of left turners in the lane, as given by

$$S_c = 1 + p_l \quad (15)$$

Thus, the HCM model assumes that  $S_c$  changes between 1 for the case of a few left turners in the lane and 2 for the case of an exclusive left-turn lane.

### Average Saturation Flow for the Entire Green Period

For the shared lane, the total capacity (number of departures) per cycle is the sum of capacities in intervals 1a, 2, and 3 (no capacity in interval 1b):

$$S = S_l + S_v + S_c \quad (16)$$

where  $S_l$ ,  $S_v$ , and  $S_c$  are given by Equations 8, 14, and 15. As shown in Figure 2, an average saturation flow,  $s_u$ , for the entire green period,  $g$ , to yield the same shared lane capacity as  $S$  can be found from  $s_u g = S$ . The average shared lane saturation flow can be expressed in terms of through traffic saturation flow as  $s_u = f_m s_l$ . Using the ideal saturation flow for through traffic,  $s_l = s_i$ , and putting  $s_u = S/g$  where  $S$  is as in Equation 16, the left-turn adjustment factor for a single lane is found as

$$f_m = S/s_i g = (S_l + S_v + S_c)/s_i g \quad (17)$$

using  $S_l$ ,  $S_v$ , and  $S_c$  from Equations 8, 14, and 15 and setting  $s_i = 0.5$  veh/s, the HCM formula for  $f_m$  given by Equation 2 is found. In other words, the HCM method uses an average saturation flow of

$$s_u = 0.5 f_m \quad (17a)$$

which applies to the entire green period,  $g$ .

### Opposed Turns in a Lane Group

For opposed turns in a lane group, the HCM method makes a further approximation. To derive the opposed left-turn adjustment factor,  $f_{l,t}$ , for a lane group of  $N$  lanes, it assumes that all lanes except the shared lane has the ideal saturation flow,  $s_i$ , and hence a capacity of  $(N - 1) s_i g$ . The capacity of the shared lane is  $s f_m g$  (from Equation 17). Therefore, the total capacity per cycle for the lane group is

$$S' = (N - 1) s_i g + s f_m g \quad (18)$$

To derive  $f_{l,t}$ , average the total capacity per cycle ( $S'$ ) over the entire green period ( $g$ ):

$$s'_u = \frac{S'}{g} = (N - 1 + f_m) s_i \quad (19)$$

where  $s'_u$  is the average saturation flow for a lane group of  $N$  lanes.

Putting  $f_v = 1$  in Equation 6 for ideal conditions,  $s = s_i N f_{l,t}$  is obtained. Putting  $s = s'_u$ , the HCM adjustment factor for opposed left turns in a lane group of  $N$  lanes is found as

$$f_{l,t} = \frac{f_m + (N - 1)}{N} \quad (20)$$

In other words, the HCM opposed left-turn adjustment factor is based on the use of an average lane group saturation flow of

$$s'_u = 0.5 f_{l,t} N \quad (20a)$$

which applies to the entire green period.

### Comparison with the Recent Australian Model

The opposed turn model in the early Australian model<sup>11</sup> used an  $E_{RT}$  factor that was derived in a similar way to the explanation given above. The only improvement in the HCM model over this early Australian model is the capacity in interval 1 (departures being blocked). This aspect of the HCM model is further discussed below.

The opposed turn adjustment factor  $E_{RT}$  method was adopted in ARR No. 123,<sup>2</sup> but its use was limited to shared lanes only. A lost time method was introduced in ARR No. 123 for opposed turns in exclusive lanes (approximate Model 2 in Figure 1). As explained in detail elsewhere,<sup>7</sup> the latest Australian method implemented in the SIDRA package<sup>3,6</sup> has entirely eliminated the use of opposed turn adjustment factors, and it uses opposed turn capacities in a direct way. The method is equivalent to using  $S = S_l + S_v + S_c$  directly without need for obtaining an average saturation flow,  $s_u$  (see Figure 2). Furthermore, it treats the blocked time ( $g_c - g_l$ ) as effective red time, thus extending the lost time method of ARR No. 123 to shared lanes. This method has advantages over the adjustment factor method in terms of capacity and performance prediction. Other important differences between the opposed turn model of SIDRA and the HCM model are discussed below.

### Blocked Departures

As discussed previously, the first term of

the HCM left-turn factor formula (Equation 2) relates to through traffic departures before being blocked by left turners,  $S_L$ , as in Equation 8. The use of this capacity component in the Swedish capacity manual was reported a decade ago.<sup>15</sup> The Swedish capacity manual gave two formulas for the cases of one or two vehicles to queue before blocking the lane ("blocking queue"). Hegarty and Pretty applied this method to opposed left turns in slip lanes (in Australia).<sup>16</sup> Their paper gave a general formula for departures before being blocked, which uses the "blocking queue" as a general parameter. They also gave a formula for the case of a blocking queue of one, which is the same as the HCM formula except that the ideal saturation flow,  $s_i = 0.5$  veh/s, is used to calculate the maximum number of departures in the HCM formula rather than the estimated through traffic saturation flow,  $s_T$ .

Although ARR No. 123 did not model departures before lane blockage in shared lanes, the SIDRA method employs a very generalized shared lane model that predicts capacities before lane blockage using the general form of the model given by Hegarty and Pretty.<sup>16</sup> The "lane interaction" model has now been used in SIDRA for a long time<sup>3</sup> and a detailed discussion on the topic can be found elsewhere.<sup>7</sup> An important limitation of the HCM formula is that it applies only to the case of a blocking queue of one (or a "free queue" of zero using the SIDRA definition). The parameter affects the results significantly (see Figure 5 in cited reference 7).

### Filter Turn Saturation Flow

The filter turn saturation flow rate,  $s_u$ , in the HCM method is given by Equation 12. This corresponds to the gap acceptance formula used in ARR No. 123, Appendix F. The HCM formula and the ARR No. 123 gap acceptance formula do not take the number of opposing lanes into account. In SIDRA, the following gap acceptance formula (see Tanner,<sup>17</sup> and Gipps,<sup>18</sup> and Troutbeck<sup>19,20</sup>) is used to estimate  $s_u$ , taking individual lane flows into account:

$$s_u = \frac{\lambda \theta e^{-\alpha \Delta} \Delta^\lambda}{1 - e^{-\beta \Delta}} \quad (21)$$

where  $\alpha$  is the accepted critical gap in seconds,  $\beta$  is the minimum departure headway in seconds (maximum opposed

turn saturation flow in veh/h is  $s_{u, \max} = 3600/\beta$ ),  $\Delta$  is the minimum headway in an opposing traffic lane in seconds, and the parameters  $\lambda$  and  $\theta$  are calculated from

$$\lambda = \sum \frac{\phi_i q_i}{1 - \Delta q_i},$$

$$\theta = \prod (1 - \Delta q_i) \quad (22)$$

where the summation and multiplication are for lanes  $i = 1$  to  $N$ ,  $\phi_i$  is a bunching factor (proportion of unbunched vehicles in  $i$ th opposing traffic lane),  $q_i$  is the flow rate in  $i$ th opposing traffic lane, and  $\Delta$  is as in Equation 21. Figure 3 shows  $s_u$  values from the HCM model (Equation 12) and the SIDRA model (Equation 21) with  $\alpha = 4.0$ ,  $\beta = 3600/1400 = 2.57$  sec,  $\Delta = 2$  sec and  $\phi = 1.0$  (no bunching). Equal lane flows are assumed for the two- and three-lane opposing flow cases in Figure 3. In the case of unequal lane flows, Equation 21 gives smaller  $s_u$  values. As the lane utilization ratio increases,  $s_u$  decreases, and it approaches the one-lane  $s_u$  value when one of the lane flows approaches the total flow value. Thus, the SIDRA model has the advantage of sensitivity to the number of opposing traffic lanes as well as the lane utilization in opposing traffic lanes.

It may be considered that when the number of opposing lanes increase, fil-

tering is more difficult, and therefore the gap acceptance parameters  $\alpha$  and  $\beta$  will increase, resulting in lower  $s_u$  values. However, there may not be a direct relation between the number of opposing traffic lanes and the gap acceptance parameters. Visibility, opposing traffic speed, grades, the actual crossing distance (which could be more than the sum of opposing lane widths), and so on are expected to affect the gap acceptance parameters. In SIDRA, the user can specify  $\alpha$  and  $\beta$  parameters for each opposed turn and can model specific situations more closely.

For the HCM option in SIDRA, the default parameters in Equation 21 have been calibrated against Equation 12 for the one-lane case ( $\alpha = 4.0$ ,  $3600/\beta = 1400$ ,  $\Delta = 2$ ,  $\phi = 1.0$ ). As seen in Figure 3, the results from the two equations are close for this case, but SIDRA may predict significantly higher  $s_u$  values in the case of multilane opposing flows, particularly for heavy opposing flows.

The HCM method implies that various adjustment factors (product  $f_i$  in Equation 6) multiplies the opposed turn saturation flow,  $s_u$  (see Equations 7 and 17). Therefore, if a direct and explicit modeling approach were used, Equation 12 would be used as  $s_u = (1400 - v_u) f_i$ , and Equation 15 would be used as  $S_c =$

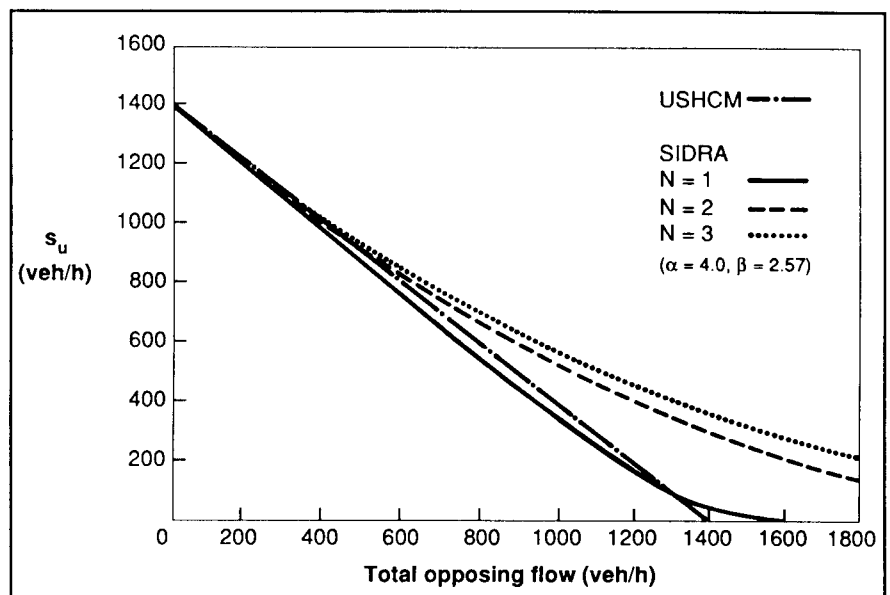


Figure 3. Opposed turn saturation flow rate ( $s_u$ ) during the unsaturated part of the opposing movement green period as a function of the total opposing flow rate (the HCM and SIDRA models).

$(1 + p_l) f_s$ . This means that the HCM method adjusts the opposed turn filter rate (basically a gap acceptance process) and the number of departures at the end of the green period by all the factors that go into  $f_s$  (including lane width, grade, area type, adjacent parking, heavy vehicles, etc.). While the correctness of these adjustments is debatable, the SIDRA method can emulate the HCM opposed turn formula by using default values of the follow-up headway as  $3600/\beta = 1400 f_s$  and the number of departures after the green period as  $S_c = (1 + p_l) f_s$ .

### Departures After the End of the Green Period

In relation to interval 3 in Figure 1, the use of the  $S_c$  value needs to be clarified. In the "Approximate Model 1" of Figure 1, and in the HCM model shown in Figure 2,  $g_u$  includes the end gain since  $g_u$  is defined as  $(g - g_s)$  where  $g$  is the effective green time ( $g =$  displayed green time plus end gain less start loss). Therefore,  $S_c$  (or  $n_s$  in Figure 1) is used as "departures after the end of effective green period." If this parameter is counted as the number of departures during the yellow and all-red intervals, that is, after the end of the displayed green period, this method will double count a small amount of departures (equal to  $s_u b$  for exclusive turns, where  $b$  is the end gain). In SIDRA, this is taken into account by using this parameter as the number of departures (per lane) after the end of the displayed green period.

### The Use of Estimated Saturation Flows

In contrast with the HCM method, the SIDRA method uses the estimated (adjusted in the HCM technology) saturation flow ( $s_s$ ) rather than the ideal saturation flow ( $s = 1800$  veh/h) for

- Unopposed traffic in shared lanes when mixing the opposed and unopposed (e.g., left and through) traffic,
- The opposing traffic to determine the  $g_u$  and  $g_s$  periods, and
- Calculating the maximum possible departures as a parameter for the formula to predict number of departures before being blocked.

Schorr and Jovanis found that the opposing traffic saturation flow is the most

sensitive and important parameter in the opposed turn model, along with the opposing flow volume.<sup>14</sup> The following example demonstrates this point clearly.

Consider a single exclusive left-turn lane where left turns are opposed by a single-lane traffic stream consisting of through and right turning vehicles. The opposed left turn volume is 80 veh/h and the opposing traffic volume is 600 veh/h (40% right turns). The following saturation flow adjustment factors apply to both streams:

- The intersection is in a central business district area ( $f_A = 0.90$ ),
- Lane widths are 10 ft ( $f_w = 0.93$ ), and
- Heavy vehicles constitute 8% of total traffic ( $f_{HV} = 0.96$ ).

For the opposing stream a right-turn adjustment factor of  $f_{RT} = 0.94$  applies. Therefore, the combined correction factor for the opposing stream is  $f_s = f_A f_w f_{HV} f_{RT} = 0.7553$ , and the saturation flow is  $s_{op} = 1800 \times 0.7553 = 1360$  veh/h. For the opposed left turns,  $f_s = f_A f_w f_{HV} = 0.8035$ , and the saturation flow is  $s = 1800 \times 0.8035 f_m = 1446 f_m$ .

Assume that the cycle time and green time are 120 sec and 57 sec, respectively ( $g/c = 0.475$ ). The results for the HCM model and the SIDRA model are summarized in Table 1. The fundamental difference between the two models for this example is that the HCM model uses the ideal saturation flow (1800 veh/h), whereas the SIDRA model uses the es-

timated saturation flow (slightly less than 1360 veh/h) for the opposing stream. As a result, the predicted  $g_u$  values are very different (25.5 sec versus 7.1 sec). The HCM method predicts  $f_m = 0.269$  and  $s = 1446 \times 0.269 = 389$  veh/h. As shown in Table 1 this is equivalent to a capacity of 6.153 veh/cycle or 185 veh/h. The corresponding SIDRA values are much less because  $g_u$  is much smaller. It is seen that the HCM model will grossly underpredict the degree of saturation and delay (level-of-service C versus F) in this case.

### Conclusion

In conclusion, neither the old<sup>9-11</sup> nor the new<sup>2-7</sup> Australian methods assume "filtration for the entire green period."<sup>8</sup> The HCM method,<sup>1</sup> as in the early Australian methods, implies the use of a saturation flow averaged over the entire green period and converted to an adjustment factor. The latest Australian method (SIDRA) has eliminated the use of opposed turn adjustment factors.<sup>3-7</sup> It employs a direct and explicit approach to model individual lane capacities, and then simply adds lane capacities to obtain the total capacity for a lane group. By contrast, the use of adjustment factors means that the capacities are first converted to adjustment factors (with loss of accuracy resulting from inevitable generalizations) and then converted to capacities again.

Table 1. An Example to Compare the HCM and SIDRA Opposed Turn Models

	HCM	SIDRA
Opposing saturation flow, $s_{op}$	1800 veh/h	1358 veh/h
Unsaturated part of opposing green period, $g_u$	25.5 sec	7.1 sec
Opposed turn saturation flow, $s_u$ , during $g_u$	643 veh/h	661 veh/h
Departures after the green period, $n_s$	1.6 veh	1.6 veh
Capacity per cycle, $S = (s_u g_u / 3600) + n_s$	6.153 veh	2.909 veh
Effective green time, $g$	57 sec	8 sec
Average saturation flow, $s = S/g$	389 veh/h	1309 veh/h
Capacity per hour, $Q = sg/c = 3600 S/c$	185 veh/h	87 veh/h
Degree of saturation	0.433	0.917
Average stopped delay		
uniform term, $d_u$	15.8	42.8
overflow term, $d_o$	1.1	48.8
total, $d_s = d_u + d_o$	16.9	91.6
Level of service	C	F

The modeling of capacities by the adjustment factor method was necessary for the simple manual methods of the past. This is no longer necessary with the widespread use of computerized methods by the traffic engineering profession. The direct modeling method, which treats the blocked intervals as lost time, allows for various differences in individual lanes to be identified. This improves performance prediction significantly. For example, shared lanes with opposed turns can have longer effective red times than adjacent lanes. This has clear advantages in the prediction of queue lengths for turn bay storage capacity calculations. The more complex cases of "protected plus permitted" phasing, opposed turns with two levels of priority (e.g. turns from slip lanes, or the Victoria and New Zealand priority rules), the cases when the opposing and opposed traffic have right of way at different times, *de facto* exclusive lanes, right turn on red (U.S.), and so on can be modeled directly. This obviates the need to develop a multiplicity of increasingly complicated and increasingly less accurate adjustment factor formulas to cope with many complex situations. The reader is referred to the article by Akçelik for a more detailed discussion on shared lane capacity models in general and the SIDRA shared lane capacity model in particular.

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