# Total Capacities at AWSC Intersection - Validation and Comparison of the HCM Procedure and the ACF Technique

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**ABSTRACT**

An iterative model for computing capacities at All-Way Stop-Controlled (AWSC) intersections has been included in the new Highway Capacity Manual (HCM) 2000. The model is based on five saturation headway values, each reflecting a different level of conflict faced by the subject approach driver. From this model the capacity and service time at any approach can be computed using iterative calculations. The model in the HCM is a so-called approach-based model, which only takes into account the conflicting cases among the approaches. The effect of turning streams or movements is not modeled in sufficient detail.

In contrast, the author (Wu, 2000a, 2000b) presented a theoretical, stream-based model for determination of capacities at AWSC intersections. This model is based on the Addition-Conflict-Flow (ACF) method developed from the graph theory. This model takes into account all the traffic streams at the intersection, which allows a systematic and realistic analysis of the traffic process at AWSC intersections. The computational procedure included in the model can be conducted without iterative calculation steps.

This paper presents a comprehensive validation of the ACF and the HCM model for intersections with single-lane approaches. In addition, this paper presents a modified version of the HCM model, which significantly enhances the features of the HCM model. The modification is based on similar principles of the HCM model, but is extended to stream-based cases.

The results of the validation indicate that the total capacity of an AWSC intersection with single-lane approaches ranges between 1450 and 1550 pc/h based on the HCM model, while the total capacity ranges between 1600 and 2000 pc/h based on the ACF model. The modified HCM model yields total capacities ranging between 1700 and 2000 pc/h. The ACF model and the modified HCM model yield similar capacity results under normal traffic flow conditions.

**Keywords:** Capacity, unsignalized intersection, AWSC intersection, HCM validation

## INTRODUCTION

All-Way Stop-Controlled (AWSC) intersections are widely used in North America. In the HCM 2000, an iterative model is used for computing capacities at AWSC intersections. The generalized model in the HCM is based on five saturation headway values, each reflecting a different degree of conflict faced by the subject approach driver. The capacity and service time for each approach can be obtained from iterative calculations. The model in the HCM is a so-called approach-based model, which only takes into account the conflicting cases among the approaches. Although headway adjustments for turning streams are included in the HCM model, the effect of the turning streams is not specifically modeled. For example, a case of conflict and the saturation headway for a subject approach vehicle is determined only based on the status of the other approaches, regardless of what turning movements they are. A through vehicle on the subject approach facing a left turn vehicle on the opposing approach is very different from facing a through vehicle or a right turn vehicle. Due to the above reasons, the HCM model is not very sensitive to turning volumes and directional volume splits. One of the advantages of the HCM model though is for calculating control delays, since the service time on the approaches can be directly obtained from the procedure.

In contrast, the author (Wu, 2000a, 2000b) presented a theoretical, stream-based model for calculating capacities at AWSC intersections. The model is based on the method of Addition-Conflict-Flow (ACF), which is developed from the graph theory. The model takes into account the conflict cases among all the traffic streams, which allows a systematic and realistic analysis of traffic operations at AWSC intersections. For practical applications, a simplified but accurate procedure without the need of iterative calculations is always desired. The purpose of this study is to compare the results between the HCM model and the ACF model in calculating capacities at AWSC intersections. Although both models can handle multilane intersections, this study focuses on the single-lane case to mainly illustrate the mechanisms and results of the two models.

The paper first documents the theoretical background and computational procedures of the HCM model and the ACF model. The capacity results obtained from both models are compared with the results from other studies. A modified HCM model is then introduced and compared with the ACF model. Conclusions of this study are provided at the end of the paper.

## THE HCM MODEL FOR SINGLE-LANE INTERSECTIONS

The model included in the HCM 2000 is based on five saturation headway values, each reflecting a different degree of conflict faced by the subject approach driver. The headway of the subject approach vehicle also depends on its vehicle type and its turning maneuver. The probability of occurrence of each conflict case is calculated based on the degree of utilization on the opposing and conflicting approaches. Because the degree of utilization is also dependent on the saturation headway, the HCM model needs iterative calculations to obtain stable estimates of an average departure headway, an average service time, and thus the capacity.

For an intersection with single-lane approaches, the base saturation headway values and the corresponding probabilities of occurrence are presented in Table 1.

**Table 1** - Probabilities and saturation headway values of degree-of-conflict cases for single-lane AWSC intersections (HCM, 2000)

| Degree-of-Conflict Case ($C_i$) | Approach | | | | Probability of Occurrence, $P(C_i)$ | Saturation headway values $h_{si}$ (s) |
|---|---|---|---|---|---|---|
| | s | o | l | r | | |
| 1 | Y | N | N | N | $(p0_o)(p0_l)(p0_r)$ | 3.9 |
| 2 | Y | Y | N | N | $(x_o)(p0_l)(p0_r)$ | 4.7 |
| 3l | Y | N | Y | N | $(p0_o)(x_l)(p0_r)$ | 5.8 |
| 3r | Y | N | N | Y | $(p0_o)(p0_l)(x_r)$ | 5.8 |
| 4or | Y | Y | N | Y | $(x_o)(p0_l)(x_r)$ | 7.0 |
| 4ol | Y | Y | Y | N | $(x_o)(x_l)(p0_r)$ | 7.0 |
| 4lr | Y | N | Y | Y | $(p0_o)(x_l)(x_r)$ | 7.0 |
| 5 | Y | Y | Y | Y | $(x_o)(x_l)(x_r)$ | 9.6 |

Note: "s" is the subject approach. "o" is the opposing approach. "l" is the conflicting approach from the left. "r" is the conflicting approach from the right. x is the degree of utilization at the considered approach. p0=1-x is the probability that no vehicle is present at the considered approach.

The base saturation headways in Table 1 need to be adjusted to account for turning movements and heavy vehicles. In the HCM, the following adjustment factors are applied: $h_{adj}$ = 0.2 s for left-turning vehicles, $h_{adj}$ = -0.6 s for right-turning vehicles, and $h_{adj}$ = 1.7 s for heavy vehicles.

The departure headway for an approach is the expected value of the saturation headway distribution, computed by

$$h_d = \sum_{i=1}^{5} P(C_i) h_{si} \qquad (1)$$

where $P(C_i)$ is the probability of the degree-of-conflict case $C_i$ and $h_{si}$ is the saturation headway for that case.

The capacity of the subject approach is computed as follows. The volume of the subject approach is increased incrementally until the degree of utilization on any one approach exceeds 1.0. This flow rate is the maximum possible flow on the subject approach under the given conditions.

For calculating the total intersection capacity, the volumes of all the approaches must be increased incrementally by the same proportion until the degree of utilization on any one approach exceeds 1.0. The sum of the flow rates on all the approaches is then the capacity, the maximum possible flow of the intersection under the given conditions.

For the purpose of model validation, the total intersection capacities under various traffic conditions are computed using the HCM model, and the results are shown in Table 2 and Figure 1. These capacities are computed with an EXCEL spreadsheet, in which a special operation procedure was used for the iterative calculations. The proportion of heavy vehicles was assumed 0 in the calculations.

**Table 2** - Total intersection capacity computed from the HCM model as a function of the proportion of turning vehicles and the street-flow-split (pc/h)

| | Proportion of turning vehicles (left / through / right) | | |
|---|---|---|---|
| Street-flow-split (Distribution of traffic on both streets) Street 1 / Street 2 (%) | 0.0/1.0/0.0 | 0.1/0.8/0.1 | 0.2/0.6/0.2 |
| 100/0 | 1549 | 1536 | 1523 |
| 90/10 | 1483 | 1472 | 1462 |
| 80/20 | 1450 | 1441 | 1432 |
| 70/30 | 1441 | 1433 | 1425 |
| 60/40 | 1452 | 1445 | 1438 |
| 50/50 | 1483 | 1477 | 1470 |

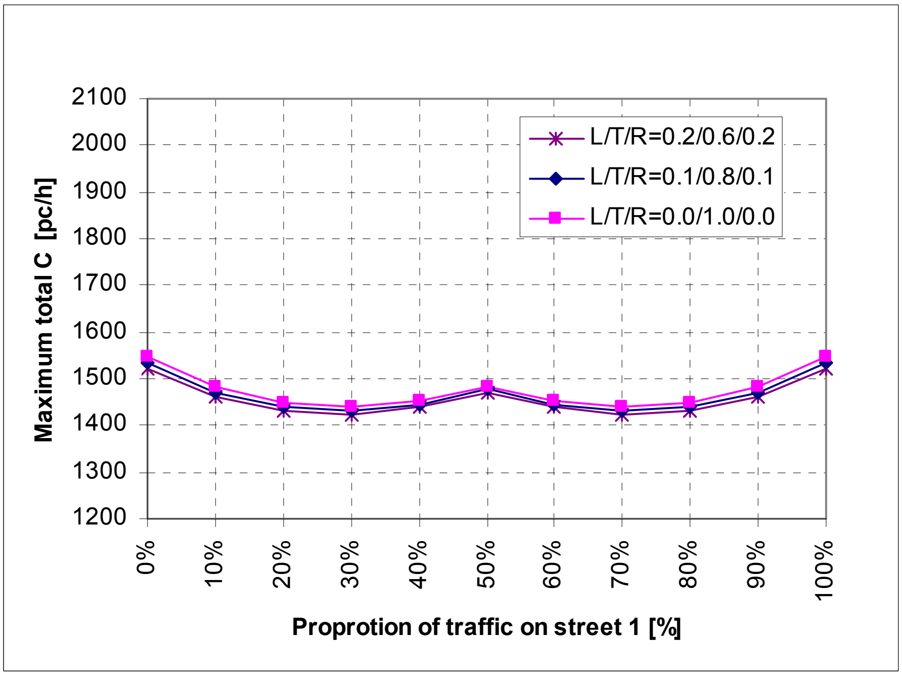


**Figure 1** - Total capacity of the intersection computed from the HCM model as a function of the proportion of turning vehicles and the street-flow-split (pc/h)

It can be seen that, according to the HCM model, the total capacity of a single-lane AWSC intersection is between 1450 and 1550 pc/h. The capacity is not sensitive to the proportion of turning vehicles. The total capacity is symmetrical to the street-flow-split. Thus, only the first half of the figure can be used for further analysis without losing important information.

When compared with the capacity values from other studies (Herbert, 1963, Richardson, 1987, Kyte et al, 1996), the total capacity values from the HCM are generally lower (Table 3 and

Figure 2). Furthermore, the capacities from the HCM are also not sensitive to the street-flow-split (proportion of traffic flow on both streets).

**Table 3** - Total capacities of AWSC intersection from different sources

| Source | Total capacity in veh/h with 5% heavy vehicles | | |
|---|---|---|---|
| | street-flow-split | | |
| | 50/50 | 70/30 | 100/0 |
| Herbert | 1900 | 1500 | - |
| Richardson | 1900 | 1560 | 1800 |
| AWSIM[1] (L/T/R=0.0/1.0/0.0) | 2100 | 1800 | 1600 |
| AWSIM[1] (L/T/R=0.2/0.6/0.2) | 1700 | 1600 | 1400 |

[1] cf. Kyte e al 1996

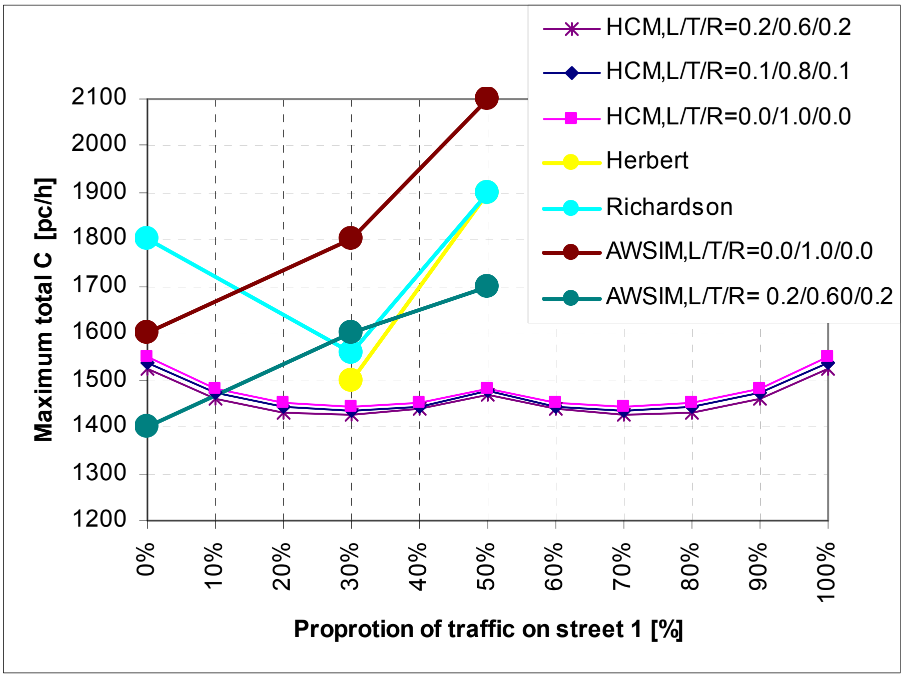


**Figure 2** - Comparison of maximum total capacities of the intersection from the HCM model to the values from other representative sources

## THE ACF MODEL FOR SINGLE-LANE INTERSECTION

The author (Wu, 2000a, 2000b) recently proposed a model for calculating capacities at AWSC intersections. The model applied the theory of Addition-Conflict-Flows (ACF), which is derived from the graph theory. The model is based essentially on several predefined departing sequences occurring in the conflict area at the intersection. Vehicles from different streams must departure sequentially one after another. The conflict area is occupied by the vehicles alternatively.

Different occupation times $t_B$ can be chosen based on the type of turning movements and heavy vehicles.

For single-lane AWSC intersections, a unique occupation time $t_B$ for all the streams is presumed. Thus, the capacity of a stream is $C_0 = 3600/t_B$. The value of $t_B$ can be chosen between 3.5 s/pc and 4 s/pc. A value of 3.5 s was found to be reasonable based on field measurements (cf. Wu, 2000a, 2000b).

According to the ACF model, the capacities of the left turning movement (L), the through movement (T), the right turn movement (R), and the capacity of the approach as a shared lane can be expressed as following.

**Capacity of the left turn movement:**

$$C_{s,L} = \max\begin{cases} C_0 - \max\left[\left(Q_{o,R} + Q_{r,T}\right), \left(Q_{o,T} + Q_{r,T} + Q_{l,L}\right), \left(Q_{o,T} + Q_{r,L} + Q_{l,T}\right)\right] \\ C_0 / 4 \end{cases} \quad \text{[pc/h]} \quad (2)$$

**Capacity of the through movement:**

$$C_{s,T} = \max\begin{cases} C_0 - \max\left[\left(Q_{r,R} + Q_{l,L}\right), \left(Q_{o,L} + Q_{r,L} + Q_{l,T}\right), \left(Q_{o,L} + Q_{r,T} + Q_{l,L}\right)\right] \\ C_0 / 4 \end{cases} \quad \text{[pc/h]} \quad (3)$$

**Capacity of the right turn movement:**

$$C_{s,R} = \max\begin{cases} C_0 - \left(Q_{o,L} + Q_{l,T}\right) \\ C_0 / 3 \end{cases} \quad \text{[pc/h]} \quad (4)$$

**Capacity of the approach as a shared lane:**

$$C_s = \frac{Q_{s,L} + Q_{s,T} + Q_{s,R}}{x_{s,L} + x_{s,T} + x_{s,R}} \quad \text{[pc/h]} \quad (5)$$

where Q denotes traffic flow rate and C denotes the capacity of the considered stream of approach. "s" is the subject approach, "o" is the opposing approach, "l" is conflicting approach from left, and "r" is the conflicting approach from right. "L" is the left turn movement on the subject approach, "T" is the through movement on the subject approach, and "R" is the right turn movement on the subject approach. x is the degree of utilization.

The capacity of the subject approach can be computed directly from this procedure. For calculating total intersection capacity, a similar approach can be applied as the HCM model, where the volumes of all the approaches are increased incrementally by the same proportion until the degree of utilization on any approach exceeds 1.0. The sum of the flow rates on all the approaches is then the maximum possible flow of the intersection under the given conditions.

Using same parameters, the total intersection capacities are computed from the ACF model, and the results are shown in Table 4 and Figure 3.

The capacity values from the ACF model are more sensitive to the proportion of turning vehicles and to the street-flow-split. The total capacity reaches its maximum value by a unique street-flow-split (50/50). If there are no turning vehicles (L/T/R=0.0/1.0/0.0), the total capacity is a constant value regardless of the street-flow-split.

The total capacity values computed from the ACF model seem to match closer to the capacity values from other studies (cf. Table 3 and Figure 4).

**Table 4** - Total capacity of the intersection computed from ACF model as a function of the proportion of turning vehicles and the street-flow-split (pc/h)

| | Proportion of turning vehicles (left / through / right) | | |
|---|---|---|---|
| Street-flow-split (Distribution of traffic on both streets) Street 1 / Street 2 (%) | 0.0/1.0/0.0 | 0.1/0.8/0.1 | 0.2/0.6/0.2 |
| 100/0 | 2057 | 1640 | 1567 |
| 90/10 | 2057 | 1688 | 1634 |
| 80/20 | 2057 | 1739 | 1708 |
| 70/30 | 2057 | 1794 | 1789 |
| 60/40 | 2057 | 1852 | 1876 |
| 50/50 | 2057 | 1914 | 1972 |

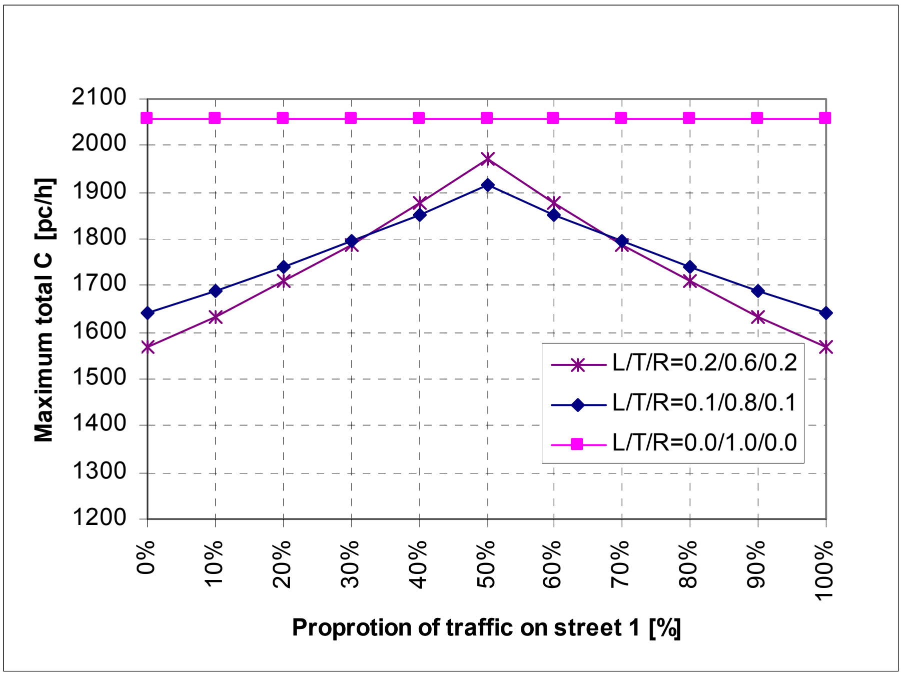


**Figure 3** - Total capacity of the intersection computed from the ACF model as a function of the proportion of turning vehicles and the street-flow-split (pc/h)

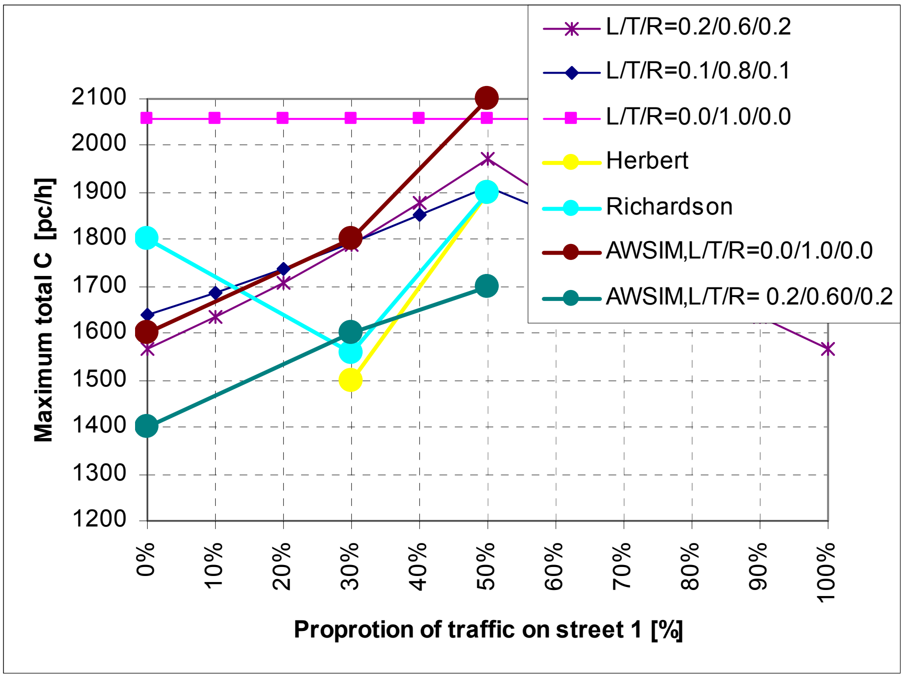


**Figure 4** - Comparison of maximum total capacity of the intersection from the ACF model to the values from other representative sources (cf. Table 3)

## THE MODIFIED HCM MODEL

The AWSC model incorporated in the HCM 2000 is an approach-based model. Thus, only the conflict cases among the approaches are considered. The conflict cases among individual streams are basically neglected. Such a model simplification results in overestimation of the degree-of-conflict and underestimation of the capacity. For instance, the degree-of-conflict between the through-ahead vehicles from two opposing approaches is considered to be case 2 in the HCM (conflict with opposing vehicles, cf. Table 1), although they can departure simultaneously. The degree-of-conflict between these vehicles is actually similar to case 1 (no conflict with other vehicles, cf. Table 1). Another extreme example of this overestimation of conflict degree is the conflict between the subject right-turning stream versus the right-turning streams from the other 3 opposing and conflicting approaches. Although no conflicts exist among these vehicles, the degree-of-conflict is considered to be case 5 (conflict with all 3 approaches, cf. Table 1). Other similar cases can be identified where overestimation of the degree-of-conflict exists in the HCM model.

In order to overcome the problem identified above, the conflict cases can be extended to be stream-based. The conflict cases among the approaches can be developed into sub-conflict cases among the streams. As an example, the 5 approach-based conflict cases included in Table 1 can be extended to a total of 192 stream-based conflict cases as shown in Table 5, where the conflict conditions and the probabilities of occurrences are illustrated. The last column shows the actual degree-of-conflict case, which is estimated to be equivalent to the conflict case used in the HCM. The saturation headway values need to be determined based on such actual conflict cases included in Table 5 for further capacity calculations.

**Table 5** - Stream-based degree-of-conflict cases and their probabilities of occurrence at single-lane AWSC intersections

| Degree-of-Conflict Case from HCM | Approach ans streams | | | | | | | | | | | | Probability of Occurrence | **Actual degree-of-confict case** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Sub (s) | | | Opp (o) | | | Con-L (l) | | | Con-R (r) | | | | |
| | L | T | R | L | T | R | L | T | R | L | T | R | | |
| 1 | Y | | | | | | | | | | | | $(p0_o)(p0_l)(p0_r)P_L$ | **1** |
| 1 | | Y | | | | | | | | | | | $(p0_o)(p0_l)(p0_r)P_T$ | **1** |
| 1 | | | Y | | | | | | | | | | $(p0_o)(p0_l)(p0_r)P_R$ | **1** |
| 2 | Y | | | Y | | | | | | | | | $(x_{o,L})(p0_l)(p0_r)P_L$ | **1** |
| 2 | Y | | | | Y | | | | | | | | $(x_{o,T})(p0_l)(p0_r)P_L$ | **2** |
| 2 | Y | | | | | Y | | | | | | | $(x_{o,R})(p0_l)(p0_r)P_L$ | **2** |
| 2 | | Y | | Y | | | | | | | | | $(x_{o,L})(p0_l)(p0_r)P_T$ | **2** |
| 2 | | Y | | | Y | | | | | | | | $(x_{o,T})(p0_l)(p0_r)P_T$ | **1** |
| 2 | | Y | | | | Y | | | | | | | $(x_{o,R})(p0_l)(p0_r)P_T$ | **1** |
| 2 | | | Y | Y | | | | | | | | | $(x_{o,L})(p0_l)(p0_r)P_R$ | **2** |
| 2 | | | Y | | Y | | | | | | | | $(x_{o,T})(p0_l)(p0_r)P_R$ | **1** |
| 2 | | | Y | | | Y | | | | | | | $(x_{o,R})(p0_l)(p0_r)P_R$ | **1** |
| 3l | Y | | | | | | Y | | | | | | $(p0_o)(x_{l,L})(p0_r)P_L$ | **3** |
| 3l | Y | | | | | | | Y | | | | | $(p0_o)(x_{l,T})(p0_r)P_L$ | **3** |
| 3l | Y | | | | | | | | Y | | | | $(p0_o)(x_{l,R})(p0_r)P_L$ | **1** |
| 3l | | Y | | | | | Y | | | | | | $(p0_o)(x_{l,L})(p0_r)P_T$ | **3** |
| 3l | | Y | | | | | | Y | | | | | $(p0_o)(x_{l,T})(p0_r)P_T$ | **3** |
| 3l | | Y | | | | | | | Y | | | | $(p0_o)(x_{l,R})(p0_r)P_T$ | **1** |
| 3l | | | Y | | | | Y | | | | | | $(p0_o)(x_{l,L})(p0_r)P_R$ | **1** |
| 3l | | | Y | | | | | Y | | | | | $(p0_o)(x_{l,T})(p0_r)P_R$ | **3** |
| 3l | | | Y | | | | | | Y | | | | $(p0_o)(x_{l,R})(p0_r)P_R$ | **1** |
| 3r | Y | | | | | | | | | Y | | | $(p0_o)(p0_l)(x_{r,L})P_L$ | **3** |
| 3r | Y | | | | | | | | | | Y | | $(p0_o)(p0_l)(x_{r,T})P_L$ | **3** |
| 3r | Y | | | | | | | | | | | Y | $(p0_o)(p0_l)(x_{r,R})P_L$ | **1** |
| 3r | | Y | | | | | | | | Y | | | $(p0_o)(p0_l)(x_{r,L})P_T$ | **3** |
| 3r | | Y | | | | | | | | | Y | | $(p0_o)(p0_l)(x_{r,T})P_T$ | **3** |
| 3r | | Y | | | | | | | | | | Y | $(p0_o)(p0_l)(x_{r,R})P_T$ | **3** |
| 3r | | | Y | | | | | | | Y | | | $(p0_o)(p0_l)(x_{r,L})P_R$ | **1** |
| 3r | | | Y | | | | | | | | Y | | $(p0_o)(p0_l)(x_{r,T})P_R$ | **1** |
| 3r | | | Y | | | | | | | | | Y | $(p0_o)(p0_l)(x_{r,R})P_R$ | **1** |
| 4or | Y | | | Y | | | | | | Y | | | $(x_{o,L})(p0_l)(x_{r,L})P_L$ | **3** |
| 4or | Y | | | Y | | | | | | | Y | | $(x_{o,L})(p0_l)(x_{r,T})P_L$ | **3** |
| 4or | Y | | | Y | | | | | | | | Y | $(x_{o,L})(p0_l)(x_{r,R})P_L$ | **1** |
| 4or | Y | | | | Y | | | | | Y | | | $(x_{o,T})(p0_l)(x_{r,L})P_L$ | **4** |
| 4or | Y | | | | Y | | | | | | Y | | $(x_{o,T})(p0_l)(x_{r,T})P_L$ | **4** |
| 4or | Y | | | | Y | | | | | | | Y | $(x_{o,T})(p0_l)(x_{r,R})P_L$ | **2** |
| 4or | Y | | | | | Y | | | | Y | | | $(x_{o,R})(p0_l)(x_{r,L})P_L$ | **4** |
| 4or | Y | | | | | Y | | | | | Y | | $(x_{o,R})(p0_l)(x_{r,T})P_L$ | **4** |
| 4or | Y | | | | | Y | | | | | | Y | $(x_{o,R})(p0_l)(x_{r,R})P_L$ | **1** |
| 4or | | Y | | Y | | | | | | Y | | | $(x_{o,L})(p0_l)(x_{r,L})P_T$ | **4** |
| 4or | | Y | | Y | | | | | | | Y | | $(x_{o,L})(p0_l)(x_{r,T})P_T$ | **4** |
| 4or | | Y | | Y | | | | | | | | Y | $(x_{o,L})(p0_l)(x_{r,R})P_T$ | **2** |
| 4or | | Y | | | Y | | | | | Y | | | $(x_{o,T})(p0_l)(x_{r,L})P_T$ | **3** |
| 4or | | Y | | | Y | | | | | | Y | | $(x_{o,T})(p0_l)(x_{r,T})P_T$ | **3** |
| 4or | | Y | | | Y | | | | | | | Y | $(x_{o,T})(p0_l)(x_{r,R})P_T$ | **1** |
| 4or | | Y | | | | Y | | | | Y | | | $(x_{o,R})(p0_l)(x_{r,L})P_T$ | **3** |
| 4or | | Y | | | | Y | | | | | Y | | $(x_{o,R})(p0_l)(x_{r,T})P_T$ | **3** |
| 4or | | Y | | | | Y | | | | | | Y | $(x_{o,R})(p0_l)(x_{r,R})P_T$ | **3** |
| 4or | | | Y | Y | | | | | | Y | | | $(x_{o,L})(p0_l)(x_{r,L})P_R$ | **2** |
| 4or | | | Y | Y | | | | | | | Y | | $(x_{o,L})(p0_l)(x_{r,T})P_R$ | **2** |
| 4or | | | Y | Y | | | | | | | | Y | $(x_{o,L})(p0_l)(x_{r,R})P_R$ | **2** |
| 4or | | | Y | | Y | | | | | Y | | | $(x_{o,T})(p0_l)(x_{r,L})P_R$ | **1** |
| 4or | | | Y | | Y | | | | | | Y | | $(x_{o,T})(p0_l)(x_{r,T})P_R$ | **1** |
| 4or | | | Y | | Y | | | | | | | Y | $(x_{o,T})(p0_l)(x_{r,R})P_R$ | **1** |
| 4or | | | Y | | | Y | | | | Y | | | $(x_{o,R})(p0_l)(x_{r,L})P_R$ | **1** |
| 4or | | | Y | | | Y | | | | | Y | | $(x_{o,R})(p0_l)(x_{r,T})P_R$ | **1** |
| 4or | | | Y | | | Y | | | | | | Y | $(x_{o,R})(p0_l)(x_{r,R})P_R$ | **1** |

**Table 5** - Stream-based degree-of-conflict cases and their probabilities of occurrence at single-lane AWSC intersections (continued)

| Degree-of-Conflict Case from HCM | Approach | | | | | | | | | | | | Probability of Occurrence | **real degree-of-confict case** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Sub (s) | | | Opp (o) | | | Con-L (l) | | | Con-R (r) | | | | |
| | L | T | R | L | T | R | L | T | R | L | T | R | | |
| 4ol | Y | | | Y | | | Y | | | | | | $(x_{o,L})(x_{l,L})(p0_r)P_L$ | **3** |
| 4ol | Y | | | Y | | | | Y | | | | | $(x_{o,L})(x_{l,T})(p0_r)P_L$ | **3** |
| 4ol | Y | | | Y | | | | | Y | | | | $(x_{o,L})(x_{l,R})(p0_r)P_L$ | **1** |
| 4ol | Y | | | | Y | | Y | | | | | | $(x_{o,T})(x_{l,L})(p0_r)P_L$ | **4** |
| 4ol | Y | | | | Y | | | Y | | | | | $(x_{o,T})(x_{l,T})(p0_r)P_L$ | **4** |
| 4ol | Y | | | | Y | | | | Y | | | | $(x_{o,T})(x_{l,R})(p0_r)P_L$ | **2** |
| 4ol | Y | | | | | Y | Y | | | | | | $(x_{o,R})(x_{l,L})(p0_r)P_L$ | **4** |
| 4ol | Y | | | | | Y | | Y | | | | | $(x_{o,R})(x_{l,T})(p0_r)P_L$ | **4** |
| 4ol | Y | | | | | Y | | | Y | | | | $(x_{o,R})(x_{l,R})(p0_r)P_L$ | **2** |
| 4ol | | Y | | Y | | | Y | | | | | | $(x_{o,L})(x_{l,L})(p0_r)P_T$ | **4** |
| 4ol | | Y | | Y | | | | Y | | | | | $(x_{o,L})(x_{l,T})(p0_r)P_T$ | **4** |
| 4ol | | Y | | Y | | | | | Y | | | | $(x_{o,L})(x_{l,R})(p0_r)P_T$ | **2** |
| 4ol | | Y | | | Y | | Y | | | | | | $(x_{o,T})(x_{l,L})(p0_r)P_T$ | **3** |
| 4ol | | Y | | | Y | | | Y | | | | | $(x_{o,T})(x_{l,T})(p0_r)P_T$ | **3** |
| 4ol | | Y | | | Y | | | | Y | | | | $(x_{o,T})(x_{l,R})(p0_r)P_T$ | **1** |
| 4ol | | Y | | | | Y | Y | | | | | | $(x_{o,R})(x_{l,L})(p0_r)P_T$ | **3** |
| 4ol | | Y | | | | Y | | Y | | | | | $(x_{o,R})(x_{l,T})(p0_r)P_T$ | **3** |
| 4ol | | Y | | | | Y | | | Y | | | | $(x_{o,R})(x_{l,R})(p0_r)P_T$ | **1** |
| 4ol | | | Y | Y | | | Y | | | | | | $(x_{o,L})(x_{l,L})(p0_r)P_R$ | **2** |
| 4ol | | | Y | Y | | | | Y | | | | | $(x_{o,L})(x_{l,T})(p0_r)P_R$ | **4** |
| 4ol | | | Y | Y | | | | | Y | | | | $(x_{o,L})(x_{l,R})(p0_r)P_R$ | **2** |
| 4ol | | | Y | | Y | | Y | | | | | | $(x_{o,T})(x_{l,L})(p0_r)P_R$ | **1** |
| 4ol | | | Y | | Y | | | Y | | | | | $(x_{o,T})(x_{l,T})(p0_r)P_R$ | **3** |
| 4ol | | | Y | | Y | | | | Y | | | | $(x_{o,T})(x_{l,R})(p0_r)P_R$ | **1** |
| 4ol | | | Y | | | Y | Y | | | | | | $(x_{o,R})(x_{l,L})(p0_r)P_R$ | **1** |
| 4ol | | | Y | | | Y | | Y | | | | | $(x_{o,R})(x_{l,T})(p0_r)P_R$ | **3** |
| 4ol | | | Y | | | Y | | | Y | | | | $(x_{o,R})(x_{l,R})(p0_r)P_R$ | **1** |
| 4lr | Y | | | | | | Y | | | Y | | | $(p0_o)(x_{l,L})(x_{r,L})P_L$ | **4** |
| 4lr | Y | | | | | | Y | | | | Y | | $(p0_o)(x_{l,L})(x_{r,T})P_L$ | **4** |
| 4lr | Y | | | | | | Y | | | | | Y | $(p0_o)(x_{l,L})(x_{r,R})P_L$ | **3** |
| 4lr | Y | | | | | | | Y | | Y | | | $(p0_o)(x_{l,T})(x_{r,L})P_L$ | **4** |
| 4lr | Y | | | | | | | Y | | | Y | | $(p0_o)(x_{l,T})(x_{r,T})P_L$ | **4** |
| 4lr | Y | | | | | | | Y | | | | Y | $(p0_o)(x_{l,T})(x_{r,R})P_L$ | **3** |
| 4lr | Y | | | | | | | | Y | Y | | | $(p0_o)(x_{l,R})(x_{r,L})P_L$ | **3** |
| 4lr | Y | | | | | | | | Y | | Y | | $(p0_o)(x_{l,R})(x_{r,T})P_L$ | **3** |
| 4lr | Y | | | | | | | | Y | | | Y | $(p0_o)(x_{l,R})(x_{r,R})P_L$ | **1** |
| 4lr | | Y | | | | | Y | | | Y | | | $(p0_o)(x_{l,L})(x_{r,L})P_T$ | **4** |
| 4lr | | Y | | | | | Y | | | | Y | | $(p0_o)(x_{l,L})(x_{r,T})P_T$ | **4** |
| 4lr | | Y | | | | | Y | | | | | Y | $(p0_o)(x_{l,L})(x_{r,R})P_T$ | **4** |
| 4lr | | Y | | | | | | Y | | Y | | | $(p0_o)(x_{l,T})(x_{r,L})P_T$ | **4** |
| 4lr | | Y | | | | | | Y | | | Y | | $(p0_o)(x_{l,T})(x_{r,T})P_T$ | **4** |
| 4lr | | Y | | | | | | Y | | | | Y | $(p0_o)(x_{l,T})(x_{r,R})P_T$ | **4** |
| 4lr | | Y | | | | | | | Y | Y | | | $(p0_o)(x_{l,R})(x_{r,L})P_T$ | **3** |
| 4lr | | Y | | | | | | | Y | | Y | | $(p0_o)(x_{l,R})(x_{r,T})P_T$ | **3** |
| 4lr | | Y | | | | | | | Y | | | Y | $(p0_o)(x_{l,R})(x_{r,R})P_L$ | **3** |
| 4lr | | | Y | | | | Y | | | Y | | | $(p0_o)(x_{l,L})(x_{r,L})P_R$ | **1** |
| 4lr | | | Y | | | | Y | | | | Y | | $(p0_o)(x_{l,L})(x_{r,T})P_R$ | **1** |
| 4lr | | | Y | | | | Y | | | | | Y | $(p0_o)(x_{l,L})(x_{r,R})P_R$ | **1** |
| 4lr | | | Y | | | | | Y | | Y | | | $(p0_o)(x_{l,T})(x_{r,L})P_R$ | **3** |
| 4lr | | | Y | | | | | Y | | | Y | | $(p0_o)(x_{l,T})(x_{r,T})P_R$ | **3** |
| 4lr | | | Y | | | | | Y | | | | Y | $(p0_o)(x_{l,T})(x_{r,R})P_R$ | **3** |
| 4lr | | | Y | | | | | | Y | Y | | | $(p0_o)(x_{l,R})(x_{r,L})P_R$ | **1** |
| 4lr | | | Y | | | | | | Y | | Y | | $(p0_o)(x_{l,R})(x_{r,T})P_R$ | **1** |
| 4lr | | | Y | | | | | | Y | | | Y | $(p0_o)(x_{l,R})(x_{r,R})P_R$ | **1** |

**Table 5** - Stream-based degree-of-conflict cases and their probabilities of occurrence at single-lane AWSC intersections (continued)

| Degree-of-Conflict Case from HCM | Approach | | | | | | | | | | | | Probability of Occurrence | **real degree-of-confict case** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Sub (s) | | | Opp (o) | | | Con-L (l) | | | Con-R (r) | | | | |
| | L | T | R | L | T | R | L | T | R | L | T | R | | |
| 5 | Y | | | Y | | | Y | | | Y | | | $(x_{o,L})(x_{l,L})(x_{r,L})P_L$ | **4** |
| 5 | Y | | | Y | | | Y | | | | Y | | $(x_{o,L})(x_{l,L})(x_{r,T})P_L$ | **4** |
| 5 | Y | | | Y | | | Y | | | | | Y | $(x_{o,L})(x_{l,L})(x_{r,R})P_L$ | **3** |
| 5 | Y | | | Y | | | | Y | | Y | | | $(x_{o,L})(x_{l,T})(x_{r,L})P_L$ | **4** |
| 5 | Y | | | Y | | | | Y | | | Y | | $(x_{o,L})(x_{l,T})(x_{r,T})P_L$ | **4** |
| 5 | Y | | | Y | | | | Y | | | | Y | $(x_{o,L})(x_{l,T})(x_{r,R})P_L$ | **3** |
| 5 | Y | | | Y | | | | | Y | Y | | | $(x_{o,L})(x_{l,R})(x_{r,L})P_L$ | **3** |
| 5 | Y | | | Y | | | | | Y | | Y | | $(x_{o,L})(x_{l,R})(x_{r,T})P_L$ | **3** |
| 5 | Y | | | Y | | | | | Y | | | Y | $(x_{o,L})(x_{l,R})(x_{r,R})P_L$ | **1** |
| 5 | Y | | | | Y | | Y | | | Y | | | $(x_{o,T})(x_{l,L})(x_{r,L})P_L$ | **5** |
| 5 | Y | | | | Y | | Y | | | | Y | | $(x_{o,T})(x_{l,L})(x_{r,T})P_L$ | **5** |
| 5 | Y | | | | Y | | Y | | | | | Y | $(x_{o,T})(x_{l,L})(x_{r,R})P_L$ | **4** |
| 5 | Y | | | | Y | | | Y | | Y | | | $(x_{o,T})(x_{l,T})(x_{r,L})P_L$ | **5** |
| 5 | Y | | | | Y | | | Y | | | Y | | $(x_{o,T})(x_{l,T})(x_{r,T})P_L$ | **5** |
| 5 | Y | | | | Y | | | Y | | | | Y | $(x_{o,T})(x_{l,T})(x_{r,R})P_L$ | **4** |
| 5 | Y | | | | Y | | | | Y | Y | | | $(x_{o,T})(x_{l,R})(x_{r,L})P_L$ | **4** |
| 5 | Y | | | | Y | | | | Y | | Y | | $(x_{o,T})(x_{l,R})(x_{r,T})P_L$ | **4** |
| 5 | Y | | | | Y | | | | Y | | | Y | $(x_{o,T})(x_{l,R})(x_{r,R})P_L$ | **2** |
| 5 | Y | | | | | Y | Y | | | Y | | | $(x_{o,R})(x_{l,L})(x_{r,L})P_L$ | **5** |
| 5 | Y | | | | | Y | Y | | | | Y | | $(x_{o,R})(x_{l,L})(x_{r,T})P_L$ | **5** |
| 5 | Y | | | | | Y | Y | | | | | Y | $(x_{o,R})(x_{l,L})(x_{r,R})P_L$ | **4** |
| 5 | Y | | | | | Y | | Y | | Y | | | $(x_{o,R})(x_{l,T})(x_{r,L})P_L$ | **5** |
| 5 | Y | | | | | Y | | Y | | | Y | | $(x_{o,R})(x_{l,T})(x_{r,T})P_L$ | **5** |
| 5 | Y | | | | | Y | | Y | | | | Y | $(x_{o,R})(x_{l,T})(x_{r,R})P_L$ | **4** |
| 5 | Y | | | | | Y | | | Y | Y | | | $(x_{o,R})(x_{l,R})(x_{r,L})P_L$ | **4** |
| 5 | Y | | | | | Y | | | Y | | Y | | $(x_{o,R})(x_{l,R})(x_{r,T})P_L$ | **4** |
| 5 | Y | | | | | Y | | | Y | | | Y | $(x_{o,R})(x_{l,R})(x_{r,R})P_L$ | **2** |
| 5 | | Y | | Y | | | Y | | | Y | | | $(x_{o,L})(x_{l,L})(x_{r,L})P_L$ | **5** |
| 5 | | Y | | Y | | | Y | | | | Y | | $(x_{o,L})(x_{l,L})(x_{r,T})P_T$ | **5** |
| 5 | | Y | | Y | | | Y | | | | | Y | $(x_{o,L})(x_{l,L})(x_{r,R})P_T$ | **5** |
| 5 | | Y | | Y | | | | Y | | Y | | | $(x_{o,L})(x_{l,T})(x_{r,L})P_T$ | **5** |
| 5 | | Y | | Y | | | | Y | | | Y | | $(x_{o,L})(x_{l,T})(x_{r,T})P_T$ | **5** |
| 5 | | Y | | Y | | | | Y | | | | Y | $(x_{o,L})(x_{l,T})(x_{r,R})P_T$ | **5** |
| 5 | | Y | | Y | | | | | Y | Y | | | $(x_{o,L})(x_{l,R})(x_{r,L})P_T$ | **4** |
| 5 | | Y | | Y | | | | | Y | | Y | | $(x_{o,L})(x_{l,R})(x_{r,T})P_T$ | **4** |
| 5 | | Y | | Y | | | | | Y | | | Y | $(x_{o,L})(x_{l,R})(x_{r,R})P_T$ | **4** |
| 5 | | Y | | | Y | | Y | | | Y | | | $(x_{o,T})(x_{l,L})(x_{r,L})P_T$ | **4** |
| 5 | | Y | | | Y | | Y | | | | Y | | $(x_{o,T})(x_{l,L})(x_{r,T})P_T$ | **4** |
| 5 | | Y | | | Y | | Y | | | | | Y | $(x_{o,T})(x_{l,L})(x_{r,R})P_T$ | **4** |
| 5 | | Y | | | Y | | | Y | | Y | | | $(x_{o,T})(x_{l,T})(x_{r,L})P_T$ | **4** |
| 5 | | Y | | | Y | | | Y | | | Y | | $(x_{o,T})(x_{l,T})(x_{r,T})P_T$ | **4** |
| 5 | | Y | | | Y | | | Y | | | | Y | $(x_{o,T})(x_{l,T})(x_{r,R})P_T$ | **4** |
| 5 | | Y | | | Y | | | | Y | Y | | | $(x_{o,T})(x_{l,R})(x_{r,L})P_T$ | **3** |
| 5 | | Y | | | Y | | | | Y | | Y | | $(x_{o,T})(x_{l,R})(x_{r,T})P_T$ | **3** |
| 5 | | Y | | | Y | | | | Y | | | Y | $(x_{o,T})(x_{l,R})(x_{r,R})P_T$ | **3** |
| 5 | | Y | | | | Y | Y | | | Y | | | $(x_{o,R})(x_{l,L})(x_{r,L})P_T$ | **4** |
| 5 | | Y | | | | Y | Y | | | | Y | | $(x_{o,R})(x_{l,L})(x_{r,T})P_T$ | **4** |
| 5 | | Y | | | | Y | Y | | | | | Y | $(x_{o,R})(x_{l,L})(x_{r,R})P_T$ | **4** |
| 5 | | Y | | | | Y | | Y | | Y | | | $(x_{o,R})(x_{l,T})(x_{r,L})P_T$ | **3** |
| 5 | | Y | | | | Y | | Y | | | Y | | $(x_{o,R})(x_{l,T})(x_{r,T})P_T$ | **3** |
| 5 | | Y | | | | Y | | Y | | | | Y | $(x_{o,R})(x_{l,T})(x_{r,R})P_T$ | **3** |
| 5 | | Y | | | | Y | | | Y | Y | | | $(x_{o,R})(x_{l,R})(x_{r,L})P_T$ | **3** |
| 5 | | Y | | | | Y | | | Y | | Y | | $(x_{o,R})(x_{l,R})(x_{r,T})P_T$ | **3** |
| 5 | | Y | | | | Y | | | Y | | | Y | $(x_{o,R})(x_{l,R})(x_{r,R})P_T$ | **3** |

**Table 5** - Stream-based degree-of-conflict cases and their probabilities of occurrence at single-lane AWSC intersections (continued)

| Degree-of-Conflict Case from HCM | Approach | | | | | | | | | | | | Probability of Occurrence | **real degree-of-conficat case** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Sub (s) | | | Opp (o) | | | Con-L (l) | | | Con-R (r) | | | | |
| | L | T | R | L | T | R | L | T | R | L | T | R | | |
| 5 | | | Y | Y | | | Y | | | Y | | | $(x_{o,L})(x_{l,L})(x_{r,L})P_R$ | **2** |
| 5 | | | Y | Y | | | Y | | | | Y | | $(x_{o,L})(x_{l,L})(x_{r,T})P_R$ | **2** |
| 5 | | | Y | Y | | | Y | | | | | Y | $(x_{o,L})(x_{l,L})(x_{r,R})P_R$ | **2** |
| 5 | | | Y | Y | | | | Y | | Y | | | $(x_{o,L})(x_{l,T})(x_{r,L})P_R$ | **4** |
| 5 | | | Y | Y | | | | Y | | | Y | | $(x_{o,L})(x_{l,T})(x_{r,T})P_R$ | **4** |
| 5 | | | Y | Y | | | | Y | | | | Y | $(x_{o,L})(x_{l,T})(x_{r,R})P_R$ | **4** |
| 5 | | | Y | Y | | | | | Y | Y | | | $(x_{o,L})(x_{l,R})(x_{r,L})P_R$ | **2** |
| 5 | | | Y | Y | | | | | Y | | Y | | $(x_{o,L})(x_{l,R})(x_{r,T})P_R$ | **2** |
| 5 | | | Y | Y | | | | | Y | | | Y | $(x_{o,L})(x_{l,R})(x_{r,R})P_R$ | **2** |
| 5 | | | Y | | Y | | Y | | | Y | | | $(x_{o,T})(x_{l,L})(x_{r,L})P_R$ | **1** |
| 5 | | | Y | | Y | | Y | | | | Y | | $(x_{o,T})(x_{l,L})(x_{r,T})P_R$ | **1** |
| 5 | | | Y | | Y | | Y | | | | | Y | $(x_{o,T})(x_{l,L})(x_{r,R})P_R$ | **1** |
| 5 | | | Y | | Y | | | Y | | Y | | | $(x_{o,T})(x_{l,T})(x_{r,L})P_R$ | **3** |
| 5 | | | Y | | Y | | | Y | | | Y | | $(x_{o,T})(x_{l,T})(x_{r,T})P_R$ | **3** |
| 5 | | | Y | | Y | | | Y | | | | Y | $(x_{o,T})(x_{l,T})(x_{r,R})P_R$ | **3** |
| 5 | | | Y | | Y | | | | Y | Y | | | $(x_{o,T})(x_{l,R})(x_{r,L})P_R$ | **1** |
| 5 | | | Y | | Y | | | | Y | | Y | | $(x_{o,T})(x_{l,R})(x_{r,T})P_R$ | **1** |
| 5 | | | Y | | Y | | | | Y | | | Y | $(x_{o,T})(x_{l,R})(x_{r,R})P_R$ | **1** |
| 5 | | | Y | | | Y | Y | | | Y | | | $(x_{o,R})(x_{l,L})(x_{r,L})P_R$ | **1** |
| 5 | | | Y | | | Y | Y | | | | Y | | $(x_{o,R})(x_{l,L})(x_{r,T})P_R$ | **1** |
| 5 | | | Y | | | Y | Y | | | | | Y | $(x_{o,R})(x_{l,L})(x_{r,R})P_R$ | **1** |
| 5 | | | Y | | | Y | | Y | | Y | | | $(x_{o,R})(x_{l,T})(x_{r,L})P_R$ | **3** |
| 5 | | | Y | | | Y | | Y | | | Y | | $(x_{o,R})(x_{l,T})(x_{r,T})P_R$ | **3** |
| 5 | | | Y | | | Y | | Y | | | | Y | $(x_{o,R})(x_{l,T})(x_{r,R})P_R$ | **3** |
| 5 | | | Y | | | Y | | | Y | Y | | | $(x_{o,R})(x_{l,R})(x_{r,L})P_R$ | **1** |
| 5 | | | Y | | | Y | | | Y | | Y | | $(x_{o,R})(x_{l,R})(x_{r,T})P_R$ | **1** |
| 5 | | | Y | | | Y | | | Y | | | Y | $(x_{o,R})(x_{l,R})(x_{r,R})P_R$ | **1** |

Note: Sub (s) is the subject approach. Opp (o) is the opposing approach. Con-L (l) is the conflicting approach from the left. Con-R (r) is the conflicting approach from the right. L is the left turn movement. T is the through movement. R is the right turn movement. x is the degree of utilization of the stream or of the approach. p0=1-x. P is the proportion of turning vehicle on the subject approach.

Applying the same principle of the HCM model, the probability of occurrence for these conflict cases can be computed as a function of the stream-based degrees of utilisation on the opposing and conflicting approaches and the proportion of turning vehicles on the subject approach. Using eq. (1), the departure headway for an approach can be computed as the expected value of the saturation headway distribution over all the 192 cases.

The modified, stream-based HCM-model still needs iterative calculations to achieve stable departure headway values. Computerised application tools must be used to perform the calculations. Using an EXCEL spreadsheet, the total intersection capacities are obtained based on the modified, stream-based HCM model, and the results are shown in Table 6 and Figure 5.

**Table 6** - Total capacity of the intersection computed from the modified, stream-based HCM model as a function of the proportion of turning vehicles and the street-flow-split (pc/h)

| | Proportion of turning vehicles (left / through / right) | | |
|---|---|---|---|
| Street-flow-split (Distribution of traffic on both streets) Street 1 / Street 2 (%) | 0.0/1.0/0.0 | 0.1/0.8/0.1 | 0.2/0.6/0.2 |
| 100/0 | 1846 | 1792 | 1760 |
| 90/10 | 1765 | 1747 | 1750 |
| 80/20 | 1758 | 1752 | 1773 |
| 70/30 | 1803 | 1796 | 1826 |
| 60/40 | 1897 | 1881 | 1912 |
| 50/50 | 2057 | 2015 | 2041 |

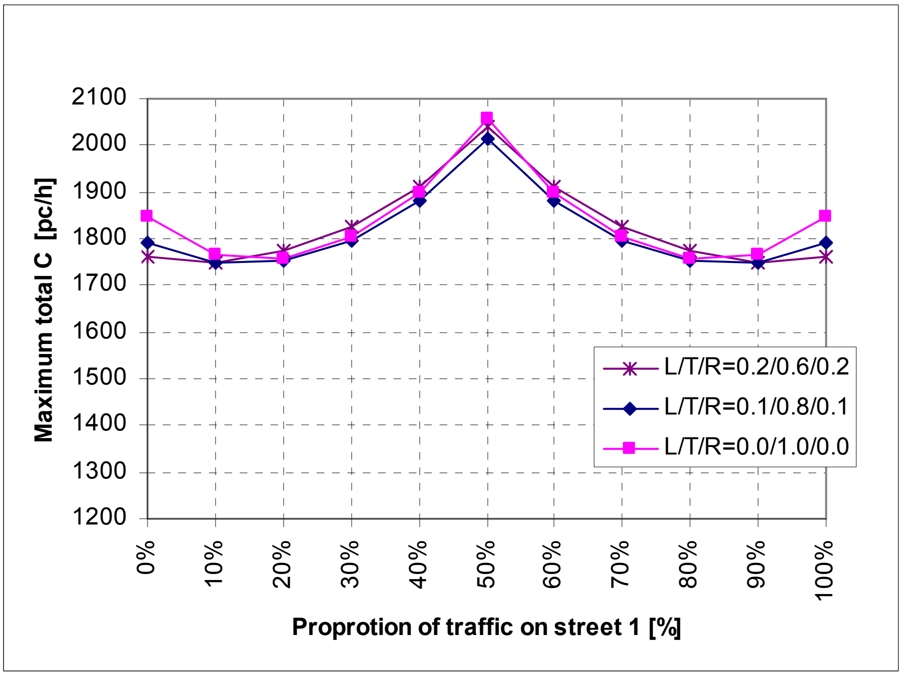


**Figure 5** - Total capacity of the intersection computed from the modified, stream-based HCM model as a function of the proportion of turning vehicles and the street-volume-split (pc/h)

As can be seen that the capacity values from the modified, stream-based HCM model are more sensitive to the street-flow-split. Compared to the approach-based HCM (Figure 6), the stream-based HCM-Model yields much higher capacity values. These value, however, seem more realistic than the approach-based values. Figure 7 shows the comparison between the values from the ACF model and the values from stream-based HCM model. As can be seen that, for the common traffic conditions (street-flow-split: 20/80 ~ 50/50; proportion of turning vehicles: 0.1/0.8/0.1 ~ 0.2/0.6/0.2), both models yield identical results in total intersection capacities at AWSC intersections.

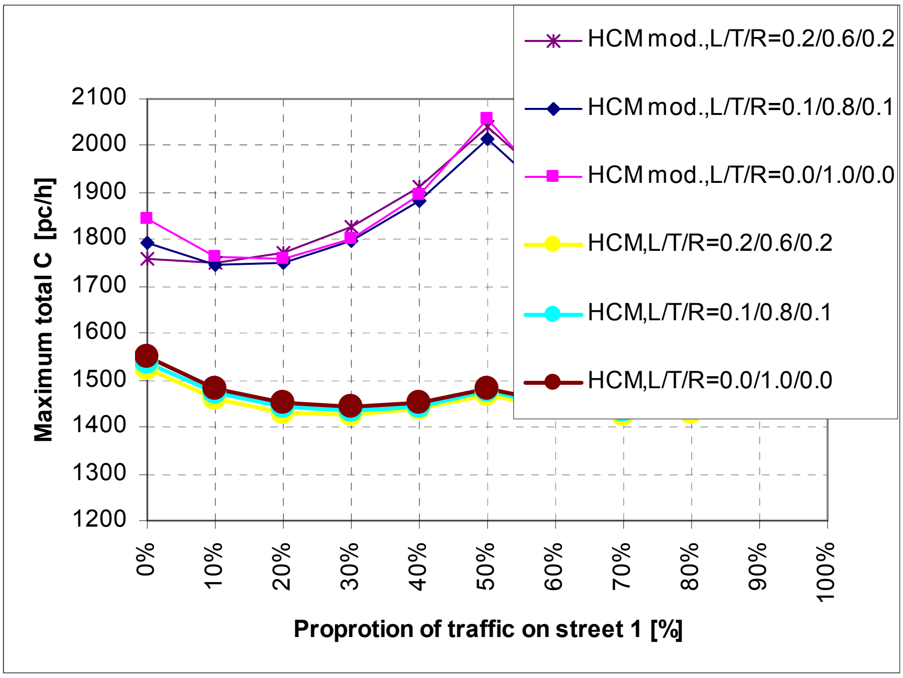


**Figure 6** - Total capacity of the intersection: comparison between the approach-based HCM model (HCM) and the modified, stream-based HCM model (HCM mod.)

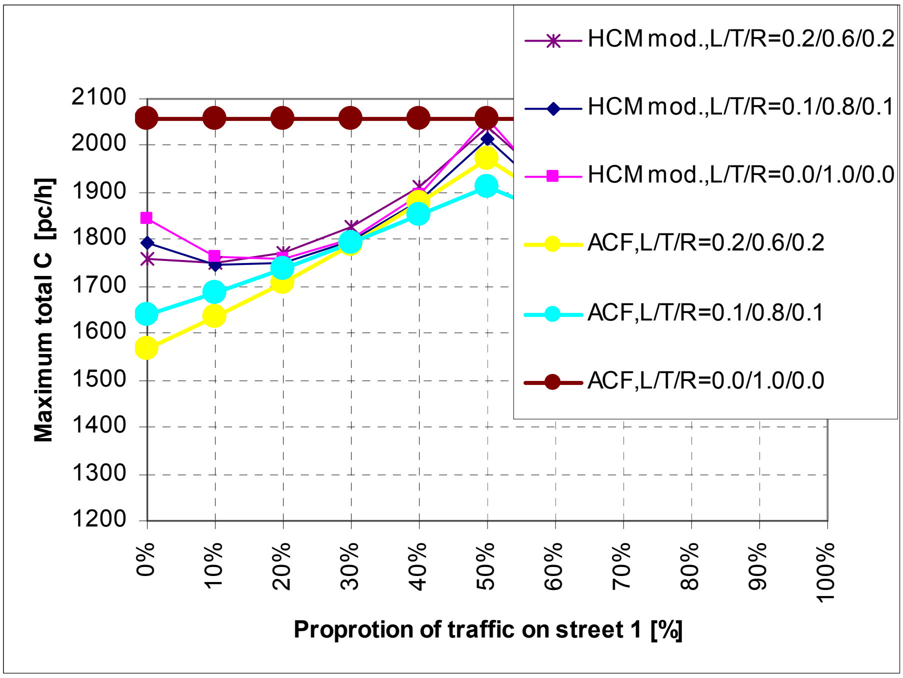


**Figure 7** - Total capacity of the intersection: comparison between the ACF model (ACF) and the modified, stream-based HCM model (HCM mod.)

## CONCLUSIONS

The AWSC model in the recent HCM 2000 is an approach-based model, which does not take the turning streams into account sufficiently. The validation of this paper shows that, compared to the stream-based ACF model and to other major studies, the HCM model seems to underestimate the total capacity of the intersection.

Applying the same principle used in HCM, the HCM model can be modified for stream-based cases. With regarding to the total intersection capacity, the modified, stream-based HCM model is consistent to the ACF and other studies.

The modified, stream-based HCM model is a very complex, iterative model. The computations have to rely on computerised tools. Modelling of multilane intersections may be too complex to accomplish. Thus, for practical applications, the ACF model seems to be a promising solution. for estimating capacity at AWSC intersections.

The study documented in this paper is limited to intersections with single-lane approaches. A similar approach can be used for model testing at multilane intersections.

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