The Signalized Intersection Method of the Highway Capacity Manual: A State of Crisis

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31 July 2015
Word Count = 5452 [4452 words + 4 exhibits]

ABSTRACT

This paper identifies critical issues relating to the signalized intersection methodology of the Highway Capacity Manual. The paper also suggests a path forward to resolve these issues.

1. INTRODUCTION

We believe the signalized intersection method of the Highway Capacity Manual (HCM) to be in a state of crisis. This paper presents the reasons that we believe this to be true and some ideas for consideration of the Committee on Highway Capacity and Quality of Service (CHCQS) to resolve this crisis.

2. WHAT WE BELIEVE TO BE TRUE

The signalized intersection method has evolved dramatically since the first publication of the HCM more than sixty years ago. The number of pages devoted to the method has grown from 39 in 1950 to 206 in 2010. As recently as 1985, an analyst could apply the method using pencil-and-paper. The 2010 method must nearly always be applied using a software tool.

- The 1950 HCM method (*1*) was based on a capacity model that has persisted through the four subsequent editions of the HCM: capacity is the product of the maximum flow rate (as it was called then) and the green ratio. The saturation flow rate (as it is called now) was calculated as a function of the approach width and other adjustment factors.
- The 1965 HCM method (*2*) added the concept of level of service, based on load factor: the ratio of the number of loaded phases to the total number of phases during the hour. The 1950 capacity model was modified to include additional adjustments to the saturation flow rate based on conditions found in the field.
- The 1985 HCM method (*3*) included a new performance measure from which to determine level of service: delay. Consideration was also given to the pattern in which vehicles arrive at the intersection and additional adjustments were made to the saturation flow rate. The capacity model remained unchanged, and signal control was still assumed to be pretimed. The concept of effective green time was introduced to clarify how much of the yellow time could be used by vehicles entering the intersection and the amount of the green interval that was lost due to vehicles starting up at the beginning of green. The lane group, rather than the intersection approach, became the basic unit of analysis.
- The 2000 HCM method (*4*) introduced a model to calculate green time based on actuated control, though pretimed control remained the default condition. Multiple analysis periods were introduced to accommodate oversaturated conditions.
- The 2010 HCM method (*5*) is based on actuated signal control as the default condition, with a complex method to estimate green time. The arrival flow rate is predicted based on conditions at an upstream signalized intersection, allowing for a more precise estimate of the proportion of vehicles arriving during green. The queue accumulation polygon is now directly used to estimate delay for all situations including complex arrival and signal phasing patterns. Level of service measures were added for two new modes (pedestrians and bicyclists) allowing for a multimodal level of service analysis.

There is a growing friction between the increased complexity of the method and the ability of users to understand the method. While funding agencies and users alike have asked that the method address geometric conditions such as distributed intersections, control conditions such as actuated-coordinated signal systems, and oversaturated demand conditions requiring multiple-time period analysis, users have also asked for simple presentations of the method and understandable representations of field conditions. Yet, for example, 20 pages of text and 45 equations are required to describe the procedure that predicts phase duration for actuated control. This friction results in a conundrum that has yet to be resolved.

Fewer committee and subcommittee members have had or taken the time to understand the full details and implications of the method for which they are responsible. This situation, while understandable as the complexity of the method has grown, should be unacceptable to those of us in the profession. As illustrated by the most recent HCM update, the committee is driven by the tight production schedule of the contractor producing the update, often with insufficient time and resources to consider the implications of the update.

The signalized intersection method is only one of many traffic analysis tools available to the transportation engineer today. This is in contrast to the situation that existed when the 1985 HCM was released. At that time, the HCM method was the primary (if not the only) method available to transportation engineers, and it was often applied using single-pass paper worksheets, a pencil, and a calculator. Today, far fewer transportation engineers use the method than in the past, choosing instead microsimulation models such as VISSIM or software tools such as Synchro. While the HCM was at one time required by the Federal Highway Administration (FHWA) for traffic analysis in federal-aid projects, this is no longer the case. While no quantitative studies exist, some engineers estimate that Trafficware's Synchro now controls over 75 percent of the traffic analysis tool market. Another complicating factor is the slow adoption rate of the HCM 2010 method. Anecdotally, it appears that most agencies continue to rely on the HCM 2000 signalized intersection method, more than five years after a major update to the signalized intersection method was published.

The evolution of the signalized intersection method has often been piecemeal, and not systematic. It can be argued that the 1985 HCM method was the first systematic approach to the analysis of signalized intersections, incorporating a set of worksheets and a linear step-by-step solution process. Since the publication of the 1985 HCM, a number of adjustment factors and sub-models have been added to the method. In most cases, the sub-model or factor makes intuitive or theoretical sense, helping to make the overall method more complete or able to cover a wider variety of traffic, geometric, and control conditions. However, rarely, if ever, has a new sub-model or factor been subjected to an important test: did it improve the final results or help the analyst to better answer the question that he or she was trying to answer. In short: did it "add value" to the signalized intersection method. For example, the upstream signals sub-model of the two-way stop-controlled (TWSC) intersection method, added to the 1997 HCM, provides a more theoretically-satisfying way of accounting for the platooned arrival patterns that result from the presence of an upstream signalized intersection. Recent research (6) has shown, however, that this sub-model doesn't make any significant difference to the prediction of capacity. No value is added to the TWSC intersection method when the upstream signals sub-model is applied.

There have been few instances in which the method has been validated during the past thirty years. Yet we are in an era of big data in which high resolution data for traffic flow and signal controllers are widely available. Automated and connected vehicles, high-resolution traffic signal data, and probe-based travel time data further enrich these data sets. However, these new sources of data have not yet been tapped for either model validation or to extend theory into new ways of thinking about signalized intersection operation.

3. IDEAS FOR CONSIDERATION

Resolving a crisis that has taken more than thirty years to develop is no easy task. The appetite for funding research on signalized intersection analysis is low among the AASHTO committees that rank projects for NCHRP, the primary source of funding for HCM research. In addition, the work of the committee continues to be a volunteer effort with, as noted earlier, the increasingly difficult task of managing the signalized intersection method.

At this point, there is no consensus on how to proceed, only that many committee members and practitioners agree that a "problem" exists. We suggest three ideas for consideration of the CHCQS, and the Signalized Intersection Subcommittee, to address this crisis. While these ideas could be implemented as a series of volunteer efforts over a period of time, we suggest that, instead, a set of research problem statements be developed and funding sought so that a more timely resolution can be achieved.

Idea #1: More clearly identify user groups of the HCM and their needs.
Perhaps the most important issue is that different HCM users have different needs and the current signalized intersection chapters are not sensitive to these differences. We suggest that there are three primary groups of HCM users: practitioners, researchers and teachers, and software developers. Each group has its own needs that must be met by the HCM.

1. The largest group of HCM users consists of practitioners, including DOTs, local agencies, and consultants. University students, as future practitioners, are also included in this group. This group needs to (a) understand basic concepts of traffic flow and signalized intersection operations, (b) know what data are needed to solve a particular type of problem, and (c) know how to interpret the results produced from an analysis. This group will almost always use software to conduct a traffic analysis.
2. Researchers and teachers have the same three needs as practitioners. In addition, they need to have access to and understand the details of all of the computational procedures that make up the signalized intersection method so that they can test them, extend them, and teach them.
3. Software developers need a complete and unambiguous description of these computational procedures, for all cases that are within the scope of the method, so that they can develop the software tools needed by practitioners.

We suggest that funding be sought through the NCHRP synthesis program to develop a comprehensive profile of practitioners who use traffic analysis tools, what tools they currently use, how they apply these tools, and what their application needs are. This study should be comprehensive in nature with a large number of users from each of the three groups. The synthesis project should also address the way in which users interact with the HCM to help the committee and TRB develop a forward-looking strategy for how HCM content on signalized intersections should be maintained, updated, and accessed over time. This examination of user needs would have implications for and benefits to all HCM chapters.

Idea #2: Present the method around the needs of each group of users.
We suggest that the presentation of the method be structured around the needs of each of these user groups. To accomplish this goal, we suggest six thoughts on how the presentation of the method might be structured:

1. We expect that this study of HCM user groups will confirm our sense that over 95 percent of HCM users are practitioners. If this is confirmed, the presentation of the chapter should be refocused on the needs of practitioners. The content of the primary signalized intersection chapter (soon to be chapter 19) should be for practitioners, while the needs of researchers, teachers, and software developers should be placed in the supplementary chapter (chapter 31).
2. Users currently have great difficulty finding the information that they need in the signalized intersection chapters. As any software user knows, what is “under the hood” is of no value unless the user interface allows easy use of the software tool. A revised chapter should provide roadmaps or other guidance to users to help them find what they want to know to accomplish what they want to do. Various parts of the method are now scattered among six chapters, two dealing with signalized intersections directly and four others dealing with signalized intersections as part of urban facilities and streets. For example, to account for the effect of an upstream signalized intersection on the arrival flow pattern at the subject signalized intersection, the user must consult three chapters of the HCM 2010. Exhibit 1 provides an example roadmap based on the structure of the HCM 2015 update.
3. Provide a number of example applications so that the practitioner can learn how each part of the method works on its own. We have listed thirteen such examples in Exhibit 2 to illustrate the application of various parts of the signalized intersection method. Twelve of these example applications are based on a set of simplified scenarios in which only one or two elements of the method are illustrated at a time. For example, Application 2, in which the calculation of uniform delay is illustrated, is based on one lane group assuming pretimed control, ideal conditions, and demand less than capacity. Application 9, which illustrates the calculation of green duration for

actuated control, is based on an intersection with two intersecting one-lane streets, two signal phases, demand less than capacity, and ideal conditions. These simplified scenarios allow the user to learn about one or two concepts at a time without having to consider other issues that complicate the learning process.

4. Describe the concepts needed to understand and apply the method at a level appropriate for the most common users. Traffic flow and signal operations concepts are currently described in both chapters 19 and 31. They need to be consolidated and focused on the needs of the practitioner. An illustration of a set of concepts focused on the needs of the practitioner is presented in Exhibit 3.
5. Refocus the presentation of the method so that an analyst can select the model attributes appropriate for the problem that he or she is trying to solve. Consideration should be given to the detail needed to represent a signalized intersection for a particular problem and the required accuracy needed from the results of an analysis. Just because an analyst is studying an actuated signalized intersection that is part of a coordinated system doesn't mean that he or she must necessarily estimate green times using a model based on actuated signal control. There are no case studies that show that this complex representation of a signalized intersection produces better results than a more simplified representation based on critical movement analysis and green time estimates using a pretimed model.
6. Provide guidance to users on what input data are needed for a particular problem type. Currently, one table in Chapter 19 presents an exhaustive list of the data required for any application of the signalized intersection operational analysis method. No guidance is given on what data are needed for particular problem types. In some cases the user has only minimal data available, such as demand and geometric data. In these cases, default values (such as peak hour factor and percentage of heavy vehicles) can be used. In other cases, when more information is known about the intersection, these data can be included in the analysis. An example presentation of data requirements based on the complexity of the problem being addressed is given in Exhibit 4.

Idea #3: Conduct a systematic assessment of the existing method.

We suggest that a systematic assessment of the existing method be undertaken to consider the following three issues. This assessment, in conjunction with the restructuring of the presentation described in the previous section, will provide the substance needed for the next version of the signalized intersection method.

1. Determine the value added by each factor and sub-model. As we suggested earlier, a number of factors and sub-models have been added to the signalized intersection method during the past thirty years. Most of these changes have been motivated by the desire for theoretical completeness or consistency. However, very rarely have numeric studies been done to determine if the results produced by these changes were better than those achieved with the preceding version of the model. The move to an actuated control model in the HCM 2010, for example, requires significantly more data and a sizable increase in knowledge for the average practitioner than does the method in the HCM 2000. Does this change improve the quality of the predictions produced by the signalized intersection method? No one can answer that question at this time.
2. There have been few instances of validation of the signalized intersection method during the past thirty years, even as these additional factors and sub-models have been added to the method. We suggest in addition to the "value added" studies proposed in the bullet above, a parallel effort be undertaken to validate the signalized intersection method, and its component models, using the increasing number of high resolution data sets now widely available.
3. Address how these advanced and emerging data sources can be integrated into the analysis of a signalized intersection, particularly the new high resolution data sets on traffic flow and signal timing. Should the basic form of the method be changed using new insights gained from these data? Should the performance indicators be changed to reflect the parameters that can now be directly measured? Should the emphasis on a deterministic queuing model be scrapped in favor of amassing a large number of data sets from which the analyst can select comparable conditions to the problem he or she is addressing? This latter idea could be developed using FHWA's Research Data Exchange (7).

4. FINAL THOUGHTS

The reader may not agree with our characterization that the signalized intersection method is in a state of crisis. But regardless of what word or phrase is used to describe the current situation, it is clear that now is the time to consider fundamental changes to the method and the way it is presented. The three ideas presented above would result in a better sense of the needs of HCM users, a method that is structured around these needs, and a series of assessments designed to produce a more effective and usable method. Now is the time to begin this work, before the pressures that understandably result from the production schedule of a new HCM surface once again.

REFERENCES

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(6) Kyte, Michael, Enas Amin, and Rod Troutbeck, "The Effect of an Upstream Traffic Signal on the Capacity of a Downstream TWSC Intersection", Transportation Research Record (In Press), A Journal of the Transportation Research Board, Washington, D.C. 2015.

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What Do You Want To Do – Example Roadmap

Task	Page Reference	Task	Page Reference
Learn about important concepts…		**Learn about extensions to the automobile methodology…**	
•Types of traffic control	19.3	•Determine critical intersection v-c ratio	19.57
•Intersection traffic movements	19.4	•Calculate uniform delay using QAP	19.61
•Signal phase sequence	19.4	•Determine lane group flow rate on multiple-lane approaches	31.22
•Operational modes	19.6	•Develop a QAP	31.42
•Left-turn phase sequence	19.7	•Determine saturation flow rate, capacity, and delay for LT movements	31.45
•Traffic flow characteristics	19.8	•Determine saturation flow rate adjustment factors for bikes-peds	31.34
•Phase duration	19.11	•Calculate initial queue delay	19.64
•Analysis type	19.12	•Determine saturation flow rate a adjustment factor for work zones	31.40
•LOS criteria	19.13	•Adjustment for sustained spillback	30.13
		•Arrival flow prediction	30.9
		•Determine phase duration for…	
		actuated operation	31.2
		pretimed operation	31.30
		•Determine queue storage ratio	31.63
Learn about the scope of the methodology…		**Apply the planning method…**	
•Basic scope	19.15	•Apply the planning method	31.78
•Control type	19.17	•Develop service volume tables	19.91
•Signal operation	19.17		
•Spatial/temporal limits	19.17		
•Performance measures	19.19		
•Limitations	19.19		
•Lane and movement groups	19.20		
Learn about the required input data…		**Conduct other tasks…**	
•Overview	19.20	•Interpret results	19.54
•Traffic characteristics	19.22	•Review an example problem	31.126
•Geometric control	19.31	•Measure control delay in field	31.98
•Signal control	19.32	•Measure saturation flow rate in field	31.104
•Other data	19.38	•Use alternative tools	19.93 31.118
Apply the automobile methodology…		•Review computational engine documentation	31.110
•Overview	19.40		
•Determine lane and movement groups	19.41		
•Determine movement group flow rate	19.43		
•Determine lane group flow rate	19.43		
•Determine adjusted saturation flow rate	19.44		
•Determine proportion arriving during green	19.48		
•Determine signal phase duration	19.49		
•Determine capacity and v-c ratio	19.49		
•Determine delay	19.49		
•Determine LOS	19.54		
•Determine queue storage ratio	19.54		

Exhibit 1

Example Applications

General Application

- Application 1. Determine units of analysis including lane groups and movement groups

Example Applications for Lane Groups

- Application 2. Calculate uniform delay using both the queue accumulation polygon and the uniform delay equation
- Application 3. Calculate the capacity of an exclusive left turn lane operating under permitted phasing
- Application 4. Calculate delay under non-uniform arrivals
- Application 5. Calculate delay when demand exceeds capacity and/or when there is a queue at the beginning of the analysis period
- Application 6. Calculate saturation flow rate when conditions are non-ideal

Example Applications for an Intersection

- Application 7. Calculate capacity sufficiency using the critical movement analysis
- Application 8. Translate signal timing information for ring-barrier control that uses NEMA phase assignments to HCM inputs
- Application 9. Determine green splits and cycle length under pretimed signal control
- Application 10. Determine green duration under actuated control

Other Example Applications

- Application 11. Determine geometric and control conditions to meet a policy target
- Application 12. Determine the sufficiency of a left turn lane
- Application 13. Determine the effectiveness of a signal timing plan

Exhibit 2

Basic Concepts

- Deterministic queuing model: The signalized intersection is represented by a deterministic queuing model.
  - Arrival and service patterns during one cycle using flow profile diagram.
  - Queuing process using cumulative vehicle diagram and queue accumulation polygon.
- Sequencing and controlling movements: Safety (primarily) and efficiency (secondarily) determine the sequence in which movements are served at a signalized intersection.
  - Movement and phase; numbering schemes.
  - Sequencing of phases using the ring barrier diagram.
- Signal timing: The elements of signal timing include the duration of the cycle and the phases that make up the cycle, and the duration of the green, yellow, and red clearance intervals.
  - Pretimed control (cycle duration, phase duration).
  - Actuated control (minimum green time, passage time, and maximum green time).
- Capacity: The capacity of a lane or approach is the maximum sustainable hourly flow rate at which persons or vehicles reasonably can be expected to traverse a point during a given time period under prevailing roadway, environmental, traffic, and control conditions.
  - Saturation flow rate.
  - Effective green and red times.
  - Green ratio.
  - Capacity as product of saturation flow rate and green ratio.
- Sufficiency of capacity: The sufficiency of capacity is the proportion of capacity that is utilized by the demand.
  - Flow ratio (Y).
  - Volume-to-capacity ratio (X).
- Control delay: Control delay is the delay associated with vehicles slowing in advance of an intersection, the time spent stopped on an intersection approach, the time spent as vehicles move up in the queue, and the time needed for vehicles to accelerate to their desired speed. Control delay includes three components: uniform delay, incremental delay, and initial queue delay.
  - Uniform delay resulting from uniform arrival flow pattern. It is the primary component of delay when demand is low or moderate. It is calculated using the uniform delay equation when demand is less than capacity. It can also be calculating using a queue accumulation polygon with demand is either less than or greater than capacity.
  - Incremental delay resulting when arrival flow is not uniform and/or when demand exceeds capacity during some parts of the analysis period. Overflow delay is the predominant component of delay when demand is high and is near capacity.
  - Illustrate initial queue delay occurs when there is an initial queue at the beginning of the analysis period.
- Queue length: The queue length is represents by the back of queue size and the queue storage ratio. The back of queue is the position of the vehicle stopped farthest from the stop line during the cycle as a consequence of the display of a red signal indication. The back-of-queue size depends on the arrival pattern of vehicles and on the number of vehicles that do not clear the intersection during the previous cycle. The queue storage ratio represents the proportion of the available queue storage distance that is occupied at the point in the cycle when the back-of-queue position is reached.

Exhibit 3

Guidance for Data Requirements

Traffic Characteristics Data			
Input Data Element	**Basis**	**Basic Methodology**	**Advanced Methodology**
Demand flow rate	Movement	x	x
Right-turn-on-red flow rate	Approach		x
Percent heavy vehicles	Movement group	x	x
Intersection peak hour factor	Intersection	x	x
Platoon ratio	Movement group		x
Upstream filtering adjustment factor	Movement group		x
Initial queue	Movement group		x
Base saturation flow rate	Movement group		x
Lane utilization adjustment factor	Movement group		x
Pedestrian flow rate	Approach	x	x
Bicycle flow rate	Approach		x
On-street parking maneuver rate	Movement group	x	x
Local bus stopping rate	Approach		x
Unsignalized movement delay			x

Geometric Design Data			
Input Data Element	**Basis**	**Basic Methodology**	**Advanced Methodology**
Number of lanes	Movement group	x	x
Average lane width	Movement group		x
Number of receiving lanes	Approach		x
Turn bay length	Movement group		x
Presence of on-street parking	Movement group	x	x
Approach grade	Approach		X

(Continued on next page)

Guidance for Data Requirements (continued)

Signal Control Data					
Input Data Element	**Basis**	**Basic Methodology**	**Advanced Methodology**		
Type of signal control	Intersection	Pretimed	Pretimed	Actuated	Actuated-Coordinated
Phase sequence	Intersection	x	x	x	x
Left-turn operational mode	Approach	x	x	x	x
Green duration	Phase	x	x		
Passage time	Phase			x	x
Maximum green	Phase			x	x
Minimum green	Phase			x	x
Yellow change	Phase	x	x	x	x
Red clearance	Phase	x	x	x	x
Walk	Phase		x	x	x
Pedestrian clear	Phase		x	x	x
Phase recall	Phase			x	x
Dual entry	Phase			x	x
Simultaneous gap-out	Approach			x	x
Cycle length	Intersection	x	x		x
Phase splits	Phase				x
Offset	Intersection				x
Offset reference point	Intersection				x
Force mode	Intersection				x

Other Data					
Input Data Element	**Basis**	**Basic Methodology**	**Advanced Methodology**		
Type of signal control		Pretimed	Pretimed	Actuated	Actuated-Coordinated
Analysis period duration	Intersection	x	x	x	x
Speed limit	Approach		x	x	x
Stop-line detector length and detection mode	Movement group			x	x
Area type	Intersection		x	x	x

Exhibit 4