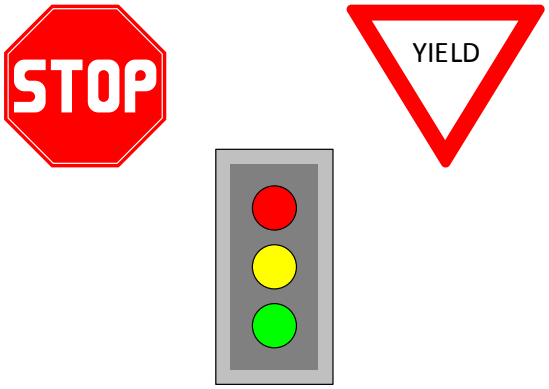
Traffic Operations at Intersections: Learning and Applying the Models and Methods of the Highway Capacity Manual Using Simplified Scenarios and Computational Engines



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Rod Troutbeck

First Edition

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Dedication

To the memory and life of Michael Perry Dixon (1970-2014), a great colleague and an even better friend.

Acknowledgements

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INTRODUCTION

> "In my first professional engineering job after I finished graduate school, I worked as part of a team studying the environmental impact of a proposed freeway in Portland, Oregon. My task was to analyze the performance of signalized intersections to be constructed on the parallel arterials as part of the freeway project. Our intersection analysis was conducted based on the 1965 Highway Capacity Manual using nomographs and worksheets. A typical analysis took about 10 to 15 minutes for each intersection."
>
> What's a nomograph? Look it up!

Intersections are where it all comes together. People in cars, buses, trains. People on bicycles. People on foot. All wanting to get through a point, the intersection, to get somewhere.

Traffic engineers spend a lot of time thinking about this flow of people through intersections using new and innovative designs, hoping to reduce the delay experienced by travelers, and increase the flow of people through the intersection.

But with each new design comes the need to understand how the intersection will operate and what experience the traveler will have at the intersection. To answer these questions, the traffic engineer often turns to a model to help predict the performance of the design. And, he or she has a choice from a selection of models now available.

The models of the Highway Capacity Manual (HCM) are often the engineer's choice to analyze the performance of an intersection. These models are complex and nearly all transportation engineers use software implementations of these models to conduct their analysis. Software applications are powerful tools that help engineers solve problems. But these applications also serve as barriers to the understanding of the complex models embedded in the software. One of the major objectives that we had in writing this book was to transform the black box of a software application into a clear box that allows the engineer to better understand how these models actually work.

Intersection Types

The HCM includes methods to analyze the operation of intersections with four different types of control, all-way stop-controlled intersections, two-way stop-controlled intersections, roundabouts, and signalized intersections.

All-way stop-controlled (AWSC) intersections require users on each approach to first stop and then decide when it is their turn to enter the intersection. The time that a user waits at the stop bar, or in a queue waiting to get to the stop bar, depends on the number of approaches on which other users are also waiting. We call this the degree of conflict between users. The operation of the intersection is dynamic as users are continually monitoring each other's behavior as they decide when it is safe for them to enter the intersection.

Two-way stop-controlled (TWSC) intersections require users on the stop-controlled approaches to stop and judge when it is safe for them to enter and pass through the intersection. We call this process gap acceptance. Users on the major street simply travel through the intersection as users on the stop-controlled approach wait for large enough gaps in the major street traffic.

Roundabouts also require users to make judgements on whether a gap in the circulating traffic stream is large enough for them to enter the circle. Unlike at a stop-controlled approach, however, a user can enter the circle, if he or she judges it is safe to do so, without stopping.

Traffic signals, by contrast, provide a clear indication to users when it is their turn to enter the intersection. If the indication is red, the driver must stop and wait. If the indication is green, the user can enter the intersection. Driver behavior and judgement, while still important to the safe operation of a signalized intersection, is much less important than for stop-controlled intersections and roundabouts. However, the manner in which green time is allocated between the conflicting traffic streams is critical to the operation of the intersection.

Evolution of the HCM Methods

The first edition of the HCM was published in 1950 and included a total of 147 pages devoted to two and three lane roads, signalized intersections, weaving sections and traffic circles, and ramps and their terminals. The sixth edition, published in 2016, includes xx pages in three hard copy volumes as well as significant online supplementary material. The methods addressing both interrupted and uninterrupted flow facilities have grown more complex as traffic science has grown more capable, the data describing traffic systems has become more detailed and ubiquitous, and the nature of transportation problems has become more challenging.

The signalized intersection method is the most widely used of the various analysis methods of the HCM. The signalized intersection method has evolved significantly since the publication of the first HCM more than sixty years ago with the number of pages devoted to the method growing from 39 in 1950 to 243 in 2016.

- The 1950 HCM method was based on a capacity model that has persisted through five 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 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 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 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 and the 6th Edition are 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.

The signalized intersection method has evolved into a rich representation of a very complex system. The system includes four elements:

- A variety of users arriving at the intersection in different and sometimes changing patterns,
- Detectors sensing when these users arrive,
- Complex intersection geometries accommodating various user movements, and
- A traffic controller determining both the sequence and the duration of the various signal indications to serve the users.

What are the traffic flow and control principles that are important for a student to understand as he or she learns the signalized intersection method of the HCM? Seven questions or ideas relating to the operation and analysis of signalized intersections have persisted through the six editions of the HCM:

- How is capacity modeled?
- What factors affect the saturation flow rate?
- How is the signal control system, including the duration of green, modeled?
- How are left turns modeled?
- How is the flow modeled as it arrives during each cycle and how does it vary during the hour?
- What is the unit of analysis by which the intersection is modeled?
- How is the performance of the intersection perceived by the user and how is it modeled?

Unsignalized intersections were briefly covered in the 1950 and 1965 editions of the HCM. Both editions included sections on traffic circles as part of the weaving section method. The 1985 HCM included a method for TWSC intersections adapting models developed in Germany and Australia. The 1997 HCM included new methods for AWSC and TWSC intersections based on the first comprehensive study of U.S. conditions. The HCM 2000 was the first to include a method to analyze roundabouts. The roundabout method was expanded in the 2010 edition based on the first studies of roundabout operation in the U.S.

Pedagogical Approach Used in this Book

How do you teach the methods of the Highway Capacity Manual? Do you read the HCM carefully, learning the method for each facility, working out the example problems, studying all of the adjustment factors? Or do you read the input screens for a software tools that implements the HCM methods, without understanding the underlying models that make up each method?

The pedagogical approach that we've taken in the preparation of this book is based on two ideas. First, the material needs to focus on the basic elements of the HCM methods for signalized and stop-controlled intersections. When we ask you to learn about one element of a model, we will focus only on that one element, within a set of very limited conditions greatly simplified from what you'd normally see in the field. By focusing only on one element at a time, you will develop a basic understanding of the operation of an intersection, one that you can later build upon as the more complex conditions found in the real world are considered. We call these simplified scenarios.

Second, the material needs to allow the students to build their own tools to implement the computational procedures developed for each simplified scenario. These computational engines provide students with the opportunity to both test their understanding of the methods as well as a means to see what each method will predict under a given set of conditions.

We consider eleven simplified scenarios in this book, two for ASWC intersections, two for TWSC intersections, and seven for signalized intersections. For example, in building your understanding of the operation of AWSC intersections, we start with an intersection of two one-lane one-way streets,

later building to a standard four-approach intersection. But even in this second scenario, you will only consider through movements and no pedestrians. When you master the concepts presented in these two scenarios, you can then confidently use software applications to consider the more complex conditions found in the field.

Similarly for signalized intersections, seven aspects of the full HCM model are presented in ways that encourage understanding of the complexity of the full method, one step at a time. For example, one of the most complex elements of the signalized intersection method in the HCM is the prediction of green times under actuated signal control. Scenario 7 in chapter 3 presents this method in the context of simplified traffic flow and geometric conditions: an intersection of two one-way streets with one lane on each approach serving through movements only. Figure 1 shows such a simplified scenario in which the subject intersection (the intersection on the right side of the figure) consists of two intersecting one-way streets with only two traffic movements, shown as movements 2 and 4 in the figure. The arrival pattern for movement 2 is based on the flow from the upstream intersection, shown in the left side of the figure. This simplified scenario allows students to focus on the concept green time estimation, free of the complications that result when considering eight-phase dual ring actuated control with a full range of turning movements from exclusive and/or shared lanes.

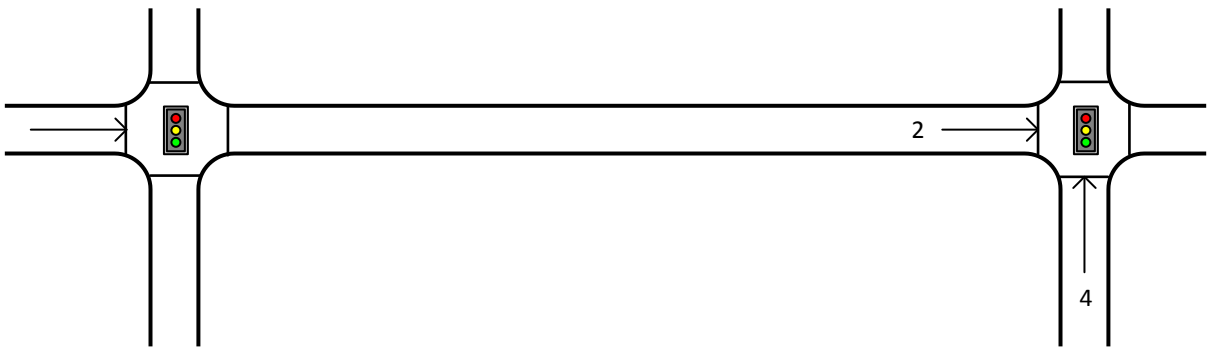

Figure 1. Simplified geometric scenario for signalized intersection method

Computational engines are developed for seven of the simplified scenarios. Templates and example formulas are given to assist students in the construction of their own computational engines. The computational engines can then be applied so that students can better understand and interpret the results that the models produce for a range of traffic and control conditions. Parametric studies further encourage this experimentation with and learning about the HCM models. Each of the models is illustrated with graphics that clearly show the concepts. More than 40 example calculations are presented to illustrate how the calculations are applied and carried out.

Most university graduate students and transportation engineering practitioners have the background to undertake the study of the materials presented in this book. We assume a basic knowledge of queuing theory and probability and statistics, as well as a general understanding of traffic flow concepts. The book can effectively be used as the primary text for a one quarter or one semester graduate level course. The material can also be adapted for a professional development course.

One final point: where is the roundabouts chapter? We decided, rightly or wrongly, that since the gap acceptance method, on which the roundabout capacity method is based, is described in chapter 2, a separate chapter on roundabouts was not needed.

Organization of the Book

Chapters 1 through 3 cover analysis methods for all-way stop-controlled intersections, two-way stop-controlled intersections, and signalized intersections. Each chapter describes what we observe in the field for each intersection type, how the models are formulated based on these observations, and a set of simplified scenarios to illustrate the key aspects of each model. Finally, computational engines are built for one or more of the simplified scenarios. Each chapter also includes worked example calculations, a summary, a glossary, and references. A companion web site (URL to be added) includes more references as well as problems that can be used to test your understanding of these methods.

We wish you safe travels on your journey through the intersections that lie ahead!