Final Report
to the
NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM
(NCHRP)

Prepared by
The University of Florida
Transportation Research Center
and
T-Concepts Corp.

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Acknowledgments

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The work was done under the general supervision of Prof. Courage. William Sampson, Director of the McTrans Center at the University of Florida, was a key advisor to the project team on traffic analysis software and on user perspectives of the Highway Capacity Manual (HCM) procedures. Michael Mahut and Pete Sykes provided valuable input to the material on dynamic traffic assignment.

The results of this effort were incorporated into the 2010 Edition of the HCM under NCHRP Project 3-92. The principal investigator for that project was Mark Vandehey, Kittelson and Associates. Jim Bonneson, Texas A and M University, provided valuable input on the HCM 2010 analysis procedures for signalized intersections and urban street facilities.

The HCM 2010 content developed by this project was reviewed extensively by the TRB Highway Capacity and Quality of Service (HCQS) Committee, the guardian of the HCM. Richard Dowling and Lily Elefteriadou chaired this committee at different times during the course of the project. The HCQS Simulation Subcommittee, chaired by Loren Bloomberg, was responsible for coordinating the adoption of most of the project results into the HCM. Subcommittee task groups led by Erik Ruehr and Grant Zammit worked closely with the project team to prepare the material for adoption.

Ray Derr was the contract manager for NCHRP. The NCHRP Project Panel members were Martin Bretherton Jr. (Chair), Troy Arseneau, Yupo Chan, Susan Gorski, Steven Jones Jr., James "Kevin" Lacy, Erik Ruehr, Rupinder Singh, and Grant Zammit.

The research team appreciates the efforts of everyone who contributed to the success of this project.
Abstract

The objective of this project was to develop guidance to assist analysts in the use of alternative traffic analysis tools in conducting the types of analyses that are within the domain of the Highway Capacity Manual (HCM). The results were incorporated into the 2010 edition of the HCM. This report describes the tasks that were carried out to produce the guidance material and summarizes the results of these tasks.

The alternative tool guidance (ATG) material that appears in the HCM 2010 is the principal output of this project. ATG results from the project have been provided to 20 of the 35 chapters. Four of those 20 chapters were devoted entirely to ATG and another three had more than 50% ATG content.

Studies that went beyond the ATG development for the HCM were carried out to cover items that were off-limits to the HCM content, (e.g., comparisons between HCM and alternative tool results), examples that were too detailed to be included in the HCM, situations in which experience with alternative tools was insufficient to support useful guidance for the HCM and the results of the research on trajectory analysis performed by this project.
1 Summary of Findings

The Highway Capacity Manual (HCM) is accepted within the professional community as a definitive reference for the estimation of capacity and evaluation of performance for a variety of highway facilities. In the pre-computer days, the HCM stood alone as the recognized evaluation methodology. As computers became more powerful, a set of parallel methodologies emerged in the form of computer modeling software products. Users often take advantage of the features of these products to expand the scope of an analysis and to improve productivity. Software products that perform functions similar to the HCM procedures are referred to in the HCM as “alternative traffic analysis tools, or simply “alternative tools.”

The TRB Highway Capacity and Quality of Service (HCQS) Committee is the guardian of the HCM, and must approve all of its contents. For purposes of this report, the HCQS Committee will be referred to simply as “the Committee.”

The objective of this project was to develop guidance to assist analysts in the use of alternative tools in conducting the type of analyses that are within the domain of the HCM. The original intent was to develop a section on alternative tool guidance (ATG) to be added to the HCM 2000. After the project started, the development of a new HCM edition (the HCM 2010) was initiated under NCHRP Project 3-92. The new HCM edition made three important changes to the ATG development process:

- It shifted the focus of this project from the conduct of research to the development of guidance material conforming to the HCM publication schedule.

- It created a whole new chapter structure that provided a better mechanism for dissemination of the ATG material developed under this project.

- It introduced an expanded multilevel review process that went well beyond the normal NCHRP review procedures. The review process consumed significant project resources but it paved the way for adoption of the results of this project as a part of the HCM 2010. As such, the review process was more of a benefit than a burden to the project.

The summary of findings is presented here in two parts. The first is an overview of the guidance that was developed on this project and adopted as a part of the HCM. The second summarizes additional research findings that were too detailed for the HCM.

1.1 Summary of Alternative Tool Guidance for the HCM 2010

The ATG material that appears in the HCM 2010 is the principal output of this project. ATG results from the project have been provided to 20 of the 35 chapters. Four of those 20 chapters were devoted entirely to ATG and another three had more than 50% ATG content.

A brief summary of the HCM 2010 ATG content is presented in Exhibit 1. An expanded summary is presented in narrative form in Section 3 of this report.
### Exhibit 1: Summary of alternative tool guidance in the HCM 2010

<table>
<thead>
<tr>
<th>Title</th>
<th>NCHRP 3-85 ATG Content</th>
<th>ATG Pages</th>
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</thead>
<tbody>
<tr>
<td>1 HCM Users Guide</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>2 Applications</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>3 Modal Characteristics</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>4 Traffic Flow and Capacity Concepts</td>
<td>Section on estimation of traffic flow parameters, introducing vehicle trajectory analysis as the most appropriate way to reproduce field data</td>
<td>4</td>
</tr>
<tr>
<td>5 Quality of Service Concepts</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>6 Analysis Tools</td>
<td>ATG Section: “Alternative Tools”</td>
<td>21</td>
</tr>
<tr>
<td>7 Interpreting and Presenting Results</td>
<td>ATG Section: “Defining and Computing Uniform Performance Measures”</td>
<td>21</td>
</tr>
<tr>
<td>8 HCM Primer (Formerly Executive Summary)</td>
<td>Reference to the need for alternative tools</td>
<td></td>
</tr>
<tr>
<td>9 Glossary and Symbols</td>
<td>Includes ATG terms</td>
<td></td>
</tr>
<tr>
<td>10 Freeway Facilities</td>
<td>ATG Section with standard headings (Note 1)</td>
<td>6</td>
</tr>
<tr>
<td>11 Basic Freeway Segments</td>
<td>ATG Section with standard headings (Note 1)</td>
<td>4</td>
</tr>
<tr>
<td>12 Freeway Weaving Segments</td>
<td>ATG Section with standard headings (Note 1)</td>
<td>3</td>
</tr>
<tr>
<td>13 Freeway Merge and Diverge Segments</td>
<td>ATG Section with standard headings (Note 1)</td>
<td>4</td>
</tr>
<tr>
<td>14 Multilane highways</td>
<td>Note 2</td>
<td></td>
</tr>
<tr>
<td>15 Two-Lane Highways</td>
<td>Note 2</td>
<td></td>
</tr>
<tr>
<td>16 Urban Street Facilities</td>
<td>Covered in Ch 17 and 18</td>
<td></td>
</tr>
<tr>
<td>17 Urban Street Segments</td>
<td>ATG Section with standard headings (Note 1)</td>
<td>3</td>
</tr>
<tr>
<td>18 Signalized Intersections</td>
<td>ATG Section with standard headings (Note 1)</td>
<td>4</td>
</tr>
<tr>
<td>19 Two-Way Stop-Controlled Intersections</td>
<td>ATG Section with standard headings (Note 1)</td>
<td>3</td>
</tr>
<tr>
<td>20 All-Way Stop-Controlled Intersections</td>
<td>Placeholder</td>
<td></td>
</tr>
<tr>
<td>21 Roundabouts</td>
<td>ATG Section with standard headings (Note 1)</td>
<td>5</td>
</tr>
<tr>
<td>22 Interchange Ramp Terminals</td>
<td>ATG Section with standard headings (Note 1)</td>
<td>4</td>
</tr>
<tr>
<td>23 Off-Street Pedestrian &amp; Bicycle Facilities</td>
<td>Note 2</td>
<td></td>
</tr>
<tr>
<td>24 Concepts: Supplemental</td>
<td>Trajectory analysis examples</td>
<td>32</td>
</tr>
<tr>
<td>25 Freeway Facilities: Supplemental</td>
<td>Reference to other supplemental problems including HCMAG</td>
<td></td>
</tr>
</tbody>
</table>
### 1.2 Additional Research Findings

Studies that went beyond the ATG development for the HCM were carried out to cover the following cases:

- Items that were off-limits to the HCM content, especially comparisons between HCM and alternative tool results
- Examples that were too detailed to be included in the HCM
- Situations in which experience with alternative tools was insufficient to support useful guidance for the HCM
- The results of the research on trajectory analysis performed by this project.
A summary of the findings is presented here.

1.2.1 General Comparison of the HCM and Alternative Tools

Most traffic analysis tools deal with similar geometric and operational features and report the same nominal performance measures, although the definitions and methods of computation vary. There are some conceptual differences between the HCM’s analytical modeling and simulation modeling that are reflected in the way analytical and simulation tools deal with various traffic flow phenomena. These differences make direct comparison of results difficult and sometimes impossible.

1.2.2 Comparison of HCM and Alternative Tools on Specific Facility Types

New procedures have been developed for the HCM 2010 for two types of facilities that comprise a number of different segment types. Computational engines have been developed for testing those procedures but there is insufficient experience to support proper guidance for their use.

The computational engine for HCM Chapter 16, Urban Street Facilities, was tested with a case study and compared with other tools. The detailed results of the comparison are presented in Appendix 1 of this report. The following findings emerged:

- The new procedure represents a substantial improvement over the previous version originally published in the HCM 2000. It internalizes computations that had to be approximated or carried out externally in the previous version.
- The computational engine that implemented the procedure performed in a robust manner.
- There were no internal inconsistencies or anomalous behaviors in the results.
- The relationships between demand levels, phase times and average speeds conformed generally to expectations.
- The numerical results could not be expected to match those of the alternative tools because of differences in model formulation. The agreement was close enough that no judgment could be offered as to the absolute accuracy of any tool.
- A single case study does not constitute a complete evaluation of any traffic analysis tool. However, within the limits of this study, it can be said that the performance of the HCM 2010 urban street facilities procedure in the automobile mode supports the conclusion that it provides a credible method for evaluating the operation of an urban street facility. It offers a substantial contribution to the methodology of highway capacity and level of service analysis.

The computational engine for HCM Chapter 10, Freeway Facilities, was tested with two case studies and compared with a typical simulation tool. A series of basic freeway segment was used in one case study, which included an incident that blocked one lane of the facility for 15 minutes. The computational engine performed as expected and gave the appearance of a robust implementation the HCM Chapter 10 methodology. Several differences in the performance measures from simulation raised some skepticism about the way that the incident was modeled.

A second case study consisted of 11 freeway segments of various types. The simulation results usually matched the HCM procedure within 10%. The largest differences occurred in a weaving segment because the complex integrations between vehicles are modeled differently by the HCM and simulation tools.
User experience with two lane highway simulation was not sufficient to support proper guidance in Chapter 15 of the HCM, mainly due to lack of available simulation tools. A set of five simulation experiments was carried out to evaluate a new version of a simulation tool that offers two-lane highway simulation features. With this new simulation capability, traffic operations on complex two-lane highways (e.g., two-lane highway with occasional signalized intersections) can be analyzed. The overall observations suggest that the simulation tool offers a realistic alternative for analyzing two-lane highways and is able to deal with situations beyond the stated limitations of HCM Chapter 15. The use of vehicle trajectory analysis techniques to analyze individual passing maneuvers was also illustrated.

1.2.3 Analysis of Vehicle Trajectories

Analysis of individual trajectories has been recommended by the Committee as the best method for computing uniform and consistent performance measures from different tools. The NCHRP Project 3-85 Panel supported this recommendation and added a task to the project to investigate the computational aspects of vehicle trajectory analysis. The following findings emerged from this task:

- Vehicle trajectory analysis was demonstrated to produce results that can be applied consistently among tools.

- It is not a practical end user technique because of the amount of data involved, especially when multiple simulation runs are required to produce statistically significant results. It is essential that the computational procedures be internalized in simulation tools by their developers.

- The computational procedures proposed in this document should offer a reasonable approximation of the performance measures that are estimated by other techniques, including field studies and the HCM. The proposed procedures depend to a certain extent on approximations and assigned thresholds but this dependency is no greater than the other techniques and should not produce issues of compatibility.

- A set of rules for computing uniform measures from trajectory analysis is proposed in this report. The same set of rules has been included in HCM Chapter 24, *Concepts: Supplemental*. These rules were developed in a manner that will make them practical for implementation in simulation tools.

- The most practical way to report performance measures from simulation tools is to assign all measures to the segment and time interval in which they accrue. It is not practical to offer a consistent trajectory analysis methodology that seeks to associate these measures with their root cause, which might be in some other part of the network or in some other time interval. While this constraint might not be consistent with the objectives of some analysts, it eliminates several intractable problems and issues.

- To ensure that all measures are fully reported, it is essential to define the analysis domain, both in time and space, such that a period of uncongested operation exists at all boundaries.
• The concept of control delay, as defined by the HCM, and the procedures by which it is computed, cannot be implemented in a consistent manner by vehicle trajectory analysis. However, a reasonable approximation of control delay is provided by the simulated “queue delay” measure, computed as prescribed in this document.

• There are now two standard formats for simulated trajectory files, including CORSIM’s animated graphics file and the Surrogate Safety Analysis model (SSAM) format that was developed by FHWA and is used by several tools. The CORSIM format was used in this project because it is better suited to computing performance measures. The SSAM format is much more detailed because it is meant for analysis of potential collisions as a surrogate safety measure. The SSAM format would be well suited to performance analysis if some additional data items were included. An expanded format for SSAM files is proposed in this report.
2 Introduction and Research Approach

2.1 Motivation and Need for the Research

The HCM is accepted within the professional community as a definitive reference for the estimation of capacity and evaluation of performance for a variety of highway facilities. In the pre-computer days, the HCM stood alone as the recognized evaluation methodology. As computers became more powerful, a set of parallel methodologies emerged in the form of computer modeling software products. Users often take advantage of the features of these products to expand the scope of an analysis and to improve productivity. Software products that perform functions similar to the HCM procedures are referred to in the HCM as “alternative traffic analysis tools,” or simply “alternative tools.”

The objective of this project was to develop guidance to assist analysts in the use of alternative tools in conducting the type of analyses that are within the domain of the HCM. The original intent was to develop a section on alternative tool guidance (ATG) to be added to the HCM 2000. After the project started, the development of a new HCM edition (the HCM 2010) was initiated under NCHRP Project 3-92. The new HCM edition made three important changes to the ATG development process:

- It shifted the focus of this project from the conduct of research to the development of guidance material to meet the HCM publication schedule.
- It created a whole new chapter structure that provided a better mechanism for dissemination of the ATG material developed under this project.
- It introduced an expanded multilevel review process that went well beyond the normal NCHRP review procedures. The review process consumed significant project resources but it paved the way for adoption of the results of this project as a part of the HCM 2010. As such, the review process was more of a benefit than a burden to the project.

2.2 Guidelines for the 2010 HCM for ATG Development

Since the objectives of the project could not be met without adoption of the results by the Committee, it was first necessary to establish guidelines for ATG development. Most of the guidelines came from Committee resolutions. Other sources included TRB policy and the NCHRP 3-92 (HCM 2010 development) team. As a starting point, a resolution was passed by the Committee in 2007 containing the following motions.

1. The Highway Capacity Manual should include guidance to developers of traffic simulation models and other traffic analysis tools to promote consistent and accurate reporting of measures of effectiveness for highway capacity analysis. This guidance should include a set of minimum criteria that all traffic analysis tools would be encouraged to achieve.

2. To promote consistency among traffic simulation models and other traffic analysis tools, the Highway Capacity Manual should include a recommended list of common measures of effectiveness (MOE’s). These MOE’s should be based on vehicle trajectories. The HCM should recommend that all traffic analysis tools include the functionality to provide those measures of effectiveness as outputs. For the purpose of this motion, vehicle trajectories shall be defined as

3. The Highway Capacity Manual should discourage the use of HCM level of service threshold tables based on measures of effectiveness reported by other traffic analysis tools that are inconsistent with HCM definitions.

4. The Highway Capacity Manual should include guidance that the measures of effectiveness produced by traffic simulation models and other traffic analysis tools are considered to be incomplete, unless they also include clear documentation of the assumptions used to handle and report vehicle queues.

5. The Highway Capacity Manual should include a discussion of the randomness inherent in the results of stochastic traffic simulation models and recommendations for dealing with this aspect of traffic simulation.

The project team coordinated with the Committee in the development of these motions and was aware of the importance of accommodating them. While the resolutions are important to the ATG development, they were not a major consideration in the development of the 2010 HCM chapter structure. Therefore a matrix relationship exists between the resolutions themselves and the proposed guidance material.

The manner in which each motion is addressed is described in Exhibit 2, which shows the matrix relationship between the motions and the guidance topics. Naturally, all guidance material was developed to be consistent with the motions. This table shows where the most relevant material was incorporated. Two levels of relevance are represented:

- “P” indicates that the principal focus of the topic will be on the specific motion.
- “M” indicates that the topic will contain specific material in direct support of the motion.

The following additional guidelines were observed:

- TRB discourages commercialism in any form in the research that it supports and publishes. The Committee has always been opposed to mentioning alternative traffic analysis tools by name in the HCM. Therefore, it was decided that no product names would be mentioned. There are a couple of cases in the supplemental material in HCM Volume 4 where the identification of specific tools was essential to a proper understanding of the material. In those cases, the identification was restricted to reference citations.

- Some of the supplemental material in HCM Volume 4 contained examples that illustrated the use of alternative tools to overcome limitations in the HCM procedures. In the development of those examples, only the limitations explicitly stated in the procedural chapters were addressed and no comparisons between the results of the HCM procedures and alternative tools were presented for situations that were within the scope of the HCM procedures. It was decided in consultation with the Committee and the NCHRP 3-92 project team that such comparisons were more appropriate to this final report.
Exhibit 2: Committee motions addressed by the proposed alternative tool guidance

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<th>Guidance Topic</th>
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<tr>
<td>Use of Vehicle Trajectory Analysis in Comparing Performance Measures</td>
<td>M</td>
<td>M</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stochastic Aspects of Simulation Analysis</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>P</td>
</tr>
<tr>
<td><strong>HCM Volumes 2 and 3: Procedures</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Strengths of the HCM Procedure</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Identified Limitations of the HCM Procedure</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Development of HCM-Compatibility Performance Measures Using Alternative Tools</td>
<td>M</td>
<td>P</td>
<td>M</td>
<td>M</td>
<td></td>
</tr>
<tr>
<td>Conceptual Differences between the HCM and Simulation Modeling that Preclude Direct Results</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>M</td>
</tr>
<tr>
<td>Comparison of Results</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Adjustment of Simulation Parameters to Match the HCM Parameters</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>M</td>
</tr>
<tr>
<td>Step-by-Step Procedure</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alternative Tool Example Problems</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Explanation of Symbols**
- **P** = Principal focus of the topic.
- **M** = Material in direct support for the motion will be included in the narrative.
2.3 HCM 2010 Chapter Review Process

The ATG material produced by this project was incorporated into HCM 2010 chapters and subjected to a formal review process prior to adoption by the Committee. The process for 2010 was considerably more comprehensive than previous versions. A team of reviewers was configured with representation from Committee members and friends of the Committee. All members of the NCHRP 3-85 Project Panel were included in the review team.

The steps in the process, which are illustrated in Exhibit 3, are summarized as follows:

1. The first draft is developed initially by the project team and posted on the HCM 2010 web site.

2. The first draft is subjected to a general review by the review team. At this point a decision is made regarding the need for a task group involving more members of the subcommittee responsible for the chapter. Task groups were appointed to work with the project team on two chapters involving substantial ATG content.

3. The general review comments are posted on the HCM 2010 web site.
4. The project team makes revisions to the first draft reflecting the review comments and posts a final draft on the web site. The project team also posts a response to each of the comments. The responses may fall into three categories:
   - Comment was accepted and changes were made
   - Comment was partially accepted but not all suggested changes were made
   - Comment was not accepted

5. The final draft is subjected to a follow up review, along with the responses to the review comments on the first draft. Follow up review comments are posted on the web site.

6. The project team then produces a draft for adoption by the Committee and posts responses to review comments on the web site. The adoption draft is first reviewed by the subcommittee responsible for the chapter to resolve any outstanding review comments to its own satisfaction. The draft is then forwarded to the full committee for adoption.

7. When the chapter has been adopted it is forwarded to TRB for an editorial review and publication.

This process consumed significant time and resources but it ensured the best possible product from the project team.

2.4 Additional Studies beyond the Scope of the 2010 HCM

Studies that went beyond the HCM scope were carried out to cover the following cases:
   - Items that were off-limits to the HCM content, especially comparisons between HCM and alternative tool results
   - Examples that were too detailed to be included in the HCM
   - Situations in which experience with alternative tools was insufficient to support useful guidance for the HCM
   - The results of the research on trajectory analysis performed by this project

The following studies were undertaken and the results are included in this report:

1. Assessment of new HCM facility-oriented procedures with good potential for alternative tool applications. New computational engines based on spreadsheets have been developed for both freeway and urban street facilities. Comparisons have been made between these spreadsheets and other methods.

2. Development of data analysis utilities that have potential application for other researchers. Three utility programs were developed and documented at a level that supports their use by other researchers.
   - CORSIM Capacity Analysis Postprocessor (CCAP)
   - Vehicle Trajectory Analysis for Performance Evaluation (VTAPE)
   - Traffic Actuated Controller Timing (TACTiming)

All of these utilities read outputs from the CORSIM simulation tool and present summaries in a format that supports the development of data relationships from multiple runs. They were all used to develop results that appear in this report.
3. Finalizing of material that was not included in the HCM chapters. There are two cases in which the research for the chapter material did not produce results that were incorporated into their respective chapters: The first was in HCM Chapter 25, *Freeway Facilities: Supplemental*. It was not possible to produce a freeway facility example that would provide useful guidance without incorporating the HCM procedure for comparison. Such comparisons are off-limits for the ATG but they are of interest to users and are therefore included in this report.

The second case involves HCM Chapter 15, *Two Lane Highways*. There were no alternative tools with sufficient user experience to support useful guidance. Recent developments in two lane highway simulation have been explored to investigate their potential as alternative tools.

4. Analysis of individual vehicle trajectories has been recommended by the Committee as the best method for computing uniform and consistent performance measures from different tools. The NCHRP Project 3-85 Panel supported this recommendation and added a task to the project to investigate the computational aspects of vehicle trajectory analysis.

This task was undertaken and material was developed for HCM Chapters 7 and 24. A data analysis utility named “Vehicle Trajectory Analysis for Performance Evaluation (VTAPE)” was developed to read and analyze simulated trajectory data. Additional results that were too detailed to include in the HCM chapters are reported in Section 3 and in Appendix 4 of this report. The VTAPE utility is documented in Appendix 5.
3 Findings

3.1 General Comparison of the HCM and Alternative Tools

There are some significant conceptual differences between the HCM’s analytical modeling and simulation modeling. Most of the differences may be described in terms of the way analytical and simulation tools deal with various traffic flow phenomena. Examples of the significant differences are identified in general terms in Exhibit 4. This exhibit was developed as a part of the general guidance for HCM Chapter 6, HCM and Alternative Analysis Tools. It has been included in HCM Chapter 6 as Exhibit 6-1.

A number of studies comparing the characteristics of simulation tools have been carried out. They were not repeated as a part of this project. One study reported by Dowling [1] compared the measures of effectiveness reported by several simulation tools. This information is summarized in Exhibit 5.

The Urban Transportation Monitor [2] conducts a comprehensive survey of simulation tool developers periodically. That agency publishes several tables with detailed information describing the features of each tool. The Urban Transportation Monitor data from Volume 4, No 4 (May 3, 2010) were analyzed to determine the number of tools that exhibited certain characteristics. Exhibit 6 presents a table of the geometric and operational features that are accommodated by some, most and all tools. Exhibit 7 presents a table of the performance measures that are reported by some, most and all tools.

3.2 Evaluation of the HCM Urban Street Facility Procedures

Chapter 16 of the 2010 HCM presents a complete procedure for evaluating the level of service (LOS) of an urban arterial street facility in terms of the average speed of the through vehicles on the facility. The development of the procedure has been documented by Bonneson et al [3]. This procedure was developed in response to criticism of the lack of detail in the HCM 2000 version. The limitations of that version have led many users to alternative traffic analysis tools for urban street facility analysis. A summary of the most significant enhancements found in the new version is presented in Exhibit 8.

A study described in Appendix 1 examined the characteristics of the new procedure and compared those characteristics with the HCM 2000 procedure and with commonly used deterministic and stochastic traffic analysis tools (CORSIM [4], Synchro [5] and TRANSYT-7F [6]). A case study based on Example Calculation 16-1 of the 2010 HCM was used for this purpose. The urban street facility included six signalized intersections operating with coordinated semi-actuated control. Demand volumes were varied from 100% to 180% of their initial values to investigate their effect on the results. While the new procedure is multimodal in scope, the study focused on the automobile mode to facilitate comparisons with alternative tools.

Appendix 1 addresses three significant considerations that create differences in the results obtained from the same input data with different tools. These considerations will be summarized here.
### Exhibit 4: Modeling treatment of traffic flow phenomena

<table>
<thead>
<tr>
<th>Traffic Phenomenon</th>
<th>Deterministic (HCM) Treatment</th>
<th>Typical Microsimulation Treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Right turn on red</td>
<td>Subtract right-turn-on-red volume from demand</td>
<td>Microscopic model of gap acceptance and follow-up time</td>
</tr>
<tr>
<td>Permitted left turns</td>
<td>Empirical model of capacity versus opposing volume, with minimum capacity determined by an assumption of two sneakers per cycle</td>
<td>Microscopic model of gap acceptance and follow-up time</td>
</tr>
<tr>
<td>Stop sign entry</td>
<td>Macroscopic model of gap acceptance and follow-up time</td>
<td>Microscopic model of gap acceptance and follow-up time</td>
</tr>
<tr>
<td>Channelized right turns</td>
<td>Subtract right-turning volume from demand</td>
<td>Microscopic model of gap acceptance and follow-up time; implicit effects of right-turn queues</td>
</tr>
<tr>
<td>Ramp merging</td>
<td>Empirical model of merge capacity versus freeway volume in the two outside lanes</td>
<td>Microscopic model of gap acceptance and follow-up time (some tools incorporate cooperative merging features)</td>
</tr>
<tr>
<td>Merging during congested conditions</td>
<td>Not addressed</td>
<td>Microscopic model of gap acceptance</td>
</tr>
<tr>
<td>Lane-changing behavior</td>
<td>Macroscopic model based on demand volumes and geometrics</td>
<td>Microscopic model of lane-changing behavior</td>
</tr>
<tr>
<td>Queue start-up on green</td>
<td>Fixed start-up lost time subtracted from the displayed green time</td>
<td>Stochastic lost time applied to the first few vehicles in the departing queue</td>
</tr>
<tr>
<td>Response to change interval</td>
<td>Fixed extension of green time added to the displayed green time</td>
<td>Kinematic model of stopping probability</td>
</tr>
<tr>
<td>Actuated signal operation</td>
<td>Deterministic model for computing green times as a function of demand and operating parameters</td>
<td>Embedded logic emulates traffic-actuated control explicitly; tools vary in the level of emulation detail</td>
</tr>
<tr>
<td>Delay accumulation</td>
<td>Analytical formulation for uniform delay based on the assumption of uniform arrivals over the cycle and uniform departures over the effective green</td>
<td>These three effects are combined implicitly in the accumulation and discharge of individual vehicles over the analysis period</td>
</tr>
<tr>
<td>Progression quality</td>
<td>Adjustment factor applied to the uniform delay term</td>
<td></td>
</tr>
<tr>
<td>Random arrivals</td>
<td>Analytical formulation for incremental delay</td>
<td></td>
</tr>
<tr>
<td>Generation of vehicles</td>
<td>Incremental delay formulation assumes Poisson arrivals (mean = variance) at the stop line; the variance–mean ratio is reduced for traffic-actuated control as a function of the unit extension</td>
<td>Individual vehicles are introduced into entry links randomly, on the basis of a specified distribution</td>
</tr>
<tr>
<td>Effect of oversaturation</td>
<td>A third analytical formulation, ( d_3 ), is introduced to cover the additional delay due to an initial queue</td>
<td>Oversaturated operation and residual queues are accounted for implicitly in the accumulation and discharge of individual vehicles</td>
</tr>
<tr>
<td>Residual queue at the end of analysis period</td>
<td>Analytical formulation computes the residual queue when ( d/c &gt; 1.0 ); the residual queue from one period becomes the initial queue for the next period</td>
<td></td>
</tr>
</tbody>
</table>
## Exhibit 5: Performance measures reported by alternative tools

<table>
<thead>
<tr>
<th>Notation</th>
<th>HCS</th>
<th>SYNCRO</th>
<th>TRANSYT-7F</th>
<th>CORSIM</th>
<th>SIMTRAFFIC</th>
<th>VISSIM</th>
<th>Q-PARAMICS</th>
<th>S-PARAMICS</th>
<th>AIMSUN</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOS</td>
<td>H</td>
<td>H</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>H</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Delay</td>
<td>H</td>
<td>P</td>
<td>P</td>
<td>H</td>
<td>I</td>
<td>I</td>
<td>I</td>
<td>X</td>
<td>I</td>
</tr>
<tr>
<td>Number of Stops</td>
<td>X</td>
<td>I</td>
<td>I</td>
<td>I</td>
<td>I</td>
<td>[3]</td>
<td>I</td>
<td>I</td>
<td>I</td>
</tr>
<tr>
<td>Stop time</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>I</td>
<td>I</td>
<td>I</td>
<td>I</td>
<td>I</td>
<td>I</td>
</tr>
<tr>
<td>Capacity</td>
<td>H</td>
<td>H</td>
<td>H</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>v/c Ratio</td>
<td>H</td>
<td>H</td>
<td>H</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Queue lengths</td>
<td>H</td>
<td>I</td>
<td>I</td>
<td>I</td>
<td>X</td>
<td>X</td>
<td>I</td>
<td>I</td>
<td>I</td>
</tr>
<tr>
<td>ICU</td>
<td>X</td>
<td>I</td>
<td>[2]</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Average speed</td>
<td>H</td>
<td>H</td>
<td>H</td>
<td>H</td>
<td>P</td>
<td>P</td>
<td>I</td>
<td>I</td>
<td>I</td>
</tr>
<tr>
<td>Speed for moving vehicles</td>
<td>H</td>
<td>H</td>
<td>X</td>
<td>I</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Travel time</td>
<td>H</td>
<td>H</td>
<td>H</td>
<td>P</td>
<td>P</td>
<td>I</td>
<td>I</td>
<td>I</td>
<td>I</td>
</tr>
<tr>
<td>Denied Entry</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>U</td>
<td>I</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>I</td>
</tr>
<tr>
<td>Freeway density</td>
<td>H</td>
<td>X</td>
<td>X</td>
<td>I</td>
<td>X</td>
<td>I</td>
<td>I</td>
<td>I</td>
<td>I</td>
</tr>
<tr>
<td>Arterial density</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>I</td>
<td>I</td>
<td>I</td>
<td>I</td>
</tr>
<tr>
<td>Density for moving vehicles</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

1: The native version of Synchro is described here (i.e., not using the HCM option).
2: The Synchro ICU measure has the same definition as the HCM $X_c$ measure when minimum phase times are not applied.
3: Stops are reported only for buses.
Exhibit 6: Geometric and operational features accommodated by simulation tools
SOURCE: THE URBAN TRANSPORTATION MONITOR, VOL. 24, NO. 4 [2]

| Geometric and operational features accommodated by all tools | • Work zones  
• Roundabouts  
• Four-way stops  
• Effect of reduced lane widths  
• Pedestrian crossings  
• Different acceleration/deceleration characteristics  
• Different speeds of vehicles negotiating different geometrics |
| Geometric and operational features accommodated by most tools | • Incident management  
• Toll plazas with or without electronic toll collection  
• Right or left side driving rules  
• Real time route guidance  
• Variable message signs with adaptive speed control  
• HOV and HOT lanes with or without barriers  
• Queue bypass for transit vehicles  
• Bus only lanes  
• Use of shoulders by general traffic during peak periods  
• Diverted traffic as a result of change in capacity  
• Weaving  
• U-Turns  
• Center turn Lanes and reversible lanes  
• Standard 8 phase dual ring signal control  
• Advanced signal control with macro language extensions  
• Hardware/software in the loop control  
• Multiple intersections controlled by a single controller  
• Transit and railroad signal priority  
• Bus and light rail transit  
• Pedestrians  
• Park and ride  
• Parked vehicles and search for parking space  
• Traffic calming measures  
• Weather conditions  
• Effect of reduced shoulder widths or no shoulder  
• Freeway ramp metering signals  
• Roundabout metering signals  
• Gap acceptance behavior  
• Different driver response times during queue discharge |
| Geometric and operational features accommodated by some tools | • Signal control test mode  
• Signal to signal communications  
• Local or system-wide adaptive control  
• Bicycles  
• Parking guidance systems  
• Multi-modal shared spaces  
• Transit malls  
• Non-vehicle use paths |

Note: The level of accommodation of these features varies among simulation tools. In some cases the features are modeled explicitly. In other cases, some user input is required to specify parameters that are associated with a particular feature.

Most tools = 3 or more, Some tools = 1 or 2
**Exhibit 7: Summary of performance measures reported by simulation tools**

**SOURCE:** THE URBAN TRANSPORTATION MONITOR, VOL. 24, NO. 4 [2]

<table>
<thead>
<tr>
<th>Performance measures produced by all tools</th>
<th>Speed and travel time</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Vehicle miles traveled</td>
</tr>
<tr>
<td></td>
<td>Stopped delay</td>
</tr>
<tr>
<td></td>
<td>Stops per vehicle</td>
</tr>
<tr>
<td></td>
<td>Queue lengths</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Performance measures produced by most tools</th>
<th>Transit travel time</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pedestrian/passenger measures</td>
</tr>
<tr>
<td></td>
<td>Control delay (definition is generally different from the HCM)</td>
</tr>
<tr>
<td></td>
<td>Level of service</td>
</tr>
<tr>
<td></td>
<td>Emissions</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Performance measures produced by some tools</th>
<th>Transit schedule reliability</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Capacity</td>
</tr>
<tr>
<td></td>
<td>Estimated number of accidents</td>
</tr>
<tr>
<td></td>
<td>Noise level</td>
</tr>
<tr>
<td></td>
<td>Fuel Consumptions</td>
</tr>
<tr>
<td></td>
<td>Vehicle operating costs</td>
</tr>
</tbody>
</table>

Most tools = 3 or more, Some tools = 1 or 2

---

**Exhibit 8: Enhancements in the HCM 2010 procedure for urban street facilities**

<table>
<thead>
<tr>
<th>Feature</th>
<th>HCM 2000 Treatment</th>
<th>HCM 2010 Treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Movements considered</td>
<td>Arterial through traffic only</td>
<td>All intersection movements</td>
</tr>
<tr>
<td>Periods analyzed</td>
<td>Single period</td>
<td>Multiple periods with residual queue carryover</td>
</tr>
<tr>
<td>Signal timing plan</td>
<td>User entry of g/C ratio</td>
<td>Computation of phase times from specified traffic-actuated controller parameters</td>
</tr>
<tr>
<td>Arterial progression effects</td>
<td>User entry of arrival type (1-6)</td>
<td>Macroscopic flow model computes vehicle arrival profiles over the cycle based on user specified offsets</td>
</tr>
<tr>
<td>Running speed</td>
<td>Model based on free flow speed and intersection spacing</td>
<td>Additional factors such as traffic volume and mid-segment activities are considered.</td>
</tr>
<tr>
<td>Control at segment boundaries</td>
<td>Signalized intersections only</td>
<td>Signalized or unsignalized intersections</td>
</tr>
<tr>
<td>Turns from cross streets entering the arterial</td>
<td>Ignored</td>
<td>Recognized in the computation of arrival profiles</td>
</tr>
<tr>
<td>Access points on the route</td>
<td>Ignored</td>
<td>Recognized in the determination of running speed and delay</td>
</tr>
<tr>
<td>Modal scope</td>
<td>Automobile mode only</td>
<td>Multimodal</td>
</tr>
</tbody>
</table>

---

NCHRP Project 3-85, Guidance for the Use of Alternative Traffic Analysis Tools for Highway Capacity Analysis
3.2.1 Arterial Volume Continuity

Traffic volume counts at the intersections are often taken on different days, so a typical volume input data set for an arterial facility will not maintain volume continuity along the route. If the total link input does not match the total link output, then some adjustment will be necessary. The adjustment methodology differs among tools and can therefore affect the comparison of results. The link volume balancing methodology of the selected tools is summarized in Exhibit 9.

Exhibit 9: Summary of link volume balancing methodology of traffic analysis tools

<table>
<thead>
<tr>
<th>Analysis Tool</th>
<th>Link Volume Balancing Procedure</th>
</tr>
</thead>
<tbody>
<tr>
<td>HCM 2000</td>
<td>None</td>
</tr>
<tr>
<td>HCM 2010</td>
<td>Proportional adjustment of output flows to match the total input. Capacity constraints are applied to the input flows.</td>
</tr>
<tr>
<td>TRANSYT-7F</td>
<td>Proportional adjustment plus warning if balance limits are exceeded</td>
</tr>
<tr>
<td>Synchro</td>
<td>Proportional adjustment combined with synthesized mid block flow</td>
</tr>
<tr>
<td>CORSIM</td>
<td>No balancing necessary because volumes are only specified at input nodes. Internal volume specifications are treated as proportions of the total link volume. When severe unbalance occurs, the volumes processed by CORSIM at any intersection could differ substantially from the specified volumes.</td>
</tr>
</tbody>
</table>

To avoid the complications of link volume balancing, a data set with fully balanced volumes was used for the case study.

3.2.2 Speed Definitions

The average speed on any segment is determined by dividing the length of the segment by the time taken by each vehicle to traverse the segment. All of the deterministic tools compute the travel time as the sum of two components:

1. The time required to travel the segment at the running speed
2. The delay time at the intersection due to the traffic control

Simulation tools compute travel times by accumulating the time spent by each vehicle in the segment.

The delay time is defined consistently by all of the deterministic tools. The running time definition and computation, on the other hand, is specific to each tool. Exhibit 10 summarizes the methodology used by the various tools to compute running speeds. It also indicates the most appropriate value to use for each tool to promote a consistent evaluation.
### Exhibit 10: Alternative tool running speed computation methodology

<table>
<thead>
<tr>
<th>Analysis Tool</th>
<th>Field Name for Speed Input</th>
<th>Running Speed Computation (FFS = Free Flow Speed)</th>
<th>Input for Consistent Comparison</th>
</tr>
</thead>
<tbody>
<tr>
<td>HCM 2000</td>
<td>Free-Flow Speed</td>
<td>Computed from FFS and segment length</td>
<td>Speed limit + 5 mph</td>
</tr>
<tr>
<td>HCM 2010</td>
<td>Speed Limit</td>
<td>FFS determined from speed limit and geometrics (usually about speed limit + 5mph). Running speed is computed from FFS and other factors</td>
<td>Speed limit</td>
</tr>
<tr>
<td>TRANSYT-7F</td>
<td>Cruise Speed</td>
<td>Running speed is assumed to be the cruise speed</td>
<td>Speed limit</td>
</tr>
<tr>
<td>Synchro</td>
<td>Link Speed</td>
<td>Computed from link speed and segment length</td>
<td>Speed limit + 5 mph</td>
</tr>
<tr>
<td>CORSIM</td>
<td>Free Flow Speed</td>
<td>Determined implicitly from interference by less aggressive drivers traveling below the FFS</td>
<td>Speed Limit + 5 mph</td>
</tr>
</tbody>
</table>

#### 3.2.3 Signal Timing Plan Synthesis

The control delay experienced at each intersection is an important component of the segment travel time. Since the delay values are strongly influenced by the green times for each movement, the signal timing plan is an essential input to the delay computation process. Earlier versions of the HCM required cycle length and green times as a user input. The HCM 2000 provided guidance on how to approximate the signal timing plan. The recommended procedures were incorporated into some tools, while other tools invoked their own computations.

Timing plans may be based on pretimed, traffic actuated, or coordinated semi-actuated control. Pretimed plans are produced by both Synchro and TRANSYT-7F as a byproduct of an optimization process. The majority of urban street facilities use coordinated semi-actuated control, so the study focused on that type of control. The HCM 2010 example used in the study assumed coordinated semi-actuated control.

Exhibit 11 summarizes the methodology used by traffic analysis tools to estimate the timing plan for an intersection with coordinated semi-actuated control. All of the tools considered here, including the new HCM procedure, model this type of control to assign unused time between phases.

The HCM 2010 timing plan estimation results are presented in Exhibit 12. To facilitate comparison of the results from different tools, the green times are normalized and shown in terms of their percent of nominal splits as a function of the percent of demand volume. Separate relationships are plotted for the arterial left turns, arterial through movements and the cross street phase times. Note that there was no protected left turn phase for the cross street.
Exhibit 11: Alternative tool timing plan estimation methodology

<table>
<thead>
<tr>
<th>Analysis Tool</th>
<th>Timing Plan Inputs</th>
<th>Computational Methodology</th>
</tr>
</thead>
<tbody>
<tr>
<td>HCM 2000</td>
<td>g/C required</td>
<td>None</td>
</tr>
<tr>
<td>HCM 2010 Actuated controller parameters</td>
<td>Deterministic modeling of traffic actuated control. Unused time from actuated phases is transferred to other phases.</td>
<td></td>
</tr>
<tr>
<td>TRANSYT-7F Nominal dual ring phase times</td>
<td>Phase times are estimated by a separate iterative process that reassigns green times. The results may be used for evaluation.</td>
<td></td>
</tr>
<tr>
<td>Synchro Actuated controller parameters</td>
<td>Stochastic model estimates green times at 10% to 90% levels. Unused time from actuated phases is reassigned to the coordinated phase.</td>
<td></td>
</tr>
<tr>
<td>CORSIM Actuated controller parameters</td>
<td>Emulation of a NEMA or Type 170 controller with detector inputs from microscopic simulation</td>
<td></td>
</tr>
</tbody>
</table>

The results are generally as anticipated. At low demand levels, the arterial through phase receives significant unused time from the actuated phases and its time exceeds the nominal split time. This effect diminishes as the demand level increases. The cross street phase time starts off well below its nominal split because of lack of demand. The time increases with demand and eventually reaches 100% of the nominal split.

Full convergence was only achieved with protected (only) left turns in this case. The permitted phase and sneaker accommodated most of the left turns with protected/permitted operation so the full time allotted to the protected phase was never used.

Similar analyses were performed using the alternative tools. The results are presented in Appendix 1.

Exhibit 12: HCM 2010 timing plan estimation results

Exhibit 12: HCM 2010 timing plan estimation results
3.2.4 Average Speed Results for the HCM

Level of service estimates in the HCM are based on the computed value of the average speed. The average speed is determined by all tools by dividing the length of the facility by the time taken by each vehicle to traverse the facility. The modeling differences among tools were discussed earlier. Differences in results could be due to differences in the computation of running speeds or control delay on each segment.

The study compared the speed results among different tools, taking into account the quality of progression. The progression design favored eastbound traffic heavily at the expense of westbound traffic, thereby creating two different cases of progression quality. Since the demand volumes are the same in both directions, differences in the overall speed can be attributed entirely to differences in progression quality.

In the results for each tool, two phenomena should be observed:
1. The overall speed should decrease as demand increases because of lower running speeds and higher delays.
2. The direction favored by the progression design (eastbound) should have higher speeds than the reverse direction (westbound).

A comparison of the HCM 2000 and HCM 2010 results was performed first to provide some insight into the differences between the two procedures. It also established the clear superiority of the new procedure. The 2010 procedure determines progression quality directly from the signal timing data. In the 2000 procedure, progression quality is generally entered in terms of an arrival type (AT), which approximates different categories of progression quality. To provide a complete picture, the analysis was repeated for AT 1-5 as defined in the HCM 2000. The results are presented in Exhibit 13.

![Exhibit 13: Effect of demand on average speed (HCM 2000 and 2010)](image)
Each arrival type is represented by a different line in this figure. As expected, AT 1 (worst progression) shows the lowest speeds and AT 5 (best progression) shows the highest speeds. The average speed value ranges from about 11 mph to 29 mph.

The HCM 2010 procedure eliminates the need for an educated guess at the arrival type by modeling the progression of traffic from segment to segment explicitly. The results for the two progression cases from this example are also shown in Exhibit 13, superimposed on the HCM 2000 results. By way of comparison, it appears that the favored direction (eastbound) had an equivalent arrival type between 4 and 5. The reverse direction was between AT2 and AT3 for most of the demand range. A direct comparison of the two methods cannot be made based on arrival type alone because the HCM 2010 procedure is also sensitive to other inputs.

3.2.5 Comparison of Speed Results

It is interesting to look at a side-by-side comparison of the results for each progression case. The two cases were described as “favorable” and “unfavorable.” Favorable progression was the result of lining up the beginning of the green phases in time and space to produce the best progression band. Unfavorable progression reflects the reverse direction that was sacrificed to produce the favorable progression.

The average speed relationships for the two progression cases are shown in Exhibit 14. A few interesting observations can be made from these figures, keeping in mind that they apply to this example only:

- In general, the demand-speed relationships of all of the tools conformed to the expected shape.
- There was a greater divergence in the results with favorable progression, especially at high demands. This suggests that there are some differences in the modeling of platoon propagation among the tools that were examined.
- With favorable progression, all tools produced very similar results, except for Synchro, where the speeds were slightly lower.
- With unfavorable progression, the differences between CORSIM and Synchro were indistinguishable.
- With unfavorable progression, The HCM 2010 procedure estimated speeds that were slightly higher than the other tools.

3.2.6 General Observations on Urban Street Facility Analysis

The objective of the case study exercise was to examine the new procedure for analysis of urban street facilities published in the 2010 edition of the HCM. Based on this study, the following observations are offered:

- The new procedure represents a substantial improvement over the previous version published in the HCM 2000. It internalizes computations that had to be approximated or carried out externally in the previous version.
- The computational engine that implemented the procedure performed in a robust manner.
- There were no internal inconsistencies or anomalous behaviors in the results.
- The relationships between demand levels, phase times and average speeds conformed generally to expectations.
The numerical results could not be expected to match those of the alternative tools because of differences in model formulation. The agreement was close enough that no judgment could be offered as to the absolute accuracy of any tool.

Exhibit 14: Effect of demand on speed for different tools

A single case study does not constitute a complete evaluation of any traffic analysis tool. However, within the limits of this study, it can be said that the performance of the HCM 2010 procedure in the automobile mode supports the conclusion that it provides a credible method for evaluating the operation of an urban street facility. It offers a substantial contribution to the methodology of highway capacity and level of service analysis.
3.3 Evaluation of the HCM Freeway Facility Analysis Procedure

HCM Chapter 10 presents a complete procedure for evaluating the level of service (LOS) of a freeway facility in terms of the average density of the vehicles on the facility. The development of this procedure began with the 2000 edition of the HCM but it was not heavily used because of the manner in which it was implemented. It was improved, both in function and documentation and is now implemented in the form of a multi-sheet Excel workbook that performs all of the required computations. The software implementation is called FREEVAL.

Appendix 2 to this report examines the characteristics of the new procedure and compares those characteristics with a commonly used micro simulation tool. Two case studies were developed to identify the systematic differences between the macroscopic approach of FREEVAL and the microscopic approach inherent in simulation. The CORSIM simulation tool was used to represent a generic simulation approach. The component of CORSIM that models freeway operations is called FRESIM.

The first case study involved a facility consisting of eight identical basic freeway segments. All segments were 1000 ft in length with two lanes and no entrance or exit ramps. The objective was to examine the relationships between traffic flow parameters as seen by each of the tools. The complications of merging, diverging and weaving were avoided to focus on the facility aspects of the modeling.

3.3.1 Comparison of Speed-Flow Curves

The default values for all parameters were used. The two tools were cross calibrated to ensure that the same capacity was used by both tools. Demand volumes were varied up to the established capacity to determine the speed-flow relationships. The results are presented in Exhibit 15. It is noted that the FREEVAL curves conform to the shape illustrated in HCM Chapter 11, with the speed falling noticeably at the point of capacity. The FRESIM speed, on the other hand, was only minimally affected by volume up to the point of capacity.

Exhibit 15: Speed-Flow curves for the basic segment configuration
3.3.2 Incident Analysis

A lane blockage incident was introduced to further compare the two tools. The incident blocked the right lane of the freeway in the last segment beginning 15 minutes after the start of the analysis period and lasting for 15 minutes. The capacity of the open lane was first established for FRESIM and that capacity was imposed on FREEVAL to create equivalent data sets.

The results are presented in Exhibit 16 in the form of density contour plots. It is clear that FRESIM produced a more concentrated queue in advance of the incident compared to FREEVAL, which distributed the queue farther upstream among more segments when the default jam density of 190 pcpmpl was used. FRESIM imposes a fixed spacing of 3 ft between vehicles in a standing queue. With the 17 ft vehicle length used here, the inter-vehicle spacing will be (17 + 3) = 20 ft, corresponding to a jam density of approximately 260 pcpmpl.

FREEVAL’s default jam density is 190 pcpmpl but a user specified value between 130 and 360 pcpmpl is recognized in multiples of 10. So the FREEVAL analysis was performed again with a jam density of 260 pcpmpl and the results shown in the same exhibit produced much better agreement with FRESIM.

The speed and density contour plots are developed by FREEVAL when the computations are performed. The pinnacle in these plots suggests a peak value at a specific point, when it is, in fact, an average value over a full segment for 15 minutes. In this case, the period began with a low density and built up to a peak at the end of the period, so the peak has almost twice the density represented by the pinnacle.
A more direct representation of the average values for the same data is presented in Exhibit 17. The numbers are the same but the alternate format is less likely to mislead the user. The format may be changed easily in the FREEVAL worksheet. When rapid backup creates pinnacles in the contour plots, the user might want to change the chart type to clarify the interpretation. The FREEVAL developers should consider whether the default chart type is best suited for this purpose.

While the contour plots provide a good overall visual image of the operation, quantitative comparisons can be performed better with line plots of the type shown in Exhibit 18. This exhibit makes it clear that the density for FREEVAL at 260 pcpmpl compares much more favorably with the corresponding FRESIM results. Both tools extend the queue backup to Segment 4, whereas the original FREEVAL run with a jam density value of 190 extended the queue back to the first segment in the facility.

A reasonable observation from this comparison is that, when properly cross-calibrated to each other, comparable results can be obtained.
3.3.3 Advance Warning Sign Simulation

An advance warning sign 1000 ft upstream was included in the simulation. The average density for each segment of the facility during the period of the incident is shown in Exhibit 19. Three conditions are represented in this exhibit:

- FRESIM results with the advance warning sign
- FRESIM results without the advance warning sign
- FREEVAL results. (The HCM Chapter 10 procedure does not accommodate advance warning).

The FREEVAL results reflect the 260 pcpmpl jam density operation for compatibility with FRESIM.

![Exhibit 19: Simulated effect of the advance warning sign](image)

The simulated effect of the advance warning sign is apparent on this figure. The advance warning shifted the congestion upstream by moving vehicles out of the blocked lane earlier. Appendix 2 presents a more complete comparison of the two modeling techniques. It also examines the following topics related to simulation:

- characteristics of the car following model in FRESIM
- Effect of the car following sensitivity parameters on shockwave formation
- Computation of backward wave speeds from a bottleneck, including comparison with field data
- Lane blockage vs. “rubbernecking” incidents
- Vehicle trajectory analysis of the incident characteristics

The results of these analyses suggest that FREVAL has implemented the HCM 2010 procedure for freeway facility analysis properly. They also raise questions as to whether FRESIM represents an accurate depiction of the real world. The following observations suggest that some skepticism is appropriate:
• The speed-flow relationships show minimal effect of demand on speed right up to the point of capacity.
• The speed-flow relationships are influenced by the length of the facility.
• The jam density is somewhat higher than commonly accepted. This has an effect on queue buildup from bottlenecks.
• The maximum flow rate past a lane blockage is questionable. It was observed in this study to reach a value greater than 2700 vphpl. It continued to increase at demand levels well in excess of capacity.
• FRESIM assumes that all drivers will attempt to vacate the blocked lane immediately at the point of the advance warning sign. This assumption is somewhat idealistic in terms of driver lane choice.

3.3.4 Example Involving a Combination of Freeway Facilities
A second case study introduced a combination of segments of various types. Example Problem 1 from HCM Chapter 10 was be used for this purpose. The facility consisted of 11 freeway segments of various types, including basic segments, on-ramps, off-ramps and a weaving segment.

Both FREEVAL and FRESIM were applied to this problem in the same manner as the previous case study. The average speeds reported by the two tools were compared for each segment. The results are presented in Exhibit 20. Visual inspection of this exhibit shows that the results were similar for the two tools. The average speed over all segments was 56.9 mph for FREEVAL and 55.7 mph for FRESIM, reflecting a difference of 2.2%.

Larger differences were observed in individual segments. The greatest difference (12.88%) occurred in Segment 6 (the weaving segment). Greater differences between the microscopic and macroscopic modeling approaches would be expected in weaving segments because of the complex interactions between vehicles that take place in weaving maneuvers. FREEVAL showed higher weaving densities and lower speeds than FRESIM. This effect is consistent with the observation from the previous case study that FRESIM speeds tend to be affected less by traffic interaction.
3.4 Evaluation of the HCM Two-lane Highway Analysis Procedure

HCM Chapter 15 presents a procedure for evaluating the level of service (LOS) of a two-lane highway facility in terms of the average travel speed (ATS) and/or the percent time spent following. Very little alternative tool guidance was incorporated into this chapter because of a lack of alternative tools and insufficient experience with their use.

Appendix 3 to this report contains a comparison of the HCM 2000/2010 procedure for analysis of two-lane highways with a recently developed version of CORSIM, a simulation based tool, which offers the following additional features:

- Basic two-lane highway segments with passing maneuvers (including passing one vehicle or multiple vehicles at a time) in the oncoming lane
- Two-lane highway segments with a passing lane
- Two-lane highway segments connecting to signalized intersections
- New inputs that allow the user to modify certain parameters of the two-lane highway modeling logic
- New performance measure outputs (e.g., percent time spent following (PTSF) and follower density) and passing maneuver data outputs

With this new simulation capability traffic operations on complex two-lane highways (e.g., two-lane highway with occasional signalized intersections) can be analyzed.

Appendix 3 describes five different experiments designed to evaluate the simulation of two-lane highways:

- Experiment 1: Level road with full passing
- Experiment 2: Level road with no passing
- Experiment 3: Rolling terrain with partial passing
- Experiment 4: Rolling terrain with exclusive passing lane in one segment
- Experiment 5: Level road with 50% no passing

The use of vehicle trajectory analysis to analyze individual passing maneuvers was also illustrated in this appendix. The overall observations suggest that the simulation tool offers a realistic alternative for analyzing two-lane highways and is able to deal with situations beyond the stated limitations of HCM Chapter 15.

3.5 Trajectory Analysis Considerations

Analysis of individual trajectories has been recommended by the Committee as the best method for computing uniform and consistent performance measures from different tools. The NCHRP Project 3-85 Panel supported this recommendation and added a task to the project to investigate the computational aspects of vehicle trajectory analysis. Appendix 4 presents a detailed discussion of the results of this task. A summary of the results is presented here.

3.5.1 Graphical Representation of Vehicle Trajectory

Graphically, vehicle trajectories are generally described in terms of a time-space diagram of the type shown in Exhibit 21, which depicts a classical queue accumulation and release at a
signalized stop line and freeway traffic flow in a single lane. Note that time and distance can be shown on either axis.

Exhibit 21: Graphical representations of vehicle trajectories

3.5.2 Mathematical Properties of Vehicle Trajectory

While the plots shown in the figure provide a good visual insight into the operation, they do not support any quantitative assessments. To develop performance measures from vehicle trajectories, it is necessary to represent them mathematically and not just visually. A mathematical representation requires the development of a set of properties that are associated with each vehicle at specific points in time and space. Because of the time step formulation of most simulation models, it is preferable to choose time as the reference point instead of distance. Typical properties of each vehicle at each point in time include

- Vehicle ID
- Position
- Speed
- Acceleration
- Space gap
- Time headway
- Lane
- Link or analysis zone
3.5.3 Sources of Vehicle Trajectory Data

Simulation tools typically produce vehicle trajectory files in some format. There are now two standard formats for simulated trajectory files, including CORSIM’s animated graphics file and the Surrogate Safety Analysis Model (SSAM) [7] format that was developed by FHWA and is used by several other tools. The CORSIM format was used in this project because it is better suited to computing performance measures. The SSAM format is much more detailed because it is meant for analysis of potential collisions as a surrogate safety measure. The SSAM format would be well suited to performance analysis if some additional data items were included.

A post processing utility called “Vehicle Trajectory Analysis for Performance Evaluation” (VTAPE) has been developed as a part of this project to read and analyze the CORSIM animated graphics files. VTAPE provides very detailed step-by-step analyses with intermediate values reported for all parameters at each time step. It is a useful tool for understanding and enhancing the trajectory analysis methodology. As such, it is intended as a research tool. Its ultimate purpose will be to serve as the computational engine for the HCQS Simulation Subcommittee. It has been developed with that purpose in mind. Full documentation for VTAPE is provided in Appendix 5 to this report.

With VTAPE, it is possible to select up to 8 links forming a continuous route for analysis. The selected links are joined together for plotting and analysis to form a linear route. Each link is configured by the following attributes:

- Upstream and downstream nodes that define the link
- Link length
- Number of lanes
- Free flow speed
- Control

VTAPE performs the following functions, all of which are demonstrated in Appendix 4:

- Plotting of trajectories, either by lane or for all lanes in the link.

- Longitudinal analysis of the trajectory of vehicles as they traverse a link. A single vehicle may be chosen for a detailed analysis to illustrate the analysis procedure or all vehicles traversing the link in a given time period may be analyzed separately, with their performance measures included. The measures determined by this type of analysis include delay measures of various types to be explained later and stop-related measures.

- Spatial analysis, which involves consideration of all of the vehicles on a link at a specific time step. The two principal spatial measures include density and queue lengths.

All of these functions produce results in comma-delimited format for further analysis and plotting by spreadsheet software.

3.5.4 Requirements for Trajectory Analysis Procedures

The following requirements were formulated to guide the development of trajectory analysis procedures. Some of the requirements were established by the HCQS committee and others are based on the objective of promoting developer participation by providing simple and
unambiguous procedures that can be implemented by developers without requiring additional data and without drastically affecting their model execution times:

1. The trajectory analysis specifications shall be limited to the analysis of trajectories produced by the traffic flow model of each simulation tool. The specifications shall not require developers to change their traffic flow modeling logic.

2. The specifications should establish when each of the proposed measures can be adequately defined by trajectories to permit a valid comparison between the HCM and other modeling approaches. If the specifications for estimating a particular measure cannot be satisfactorily defined then the guidance should indicated that comparisons should not be made.

3. All performance measures that accrue over time and space shall be assigned to the link and time interval in which they occur. There are subtle complexities that make it impractical to do otherwise. For example, the root cause of a specific backup might not be within the link or the immediate downstream link. In fact, the backup might be secondary to a problem at some distant location in the network and in a different time interval.

4. The guidance must state that the spatial and temporal boundaries of the analysis domain must include a period that is free of congestion on all sides. This principle is already stated in the HCM for multi-period signalized intersection analysis. To ensure that delays to vehicles that are denied entry to the system during a given period are properly recognized, it might be necessary to create fictitious links outside of the physical network to hold such vehicles.

5. The algorithms must be suitable for computation “on the fly.” They must not require information from a future time step that would complicate the data handling within the simulation process.

6. Arbitrary thresholds should be kept to a minimum because of the difficulty of obtaining acceptance throughout the user community for specific thresholds. Where arbitrary thresholds can’t be avoided they should be justified to the extent possible by definitions in the literature and, above all, they should be applied consistently for different types of analysis.

7. Computationally complex and time consuming methods should be avoided to minimize the additional load on the model. Methods should be developed to simplify situations with many special cases because of the difficulty of enumerating all special cases.

3.5.5 Performance Measures to be Estimated

Appendix 4 presents computational procedures for all of the performance measures reported by the HCM procedural chapters. The following performance measures are addressed:

- Speed and travel time related measures
  - Average speed
  - Proportion of slow vehicles (i.e., travelling below a specified speed threshold)
• Queue related measures
  o Queued state
  o Queue length
  o Back of queue (BOQ)
  o Queue delay
  o Proportion of vehicles queued in a freeway segment
• Stop related measures
  o Stopped state: Based on a stop threshold of 5 mph for compatibility with other HCM chapters
  o Release from stopped state
  o Number of stops (both full and partial)
  o Stopped delay
• Delay related measures
  o Reference speed for delay
  o Aggregated delay vs. unit delay
  o Time step delay
  o Segment delay
  o Queue delay
  o HCM control delay
• Density related measures
  o Average density on a segment
  o Merge area density in Lanes 1 and 2

Specific procedures for computing these measures from vehicle trajectories are included in Appendix 4 of this report and in HCM Chapter 24.

3.5.6 Trajectory Analysis Examples
Several vehicle trajectory examples are presented through this report and its appendices. The following sample plots are presented in this section:
• Exhibit 22 shows a sample speed and acceleration plot for a single vehicle. Other measures such as delay may be determined from this trajectory.
• Exhibit 23 shows the derivation of the number of stops from a single vehicle speed plot. The maximum speed since the last stop is used to determine the magnitude of the next stop.
Exhibit 22: Example speed and acceleration plot for one vehicle

Exhibit 23: Example of stops analysis for one vehicle
• Exhibit 24 illustrates the queue length per step on a signalized approach over all of the time steps in the period. Note that ten cycles are discernable on this figure. Note also that a considerable variation in the cyclical maximum BOQ is evident. The queuing measures for each lane are also included on this figure.

![Exhibit 24: Sample plot and analysis of queue length](image)

<table>
<thead>
<tr>
<th>Lane</th>
<th>1</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Queue</td>
<td>174</td>
<td>165</td>
</tr>
<tr>
<td>Std Dev</td>
<td>110</td>
<td>106</td>
</tr>
<tr>
<td>95 Percentile</td>
<td>395</td>
<td>377</td>
</tr>
<tr>
<td>Max</td>
<td>440</td>
<td>440</td>
</tr>
</tbody>
</table>

A performance analysis of a freeway merge area is presented in Exhibit 25. A single vehicle was selected from the trajectory plot and its trajectory was analyzed. Note that the analysis produced segment delay and queue delay. This was a very congested segment as indicated by the trajectory plot. No stopped delay was produced because the vehicle never actually came to a stop (i.e., its speed stayed above 5 mph). No control delay was produced because this was an uninterrupted flow segment.
Exhibit 25: Sample analysis for a freeway vehicle

A spatial analysis of the entire segment was also performed to produce the following measures by lane:

- Average density over the segment
- Percent slow vehicles (i.e., traveling at less than 2/3 of the target speed.
- Percent queued vehicles
- Average queue length (measured from front of queue to back of queue)
- Average back of queue position
- Maximum back of queue position
- Percent of time steps when the queue overflowed the segment

The results are presented in Exhibit 26.

<table>
<thead>
<tr>
<th>Lane</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Density</td>
<td>73.4</td>
<td>51</td>
<td>43.6</td>
<td>9.9</td>
</tr>
<tr>
<td>Percent Slow Vehicles</td>
<td>88.4</td>
<td>68.5</td>
<td>41.5</td>
<td>65.7</td>
</tr>
<tr>
<td>Percent Queued Vehicles</td>
<td>63.4</td>
<td>22</td>
<td>2.4</td>
<td>26.7</td>
</tr>
<tr>
<td>Average Queue Length</td>
<td>600</td>
<td>215</td>
<td>15</td>
<td>40</td>
</tr>
<tr>
<td>Average Back of Queue</td>
<td>1471</td>
<td>1119</td>
<td>135</td>
<td>562</td>
</tr>
<tr>
<td>Maximum Back of Queue</td>
<td>1497</td>
<td>1497</td>
<td>1492</td>
<td>1474</td>
</tr>
<tr>
<td>Percent Overflow</td>
<td>66.1</td>
<td>29.6</td>
<td>0.5</td>
<td>0.17</td>
</tr>
</tbody>
</table>

Average Lane 1&2 Density 62.2

Exhibit 26: Example spatial analysis by lane
The use of vehicle trajectory analysis in modeling overtaking of vehicles on a two lane highway was demonstrated in Appendix 3 to this report. The speeds of the leading and following vehicles are shown in Exhibit 27 as a function of the follower’s position on the facility. The followers’ speed remains about 8 ft/sec faster than the leader until the gap closes to the point where the follower must begin to slow down. There is an apparent oscillation as the follower assumes the leader’s speed. When the passing maneuver begins, the follower’s speed increases to about 108 ft/sec to overtake the leader in the passing lane. When the passing maneuver has been completed, the passing vehicle slows down to match the speed of the new leader. The leader speed drops to zero during the passing maneuver because there is no leader present during this time.

Exhibit 27: Leader and follower speeds in a two-lane highway passing maneuver

In addition to the quantitative aspects, visual inspection of vehicle trajectory plots can also provide useful insight into the operation of a facility. The following visual examples are presented:

- An example of the trajectories of vehicles attempting to change lanes in advance of an incident is presented in Appendix 2.
- Appendix 2 also shows an example of a shock wave created by heavy traffic with a high car following sensitivity factor.
- An example is presented in Appendix 1 to illustrate the effect of favorable and unfavorable progression on the movement of vehicles through a series of traffic signals.
3.5.7 **General Observations on Vehicle Trajectory Analysis**

The objectives of this effort were to investigate the computational aspects of vehicle trajectory analysis and develop ATG material for the 2010 HCM from the results of the investigation. Based on this study, the following observations are offered:

- Vehicle trajectory analysis was demonstrated to produce results that can be applied consistently between tools.

- It is not a practical end user technique because of the amount of data involved, especially when multiple simulation runs are required to produce statistically significant results. It is essential that the computational procedures be internalized in simulation tools by their developers.

- The computational procedures proposed in this document offer a reasonable approximation of the performance measures that are estimated by other techniques, including field studies and the HCM. The proposed procedures depend to a certain extent on approximations and assigned thresholds but this dependency is no greater than the other techniques and should not produce issues of compatibility.

- A set of rules for computing uniform measures from trajectory analysis is proposed in this report. The same set of rules has been included in HCM Chapter 24, *Concepts: Supplemental*. These rules were developed in a manner that will make them practical for implementation in simulation tools.

- The most practical way to report performance measures from simulation tools is to assign all measures to the segment and time interval in which they accrue. It is not practical to offer a consistent trajectory analysis methodology that seeks to associate these measures with their root cause, which might be in some other part of the network or in some other time interval. While this constraint might not be consistent with the objectives of some analysts, it eliminates several intractable problems and issues.

- To ensure that all measures are fully reported, it is essential to define the analysis domain, both in time and space, such that a period of uncongested operation exists at all boundaries.

- The concept of control delay, as defined by the HCM, and the procedures by which it is computed, cannot be implemented in a consistent manner by vehicle trajectory analysis. However, a reasonable approximation of control delay is provided by the simulated “queue delay” measure, computed as prescribed in this document.
There are now two standard formats for simulated trajectory files, including CORSIM’s animated graphics file and the Surrogate Safety Analysis model (SSAM) format that was developed by FHWA and is used by several tools. The CORSIM format was used in this project because it is better suited to computing performance measures. The SSAM format is much more detailed because it is meant for analysis of potential collisions as a surrogate safety measure. The SSAM format would be well suited to performance analysis if some additional data items were included.

An expansion of the SSAM Version 1.4 specification is proposed to provide additional information for more general research applications. All fields covered in the Version 1.4 specification are left intact. The recommended format is presented in Exhibit 28. The following additional fields are proposed:

- All Records: One spare four-byte field for future or source model specific use
- Format record: The name and version number of the source program that produced the file. This information is useful for comparing traffic analysis tools. It may be required for interpretation of some fields containing codes (e.g., vehicle type) that may differ among tools.
- Vehicle Record:
  - A code to identify the intended movement (left, through, right, etc.) at the downstream link end
  - A code to identify the vehicle type in the classification scheme used by the source model
  - Upstream and downstream node ID (required because not all tools assign a unique number to each link)
  - Distance from the upstream and downstream link end
  - Control Status at the downstream link end, indicating what the driver is seeing during the time step.

It is recognized that not all traffic analysis tools organize their data in a manner that will support all of the fields in the proposed format. Furthermore, useful analyses may be performed on data sets with some empty fields. Fields for which data are not provided by a specific tool should be left empty.
Exhibit 28: Proposed SSAM Version 2 record specification
(* Indicates proposed additional fields)

<table>
<thead>
<tr>
<th>Format Record</th>
<th>Type</th>
<th>Value Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Record Type</td>
<td>Byte</td>
<td>0 = FORMAT record type</td>
</tr>
<tr>
<td>Endian</td>
<td>Byte</td>
<td>ASCII ‘L’ = little endian, used by Intel platforms ASCII ‘B’ = big endian, used by Motorola (Mac/Unix)</td>
</tr>
<tr>
<td>Version</td>
<td>Float</td>
<td>Allows decimal version number, which is currently 2.01</td>
</tr>
<tr>
<td>*SourceID</td>
<td>String*8</td>
<td>8 Byte ASCII String identifying source model (e.g. TEXAS)</td>
</tr>
<tr>
<td>*SourceVersion</td>
<td>Float</td>
<td>Version number for source model</td>
</tr>
<tr>
<td>*Spare1</td>
<td>4 Bytes</td>
<td>Source model specific</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Dimensions Record</th>
<th>Type</th>
<th>Value Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Record Type</td>
<td>Byte</td>
<td>1 = DIMENSIONS record type</td>
</tr>
<tr>
<td>Units</td>
<td>Byte</td>
<td>0 = English (i.e., feet, feet/sec, feet/sec²)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 = Metric (i.e., meters, meters/sec, meters/sec²)</td>
</tr>
<tr>
<td>Scale</td>
<td>Float</td>
<td>Distance per unit of X or Y (i.e., per “pixel”) (e.g., if scale is 0.25 and the units are metric, then x = 0 is 0.25 meters left of x = 1)</td>
</tr>
<tr>
<td>MinX</td>
<td>Integer</td>
<td>Left edge of the observation area.</td>
</tr>
<tr>
<td>MinY</td>
<td>Integer</td>
<td>Bottom edge of the observation area.</td>
</tr>
<tr>
<td>MaxX</td>
<td>Integer</td>
<td>Right edge of the observation area.</td>
</tr>
<tr>
<td>MaxY</td>
<td>Integer</td>
<td>Top edge of the observation area.</td>
</tr>
<tr>
<td>*Spare2</td>
<td>4 Bytes</td>
<td>Source model specific</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TimeStep Record</th>
<th>Type</th>
<th>Value Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Record Type</td>
<td>Byte</td>
<td>2 = TIMESTEP record type</td>
</tr>
<tr>
<td>Timestep</td>
<td>Float</td>
<td>Seconds since the start of the simulation</td>
</tr>
<tr>
<td>*Spare3</td>
<td>4 Bytes</td>
<td>Source model specific</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Vehicle Record</th>
<th>Type</th>
<th>Value Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Record Type</td>
<td>Byte</td>
<td>3 = VEHICLE record type</td>
</tr>
<tr>
<td>Vehicle ID</td>
<td>Integer</td>
<td>Unique identifier number of the vehicle</td>
</tr>
<tr>
<td>Link ID</td>
<td>Integer</td>
<td>Unique identifier number of the link (where possible)</td>
</tr>
<tr>
<td>Lane ID</td>
<td>Byte</td>
<td>Unique identifier number of the lane (where possible)</td>
</tr>
<tr>
<td>Front X</td>
<td>Float</td>
<td>X coordinate of the middle front bumper of the vehicle</td>
</tr>
<tr>
<td>Front Y</td>
<td>Float</td>
<td>Y coordinate of the middle front bumper of the vehicle</td>
</tr>
<tr>
<td>Rear X</td>
<td>Float</td>
<td>X coordinate of the middle rear bumper of the vehicle</td>
</tr>
<tr>
<td>Rear Y</td>
<td>Float</td>
<td>Y coordinate of the middle rear bumper of the vehicle</td>
</tr>
<tr>
<td>Length</td>
<td>Float</td>
<td>Vehicle length (front to back) in Units (feet or meters)</td>
</tr>
<tr>
<td>Width</td>
<td>Float</td>
<td>Vehicle width (left to right) in Units (feet or meters)</td>
</tr>
<tr>
<td>Speed</td>
<td>Float</td>
<td>Instantaneous forward speed (Units/sec)</td>
</tr>
<tr>
<td>Acceleration</td>
<td>Float</td>
<td>Instantaneous forward acceleration (Units/sec²)</td>
</tr>
<tr>
<td>*MovtCode</td>
<td>Byte</td>
<td>Left, through, right, other</td>
</tr>
<tr>
<td>*VehType</td>
<td>Byte</td>
<td>Vehicle type by source model definition</td>
</tr>
<tr>
<td>*UpNodeID</td>
<td>Integer</td>
<td>Upstream node ID</td>
</tr>
<tr>
<td>*UpNodeDX</td>
<td>Integer</td>
<td>Distance from upstream node</td>
</tr>
<tr>
<td>*DnNodeID</td>
<td>Integer</td>
<td>Downstream node ID</td>
</tr>
<tr>
<td>*DnNodeDX</td>
<td>Integer</td>
<td>Distance from downstream node</td>
</tr>
<tr>
<td>*ControlStatus</td>
<td>Byte</td>
<td>Status of control at downstream link end: (ASCII Code) (N)o control, (Y)ield, (S)top, (G)reen, (Y)ellow, (A)ll Red, (R)ed</td>
</tr>
<tr>
<td>*Spare4</td>
<td>4 Bytes</td>
<td>Source model specific</td>
</tr>
</tbody>
</table>
3.6 Application to Area Wide Systems

The HCM analysis procedures apply to specific roadway segments and to facilities comprising a number of segments of different types. The HCM procedures are difficult to apply to multiple facility corridors and area wide systems because of the quantity of data involved and the interactions between different facilities in a system. The HCM 2000 contained some material on large scale system applications of HCM procedures but this material was removed from the 2010 edition due to a perceived lack of user interest in using the HCM for this purpose.

The guidance in HCM Chapter 6, *HCM and Alternative Tools*, encourages the use of simulation tools for multiple facility systems. A case study involving simulation of a multiple facility system was developed as a project activity and has been included in HCM Volume 4. The case study content is summarized in Section 4.3.13 of this report.

3.7 Dynamic Traffic Assignment

HCM Chapter 6 also provides a brief summary of dynamic traffic assignment (DTA) considerations for area wide systems. One of the example problems in the HCM Volume 4 case study dealt with a comparison of static and dynamic traffic assignment. Apart from that, a detailed treatment of DTA was beyond the scope of this project. There is an abundance of material in the literature offering general guidance on DTA.

The TRB Transportation Network Modeling Committee has prepared a primer on DTA [8] that has been published by the Transportation Research Board. The specific objectives of this primer are as follows:

- Explain the basic concepts of DTA and various DTA definitions and implementations
- Highlight the types of transportation analysis applications for which DTA models could be found useful
- Provide information about how to select a DTA model that best serves the intended application
- Provide information regarding planning for and executing a DTA traffic analysis activity
- Describe the general DTA modeling procedure and modeling issues that may concern a model user.

A Comparison of the DTA features of several commonly used simulation tools was developed by Jeihani [9]. The paper describes demand estimation, supply presentation, methods for computing dynamic user equilibrium, and convergence among these tools. The computational procedures for the automobile mode are categorized according to the following criteria:

- Modeling level (mesoscopic or microscopic)
- Convergence criteria for equilibrium
- Basis for choice (route or destination)
- Basis for routing (Link or path)
The tools of interest to this project are summarized briefly as follows:

- **DYNAMIT-P**: is a mesoscopic model that achieves equilibrium using the expected travel time is equal to experienced travel time. It is route or destination based, trip based and path based.
- **DYNASMART-P**: is a mesoscopic model that achieves equilibrium when the link volumes in the current iteration are the same as the previous iteration. It is route-based, trip-based and path based.
- **PARAMICS**: is a microscopic model that achieves equilibrium when no new routing tree is made. It is route-based, trip-based and link-based.
- **VISSIM**: is a microscopic model that achieves equilibrium when the link volumes in the current iteration are the same as the previous iteration. It is route-based, trip-based and path based.

The paper also described the TRANSIMS simulation tool whose characteristics are beyond the scope of this project.
4 Summary of Alternative Tool Guidance in the 2010 HCM

The ATG material that appears in the HCM 2010 is the principal output of this project. ATG input from the project has been provided to 20 of the 35 chapters. Four of those 20 chapters were devoted entirely to ATG and another three had more than 50% ATG content. This section of the report summarizes the ATG content developed by the project team and adopted as a part of the HCM. Each HCM chapter is discussed separately in terms of its overall purpose and the ATG content that was provided by this project.

The 2010 HCM is multimodal in scope. It covers four modes with respect to their performance measures and quality of service:

1. Automobiles
2. Bicycles
3. Pedestrians
4. On-street transit

The ATG material focuses on the automobile mode because that mode is the main target of alternative traffic analysis tools.

4.1 HCM Volume 1: Concepts

HCM Volume 1 is published as bound hardcover book. It is intended to serve as an enduring reference for students and practitioners. It deals with accepted definitions, principles and relationships, most of which are documented in the literature. The following chapters are included in HCM Volume 1:

4.1.1 HCM Chapter 1: HCM Users Guide

HCM Chapter 1 is the starting point for learning how to use this edition of the HCM. This chapter presents the purpose, objectives, intended use, and target users of the 2010 HCM, describes the contents of each of the four volumes that make up the HCM, summarizes the major changes that have been made to HCM 2000 methodologies and mentions some of the important companion documents to the HCM. No ATG is included in this chapter.

4.1.2 HCM Chapter 2: Applications

HCM Chapter 2 introduces the wide range of potential HCM applications at the operational, design, preliminary engineering, and planning analysis levels. It covers all modes and all facility types. No ATG is included in this chapter.

4.1.3 HCM Chapter 3: Modal Characteristics

HCM Chapter 3 introduces some basic characteristics of the four major modes addressed by the HCM. The characteristics considered in this chapter for each mode include factors that contribute to a traveler’s experience when making a trip, observed seasonal and daily variations in travel demand, types of transportation facilities employed by a given mode notable capacity and/or volume observations, and descriptions of the interactions that occur between modes. No ATG is included in this chapter.
4.1.4 HCM Chapter 4: Traffic Flow and Capacity Concepts

HCM Chapter 4 describes the characteristics of traffic flow and demonstrates how the basic relationships between volume, speed and density apply to the four modes covered by the HCM. A four page discussion on the use of vehicle trajectory analysis for estimating traffic flow parameters is included in this chapter.

4.1.5 HCM Chapter 5: Quality of Service Concepts

HCM Chapter 5 presents the concepts that the HCM uses to describe performance from the traveler point-of-view in a way that is designed to be useful to roadway operators, decision-makers and members of the community. No ATG is included in this chapter.

4.1.6 HCM Chapter 6: HCM and Alternative Analysis Tools

HCM Chapter 6 begins by describing the HCM-based tools available to the analyst. The ATG includes a 21 page discussion of the following topics:

- Overview: Describes the purpose and content of the section and introduces the FHWA Traffic Engineering Toolbox [10] as an authoritative reference on alternative tools.

- Traffic Modeling Concepts and Terminology: Defines a hierarchy of modeling terms that have evolved somewhat inconsistently in the literature. Describes the various ways in which models can be categorized.

- Conceptual Differences between Deterministic and Simulation Tools: Presents a table identifying the various phenomena involved in traffic modeling and indicates the treatment of those phenomena by deterministic and simulation tools.

- Appropriate Use of Alternative Tools: Presents a detailed list of conditions under which it might be appropriate to apply alternative tools in addition to or instead of the HCM. Identifies typical applications for alternative tools to overcome the stated limitations of the HCM procedures in each chapter.

- Application Framework for Alternative Tools: Provides diagrams for each type of facility identifying the classes of alternative tools, with their general characteristics, inputs and outputs. Also indicates potential flow of information between tools.

- Performance Measures from Alternative Tools: Provides a table identifying the performance measures used by each HCM chapter and indicating which measures are also addressed by alternative tools.

- Traffic Analysis Tool Selection Criteria: Presents a set of considerations for selecting the most appropriate tool as a series of steps.

- Application Guidelines for Simulation Tools: Based on a highly abridged version of the general simulation guidelines presented in the Traffic Analysis Toolbox and other references. It was emphasized that the HCM is not trying to provide a general tutorial on simulation. It was also emphasized that alternative tools have been used for many years to provide decision support and that not all of their applications have any particular
requirement for HCM compatibility. Therefore HCM compatibility is not a universal requirement or desire. The guidance is addressed specifically to analysts who are seeking some degree of compatibility with the HCM procedures through the use of alternative tools.

4.1.7 HCM Chapter 7: Interpreting and Presenting Results
HCM Chapter 7 contains three sections:
- Uncertainty and Variability
- Defining and Computing Uniform Performance Measures
- Presentation of Results

The section on defining and computing uniform performance measures contains 21 ATG pages developed by this project. The following topics are included:
- Performance Measures Reported by HCM Procedures: Describes how each procedural chapter of the HCM defines and computes measures related to queues, stops, speed, delay and density.
- Use of Vehicle Trajectory Analysis in Comparing Performance Measures: Identifies the mathematical properties of vehicle trajectories, the types of analyses that can be performed and the limitations of vehicle trajectory analysis. Provides examples of the use of vehicle trajectory analysis on undersaturated and oversaturated approaches to a signal.
- Requirements for Computing Performance Measures by Vehicle Trajectory Analysis: Some general guidelines are presented first, followed by definitions and computational requirements for all performance measures addressed by the HCM.
- Stochastic Aspects of Simulation Analysis: Identifies specific references that provide tutorial material on statistical principles, discusses the procedure for determining the number of runs required to achieve a desired level of confidence and accuracy and describes the general characteristics of variability among runs.
- Comparing HCM Analysis Results with Alternative Tools: Identifies the conceptual differences between deterministic and stochastic modeling, provides a step-by-step framework for comparison, suggests a procedure for estimating capacity by simulation and explores the differences in temporal boundaries for multi-period delay models.

4.1.8 HCM Chapter 8: HCM Primer, Formerly Executive Summary
HCM Chapter 8 is written for a non-technical audience, and is a synopsis of Volume 1 of the HCM. Reference is made to the need for alternative tools but no specific ATG is included in this chapter.

4.1.9 HCM Chapter 9: Glossary and Symbols
HCM Chapter 9 defines all of the terms and symbols used throughout the HCM. ATG related terms are included in the glossary.
4.2  HCM Volumes 2 and 3: Analysis Procedures

These two volumes are published in loose-leaf format. Together they cover the material presented in Part III of the HCM 2000. Each facility (e.g., signalized intersections) is covered in a separate chapter. Each procedural chapter with potential applications for alternative tools contains a section with the heading “Use of Alternative Tools.” This section presents succinct guidance with occasional references to other documents such as the Traffic Analysis Toolbox.

4.2.1  Common ATG Section Structure for Procedural Chapters

The organization of the material is the same for all procedural chapters. The alternative tool guidance for each procedural chapter was developed around the following outline:

- **Strengths of the HCM Procedure**
  The section starts by explaining the strong points of the HCM procedure that justify its use as the default traffic analysis tool.

- **Limitations of the HCM Procedures that Might Be Addressed by Alternative Tools**
  Each chapter contains a list or table describing the identified limitations of the HCM procedure and an assessment of the potential of alternative tools to overcome these limitations. Follow up narrative identifies the most common types of applications in which alternative tools are typically employed.

- **Additional Features and Performance Measures Available from Alternative Tools**
  Alternative tools typically report a more comprehensive set of performance measures than the HCM procedures. The additional measures for each chapter are described in this section.

- **Development of HCM-Compatible Performance Measures Using Alternative Tools**
  In some cases the performance measures produced by alternative tools are based on different definitions than those with similar terminology in the HCM. Guidance is given here on how to recognize the differences and what, if any adjustments can be made to improve compatibility. When direct comparison with HCM based measures is not meaningful, guidance is provided on how the alternative tools can be used to produce relative measures that may be used to compare alternative design treatments.

- **Conceptual Differences between the HCM and Simulation Modeling that Preclude Direct Comparison of Results**
  Even when the HCM performance measure definitions are compatible with those of an alternative tool, direct comparisons may still not be meaningful because differences in the computational methodology may be expected to lead to different results. For example, random arrivals at a signalized intersection are treated entirely differently by analytical and simulation tools. Most analysts are unaware of the difference and are at a loss to explain why HCM delays can differ considerably from simulated delays with the same input data. The literature is full of studies that have found such inexplicable differences.
• **Adjustment of Simulation Parameters to the HCM Parameters**
  Some adjustments will generally be required before an alternative tool can be used effectively to supplement or replace an HCM procedure. For example, the parameters that determine the capacity of a signalized approach (e.g., steady state headway and startup lost time) should be adjusted to ensure that the simulated approach capacities match the HCM values. One exception to this rule is the case when HCM limitations prevent credible computations of capacity (e.g., short turn lane spillback). This section indicates the most important simulation parameters that should be fine tuned to put alternative tools on a “level playing field” with the HCM.

• **Step by Step Instructions for Applying Alternative Tools**
  Many of the steps required to conduct highway capacity analyses with alternative tools are common to all procedural chapters and are therefore covered in the “Application Framework” section of the general guidance in HCM Chapter 6. Steps that are specific to a particular chapter are covered here.

• **Sample Calculations Illustrating Alternative Tool Applications**
  Most alternative tools are constantly being updated by their developers. Therefore, all sample calculations involving alternative tools are included in the HCM Volume 4 supplemental material chapters (24 through 33). This section in the HCM Volume 2 and 3 chapters summarizes the characteristics of the supplemental examples.

The following chapters are included in HCM Volumes 2 and 3:

**4.2.2 HCM Chapter 10: Freeway Facilities**
An ATG section with the standard heading structure was included in this chapter.

**4.2.3 HCM Chapter 11: Basic Freeway Segments**
An ATG section with the standard heading structure was included in this chapter.

**4.2.4 HCM Chapter 12: Freeway Weaving Segments**
An ATG section with the standard heading structure was included in this chapter.

**4.2.5 HCM Chapter 13: Freeway Merge and Diverge Segments**
An ATG section with the standard heading structure was included in this chapter.

**4.2.6 HCM Chapter 14 Multilane Highways**
Simulation is not used to any extent for unsignalized multilane highways. A placeholder was created with a paragraph to that effect.

**4.2.7 HCM Chapter 15: Two-Lane Highways**
A limited set of ATG material was developed for this chapter because of the lack of user experience with simulation of two-lane highways. The potential uses for simulation of two lane highways were mentioned along with the fact that two lane highway capabilities are now being added to existing tools. Additional research is covered in Appendix 3 of this report.
4.2.8 **HCM Chapter 16: Urban Street Facilities**
The same ATG applies to urban street segments (Chapter 17) and facilities (Chapter 16). To avoid repetition, the presentation of guidance was confined to HCM Chapter 17.

4.2.9 **HCM Chapter 17: Urban Street Segments**
An ATG section was developed for this chapter using the standard heading structure.

4.2.10 **HCM Chapter 18: Signalized Intersections**
An ATG section was developed for this chapter using the standard heading structure.

4.2.11 **HCM Chapter 19: Two-Way Stop-Controlled Intersections**
An ATG section was developed for this chapter using the standard heading structure.

4.2.12 **HCM Chapter 20: All-Way Stop-Controlled Intersections**
Because of the lack of user experience with simulation of all-way stop control, a placeholder was included in this chapter in lieu of a full ATG section.

4.2.13 **HCM Chapter 21: Roundabouts**
An ATG section was developed for this chapter using the standard heading structure.

4.2.14 **HCM Chapter 22: Interchange Ramp Terminals**
An ATG section was developed for this chapter using the standard heading structure.

4.2.15 **HCM Chapter 23 Pedestrian-Bicycle Facilities**
Because of the lack of user experience with simulation of ped-bike facilities, a placeholder was included in this chapter in lieu of a full ATG section.

4.3 **HCM Volume 4: Applications Guide**
The introduction of HCM Volume 4 as a virtual document represents a significant departure from previous editions of the HCM. This decision was made in recognition of the growth in the body of knowledge and the size limitations of a paper document. HCM Volume 4 contains three parts:

1. Supplemental examples that are too detailed to include in the procedural chapters of HCM Volumes 2 and 3
2. The case studies currently presented in the Highway Capacity Manual Applications Guide (HCMAG), supplemented by a simulation based case study prepared by NCHRP Project 3-85
3. A reference library containing works related to the general subject of highway capacity analysis. The final report for NCHRP Project 3-85 (i.e., this document) will be included in the reference library.

The following chapters are included in HCM Volume 4:

4.3.1 **HCM Chapter 24: Concepts: Supplemental**
HCM Chapter 24 includes all of the supplemental material connected with the HCM Volume 1 chapters. It consists entirely of ATG material on the use of vehicle trajectory analysis developed
under this project. The trajectory analysis development effort is summarized in Section 3.5 of this report. A detailed description of the effort and the results is presented in Appendix 4.

The following topics are covered in HCM Chapter 24:
- Mathematical Properties of Vehicle Trajectories
- Vehicle Trajectory Analysis Mechanism
- Signalized Intersection Examples
  - Basic Signalized Intersection
  - Oversaturated Operation
  - More Complex Signal Phasing
- Freeway Examples
  - Weaving Section
  - Entrance Ramp Merging
- Requirements for Trajectory Analysis Algorithm Development
- Summary of Computational Procedures
- Analysis of a Signalized Approach
- Analysis of a Freeway Segment

### 4.3.2 HCM Chapter 25: Freeway Facilities, Supplemental

HCM Chapter 25 provides details on FREEVAL, a spreadsheet based computational engine that implements the procedures of HCM Chapter 10, *Freeway Facilities*, and presents some examples of its application. It was decided not to include supplemental examples of freeway facility simulation in this chapter for the following reasons:
- They don't generally address specific limitations stated in the chapter. They only prove that you will get different answers from simulation. Specific limitations are hard to address except with a comprehensive example much larger than the chapter itself.
- They can't avoid comparison of simulation results with the results of the HCM procedures. Such comparisons are off-limits for the ATG.
- They are likely to raise more questions than they answer.
- Supplemental examples illustrating interactions between segments are presented in HCM Chapters 26 and 34.
- A comprehensive example of the application of simulation tools to a major freeway reconstruction project is presented as Case Study 6 of the Applications Guide in HCM Volume 4.

### 4.3.3 HCM Chapter 26: Basic Freeway Segments, Supplemental

ATG material provides about 85% of the content of this chapter. Two example problems covering an HOV lane and an incident, both of which are beyond the stated limits of the HCM procedure, were presented. The examples were both based on Example Problem 3 in HCM Chapter 11, *Basic Freeway Segments*.

### 4.3.4 HCM Chapter 27: Freeway Weaving Segments, Supplemental

ATG material provides all of the content of this chapter. Three example problems covering situations that are beyond the stated limits of the HCM procedure were presented. They covered the following situations:
• Determining the weaving segment capacity
• Effect of demand on performance when the weaving area becomes congested
• Effect of queue backup from a downstream signal on the exit ramp

The examples were all based on Example Problem 1 in HCM Chapter 12, Freeway Weaving Segments.

4.3.5 HCM Chapter 28: Freeway Merge and Diverge Segments, Supplemental
ATG material provides all of the content of this chapter. Two example problems covering an HOV lane and a ramp metering operation, both of which are beyond the stated limits of the HCM procedure, were presented. The examples were both based on Example Problem 3 in HCM Chapter 13, Freeway Merge and Diverge Segments.

4.3.6 HCM Chapter 29: Urban Street Facilities, Supplemental
ATG material provides all of the content of this chapter. The chapter presents a set of four examples to illustrate the use of alternative tools to address the stated limitations of the HCM in urban street analysis. All of the examples are based on an arterial route with five intersections. Specifically, these examples are used to illustrate the following situations that are beyond the HCM limitations:

• The application of deterministic tools to optimize the signal timing. The features of TRANSYT-7F and SYNCHRO were described in this section.

• The effect of using a roundabout as a segment boundary instead of a traffic signal. Two different progression schemes were examined. The first had platoons from both directions arriving at the roundabout simultaneously. The second had them arriving in an alternating manner. VISSIM [11] was used as the simulation tool for this example. The results indicated that the delays on the arterial approaches to the roundabout were about 10% lower with simultaneous arrivals.

• The effect of mid-segment parking maneuvers on facility operation. It was demonstrated using CORSIM that mid-segment parking maneuvers had a detrimental effect on the operation of the arterial. The effect was quantified in terms of the number of parking maneuvers per hour.

• The use of simulated vehicle trajectories to evaluate the proportion of time that the back of the queue on the minor street approach to a two way stop-controlled (TWSC) intersection operating within a coordinated signal system exceeds a specified distance from the stop line. This measure is not evaluated by the HCM procedures.

The last example is of special interest to NCHRP Project 3-85 because it includes a demonstration of the vehicle trajectory analysis procedures developed as a part of this project. The queuing characteristics of simultaneous and alternating progression schemes were compared and the proportion of time that a queue could be expected to extend beyond a specified point was computed using trajectory analysis. Some of the analyses in this section were too detailed for the HCM chapter. These analyses are included in Appendix 4 to this report.
4.3.7 HCM Chapter 30: Urban Street Segments, Supplemental
This chapter presents some detailed material that is supplemental to the procedure described in HCM Chapter 17, Urban Street Segments. Individual segments were considered in the supplemental examples presented in HCM Chapters 18, Signalized Intersections, and 29, Urban Street Facilities. No additional examples involving alternative tools were presented in this chapter.

4.3.8 HCM Chapter 31: Signalized Intersections, Supplemental
Four supplemental examples illustrating how simulation might be used to address the limitations of the HCM procedure were presented. They covered the following situations:
- Effect of Storage Bay Overflow
- Effect of Right-Turn-on-Red Operation
- Effect of Short Through Lanes
- Effect of Closely-Spaced Intersections

The examples were all based on Example Problem 1 in HCM Chapter 18, Signalized Intersections.

4.3.9 HCM Chapter 32: Stop-Controlled Intersections, Supplemental
Most of the applications for alternative tools at stop controlled intersections involve stop controlled intersections within a coordinated arterial signal system. An example of a two-way stop controlled intersection within an urban freeway facility was included in HCM Chapter 29. Another example involving a two way stop controlled intersection in close proximity to diamond interchange was included in HCM Chapter 34. No additional examples were included in HCM Chapter 32.

4.3.10 HCM Chapter 33: Roundabouts, Supplemental
Most of the applications for alternative tools at roundabouts involve roundabouts within a coordinated arterial signal system. An example of a roundabout within an urban freeway facility was included in HCM Chapter 29. No additional roundabout examples were included in HCM Chapter 33.

4.3.11 HCM Chapter 34: Interchange Ramp Terminals, Supplemental
Several supplemental examples illustrating how simulation might be used to address the limitations of the HCM procedure were presented. The following phenomena were demonstrated:
- Oversaturated diamond interchange showing overflow of the internal left turn bays
- Effect of backup from the interchange into a two-way stop controlled intersection
- Effect of backup from ramp metering signals into the interchange

The examples were all based on Example Problem 1 in HCM Chapter 22, Interchange Ramp Terminals.

4.3.12 HCM Chapter 35: Active Traffic Management
This chapter was developed under separate contract. There were no potential topics for which to develop guidance for the use of alternative tools.
4.3.13 HCMAG Case Study 6

The Highway Capacity Manual Applications Guide (HCMAG) was developed under NCHRP Project 3-64 to provide supplemental information to HCM users through a series of case studies. Five case studies were developed under that project to cover a wide range of analysis situations. The case studies are included in Volume 4 of the 2010 HCM.

A sixth case study was developed under NCHRP Project 3-85 to illustrate the use of alternative tools to analyze a complex corridor consisting of a freeway and parallel surface routes. The case study is based on the I-465 west leg reconstruction project in Indianapolis. The project corridor is a 9-mile urban freeway segment with a total of 8 interchanges. A single lane in each direction is to be added, totaling 8 lanes, and individual interchanges are to be modernized. An overview of this site is presented in Exhibit 29. This case study illustrates how alternative tools were successfully used during the course of the I-465 project. Emphasis was given to how to interpret simulation results from a system level perspective. Paramics [12] was used as the simulation tool. This site offers an excellent combination of freeway and surface street facilities to which a variety of analytical and simulation tools may be applied. Five problems that illustrate the analysis methodology were developed for this case study:

- **Problem 1: Analysis of an Interchange as a Multi-Segment System:** This problem illustrates how an interchange can be analyzed as a multi-segment system using simulation. A typical interchange consists of freeway mainline lanes, on and off-ramps, and local streets serving the freeway as well as local traffic. The HCM procedures provide performance measures and LOS results at various locations within the interchange, including freeway basic segments, ramp junctions, weaving areas, intersections, and cross streets. This approach makes it difficult to analyze close interactions between the freeway and the cross streets and to describe overall traffic operations conditions of the interchange itself. Chapter 22 of the HCM deals with interchanges and ramp terminals, but cloverleaf interchanges are outside of the scope of the chapter. Therefore, the evaluation of different design configurations from a traffic operations perspective is not practical using the HCM procedures.

- **Problem 2: Analysis of Interactions with Closely-Spaced Adjacent Intersections:** This problem highlights the interaction of a freeway interchange with closely-spaced adjacent intersections. As mentioned earlier, interchanges are multi-segment systems and their efficiency depends on the interactions between facilities. This problem concentrates on interactions between the I-465 SB off-ramp and the adjacent intersection on Rockville Road and High School Road. The distance between the I-465 SB off-ramp terminal and the Rockville Road/High School Road intersection is less than 150 ft. Simulation was used to illustrate how a signal timing plan at this intersection affects the overall interchange performance.

- **Problem 3: Evaluation of Interchange Design Alternatives from an Operations Perspective:** The interchange at freeway I-465 and Rockville Road was again chosen for this problem. The study area consists of a typical interchange at I-465 and Rockville Road. This is a full cloverleaf configuration where loops have posted speed limits of 25 mph. The study area also includes two adjacent signalized intersections on Rockville Road.
Road located on either side of I-465 at High School Rd (West of I-465) and Mickley Ave (East of I-465).

- **Problem 4: Evaluation of Work-Zone Mobility Impacts for the Interchange Reconstruction:** This problem demonstrates the evaluation of work-zone mobility impacts due to various lane closure scenarios for an interchange reconstruction. A tradeoff always exists between the duration of construction and the level of closures. Construction will be completed sooner if the construction site provides more space as a result of roadway or lane closures. Simulation generates various system wide performance measures that can be used to select the most suitable roadway or lane closure scenario for the interchange reconstruction.

- **Problem 5: Comparison of Static and Dynamic Traffic Assignment Techniques:** Traffic assignment, either static or dynamic, utilizes a generalized link cost function to estimate travel costs between every origin-destination pair for assigning traffic to these routes. By definition, the static assignment assumes that the travel costs between every origin-destination pair remain the same throughout simulation regardless of the level of ongoing congestion in the network. Meanwhile, the dynamic traffic assignment periodically reevaluates the travel costs and modifies the shortest paths during their trips accordingly. The objective of this problem was to illustrate differences between the static and dynamic traffic assignment techniques in carrying out real-world simulations.
Exhibit 29: Overview of the case study site
5 Conclusions and Recommendations

The principal product of this project is the guidance for the use of alternative tools that was incorporated into the 2010 edition if the HCM. Most of the research effort was carried out to develop the guidance. The conclusions and recommendations supported by the study are summarized here.

5.1 Conclusions:

Within the limits of the study, the following observations and conclusions are offered:

- Most traffic analysis tools deal with similar geometric and operational features and report the same nominal performance measures, although the definitions and methods of computation vary.

- There are some conceptual differences between the HCM’s analytical modeling and simulation modeling that are reflected in the way analytical and simulation tools deal with various traffic flow phenomena. These differences make direct comparison of results difficult and sometimes impossible.

- The new urban street facilities analysis procedure represents a substantial improvement over the previous version published in the HCM 2000. It internalizes computations that had to be approximated or carried out externally in the previous version.
  - The computational engine that implemented the procedure performed in a robust manner.
  - There were no internal inconsistencies or anomalous behaviors in the results.
  - The relationships between demand levels, phase times and average speeds conformed generally to expectations.
  - The numerical results could not be expected to match those of the alternative tools because of differences in model formulation. The agreement was close enough that no judgment could be offered as to the absolute accuracy of any tool.

A single case study does not constitute a complete evaluation of any traffic analysis tool. However, within the limits of this study, it can be said that the performance of the HCM 2010 urban street facilities procedure in the automobile mode supports the conclusion that it provides a credible method for evaluating the operation of an urban street facility. It offers a substantial contribution to the methodology of highway capacity and level of service analysis.

- Vehicle trajectory analysis was demonstrated to produce results that can be applied consistently among tools. The computational procedures proposed in this document should offer a reasonable approximation of the performance measures that are estimated by other techniques, including field studies and the HCM. The proposed procedures depend to a certain extent on approximations and assigned thresholds but this dependency is no greater than the other techniques and should not produce issues of compatibility.
The following observations emerged from the vehicle trajectory analysis task:

- It is not a practical end user technique because of the amount of data involved, especially when multiple simulation runs are required to produce statistically significant results. It is essential that the computational procedures be internalized in simulation tools by their developers.

- The computational procedures for estimating uniform performance measures from trajectory analysis proposed in this report were developed in a manner that should make them practical for implementation in simulation tools.

- It is essential to assign all performance measures to the segment and time interval in which they accrue. It is not practical to offer a consistent trajectory analysis methodology that seeks to associate these measures with their root cause, which might be in some other part of the network or in some other time interval. While this constraint might not be consistent with the objectives of some analysts, it eliminates several intractable problems and issues.

- To ensure that all measures are fully reported, it is essential to define the analysis domain, both in time and space, such that a period of uncongested operation exists at all boundaries.

- The concept of control delay, as defined by the HCM, and the procedures by which it is computed, cannot be implemented in a consistent manner by vehicle trajectory analysis. However, a reasonable approximation of control delay is provided by the simulated “queue delay” measure, computed as prescribed in this document.

### 5.2 Recommendations

In addition to the extensive guidance for the use of alternative tools incorporated into the 2010 HCM, the following recommendations emerged from this study:

- Developers should be encouraged to implement the trajectory analysis logic developed by this project in their products to promote uniform and consistent reporting of performance measures.

- The SSAM vehicle trajectory file format would be well suited to performance analysis if some additional data items were included. Developers of simulation tools should be encouraged to adopt the expanded format for SSAM files proposed in this report.

- Developers of deterministic tools should be encouraged to incorporate the advancements in the urban streets analysis procedures developed for the HCM 2010.

- The developers of the computational engine for freeway facilities (FREEVAL) should consider whether the default graphics chart type is best suited for representing average values of speed and density on a facility in which demand exceeds capacity.
References

2. *The Urban Transportation Monitor*, ISSN 10404880, published by Lawley Publications, Fairfax Station, VA 22039.
Technical Appendices
The following technical appendices contain relevant information relevant that was too detailed to include in the body of the report:

Appendix 1: Urban Street Facility Case Study

Appendix 2: Freeway Facility Case Study

Appendix 3: Two Lane Highway Case Study

Appendix 4: Vehicle Trajectory Analysis Considerations

Appendix 5: Data Analysis Utility Documentation
Urban Street Facility Case Study

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Introduction

Chapter 16 of the 2010 Highway Capacity Manual (HCM) presents a complete procedure for evaluating the level of service (LOS) of an urban arterial street facility in terms of the average speed of the through vehicles on the facility. This procedure was developed in response to criticism of the lack of detail in the HCM 2000 version. The limitations of that version have led many users to alternative traffic analysis tools for urban street facility analysis. The new procedure is based on the work of Bonneson et al [1].

This discussion examines the characteristics of the new procedure and compares those characteristics with the HCM 2000 procedure and with commonly used deterministic and stochastic traffic analysis tools. While the new procedure is multimodal in scope, this discussion will focus on the automobile mode to facilitate comparisons with alternative tools.

Enhancements to the HCM 2000 Procedure

The procedure offers significant improvements over the methodology presented in the HCM 2000. It represents one of the most important enhancements to the 2010 version. Exhibit 1 summarizes the principal new features that have been added to the procedure. Reference 1 provides more detailed information on the model development.

<table>
<thead>
<tr>
<th>Feature</th>
<th>HCM 2000 Treatment</th>
<th>HCM 2010 Treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Movements considered</td>
<td>Arterial through traffic only</td>
<td>All intersection movements</td>
</tr>
<tr>
<td>Periods analyzed</td>
<td>Single period</td>
<td>Multiple periods with residual queue carryover</td>
</tr>
<tr>
<td>Signal timing Plan</td>
<td>User entry of g/C ratio</td>
<td>Computation of phase times from specified traffic-actuated controller parameters</td>
</tr>
<tr>
<td>Arterial progression effects</td>
<td>User entry of arrival type (1-6)</td>
<td>Macroscopic flow model computes vehicle arrival profiles over the cycle based on user specified offsets</td>
</tr>
<tr>
<td>Running speed</td>
<td>Model based on free flow speed and intersection spacing</td>
<td>Additional factors such as traffic volume and mid-segment activities are considered.</td>
</tr>
<tr>
<td>Control at segment boundaries</td>
<td>Signalized intersections only</td>
<td>Signalized or Unsignalized intersections</td>
</tr>
<tr>
<td>Turns from cross streets</td>
<td>Ignored</td>
<td>Recognized in the computation of arrival profiles</td>
</tr>
<tr>
<td>Access points on the route</td>
<td>Ignored</td>
<td>Recognized in the determination of running speed and delay</td>
</tr>
<tr>
<td>Modal scope</td>
<td>Automobile mode only</td>
<td>Multimodal</td>
</tr>
</tbody>
</table>
Chapters 16 through 18 of the 2010 HCM describe the general features of the HCM procedure, including its stated limitations. Chapter 29 provides more detail on the analysis methodology and illustrates the use of commonly used alternative tools to overcome those limitations. No comparisons between the results from different tools were presented in Chapter 29. The purpose of this discussion is to extend the analysis in Chapter 29 to include a comparison of the following relationships:

- The effect of demand volume on the signal timing plan
- The effect of demand volume on the average speed
- The effect of progression quality on the average speed

A case study example will be used for this purpose. Example Calculation 16-1, presented in Chapter 16 of the HCM 2010 provides an ideal starting point for the discussion because it presents some detailed results from the new procedure.

**Case Study Description**

The arterial route contains five segments as shown in Exhibit 2. Each segment has two access points (i.e., driveways). The explicit treatment of access points is one of the new features in 2010.
The following additional information was provided as a part of the case study description:

- 200 ft left turn bays are provided on each approach.
- All movements have 3% heavy vehicles.
- Right turn on red (RTOR) volume was estimated as 5% of the right turn volume. RTOR was eliminated from the case study here to facilitate comparison of tools because of the differences in the treatment of RTOR by different tools. Some tools subtract a portion of the right turn demand while others model RTOR explicitly. An example of RTOR differences was presented in Chapter 31 of the 2010 HCM.
- 1.5 ft curb and gutter is provided on both sides.
- Arterial approaches have protected/permitted left turns from 200 ft bays.
- Cross street approaches have permitted left turns from 200 ft bays.
- Minimum green times are 5 sec for left turns and 18 sec for through movements.
- All intersections operate under coordinated semi-actuated control with a background cycle length of 100 sec. Nominal signal phase splits are
  - EW left turns: 20 sec
  - EW green 45 sec
  - NS green 35 sec
- Yellow + all-red times are 4 sec for all movements.
- Passage time is 2 sec for all detected approaches.

Additional information was provided to evaluate other modes of travel but it will not be included in this discussion, which is limited to the automobile mode.

Saturation flow rates provided with the problem description were obtained from the Chapter 18 (Signalized Intersections) procedure. The following values were given in units of vphg/lane:

- EB & WB: 1760 left, 1829 through and right
- NB & SB: 1826 left, 1838 through and right

To establish the relationships for investigation, the demand volumes were varied from 100% to 180% of the specified values. The 180% demand level produced a degree of saturation close to 100%. To balance the degree of saturation at this level, it was necessary to adjust the nominal signal phase splits from those given in the original example. The 100 sec cycle was retained and the splits were adjusted as follows:

- EW left turns: 13 sec
- EW green 45 sec
- NS green 42 sec

The original signal offsets were designed for balanced progression in both directions. To create two different progression schemes for comparison, the offsets were changed to give full band progression eastbound at the expense of the westbound flow. So the eastbound progression will be close to “ideal” and the westbound progression will be mediocre at best. This difference should be reflected in the average speed results for all tools. The offset reference point was also moved from the end of green to the beginning of green to facilitate comparison of results between tools because not all of the tools accommodate end-of-green reference points. The new offsets starting at the west end of the facility are 0, 26, 51, 77, 92 and 6 seconds, respectively. More detail on the progression bandwidths will be provided later.
Data Preparation

Results from the following analysis tools will be used for comparison with the 2010 urban street facilities analysis procedure:

- The procedure originally presented in the HCM 2000
- CORSIM [2]
- Synchro 7 [3]
- TRANSYT-7F [4]

Data preparation for each of the tools must consider the differences in the way that they define and perform computations. The data preparation for each tool will be discussed separately to illustrate the different requirements and to provide guidance on their use.

Demand Volumes

To create the required range of demand volumes for investigation, the initial volumes given for the intersections were adjusted as shown in Exhibit 3. Access point volumes were adjusted as shown in Exhibit 4. Separate adjustments are required for both access points because the initial volumes were different.

### Exhibit 3: Adjusted intersection volumes by percent of initial volumes

<table>
<thead>
<tr>
<th>Percent</th>
<th>EWLT</th>
<th>EW Thru</th>
<th>EWRT</th>
<th>NSLT</th>
<th>NS Thru</th>
<th>NSRT</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>80</td>
<td>640</td>
<td>80</td>
<td>60</td>
<td>480</td>
<td>60</td>
</tr>
<tr>
<td>120</td>
<td>96</td>
<td>768</td>
<td>96</td>
<td>72</td>
<td>576</td>
<td>72</td>
</tr>
<tr>
<td>140</td>
<td>112</td>
<td>896</td>
<td>112</td>
<td>84</td>
<td>672</td>
<td>84</td>
</tr>
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<td>160</td>
<td>128</td>
<td>1024</td>
<td>128</td>
<td>96</td>
<td>768</td>
<td>96</td>
</tr>
<tr>
<td>180</td>
<td>144</td>
<td>1152</td>
<td>144</td>
<td>108</td>
<td>864</td>
<td>108</td>
</tr>
</tbody>
</table>

### Exhibit 4: Adjusted access point volumes by percent of initial volume

<table>
<thead>
<tr>
<th>Access Point</th>
<th>EBL</th>
<th>EBT</th>
<th>EBR</th>
<th>WBL</th>
<th>WBT</th>
<th>WBR</th>
<th>NBL</th>
<th>NBR</th>
<th>SBL</th>
<th>SBR</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 Percent of Initial Volume</td>
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<td></td>
<td></td>
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<tr>
<td>1</td>
<td>38</td>
<td>684</td>
<td>38</td>
<td>39</td>
<td>702</td>
<td>39</td>
<td>49</td>
<td>48</td>
<td>48</td>
<td>49</td>
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<td>2</td>
<td>39</td>
<td>702</td>
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<td>38</td>
<td>684</td>
<td>38</td>
<td>48</td>
<td>49</td>
<td>49</td>
<td>48</td>
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<tr>
<td>120 Percent of Initial Volume</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>46</td>
<td>821</td>
<td>46</td>
<td>47</td>
<td>842</td>
<td>47</td>
<td>59</td>
<td>58</td>
<td>58</td>
<td>59</td>
</tr>
<tr>
<td>2</td>
<td>47</td>
<td>842</td>
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<td>46</td>
<td>821</td>
<td>46</td>
<td>58</td>
<td>59</td>
<td>59</td>
<td>59</td>
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<tr>
<td>140 Percent of Initial Volume</td>
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<tr>
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<td>983</td>
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<td>53</td>
<td>958</td>
<td>53</td>
<td>67</td>
<td>69</td>
<td>69</td>
<td>67</td>
</tr>
<tr>
<td>160 Percent of Initial Volume</td>
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<td>1</td>
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<td>1094</td>
<td>61</td>
<td>62</td>
<td>1123</td>
<td>62</td>
<td>78</td>
<td>77</td>
<td>77</td>
<td>78</td>
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<tr>
<td>2</td>
<td>62</td>
<td>1123</td>
<td>62</td>
<td>61</td>
<td>1094</td>
<td>61</td>
<td>77</td>
<td>78</td>
<td>78</td>
<td>77</td>
</tr>
<tr>
<td>180 Percent of Initial Volume</td>
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<tr>
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<td>68</td>
<td>1231</td>
<td>68</td>
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</tr>
<tr>
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<td>70</td>
<td>1264</td>
<td>70</td>
<td>68</td>
<td>1231</td>
<td>68</td>
<td>86</td>
<td>86</td>
<td>86</td>
<td>88</td>
</tr>
</tbody>
</table>
The access point adjustments require more explanation. Initial experiments with an “across the board” adjustment indicated that the volumes entering the arterial from the access point became large enough to cause congestion at the access points. Essentially, these points operated as unsignalized intersections, which was not the intent of the case study. So, the volumes entering at the access points were kept constant, and only the arterial volumes were increased.

Arterial Volume Continuity

Traffic volume counts at the intersections are often taken on different days, so a typical volume input data set for an arterial facility will not maintain volume continuity along the route. If the total link input does not match the total link output, then some adjustment will be necessary. The adjustment methodology differs among tools and can therefore affect the comparison of results. The link volume balancing methodology of the analysis tools discussed here is summarized in Exhibit 5.

<table>
<thead>
<tr>
<th>Analysis Tool</th>
<th>Link Volume Balancing Procedure</th>
</tr>
</thead>
<tbody>
<tr>
<td>HCM 2000</td>
<td>None:</td>
</tr>
<tr>
<td>HCM 2010</td>
<td>Proportional adjustment of output flows to match the total input. Capacity constraints are applied to the input flows.</td>
</tr>
<tr>
<td>TRANSYT-7F</td>
<td>Proportional adjustment plus warning if balance limits are exceeded</td>
</tr>
<tr>
<td>Synchro</td>
<td>Proportional adjustment combined with synthesized mid block flow</td>
</tr>
<tr>
<td>CORSIM</td>
<td>No balancing necessary because volumes are only specified at input nodes. Internal volume specifications are treated as proportions of the total link volume. When severe unbalance occurs, the volumes processed by CORSIM at any intersection could differ substantially from the specified volumes.</td>
</tr>
</tbody>
</table>

Because of the differences shown in this table, it is clear that comparison of results is best accomplished with balanced volume data. The initial volume data for the example was balanced. The total exiting volume at each signalized intersection exceeded the total entering volume by 40 vph. This loss was balanced by a gain of 40 vph at the access points. However, when the intersection volumes are increased and the access point entry is held constant, as explained previously, the balance will be disturbed because some traffic will be lost.

The lost volume can be offset by specifying a mid-segment entry volume with tools that recognize mid-segment entry. TRANSYT-7F, Synchro and CORSIM all recognize mid-segment entry as explicit inputs. The HCM 2010 procedure accommodates mid-segment entry through access points.

To offset the volume loss on each link, the following mid-segment entry values were used:
- 40 vph with 100% of initial volume
- 48 vph with 120% of initial volume
- 56 vph with 140% of initial volume
- 64 vph with 160% of initial volume
- 72 vph with 180% of initial volume
Speed Definitions

The average speed on any segment is determined by dividing the length of the segment by the time taken by each vehicle to traverse the segment. All of the deterministic tools compute the travel time as the sum of two components:

1. The time required to travel the segment at the running speed
2. The delay time at the intersection due to the traffic control.

Simulation tools compute travel times by accumulating the time spent by each vehicle in the segment.

The delay time is defined consistently by all of the deterministic tools. The running time definition and computation, on the other hand, is specific to each tool. Exhibit 6 summarizes the methodology used by the various tools to compute running speeds. It also indicates the most appropriate value to use for each tool to promote a consistent evaluation.

<table>
<thead>
<tr>
<th>Analysis Tool</th>
<th>Field Name for Speed Input</th>
<th>Running Speed Computation</th>
<th>(FFS = Free Flow Speed)</th>
<th>Input for Consistent Comparison</th>
</tr>
</thead>
<tbody>
<tr>
<td>HCM 2000</td>
<td>Free-Flow Speed</td>
<td>Computed from FFS and segment length</td>
<td>Speed limit + 5 mph</td>
<td></td>
</tr>
<tr>
<td>HCM 2010</td>
<td>Speed Limit</td>
<td>FFS determined from speed limit and geometrics (usually about speed limit + 5mph). Running speed is computed from FFS and other factors</td>
<td>Speed limit</td>
<td></td>
</tr>
<tr>
<td>TRANSYT-7F</td>
<td>Cruise Speed</td>
<td>Running speed is assumed to be the cruise speed</td>
<td>Speed limit</td>
<td></td>
</tr>
<tr>
<td>Synchro</td>
<td>Link Speed</td>
<td>Computed from link speed and segment length</td>
<td>Speed limit + 5 mph</td>
<td></td>
</tr>
<tr>
<td>CORSIM</td>
<td>Free Flow Speed</td>
<td>Determined implicitly from interference by less aggressive drivers traveling below the FFS</td>
<td>Speed Limit + 5 mph</td>
<td></td>
</tr>
</tbody>
</table>

Signal Timing Plan Synthesis Results

The control delay experienced at each intersection is an important component of the segment travel time. Since the delay values are strongly influenced by the green times for each movement, the signal plan is an essential input to the delay computation process. Earlier versions of the HCM required cycle length and green times as a user input. The HCM 2000 provided guidance on how to approximate the signal timing plan. The recommended procedures were incorporated into some tools, while other tools invoked their own computations.

Timing plans may be based on pretimed, traffic actuated, or coordinated semi-actuated control. Pretimed plans are produced by both Synchro and TRANSYT-7F as a product of an optimization process. The majority of urban street facilities use coordinated semi-actuated control, so this discussion will focus on that type of control. It was noted earlier that the HCM 2010 example used in this discussion assumed coordinated semi-actuated control.
Exhibit 7 summarizes the methodology used by traffic analysis tools to estimate the timing plan for an intersection with coordinated semi-actuated control. All of the tools considered here model this type of control to assign unused time between phases but the computational methodology differs among tools.

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<td>HCM 2010</td>
<td>Actuated controller parameters</td>
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The timing plan results for these tools will now be examined. Each tool was used with a range of demand volumes from 100 to 180% of the initial volumes. The v/c ratios for the initial volumes were very low, so a significant transfer of time from the actuated phases to the coordinated phase (EW through) could be expected. At higher demand levels, less time will be transferred and the timing plan should converge to the nominal splits.

The other analysis tools do not model access points in the same manner as the HCM 2010 procedure. To focus on the timing plan estimation results and to produce a more consistent comparison, the access points were removed from the facility for this part of the study.
HCM 2010 Timing Plans

The HCM 2010 timing plan estimation results are presented in Exhibit 8. The green times are shown in terms of their percent of nominal splits as a function of the percent of demand volume. Separate relationships are plotted for the arterial left turns, arterial through movements and the cross street phase times. Note that there was no protected left turn phase for the cross streets.

![Exhibit 8: HCM 2010 effect of demand on phase times](image)

The results are generally as anticipated. At low demand levels, the arterial through phase receives significant unused time from the actuated phases and its time exceeds the nominal split time. This effect diminishes as the demand level increases. The cross street phase time starts off well below its nominal split because of lack of demand. The time increases with demand and eventually reaches 100% of the nominal split.

Full convergence to 100% was not achieved for the other two movements. Even at 180% of the initial demand, the arterial left turn phase only reached 75% of the nominal split. It could be expected to converge at higher demand levels, but the upper limit was constrained to 180% to accommodate all of the other experiments at a degree of saturation below 1.0. The 180% demand amounts to 128 vph or 3.5 veh per cycle for the left turn. The permitted green and sneakers are able to accommodate most of the left turns.
To verify this explanation, the “protected only” case was also examined. The same demand, timing parameters and demand levels were used. The only difference in the two cases was the elimination of the permitted green phase for the left turns. The results are presented in Exhibit 9, which shows that all phases converged to their nominal splits at the 180% level.

Exhibit 9: Effect of demand on phase times without the permitted left turn

The balance of the discussion will revert to the original example data, which included the permitted left turn phase. The HCM 2010 results will be compared with CORSIM, Synchro and TRANSYT-7F.

CORSIM Timing Plans

CORSIM has the ability to emulate the operation of a traffic-actuated controller responding to simulated detector inputs produced by microscopic simulation of vehicles under signal control. CORSIM does not accumulate green times to generate direct timing plan outputs. A software utility was therefore developed to extract the signal status information from CORSIM’s animated graphics. The software utility, called TACTiming, is described in more detail in Appendix 5 to this report.

The same input data were analyzed by CORSIM. The results, which are presented in Exhibit 10, are similar to those produced by the HCM 2010 procedure. The cross street phase times reached their nominal split at high demand levels but the other phases did not. CORSIM treated the arterial left turn somewhat more optimistically than the HCM 2010 procedure, giving lower phase times throughout the entire range. The deterministic and stochastic models for permitted left turns and sneakers are quite different, so some difference in the results should be anticipated. The important point here is that the general characteristics are similar.
Synchro Timing Plans

The Synchro traffic flow model is macroscopic and deterministic. Its formulation is different from the HCM 2010 and it presents the estimated phase times in terms of percentile values from 10% to 90%. The 50th percentile value was used for comparison purposes because the average values are presented by the other tools.

The Synchro results are presented in Exhibit 11. The same general characteristics are observed in this exhibit. Unlike the other two tools, all of the phase times converged to their nominal splits at high demand levels. This suggests that there are some differences in Synchro’s modeling of permitted left turns and sneakers that caused it to take a less optimistic view of the permitted left turn phase.
TRANSYT-7F Timing Plans

The TRANSYT-7F results are presented in Exhibit 12. The phase times converged to their nominal splits at about the same demand levels as Synchro, suggesting that these two macroscopic models take a similar view of the green time requirements of traffic actuated phases.

Exhibit 12: TRANSYT-7F effect of demand on phase times
Average Speed Results

Level of service estimates in the HCM are based on the computed value of the average speed. The average speed on any segment is determined by all tools by dividing the length of the segment by the time taken by each vehicle to traverse the segment. The average speed for the facility divides the sum of the segment lengths by the sum of the segment travel times. The modeling differences among tools were discussed earlier. Differences in results could be due to differences in the computation of running speeds or control delay on each segment.

This section compares the speed results among different tools, taking into account the quality of progression. The progression design favors eastbound traffic heavily at the expense of westbound traffic, thereby creating two different cases of progression quality. Since the demand volumes are the same in both directions, differences in the overall speed can be attributed entirely to differences in progression quality. In the results for each tool, two phenomena should be observed:

1. The overall speed should decrease as demand increases because of lower running speeds and higher delays.
2. The direction favored by the progression design (eastbound) should have higher speeds than the reverse direction (westbound).

The same analysis tools will be examined in this section. The HCM 2000 procedure will also be considered here. It was not considered in the previous section because it does not include a timing plan computation model.

HCM 2000 and 2010 Speeds

The investigation will begin with a comparison of the HCM 2000 and HCM 2010 results. This comparison will provide some insight into the differences between the two procedures. It will also establish the clear superiority of the new procedure.

The HCM 2000 procedure does not perform any signal timing computations. The g/C time for each segment is a user input. The HCS software is able to obtain this input from the signalized intersections module. The signal timing plan must be entered into that module to determine the g/C ratios. So, to apply the HCM 2000 urban street analysis procedure, the timing plan computed by the HCM 2010 procedure was entered into the HCM 2000 signalized intersection software and the results were imported into the HCM 2000 urban streets software.

Progression quality is another user input to the HCM 2000 procedure. It is generally entered in terms of an arrival type (AT). To provide a complete picture, the analysis was repeated for AT 1-5 as defined in the HCM 2000. The results are presented in Exhibit 13. Each arrival type is represented by a different line in this figure. As expected, AT 1 (worst progression) shows the lowest speeds and AT 5 (best progression) shows the highest speeds. The average speed value ranges from about 12 mph to 30 mph.
Proper application of the HCM 2000 procedure required an intelligent estimate of the arrival type. Normally, AT3 would be assigned to isolated operation, AT 4 would be assigned to coordinated operation with favorable progression and AT 2 would be assigned to unfavorable progression.

The HCM 2010 procedure eliminates the need for an educated guess at the arrival type by modeling the progression of traffic from segment to segment. The results for the two progression cases from this example are also shown in Exhibit 13, superimposed on the HCM 2000 results. By way of comparison, it appears that the favored direction (eastbound) had an equivalent Arrival Type between 4 and 5. The reverse direction was between AT-2 and AT-3 for most of the demand range. A direct comparison of the two methods cannot be made based on arrival type alone because the HCM 2010 procedure is also sensitive to other inputs.

![Exhibit 13: Effect of demand on average speed (HCM 2000 and 2010)](image)

**TRANSYT-7F Speeds**

TRANSYT-7F incorporates a detailed macroscopic traffic flow model that recognizes signal splits and offsets, turning traffic entering from the cross street and platoon dispersion. Some aspects of this model were incorporated into the new HCM 2010 procedure. The main limitation of TRANSYT-7F is its requirement for user input of running speed because the input values are not affected by demand volumes. TRANSYT-7F results are therefore somewhat different from the other tools.

The results are shown in Exhibit 14. Note that the demand level has only a minimal effect on speeds because it only increases the control delay at the signals. It does not reduce the running
speed. To produce demand-speed relationships similar to the other tools, the phase times and running speeds from one of the other tools would have to be entered for each demand level.

![Graph showing effect of demand on average speed](image)

**Exhibit 14: Effect of demand on average speed (TRANSYT-7F)**

**CORSIM Speeds**

CORSIM estimates average speeds by microscopic simulation from the accumulated travel times of each vehicle. The coordinated-actuated phase times are estimated by internal emulation of a NEMA or Type 170 controller. It was demonstrated earlier that CORSIM’s phase times were sensitive to demand in this example in much the same manner as the HCM 2010.

Running times are estimated by assigning an aggressiveness index (1-10) to each driver. With the default parameters, the target speed for each driver varies from 75% to 127% of the specified free flow speed. Slower drivers will cause interference and reduce the running speed accordingly. The extent of reduction will depend on the demand level, passing opportunities etc.

The speed relationships produced by CORSIM are presented in Exhibit 15. These relationships are very close to those observed in Exhibit 13 for the 2010 HCM.
Synchro Speeds

Synchro estimates travel time as the sum of the running time and the control delay time. Both times are estimated by a macroscopic formulation similar to the HCM2000. The phase times are estimated by a proprietary algorithm that is sensitive to all of the common traffic actuated control parameters. It was demonstrated earlier that CORSIM’s phase times were sensitive to demand, although they differed to some degree in this example from CORSIM and the HCM 2010.

The Synchro speed relationships are presented in Exhibit 16. The characteristics are similar to the other tools. The estimated speeds were generally slightly lower for all conditions. The difference between the favorable and unfavorable progression results was also slightly smaller. Again, only relative values can be offered and no judgments on accuracy can be made.
The previous discussion presented the speed computation results for each tool separately. It is also interesting to look at a side-by-side comparison of the results for each progression case. The two cases have been described as “favorable” and “unfavorable.” Favorable progression was the result of lining up the beginning of the green phases in time and space to produce the best progression band. Unfavorable progression reflects the reverse direction that was sacrificed to produce the favorable progression. The band widths associated with both progression cases are shown in Exhibit 17.
The progression band widths change with the demand level because higher demand levels reduce the amount of unused time that can be reassigned to the coordinated phase. The average speed relationships for the two progression cases are shown in Exhibit 18. The comparison includes only the tools that determine phase times internally for coordinated semi-actuated control.

Exhibit 18: Average speeds for favorable and unfavorable progression

All tools reported higher delays with unfavorable progression. The average ratio of unfavorable progression delay to favorable progression delay throughout the demand range was as follows:

- Synchro: 1.36
- CORSIM: 1.49
- TRANSYT-7F: 2.31
- HCM 2010: 2.39
A few interesting observations can be made from these figures, keeping in mind that they apply to this example only:

- In general, the demand-speed relationships of all of the tools conformed to the expected shape.
- There was a greater divergence in the results with favorable progression, especially at high demands. This suggests that there are some differences in the modeling of platoon propagation among the tools that were examined.
- With favorable progression, all tools produced very similar results, except for Synchro, where the speeds were consistently a few mph lower.
- With unfavorable progression, the differences between CORSIM and Synchro were indistinguishable.
- With unfavorable progression, The HCM 2010 procedure estimated speeds that were slightly higher than the other tools.
- There was a substantial difference in the treatment of progression among the tools in determining delay. The effect of progression quality on delay was lowest in Synchro and highest in the HCM 2010.

**Vehicle Trajectory Plots**

Development of performance measures from vehicle trajectories is very difficult for urban street analysis because the measures are generally based on the average values for multiple simulation runs. The main contribution of the trajectory analysis procedures developed by this project will be realized only after the developers of traffic analysis tools internalize the procedures in their own products. Nevertheless, it is interesting to look at the trajectory plots obtained for both directions on this facility because they can provide some insight into the progressive movement of vehicles along the route.

Trajectory plots for the eastbound (favorable progression) and westbound (unfavorable progression) directions are presented in Exhibit 19. The 180% demand adjusted data were used for these plots. The “favorable progression” plot is not ideal because of platoon dispersion and cross street entry. Note that most of the vehicle traces that are stopped for a significant time have originated in the upstream link, either as cross street vehicles or mid segment entries. The unfavorable progression plot speaks for itself, with long delays and queues forming at each intersection.
Exhibit 19: Vehicle trajectory plots for favorable and unfavorable progression
Conclusions

The objective of this case study exercise was to examine the new procedure for analysis of urban street facilities published in the 2010 edition of the HCM. Several data sets were created with different demand volumes, progression characteristics and phasing plans. Parallel data sets were created for commonly used alternative analysis tools for comparison purposes. Based on this study, the following conclusions are offered:

- The new procedure represents a substantial improvement over the previous version published in the HCM 2000. It internalizes computations that had to be approximated or carried out externally in the previous version.
- The computational engine that implemented the procedure performed in a robust manner.
- There were no internal inconsistencies or anomalous behaviors in the results.
- The relationships between demand levels, phase times and average speeds conformed generally to expectations.
- The numerical results could not be expected to match those of the alternative tools exactly because of differences in model formulation. The agreement was close enough that no judgment could be offered as to the absolute accuracy of any tool.

A single case study does not constitute a complete evaluation of any traffic analysis tool. However, within the limits of this study, it can be said that the performance of the HCM 2010 procedure in the automobile mode supports the conclusion that it provides a credible method for evaluating the operation of an urban street facility. It offers a substantial contribution to the methodology of highway capacity and level of service analysis. For the sake of uniformity, developers of macroscopic traffic analysis tools should be encouraged to consider incorporating the results of the underlying research into their products.

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Introduction

Chapter 10 of the 2010 HCM presents a complete procedure for evaluating the level of service (LOS) of a freeway facility in terms of the average density of the vehicles on the facility. The development of this procedure began with the 2000 edition of the HCM but it was not heavily used because of the manner in which it was implemented. It was improved, both in function and documentation and is now implemented in the form of an Excel Workbook that performs all of the required computations. The software implementation is called FREEVAL [1].

This discussion examines the characteristics of the new procedure and compares those characteristics with a commonly used micro simulation tool. Two case studies will be used for this purpose. The first is a basic configuration developed to identify the systematic differences between the macroscopic approach of FREEVAL and the microscopic approach inherent in simulation. The second case study compares the results obtained from the HCM procedure to those obtained from a micro simulation tool for some varying traffic conditions on a typical multi-segment freeway facility of moderate length. The CORSIM simulation tool [2] was used to represent a generic simulation approach. The component of CORSIM that models freeway operations is called FRESIM.

Case Study 1: Basic Freeway Segments

A facility consisting of eight identical basic freeway segments will be examined in this section. All segments are 1000 ft in length with two lanes. There are no entrance or exit ramps. The objective here is to examine the relationships between traffic flow parameters as seen by each of the tools. The complications of merging, diverging and weaving will be avoided to focus on the basic aspects of the modeling. To avoid passenger car equivalency issues, no heavy vehicles or grades will be included in this example. Practical features of this type will be examined in the second case study.

Since there are no entrance or exit points, the demand volume on each link will be the same. Four consecutive periods of 15 min each will be analyzed.

Both of the tools recognize several user specified parameters that are used in computing the performance measures. Default values are provided in most cases. Since this is a hypothetical example, the default values will be applied initially. The effect of modifying the user-specified parameters will be considered in a later section.
Speed-Flow-Density Relationships

The macroscopic descriptors of traffic flow are flow rate, speed and density. Mathematically, these descriptors are related by a simple equation:

\[ Q = K \times U \]

Where (using the common symbols from the literature and commonly applied dimensions)

- \( Q \) = Flow rate (vehicles per hour)
- \( K \) = Density (vehicles per mile)
- \( U \) = Speed (miles per hour)

Thus, any of the three parameters may be computed deterministically given the other two. The nature of traffic flow creates certain internal dependencies between the parameters based on the widely observed phenomenon that speed drops as density increases. These internal relationships have been incorporated into several empirical models that make it possible to compute the value of any two parameters given the third.

The Fundamental Diagram

The original model of these relationships was developed by Greenshields in 1935 [1]. Greenshields proposed a linear relationship between speed and density, thereby creating parabolic speed-flow and flow-density relationships. Known at the time as the “fundamental diagram,” the Greenshields relationships endured for many years. The fundamental diagram is illustrated in Exhibit 1.

Some other important parameters can be derived from the individual relationships in the fundamental diagram shown in this exhibit. The density at any point on the speed flow curve may be determined as the slope of the radius vector from the origin to that point. The speed of a backward wave during a shift in the operating point of the flow-density curve (usually caused by an incident) may be obtained as the rate of change of flow with respect to density or \( \frac{dQ}{dK} \). Backward wave speed speeds are generally computed numerically from a shift in speeds from Point 1 to Point 2 points as \( \frac{(Q_2 - Q_1)}{(K_2 - K_1)} \).
HCM Treatment of Speed, Flow and Density

While the basic principles have remained the same, more recent empirical data have changed the current view of the speed-flow-density relationships. Two important differences have emerged in current models.

- The continuous relationships have been abandoned in favor of a discontinuity at the point of capacity. Undersaturated and oversaturated conditions are modeled separately.
- In the undersaturated region, the speed remains constant up to a 1200 pcphpl demand level at a free flow speed (FFS) of 70 mph and slightly higher with lower free flow speeds. Beyond that point, it decreases in a non-linear fashion up to the capacity of the facility.

The HCM speed-flow curves for undersaturated conditions are illustrated in Exhibit 2.
Separate curves are plotted for FFS values from 55 mph to 75 mph. The relationships are carried up to the point of capacity, which has been determined to occur at 45 pcpmpl for all values of FFS. As a faithful implementation of the HCM procedure, FREEVAL uses this relationship for all undersaturated basic freeway segments.

The HCM treatment of oversaturated conditions is represented by the flow-density curve illustrated in Exhibit 3.

This model assumes a linear decrease in flow rate with increasing density between 45 pcpmpl (i.e., the capacity) and the jam density, which is set at 190 pcpmpl. The assumed jam density reflects a spacing of \((5280/190) = 27.8\) feet between the front bumpers of successive vehicles.

**Comparison of Speed-Flow-Curves**

The basic speed-flow curves were developed for FRESIM and FREEVAL on the example facility using a demand volume range of 1000 to 5000 vph. Average values from thirty FRESIM runs were used to compute the performance measures for this example and all other examples that involve performance measures in this case study. The FRESIM capacity was first established by determining the upper limit of the throughput when the demand exceeded that upper limit. A value of 4500 vph was established by that process, based on FRESIM’s default operating parameters. The corresponding FREEVAL capacity was 4800 vph.

A proper comparison of the speed-flow relationships between these tools requires that they both adopt the same capacity value. FREEVAL offers a direct adjustment of capacity through a user-specified capacity adjustment factor. So, to create equivalent capacities, the FREEVAL runs were made using a capacity adjustment factor of \((4500/4800) = .94\).

The resulting speed-flow curves are presented in Exhibit 4.
The FREEVAL curve resembles the relationship originally presented in Exhibit 2, suggesting that FREEVAL is implementing the HCM procedure correctly. The FRESIM curve presents a different picture in which the average speed is only minimally and linearly affected by the demand volume. This result deserves further consideration.

Since the characteristics of the eight segments are identical the performance measures for each segment should be the same. This was true for FREEVAL but, as illustrated in Exhibit 5, the average speeds varied noticeably with distance from the beginning of the facility.

Speed reduction below FFS in the FRESIM traffic flow model is the result of the blocking effect of less aggressive drivers, whose target speed is below the free flow speed. The effect of this phenomenon naturally increases with demand volume. It appears, however, that the effect also
increases with the length of the facility. This will make comparisons more difficult. The speed represented in the comparison in Exhibit 4 was the average speed over all segments.

**Wave Propagation**

It was mentioned previously that the shape of the flow-density curve illustrated in Exhibit 3 determines the propagation speed of waves that are generated from discontinuities in the traffic flow caused by incidents. It is therefore worth looking at the speed-density curves. This example will use a complete blockage of both lanes of the facility to create a jam density condition.

Looking at FREEVAL first, Exhibit 6 bears a close resemblance to the HCM curve presented previously in Exhibit 3. The jam density is the HCM’s assumed value of 190 pcpmpl. The peak flow is 2250 pcppl because the FREEVAL runs were constrained to this level.

The corresponding relationship for FRESIM is presented in Exhibit 7. The same general shape is shown here, except that the jam density is much higher for FRESIM. The jam density results from a fixed spacing of 3 ft between vehicles imposed by FRESIM. The length of all vehicles was specified as 17 ft, resulting in a 20 ft spacing, which yields a density of \( \frac{5280}{20} = 264 \) pcpmpl. The maximum flow rate is the same because of the specified capacity but the undersaturated portion of the curve is more linear because of the linear speed-flow relationship presented in Exhibit 4.
The results from some field data collected by Courage and Lee [4], shown in Exhibit 8 provide an interesting comparison with the modeling results. The density values were computed from one-minute detector occupancy samples obtained from an ITS site in Florida. There were no jam density conditions but there were several data points involving the backup of queues from downstream bottlenecks.

It is interesting to note that the capacity was about the same as the model values and that it occurred at about the same density as FREEVAL’s estimate. A projection of the oversaturated relationship to the horizontal axis suggested a jam density of 226 pcpmpl, which is about halfway between the two modeled values. Jam density is a somewhat abstract concept because it never actually occurs except in the case of complete blockage of all lanes. It is simply a mathematical property of the speed-flow-density model that is useful for computing wave speeds.

The computed wave speeds are presented in Exhibit 9. The wave speed from field data also fell about halfway between the two modeled values.

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Exhibit 8: Density-flow relationship from field data
Incident Types

Modeling of incidents is an important application for both deterministic and simulation-based analysis tools. The effect of an incident is a reduction in capacity at a point or over a distance. The result is frequently an oversaturated condition that creates queues for the duration of the incident and releases them after the incident is resolved.

Incidents are created in FREEVAL by specifying a capacity reduction factor for one of the analysis periods. The incident is assumed to take place at the beginning of the segment in which it occurs and to last throughout the analysis period.

FRESIM determines the extent of capacity reduction by simulating the operation with the following user-specified incident characteristics:

- Time of onset (sec)
- Duration of incident (sec)
- Location with respect to the upstream end of the segment (ft)
- Length of roadway affected (ft)
- Effect of the incident on each lane of the segment.
  - Normal speed (i.e., no effect)
  - Traffic capacity reduced by a specified “rubberneck” factor
  - Complete lane blockage at the point of the incident
- The location of an advanced warning sign (up to 1500 ft) may also be specified.

To compare the two tools, an incident will be created in the last segment of the facility (i.e., Segment 8). For compatibility between the tools, it will be assumed to take place at the upstream end of the segment and to last throughout the second of the four periods analyzed. The buildup and release of queues will be compared in addition to the key performance measures.

Incident capacity is an input parameter for FREEVAL. Therefore to provide a basis for comparison, the capacity at the point of the incident must be determined by FRESIM and the same value must be entered directly for FREEVAL.

Rubberneck Incident Characteristics

The effect of some of the incident characteristics on the FRESIM capacity will be examined first. For this purpose, a shoulder incident will be created with a rubberneck factor applied to each lane. The length of the affected section and the rubberneck factor will be varied.

The first thing that was learned from this exercise was that the rubberneck factor produced a much smaller capacity reduction than its specified value. It had very little effect on incidents that cover a short length. In fact, it had no effect at all on incidents less covering less than 200 ft.
To ensure that the rubberneck factor had some effect, an incident covering the entire 1000 ft of the link was created. The specified rubberneck factor was varied from 10% to 50% and the actual capacity reduction was compared with the specified capacity reduction of the rubberneck factor.

The results are shown in Exhibit 10. It is noted that, even when the incident covered the entire 1000 ft link, there was no actual capacity reduction below a specified rubberneck factor of 30%. The effect became apparent at higher values, giving an actual reduction of about half of the specified rubberneck factor.

There was also a large variation in the results among the 30 simulation runs involved in this example. For example at a specified rubberneck factor of 40%, the average actual reduction was 20% but the range among all of the runs was 14.3% to 22.5%. Because the incident covered the entire link, the point at which the queue backup commenced was also hard to define and equate with FREEVAL’s assumption that the blockage originated at the upstream end of the segment. Therefore, it was decided to examine a different type of incident.

**Lane Blockage Incident Characteristics**

An incident involving complete blockage of one lane is much easier to define and compare, because the length and rubberneck factor are not involved. So a simple incident with a complete blockage of the right lane throughout Period 2 was created. The traditional way to determine capacity from simulation is to slightly overload a segment and estimate the capacity from the point at which the output levels off. That approach was not successful in this case because the output of the segment kept increasing well beyond any reasonable value even though it remained well below the demand volume. The details are shown in Exhibit 11.
To proceed with a comparison, it is necessary to choose a demand volume level, to determine the capacity associated with that level and to enter the demand and capacity reduction values into FREEVAL. For this purpose a demand volume of 3200 vph was chosen. The resulting capacity was 2684 vph. The appropriate capacity reduction value for FREEVAL was \((2684/4500) = .559\).

**Density Comparisons**

Density is an unambiguous indicator of congestion and delay in a freeway facility. It is the basis for LOS estimates in most uninterrupted flow chapters of the HCM. It is therefore the measure of primary interest for this example. It will be examined through two different graphics formats.

**Contour Plots of Density**

Contour plots provide a complete picture of density over time and space. Exhibit 12 shows contour plots for both FRESIM and FREEVAL. Given the differences between previous results, it is not surprising to observe significant differences here.

FRESIM clearly concentrates a more intense congestion into fewer segments than FREEVAL. This is primarily due to the difference in default jam density (264 vs. 190 pcpmpl) produced by the two tools.

In spite of the differences in density distribution, the total travel time of 101 vehicle hours was the same for both tools. This is not too surprising since both tools were given the same demand volumes and capacities for each period. The queues were accumulated macroscopically in one case and microscopically in the other but the net result was the same for both processes. Only the spatial distribution was different.
Line plots of Density

The total travel time is represented by the volume under the surfaces presented in Exhibit 12. Inspection of this exhibit suggests that the surface volume might be smaller for FREEVAL but since both tools produced equal total travel times, the volumes were actually the same. The lesson here is that contour plots are able to provide a good overview of the big picture, but they are not always a good vehicle for quantitative analysis.

Simple line plots showing each period by a separate line can provide more quantitative detail. The differences between the two models of queue accumulation and release are illustrated in Exhibit 13. The FRESIM queuing was confined to Period 2 but it was extended into Period 3 by FREEVAL. The interpretation here is that the FREEVAL queue took longer to disperse because it covered a greater portion of the freeway behind the incident.

It is interesting to look at the FREEVAL density by segment in Period 3. The queue appears to have dispersed in waves. A more linear dispersion would have been expected from a macroscopic modeling process. The reason for this phenomenon is not known.
Queue Buildup and Release

The queue buildup and release characteristics are also of interest. A vehicle trajectory analysis of the type described in Appendix 4 of this report was conducted for FRESIM to examine these characteristics. The results are presented in Exhibit 14. The queue buildup begins at the start of Period 2 (900 sec simulation time). The queue release begins when the blockage ends at the start of Period 3 (1800 sec simulation time). The wave speed on buildup was estimated from the slope of the line at 8.08 mph, which is reasonably close to the theoretical value of 9.80 mph presented in Exhibit 9. The wave speed on release is more difficult to estimate because of the non-linear nature of the curve. In the linear portion, the speed was estimated at 7.9 mph.

Exhibit 14: Queue buildup and release characteristics
Vehicle Trajectory Analysis

Plotting and analysis of vehicle trajectories was an important task of this project. A software utility called VTAPE that reads trajectory files from FRESIM is described in Appendix 5 to this report. Several examples of vehicle trajectory analysis were presented in Appendix 4. This section discusses the interpretation of FRESIM’s modeling of the incident in terms of vehicle trajectories.

A set of vehicle trajectory plots showing the queue buildup in both lanes during the incident is presented in Exhibit 15. The first three segments were truncated to maximize the level of detail in the figures and the plots focused on the first and last five minutes of the blockage. The distance scale shows a 5,000 ft facility configured as follows:

- Segment 4 begins at the origin (zero ft)
- Segment 5 begins at 1000 ft
- Segment 6 begins at 2000 ft
- Segment 7 begins at 3000 ft. This is the segment immediately upstream of the blockage.
- Segment 8 begins at 4000 ft. This is the segment immediately downstream of the blockage.
- The blockage was defined to occur at 4000 ft (i.e., the boundary between segment 7 and 8). It is indicated on all of the plots with the icon shown at the right.

It is clear that, because of its location, the incident had the greatest effect on the right lane. The first five minutes indicated a slowdown in the left lane at the point of the incident, followed by a recovery in speed downstream of the incident. While some queuing took place in this lane in the upstream segment, it was not nearly as noticeable as the queue in the right lane. Note the discontinuity in the right lane trajectories at the point of the incident. This is caused by the blockage itself. No vehicles are able to pass the incident in the right lane and therefore a short blank space is observed. Vehicles shown in the right lane downstream of this point have passed the incident in the left lane and taken an early opportunity to change into the free-flowing right lane.

In the last five minutes of the blockage, the queue of stopped vehicles, as evident in the near horizontal trajectories, has built up substantially in the right lane but the left lane does not look much different than the first five minutes. In both periods a moving queue extends throughout most of Segment 7.
It is also interesting to observe the queue release after the end of the blockage. The trajectory plots for this condition are presented in Exhibit 16. The queue release began at the end of Period 2, at 1800 sec into the simulation time. At this point, both lanes were open. The right lane had a substantial queue of stopped vehicles to service while the left lane released its moving queue. The left lane cleared at about 200 seconds into Period 3 and the right lane cleared at 240 seconds.

Exhibit 16: Vehicle trajectory plots showing queue release after the incident
**Advance Warning Sign Considerations**

FRESIM accommodates an advance warning sign to advise motorists of a lane blockage. The location of the sign with respect to the blockage must be specified. The maximum distance upstream of the incident is 1500 ft.

**Density and Travel Times**

The FRESIM runs were repeated with an advance warning sign at the upstream end of Segment 7 (i.e., 1000 ft from the incident). The density contour plot is presented in Exhibit 17, which resembles the previous plot shown in Exhibit 12, except for the density pinnacle that occurs at the peak.

Again, it is necessary to return to the line plot for more detailed observations. This plot for Period 2 is presented in Exhibit 18.
It is clear from this plot that the advance warning sign has shifted the congestion from Segment 7 to Segment 6, upstream of the warning sign. It has also created a more pronounced peak in the congestion, as observed on the contour plot. The question at this point is whether the sign simply redistributed the congestion or whether it reduced the total travel time. A comparison of the 30 runs for both conditions indicated that there was indeed a reduction in the total travel time for all periods from 101.4 veh-hr to 92.6 veh-hr.

The distribution of travel times by segment is presented in Exhibit 19. The travel times were similar in all segments except for the one between the sign and the incident. All of the travel time reduction took place in that segment.

A comparison of the segment output flow rates can provide more insight into the effect of the warning sign. Exhibit 20 shows the output flow rates for all of the segments that experience queuing. The output flows decreased in Segments 5 and 6 with the warning sign but they increased in Segment 7. Since segment 7 represents the output of the facility it is the critical segment governing the facility capacity. The increase in this output flow with the sign explains why the overall travel time for the facility was decreased.
Vehicle Trajectory Analysis

Vehicle trajectories can provide additional insight into the operation of the advance warning sign in FRESIM. The vehicle trajectory plots were repeated to reflect this operation. The results are presented in Exhibit 21, following the same format that was represented in Exhibit 15. The position of the sign is indicated by the icon at the right.

It is clear from these plots that FRESIM assumes that all vehicles will attempt to leave the lane with the downstream blockage as soon as possible after the sign. In the first few minutes most of the vehicles are able to vacate the right lane at the point of the sign as evident in the trajectory traces that terminate abruptly in lane 1 at the sign location. Then, a few traces continue past the sign and disappear in the middle of link 7, indicating a transfer out of the blocked lane. By the end of the period, most of the vehicles in the right lane reach the end of link 7 and stop. The opposite effect occurs in the left lane, with vehicle traces appearing abruptly at the start of the period. The number of entry traces declines as lane changing becomes more difficult.

The last five minutes presents a different picture. The nearly stopped queue in the left lane now prevents any lane changes from the right lane. The result is substantial queuing in both lanes with the right lane completely empty between the sign and the blockage. The higher concentration of vehicles in the left lane has apparently increased the output of the facility, thus decreasing the overall travel time.

Summary of Observations

The various exhibits presented here indicate how FRESIM views the operation of the freeway, the bottleneck and the advance warning sign. The performance measures are clearly consistent with that view. The question is whether FRESIM’s view represents a reasonable depiction of the real world. The following observations suggest that some skepticism is appropriate:

- The speed-flow relationships show minimal effect of demand on speed right up to the point of capacity.
- The speed-flow relationships are influenced by the length of the facility.
- The jam density is somewhat higher than commonly accepted. This has an effect on queue buildup from bottlenecks.
- The capacity reduction due to rubbernecking deviates substantially from the user-specified rubberneck factor. It is clear that this factor is not a direct measure of capacity reduction. The actual relationship is not described in the CORSIM documentation.
- The maximum flow rate past a lane blockage is questionable. It was observed in this study to reach a value greater than 2700 vphpl. It continued to increase at demand levels well in excess of a reasonable capacity value.
- While the effect of the advanced warning sign may be readily observed, the modeling somewhat idealistic in terms of driver lane choice.
Exhibit 21: Vehicle trajectory analysis for the advanced warning sign operation

Appendix 2: Freeway Facility Case Study
The operation of FREEVAL was found to be consistent in all respects with the HCM procedures for basic freeway segments and freeway facilities. The only unexplainable phenomenon was the release of a multi-segment queue in waves following the end of a capacity reducing incident.

The developers of both tools were asked to review these observations. Based on their review and responses, the following additional investigations were performed.

**Effect of Simulation Parameters on Results**

The analyses performed to this point used the default values for all parameters that could affect the performance measures computed by simulation. Several relationships presented previously raised questions about the results; particularly their representation of the real world. There are a few parameters that may be adjusted to calibrate the models. Since this is a hypothetical example, no calibration to field data is possible. It is, however, useful to examine the effect of the simulation parameters by varying them individually. The following discussion describes the effect of variations in a few of the key parameters.

**Minimum Separation for Generation of Vehicles**

Vehicles are introduced into the system at external nodes by a random process that caused the headways to conform to a prescribed distribution. Because the process is purely mathematical, it would be possible to introduce unrealistically short headways if a minimum value were not imposed.

The default value for FRESIM is 1.6 sec. This value constrains the number of vehicles that can be processed in a given time period. It establishes the capacity of a basic freeway segment to $(3600/1.6) = 2250$ vphpl. This constraint explains why the maximum throughput obtained earlier was 4500 vph in a two lane facility. A value of 1.5 would give a capacity of $(3600/1.5) = 2400$ vphpl, which is the capacity that has been adopted for basic freeway segments with 70 mph FFS by the 2010 HCM. This value should be used when HCM compatibility is desired.

**Advance Segment Length**

It was noted earlier that the average speed showed a counterintuitive decrease with increasing segment numbers. To examine this phenomenon further an advance segment with the same characteristics was incorporated into the facility. The length of this segment was varied from 2000 to 10000 ft with a demand volume of 4000 vph. The effect of the advance segment length in terms of the average speeds on the downstream segments is shown in Exhibit 22. The previously depicted condition of no advance segment is also shown on this figure.
Note that the introduction of an advance segment stabilized the speeds within the facility. The speeds became more stable as the length of the advance link increased. This effect is illustrated in more detail in Exhibit 23. The speed variability is presented in this figure in terms of the range (maximum – minimum) and standard deviation. The variability was reduced sharply with an advance link of 2000 ft. After that point, a more gradual reduction in variability is observed. The interpretation of this effect is that it might be desirable to add a fictitious link of at least 2000 feet ahead of a facility to produce a more stable range of speeds.

Car Following Sensitivity

The FRESIM speed-flow relationship was shown to be essentially linear with a speed reduction of 6.5% between free-flow conditions and capacity. This relationship differed substantially from the HCM, which showed a 28% non-linear reduction in the same demand range.

The FRESIM traffic flow model assigns a target speed to each vehicle based on driver aggressiveness, which is randomly assigned to one of ten categories. The least aggressive driver is given a default target speed of 88% of the free-flow speed. So, with stable flow conditions, the minimum attainable speed is 88% of the free flow speed, assuming that every vehicle is in a platoon constrained by the least aggressive vehicle. Further reductions in speed require that
shock waves occur at high demand levels. Shock waves produce a temporary reduction in speed that is propagated backwards.

The FRESIM traffic flow model uses the Pitt car following formulation described by Rakha and Gao [5]. This formulation uses a car-following sensitivity factor for which default values are provided by FRESIM. These defaults can be overridden by the user in terms of a percentage adjustment to the default value, with 100% representing zero adjustment. To examine the effect of the car following sensitivity (CFS) adjustments, several runs were made using adjustments of 125%, 150%, 175% and 200%. The demand level was set at the originally established capacity of 4500 vph.

**Shock Wave Formation**

No shock waves were observed in the vehicle trajectories when the default CFS adjustment factors were used (i.e., the adjustment was 100%). When a 125% adjustment was used, it was possible to observe a few shock waves of the type shown in Exhibit 24. More waves were observed with higher CFS values.

![Exhibit 24: Illustration of shock wave formation with increased car-following sensitivity.](image)

When shock waves of this type occur frequently the average speed and capacity of a segment are likely to be reduced. Therefore it is useful to examine the effect of the CFS adjustment on the speed and capacity. No attempt has been made to assess these adjustments in terms of whether or not they are reasonable. The focus at this point is purely on their numerical effects.
Effect on Speed and Capacity

The effect of the CFS on capacity is illustrated in Exhibit 26. The full capacity of 4500 vph is maintained through a CFS adjustment of 125%. Beyond that point, it drops linearly to a value of about 3200 vph as a result of shock waves formed by the mutual interactions among vehicles.

The effect of the CFS on speed is illustrated in Exhibit 25. There are two distinct shapes here. The two cases that were not oversaturated (100% and 125%) maintained speeds close to the FFS in all segments. The three oversaturated cases showed speeds below 30 mph in the first segment. Speeds gradually increased and reached values close to the undersaturated cases by Segment 4. The farthest upstream segments had the lowest speeds because the shock waves generally originated in those segments. The shock waves served to meter the flow into the downstream segments, backing up a queue of vehicles beyond the origin of the facility. The reduced flow rates downstream were easily accommodated at the higher speeds.

Effect on Speed-Flow Relationships

One question to ask is whether the existence of shock waves changed the shape of the speed-flow curve. Runs were made with an adjustment of 125%, which reflected the highest CFS that would accommodate the established capacity of 4500 vph. The new curve is shown in Exhibit 27. There appears to be more of a bend in the curve at high demand levels. In fact, the speed reduction here was 11%, compared to 6.5% with no CFS adjustment. So, it
appears that the CFS has reduced the speeds but still nowhere near the 28% reduction of the HCM.

**Effect on Speed-Density Relationships**

The low speeds and high densities apparent in the upstream segments should produce an interesting speed-density relationship. Scatter plots of speed and density are shown in Exhibit 28 for three CFS adjustment cases.

In the 100% case (i.e., no adjustment) all of the speeds and densities are clustered around a very narrow range of speed and density, essentially depicting stable-flow conditions. The shock waves that were introduced by the 125% CFS adjustment added some lower speeds and higher densities to the relationship. Further expansion of the curve took place with the 150% adjustment, which showed speeds ranging from 25 to 65 mph and densities ranging from 35 to 80 vpmpl.

**Closing Observations on FRESIM Parameters**

The additional analyses presented in this section have extended the previous discussion to include some consideration of the modeling parameters used by FRESIM. The influence of several parameters was demonstrated numerically by means of hypothetical examples. It was not, however, possible to determine how well the ranges of parameters would fit into real-world data.

**Effect of Macroscopic Parameters**

The FREEVAL results conformed very well to expectations and there were very few issues to be addressed. The jam density is the only additional parameter that can be adjusted for purposed of this example. FRESIM imposes a fixed spacing of 3 ft between vehicles in a standing queue. With the 17 ft vehicle length used here, the inter-vehicle spacing will be \((17 + 3) = 20\) ft, corresponding to a jam density of 264 pcpmpl. FREEVAL’s default jam density is 190 pcpmpl but a user specified value between 130 and 360 pcpmpl is recognized in multiples of 10. So the FREEVAL analysis was performed again with a jam density of 260 pcpmpl.
The results are presented in Exhibit 29. The density plot for FREEVAL at 260 pcpmpl compares much more favorably with the corresponding FRESIM results. Both tools extend the queue backup to Segment 4, whereas the original FREEVAL run with a jam density value of 190 extended the queue back to the first segment in the facility.

![Exhibit 29: Effect of jam density on queue backup](image)

The end result of this comparison is the observation that when properly cross-calibrated to each other, comparable results can be obtained. In this case, both the FRESIM capacities and jam densities were imposed on FREEVAL.

**Representation of Density in the Results**

The speed and density contour plots are developed by FREEVAL when the computations are performed. Several of these plots, taken directly from FREEVAL have been presented previously. An example is shown in Exhibit 30. The pinnacle in this plot suggests a peak value at a specific point, when it is, in fact, an average value over a full segment for 15 minutes. In this case, the period began with a low density and built up to a peak at the end of the period, so the peak has almost twice the density represented by the pinnacle.

A more direct representation of the average values for the same data is presented in Exhibit 31. The numbers are the same but the alternate format is less likely to mislead the user. The format may be modified easily in the worksheet. When rapid backup creates pinacles in the contour plots, the user might want to change the chart type to clarify the interpretation. The FREEVAL developers should consider whether the default chart type is best suited for this purpose.
Exhibit 30: FREEVAL's density contour plot format

Exhibit 31: Alternative density plot format depicting average values
Case Study 2: Combination of Segments

The previous case study was intended to examine the basic systematic differences between the 2010 HCM procedure and a typical simulation tool. The next case study will introduce a combination of segments of various types. Example Problem 1 from HCM Chapter 10 will be used for this purpose.

Facility Description

The facility consists of 11 freeway segments of various types as illustrated in Exhibit 32.

Exhibit 32: Freeway facility layout for Case Study 2
The demand volume data, taken from the HCM 2010 sample problem, is given in Exhibit 33.

![Table](image)

Exhibit 33: Demand volume data for Case Study 2

The other data applicable to this problem were given as follows:

- Heavy vehicles = 5% trucks, 0% RVs (all movements)
- Driver population = regular commuters
- FFS = 60 mi/h (all mainline segments)
- Ramp FFS = 40 mi/h (all ramps)
- Acceleration lane length = 500 ft (all ramps)
- Deceleration lane length = 500 ft (all ramps)
- Jam Density = 190 pc/mi/ln
- Influence area = 1,640 ft (for weaving segment 6)
- Ramp Density = 1.0 ramps/mi
- Terrain = Level

Comparison of Results

Both FREEVAL and FRESIM were applied to this problem in the same manner as the previous case study. The average speeds and densities reported by the two tools were compared for each segment. The results are presented in Exhibit 34. Visual inspection of this exhibit shows that the results were similar for the two tools. The average speed over all segments was 56.9 mph for FREEVAL and 55.7 mph for FRESIM, reflecting a difference of 2.2%.
Larger differences were observed in individual segments. The greatest difference (12.88%) occurred in Segment 6 (the weaving segment). Greater differences between the microscopic and macroscopic modeling approaches would be expected in weaving segments because of the complex interactions between vehicles that take place in weaving maneuvers. FREEVAL showed higher weaving densities and lower speeds than FRESIM. This effect is consistent with the observation from Case Study 1 that FRESIM speeds tend to be affected less by traffic interaction.

Exhibit 34: Comparison of speed and density by segment for Case Study 2
References

Two-Lane Highway Case Study

Appendix 3
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Introduction

The options for two-lane highway analysis tools, until recently, have been very limited. TWOPAS (TWO lane highways with PAssing) was used to develop the analytical procedure contained in the two-lane highway chapter of the HCM. This program has a lengthy development history, which will not be repeated here, but can be found elsewhere [1, 2]. The original version of TWOPAS was designed for the Microsoft Disk Operating System (MS-DOS) and running it on a modern computer is difficult at best. It is currently integrated within the Interactive Highway Safety Design Model (IHSDM), which provides a Windows-based front end for the user input. However, the program provides a limited set of outputs and does not have an animation option, thus limiting the research applications of the program. Another program, TRARR (TRAfic on Rural Roads), was developed by the Australian Road Research Board. TRARR is a microscopic simulation model that was designed to model two-lane rural highways, with occasional passing lane sections. More information on TRARR can be found in Reference [3]. This program appears to be no longer publicly available.

The CORSIM (CORridor SIMulation) program [4] is a well-established microscopic simulation platform. The capability to model two-lane highways was recently added to CORSIM. The two-lane highway modeling capabilities and features incorporated into CORSIM include:

- Basic two-lane highway segments with passing maneuvers (including passing one vehicle or multiple vehicles at a time) in the oncoming lane.
- Two-lane highway segments with a passing lane.
- Two-lane highway segments connecting to signalized intersections.
- New TRF file inputs that allow the user to modify certain parameters of the two-lane highway modeling logic.
- New performance measure outputs (e.g., PTSF and follower density) and passing maneuver data outputs.

The full details of the implementation of these modeling capabilities and features can be found elsewhere [5].

This document describes several experiments in which the results from the HCM two-lane highway analysis procedure are compared to the results generated by CORSIM. The main measures of interest for these comparison exercises were Percent Time Spent Following (PTSF) and Average Travel Speed (ATS). These two performance measures are the primary measures reported by both CORSIM and the HCM, and are also the performance measures upon which level of service is based upon in the HCM analysis procedure. The HCM results are based on the 2010 version of the methodology, which is largely the same as the 2000 version. The CORSIM results represent the average of ten simulation runs for each experiment scenario. Note that, for all experiments, a directional analysis was performed (as opposed to a two-way analysis); thus, the reported results reflect one direction of travel, namely ‘Direction 1’. 
CORSIM Network Setup

In trying to establish highway network conditions that will provide as compatible of a comparison as possible between the HCM and CORSIM, it is important to recognize that segment length is not an input to the HCM average speed or PTSF calculations. The assumption with the HCM analysis procedure is that vehicles entering the analysis segment are in a platoon structure as affected by some upstream length of two-lane highway. Therefore, when specifying the CORSIM network, it is necessary to include a length of highway upstream of the starting point for the collection of performance measures.

The length of the upstream segment (hereafter referred to as the ‘lead up length’), must be such that the vehicle platoon structure would be relatively stable. In CORSIM, vehicles enter the highway network through entry nodes. Vehicles enter the network according to the specified headway distribution (negative exponential in the case of these comparisons). As such, it takes some time for vehicles get into a platoon structure. Thus, enough lead up length of highway must be provided to allow this platoon structure to develop before the vehicles arrive to the point of the network where performance measures will be collected.

A simple experiment was conducted where the length of the lead up segment was varied from 1 to 6 miles, in increments of 1 mile. This test was performed with a traffic demand of 1200 veh/h under a 50/50 directional split. The grade and percentage of heavy vehicles were both zero and the free flow speed (FFS) was 60 mi/h. The analysis segment length was five miles. A segment downstream of the analysis segment was also included, because the passing logic used in CORSIM requires vehicles to complete their pass before the end of the network. The passing logic in CORSIM also allows a certain percentage of the length of a passing maneuver to be made beyond the length of a passing allowed zone. Thus, if the last analysis segment in the network allows passing, another segment should be included in the network downstream of this segment. For this experiment, as well as the rest of the experiments described in this document, a 5-mi length of segment was included downstream of the analysis segment. The length of the analysis segment (i.e., the middle segment) used in this experiment was 5 miles. Exhibit 1 shows the PTSF results of this experiment. Preliminary experimentation showed that average travel speed varied much less than PTSF as a function of lead up length; thus, PTSF is the critical measure in this regard.

These results show that the PTSF values for the analysis segment become fairly consistent with a lead up segment length of five miles or longer. Significantly different demand characteristics may affect the necessary length of the lead up segment, but this lead up length is generally sufficient for the experiments described in this document.
Experiments

The segment lengths given in the descriptions of the five following experiments, as well as the corresponding results, refer to just the length of the analysis segment(s). Each experiment also includes the 5-mile lead up and 5-mi end segment lengths.

Experiment 1: Level Road with Full Passing

The first experiment involved comparisons between the HCM and CORSIM that were very basic in nature. The experiment was kept as basic as possible to facilitate the identification of the factors that influence the compatibility of the CORSIM results with the results from the HCM. The same values were used for common input variables between the two tools. Generally, CORSIM has more input variables than the HCM due to its microscopic level of detail. For input variables not included within the HCM procedure, values were assumed that most likely minimized the impact on the results.

For this experiment, the analysis segment length is 5-miles long and generally consists of ideal roadway and traffic conditions. The traffic volume was moderate, with an equal directional split. Exhibit 2 lists the specific input variables, and their corresponding values used in the two experiments, for CORSIM and the HCM. Exhibit 3 presents a comparison of the PTSF and ATS results computed by the two tools.
Exhibit 2: Input Data for Experiment 1

<table>
<thead>
<tr>
<th>Roadway variables</th>
<th>CORSIM</th>
<th>HCM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Segment length (mi)</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Grade (%)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Radius of Curvature (ft)</td>
<td>0</td>
<td>N/A</td>
</tr>
<tr>
<td>Lane width (ft)</td>
<td>N/A</td>
<td>12</td>
</tr>
<tr>
<td>Shoulder width (ft)</td>
<td>N/A</td>
<td>6</td>
</tr>
<tr>
<td>Access points (points/mi)</td>
<td>N/A</td>
<td>0</td>
</tr>
<tr>
<td>Segment length with passing allowed (mi)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Percentage of no-passing zones</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Highway class</td>
<td>N/A</td>
<td>1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Traffic variables</th>
<th>CORSIM</th>
<th>HCM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percentage of passenger cars</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Percentage of trucks</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Base FFS (mi/h)</td>
<td>N/A</td>
<td>60</td>
</tr>
<tr>
<td>FFS (mi/h)</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>Eastbound traffic volume (veh/h)</td>
<td>600</td>
<td>600</td>
</tr>
<tr>
<td>Westbound traffic volume (veh/h)</td>
<td>600</td>
<td>600</td>
</tr>
<tr>
<td>PHF</td>
<td>N/A</td>
<td>1</td>
</tr>
</tbody>
</table>

Exhibit 3: Performance measure results for Experiment 1

<table>
<thead>
<tr>
<th></th>
<th>PTSF</th>
<th>ATS</th>
</tr>
</thead>
<tbody>
<tr>
<td>CORSIM</td>
<td>77.4</td>
<td>53.2</td>
</tr>
<tr>
<td>HCM</td>
<td>75.1</td>
<td>48.7</td>
</tr>
<tr>
<td>% Difference</td>
<td>3.0</td>
<td>8.6</td>
</tr>
</tbody>
</table>

Experiment 2: Level Road with No Passing

The input values were the same for this experiment as for Experiment 1, except for the percentage of no-passing zones being set to zero instead of 100 percent. The results for this experiment are given in Exhibit 4.

As expected, the performance measure results improve when 100% passing is allowed versus no passing allowed. The percent difference between the CORSIM and HCM results are similar to the Experiment 1 results.

<table>
<thead>
<tr>
<th></th>
<th>PTSF</th>
<th>ATS</th>
</tr>
</thead>
<tbody>
<tr>
<td>CORSIM</td>
<td>69.8</td>
<td>54.3</td>
</tr>
<tr>
<td>HCM</td>
<td>64.7</td>
<td>49.6</td>
</tr>
<tr>
<td>% Difference</td>
<td>7.4</td>
<td>8.7</td>
</tr>
</tbody>
</table>

Exhibit 4: Performance measure results for Experiment 2
The cases with all passing allowed and no passing allowed were used for the first two experiments to avoid any potential differences that might be a function of the distribution of the percentage of no-passing zones, as this is not an input in the HCM procedure. The situation of varying percent no-passing zone configurations is tested in Experiment 5.

As the results of the first two experiments indicate, the difference between the average travel speeds is greater than the difference for PTSF. To further explore these differences, the input values for both of these experiments were analyzed over a broad range of traffic demands with equal directional splits. The following four figures illustrate these results:

- Exhibit 5 shows the effect of the two-way flow rate on PTSF for Experiment 1
- Exhibit 6 shows the effect of the two-way flow rate on ATS for Experiment 1
- Exhibit 7 shows the effect of the two-way flow rate on PTSF for Experiment 2
- Exhibit 8 shows the effect of the two-way flow rate on ATS for Experiment 2

![Exhibit 5: PTSF vs. flow rate for Experiment 1](image-url)
Exhibit 6: ATS vs. flow rate for Experiment 1

Exhibit 7: PTSF vs. flow rate for Experiment 2
These results indicate that the PTSF results track fairly well between the HCM and CORSIM. The average speed results, on the other hand, start to deviate significantly beyond low traffic demand flow rates. As the average travel speed graphs illustrate, the HCM calculation assumes a linear speed-flow relationship, with a fairly significant slope. The speed-flow relationship in CORSIM is initially concave and then transitions to linear with a very gradual slope. The CORSIM relationship is more consistent with observations of field data, as discussed further in reference (5). It is expected that for any significant amount of traffic demand, the HCM speed results will be lower than the CORSIM speed results. The following two exhibits illustrate the combined PTSF vs. Flow and the Speed vs. Flow results for the two experiments. They present the same data as the previous four exhibits grouped to facilitate comparison.

- Exhibit 9 shows the effect on PTSF for all cases.
- Exhibit 10 shows the effect on ATS for all cases.
Exhibit 9: PTSF vs. flow rate for Experiments 1 and 2

Exhibit 10: ATS vs. flow rate for Experiments 1 and 2
Experiment 3: Rolling Terrain

The HCM defines rolling terrain as “any combination of horizontal and vertical alignment causing heavy vehicles to reduce their speeds substantially below those of passenger cars, but not to operate at crawl speeds for any significant length of time or at frequent intervals. Generally, this includes short and medium length grades of no more than 4 percent.”

The problem with performing a comparison using rolling terrain is that there are an unlimited number of ways in which to specify horizontal and/or vertical curve combinations within the analysis segment such that it meets the definition of rolling terrain. Thus, it should be possible to eventually find a combination that produces very similar results as the HCM analysis procedure, which defeats the purpose of setting up an experiment to identify systematic differences.

Two different specific grade scenarios were tested in this experiment. The first scenario, Experiment 3a, tested a facility that included a 5-mile segment with a constant 5% grade. The second scenario, Experiment 3b, tested a facility that included a 1-mile segment with a 5% grade, preceded and followed by two 1-mile segments with a 0% grade. In CORSIM, the second and third links of the facility were specified as no-passing zones and all other links were specified as passing zones, as shown in Exhibit 11.

<table>
<thead>
<tr>
<th>1 mi</th>
<th>1 mi</th>
<th>1 mi</th>
<th>1 mi</th>
<th>1 mi</th>
</tr>
</thead>
<tbody>
<tr>
<td>0%</td>
<td>0%</td>
<td>5%</td>
<td>0%</td>
<td>C%</td>
</tr>
</tbody>
</table>

Exhibit 11: Experiment 3b facility schematic for CORSIM

For the HCM analysis of Experiment 3b, the facility had to be separated into different sections with similar characteristics as illustrated in Exhibit 12. There were five middle segments. Since the third segment had a grade of 5%, the facility was split into three parts. The first and third parts were each two miles long with a 0% grade. The second part was one mile long with a grade of 5%.

No-passing zone specification is different between CORSIM and the HCM. In CORSIM, each link is designated separately as a passing or no-passing zone. In the HCM, a certain percentage of no-passing allowed is specified for the entire facility, but the location of the no-passing zones is unknown. For the HCM analysis of Experiment 3b, the first section, which was two miles long, was analyzed as a 50% no-passing zone. This corresponded with segments one and two in...
CORSIM, which were specified as passing and no-passing zones, respectively. The second HCM section was specified as a 100% no-passing zone, which corresponded with the third segment in CORSIM. The third HCM section was specified as a 0% no-passing zone, which corresponded to segments 4 and 5 in CORSIM.

Exhibit 12: Experiment 3b facility schematic for HCM

Different distributions of truck types were also tested in Experiment 3. There are four different types of trucks in CORSIM, defined as Types 3 through 6. Type 3 trucks are 35 ft long bumper to bumper. Type 4 trucks are 53 ft long and they are carrying a medium load. Type 5 trucks are 53 ft long and they are carrying a full load. Type 6 trucks are 64 ft long. Experiments 3a and 3b were tested with 60% of the trucks being Type 3 and 40% of the trucks being Type 6. Type 6 trucks typically travel at a speed much lower than the FFS. Therefore, it was necessary to run a separate set of tests for a different truck distribution. Experiments 3c and 3d are identical to 3a and 3b, respectively, except the Type 6 trucks were replaced with Type 4 trucks. The HCM procedure does not have inputs for truck type. Therefore, 3a and 3c will have the same HCM results as well as 3b and 3d. Exhibit 13 lists the input data for this experiment. Any variables not specified have the same values as specified in Exhibit 2. A comparison of the resulting performance measures is presented in Exhibit 14.
<table>
<thead>
<tr>
<th>Roadway variables</th>
<th>3a</th>
<th>3b</th>
<th>3c</th>
<th>3d</th>
</tr>
</thead>
<tbody>
<tr>
<td>Segment length (mi)</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>5% grade length (mi)</td>
<td>5</td>
<td>1</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>Segment length with passing allowed (mi)</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Percentage of no-passing zones</td>
<td>40</td>
<td>40</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>Traffic variables</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Percentage of passenger cars</td>
<td>88</td>
<td>88</td>
<td>88</td>
<td>88</td>
</tr>
<tr>
<td>Percentage of trucks</td>
<td>12</td>
<td>12</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>Percentage of Type 3 trucks</td>
<td>60</td>
<td>60</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>Percentage of Type 4 trucks</td>
<td>0</td>
<td>0</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>Percentage of Type 5 trucks</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Percentage of Type 6 trucks</td>
<td>40</td>
<td>40</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>FFS (mi/h)</td>
<td>60</td>
<td>60</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>Eastbound traffic volume (veh/h)</td>
<td>1200</td>
<td>1200</td>
<td>1200</td>
<td>1200</td>
</tr>
<tr>
<td>Westbound traffic volume (veh/h)</td>
<td>400</td>
<td>400</td>
<td>400</td>
<td>400</td>
</tr>
</tbody>
</table>

Exhibit 13: Input data for Experiment 3

<table>
<thead>
<tr>
<th></th>
<th>PTSF</th>
<th>ATS</th>
</tr>
</thead>
<tbody>
<tr>
<td>CORSIM</td>
<td>92.8</td>
<td>35.4</td>
</tr>
<tr>
<td>HCM</td>
<td>91.2</td>
<td>32.5</td>
</tr>
<tr>
<td>% Difference</td>
<td>1.7</td>
<td>8.1</td>
</tr>
</tbody>
</table>

Exhibit 14: Performance measure results for Experiment 3a

Exhibit 15 shows the variables and values for the HCM analysis in Experiment 3b. The vehicle-miles traveled (VMT) and travel times (TT) were calculated for each section. The performance measures for the entire facility were reported as the weighted averages of each section of the highway. For more detailed information on the HCM calculations used in 3b, see Chapter 15 in the 2010 HCM. The combined PTSF, denoted as PTSF_c, and the combined ATS, denoted as ATS_c, are reported in Exhibit 16.

<table>
<thead>
<tr>
<th>Section</th>
<th>Grade</th>
<th>V_i</th>
<th>LT</th>
<th>VMT_i</th>
<th>ATS_i</th>
<th>TT_i</th>
<th>PTSF_i</th>
<th>TT_i×PTSF_i</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>1200</td>
<td>2</td>
<td>600</td>
<td>45.3</td>
<td>13.2</td>
<td>89.8</td>
<td>1188.8</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>1200</td>
<td>2</td>
<td>600</td>
<td>46.2</td>
<td>13.0</td>
<td>82.6</td>
<td>1072.5</td>
</tr>
<tr>
<td>2</td>
<td>5</td>
<td>1200</td>
<td>1</td>
<td>300</td>
<td>34.5</td>
<td>8.7</td>
<td>95.1</td>
<td>827.4</td>
</tr>
</tbody>
</table>

Exhibit 15: Experiment 3b HCM calculations

\[ PTSF_c = \frac{1188.8 + 1072.5 + 827.4}{13.2 + 13.0 + 8.7} \]
The PTSF is essentially unaffected by the different grade configurations in this experiment for the CORSIM analyses. When vehicles enter the analysis segment, platoons have already been formed and whether or not there is a grade does not have a great impact on platoon dispersion. With 1200 veh/h in the major direction and 400 veh in the minor direction, the vehicles do not have many opportunities to pass because they are stuck in their platoons; which explains the small difference in PTSF. The ATS, however, increased by about 3 mi/h when only the third link had a 5% grade, which is realistic because grade has a large effect on truck speeds. If a slow-moving truck is leading a platoon, then all of the following vehicles will have a speed less than or equal to the leading truck’s speed.

For the HCM analysis, PTSF decreased by about 3% and ATS increased by about 10.5 mi/h from Experiment 3a to 3b. This increase in speed seems unrealistic for having only four links change their grade from 5% to 0%. This change can mostly be attributed to the difference in the passenger car equivalent values for trucks (ET). The result for Experiment 3a is based on an ET of 10. Experiment 3b is based on the weighted average of three segments with ET values of 1, 8.8, and 1, which results in a lower average ET and, consequently, a higher ATS.

The difference in PTSF and ATS between CORSIM and the HCM in Experiment 3a is small. Overall, the speed results for Experiments 3a and 3b are probably unrealistically low because the FFS is 60 mi/h and it is unlikely that the ATS would be reduced by about 20 mi/h with a moderate traffic flow and a fairly shallow grade. However, the performance characteristics of a Type 6 truck in CORSIM are very poor. Thus, the CORSIM speed result is probably fairly accurate. In Experiment 3b, the difference in PTSF is small. PTSF differences between the HCM and CORSIM may be primarily due to the differences in handling passing zones.

Experiments 3c and 3d represent probably a more realistic scenario in terms of the performance capabilities of the trucks present in the traffic stream. These results are given in Exhibit 17 and Exhibit 18.
The change from 40% Type 6 trucks to 40% Type 4 trucks had a small positive impact on PTSF for both grade scenarios, but the ATS improved significantly, especially for the scenario with only the middle segment having the 5% grade. The speeds between the HCM and CORSIM have a high percentage difference. These results illustrate that significant differences in operations can occur for significant differences in the truck performance capabilities. To obtain the most accurate analysis results, especially for two-lane highways where more significant vertical terrain is often present, it is important to make sure the modeled traffic stream is representative of the actual traffic stream in terms of vehicle composition and performance capabilities. CORSIM has much more flexibility in this regard than the HCM analysis methodology.

### Experiment 4: Rolling Terrain with Exclusive Passing Lane

This experiment is the same as Experiment 3, but with the addition of a passing lane in the peak direction within the facility. In the CORSIM analysis, the passing lane is located on the third link. In the HCM analysis, the passing lane adjustments were applied to the PTSF and ATS that were reported in Exhibits 14 and 16. Experiments 4a and 4b correspond to 3a and 3b. Truck distributions were not tested in this experiment.

<table>
<thead>
<tr>
<th>Passing Lane Inputs</th>
</tr>
</thead>
<tbody>
<tr>
<td>CORSIM</td>
</tr>
<tr>
<td>Upstream Length (mi)</td>
</tr>
<tr>
<td>Passing Lane Length (mi)</td>
</tr>
<tr>
<td>Total Length (mi)</td>
</tr>
</tbody>
</table>

### Exhibit 19: Passing lane input data for Experiment 4

<table>
<thead>
<tr>
<th></th>
<th>PTSF</th>
<th>ATS</th>
</tr>
</thead>
<tbody>
<tr>
<td>CORSIM</td>
<td>87.3</td>
<td>37.1</td>
</tr>
<tr>
<td>HCM</td>
<td>74.3</td>
<td>33.8</td>
</tr>
<tr>
<td>% Difference</td>
<td>14.9</td>
<td>9.0</td>
</tr>
</tbody>
</table>

### Exhibit 20: Performance measure results for Experiment 4a
## Exhibit 21: Performance measure results for Experiment 4b

<table>
<thead>
<tr>
<th></th>
<th>PTSF</th>
<th>ATS</th>
</tr>
</thead>
<tbody>
<tr>
<td>CORSIM</td>
<td>86.7</td>
<td>40.8</td>
</tr>
<tr>
<td>HCM</td>
<td>72.0</td>
<td>44.6</td>
</tr>
<tr>
<td>% Difference</td>
<td>16.9</td>
<td>-9.3</td>
</tr>
</tbody>
</table>

The differences between the results of Experiment 4a and 4b are higher than the differences between Experiment 3a and 3b. The PTSF values are lower than in Experiment 3 for both CORSIM and the HCM because of the passing lane, as expected. However, the differences in the HCM PTSF results are quite large. Previous (undocumented) testing of the methodology has led to the belief by some members of the two-lane highway subcommittee (of the Highway Capacity and Quality of Service committee) that the HCM analysis methodology overestimates the improvements to the operating conditions due to a passing lane. This is an area that needs additional research. The following four exhibits illustrate the CORSIM results with and without a passing lane:

- Exhibit 22 presents the CORSIM PTSF results for Experiments 3a and 4a.
- Exhibit 23 presents the CORSIM PTSF results for Experiments 3b and 4b.
- Exhibit 24 presents the CORSIM ATS results for Experiments 3a and 4a.
- Exhibit 25 presents the CORSIM ATS results for Experiments 3b and 4b.
Appendix 3: Two lane Highway Case Study
The PTSF drops sharply at the passing lane and eventually climbs back to the original value. The passing lane allows the slow moving vehicle(s) to move out of the way of faster vehicles, which temporarily break up the platoons. The passing lane effects last for some distance downstream of the passing lane location. The trend for ATS is similar, but the effect of the passing lane on speed is not as pronounced as for PTSF. This is consistent with the HCM analysis methodology. In this experiment, the improvement to speed is further reduced by the grade, which limits the acceleration capabilities of some of the vehicles.

**Experiment 5: Level Road with 50% No Passing**

This experiment uses the same input values as Experiment 1, except that all three scenarios have a 50% no-passing zone. Each scenario has a different configuration of the 50% no-passing zone. As previously mentioned, the HCM only includes an input for the percentage of no-passing zones. The user cannot select how those zones are specifically distributed along the length of the analysis segment. Thus, this experiment looks at how different distributions of the same overall percentage of no-passing zones can affect the results. Exhibit 26 shows the different percent no-passing zone distribution scenarios investigated in this experiment. Exhibit 27 gives the results for this experiment.
There are three sets of results for CORSIM, and only one set of results for the HCM analysis method. The values of PTSF for all three trials in CORSIM are fairly consistent with the HCM value for PTSF, especially for scenarios 5b and 5c. As the passing-zone configuration was broken down into shorter alternating sections, the PTSF decreased. If vehicles join platoons near the beginning of the facility in Experiment 5a, then they do not have a chance to pass until they are halfway through the facility. However, in Experiment 5c, the vehicles that are in platoons have more frequent opportunities to pass. Even though the passing zones are shorter in Experiment 5c, one-mile passing zones were sufficient for many passing maneuvers to be completed. Thus, in general, it appears that more frequent, shorter passing zones (as long as they are still long enough for passing maneuvers to be completed) are preferable to less frequent, longer passing zones, for the same overall percentage of passing zones along the facility. Nonetheless, the results between scenarios 5a, 5b and 5c were consistent enough that the exclusion of an additional variable, or variables, to account for the configuration of the passing zones, in the HCM analysis procedures seems reasonable. However, more research on this topic is desirable.

The ATS increased as the passing zone configurations were broken down into shorter alternating
sections. This could be because of the greater number of free vehicles in the traffic stream due to more passing opportunities. The ATS given by the HCM is about 5 mi/h lower than all three ATS values reported from CORSIM. Experiment 5 should be tested with different flow rates in a future project.

**Trajectory Analysis of Passing on a Two-lane Highway**

The previous section of this appendix dealt with a comparison of performance measures obtained from the HCM and CORSIM under a variety of conditions. The remainder of this discussion examines the use of vehicle trajectory analysis of passing maneuvers on a two-lane highway using an example facility with three contiguous segments one mile in length. The free-flow speed (FFS) was 65 mph. The “Vehicle Trajectory Analysis for Performance Evaluation (VTAPE) program, described in more detail in Appendix 5 of this report, was used to examine the vehicle trajectory plots in the passing and non-passing lanes and to record the characteristics of a passing maneuver. A sample of 300 seconds within the simulation period was used. The results are presented as follows:

**Vehicle Trajectory Plots**

The vehicle trajectories in the non-passing lanes are shown in Exhibit 28. The trajectories in this exhibit are unusual for single lane trajectory plots because the vehicle traces cross each other as a result of passing maneuvers. The passing maneuvers are represented on this plot by gaps in the individual traces because passing vehicles are in a different lane.

![Exhibit 28: Vehicle trajectories in the non-passing lane](image-url)
The vehicle trajectories in the passing lane are shown in Exhibit 29. The short traces show vehicles that have entered the oncoming lane for a passing maneuver. These traces correspond to the trajectory gaps in the non-passing lane shown in Exhibit 28.

Exhibit 29: Vehicle trajectories in the passing lane

One vehicle (ID# 342) will now be selected for analysis of the characteristics of its passing maneuver.

**Change in Leader Vehicle**

A vehicle making a passing maneuver would be expected to follow a specified leader until the maneuver, at which point there will be no leader unless a multiple-vehicle passing maneuver is in progress. After the maneuver, the vehicle would be expected to take on a new leader if one is present on the link. These expectations are confirmed in Exhibit 30, which shows a change in leader from #340 to #337 after a short distance with no leader.

Exhibit 30: Leader ID before and after the passing maneuver.
Following Distance to Leader

The following distance of the passing vehicle throughout the facility is illustrated in Exhibit 31. The distance begins at about 500 ft and gradually closes to just below 100 ft because of the difference in leader and follower speeds. It levels off at this point for about one mile until the follower is able to find a passing opportunity. At that point, the following distance drops to zero because there is no leader in the passing lane. When the maneuver is complete, a new leader is acquired and the following process begins again.

Exhibit 31: Following distance to leader through the facility

Leader and Follower Speeds

The speed of the two vehicles is shown in Exhibit 32 as a function of the follower’s position on the facility. The follower’s speed remains about 8 ft/sec faster than the leader until the gap closes to the point where the follower must begin to slow down. There is an apparent oscillation as the follower assumes the leader’s speed. When the passing maneuver begins, the follower’s speed increases to about 108 ft/sec to overtake the leader in the passing lane. This is consistent with the CORSIM passing logic, which accelerates a passing vehicle to a speed 12 mi/h (18 ft/s) greater than that of the speed of the vehicle being passed (i.e., 90 + 18 = 108 ft/s).

During the passing maneuver, the passing vehicle passed two vehicles. When the passing maneuver has been completed, the passing vehicle slows down to match the speed of the new leader. Again some oscillation is apparent before the speed stabilizes. When the passing vehicle returned to the normal lane, it pulled into small gap between a leading vehicle and the second vehicle that it had passed. This new leading vehicle was traveling at only 57 mi/h (84 ft/s). The passing vehicle thus had to undergo rapid deceleration, which explains the significant drop in speed after completing the passing maneuver.
The leader speed drops to zero during the passing maneuver because there is no leader present during this time.

![Graph showing leader and follower speeds](image)

**Exhibit 32: Leader and follower speeds throughout the facility**

**General Observations on Trajectory Analysis**

This discussion has demonstrated that the characteristics of a passing maneuver on a two lane highway can be effectively represented by the type of vehicle trajectory analysis performed by VTAPE. The characteristics all appear to be reasonable in terms of expectations. The VTAPE analysis should be useful in supporting the further refinement of the two lane highway simulation capabilities of CORSIM. It should be especially useful in the development of an improved car-following model.
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Vehicle Trajectory Analysis Considerations

Appendix 4
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Introduction

The 2010 Highway Capacity Manual (HCM) contains expanded guidance for the use of alternative traffic analysis tools (mostly micro simulation tools) in assessing the performance of highway facilities. The guidance is distributed throughout the HCM as follows:

- Volume 1 (Concepts) provides guidance in three chapters:
  - Chapter 4 (Traffic Flow Analysis Concepts) introduces the concept of vehicle trajectory analysis as a technique for developing performance measures.
  - Chapter 6 (Analysis tools) includes material on simulation concepts, appropriate use of alternative tools and application guidelines for alternative tools.
  - Chapter 7 (Interpreting and Presenting Results) provides guidance on systematic modeling differences between the HCM and simulation tools, use of vehicle trajectory analysis in comparing performance measures and stochastic aspects of simulation analysis.

- Volumes 2 and 3 provide facility-specific alternative tool guidance for uninterrupted flow and interrupted flow facilities, respectively.

- Volume 4 is a virtual volume containing supplementary material including alternative tool examples, case studies and a reference library.

Use of Vehicle Trajectories in Determining Performance

There is a growing school of thought suggesting that comparison of results between traffic analysis tools and methods is possible only if the analyst looks at the vehicle trajectories shared by all field data collection and analytical tools. For example, Dowling [1] has recommended that direct conversion of the performance measures to HCM measures such as level of service should be discouraged because of the differences in definitions among the tools. Dowling suggests that analysis of vehicle trajectories is the “lowest common denominator” in developing performance measures that are consistent with HCM definitions, with field measurement techniques and with each other.

This discussion explores the potential benefits, methodology and issues associated with using vehicle trajectories from simulation to achieve compatibility with corresponding HCM measures of effectiveness (MOEs). It also attempts to establish some parameters to guide simulation software developers in the quest for a common set of trajectory based measurements.

Estimation of Traffic Flow Parameters

The analysis of the performance of a highway facility involves the assignment of estimated values to the traffic flow parameters described in HCM Chapter 4 as a function of time or distance. There are three common approaches to the estimation of traffic flow parameters:

1. Deterministic models, such as those presented in the HCM
2. Simulation models, which take a microscopic and stochastic approach to the representation of traffic flow
3. Field data observations, which attempt to measure the parameters directly by data collection and analysis.
It must be recognized that all of these approaches can only produce estimates of the parameters of interest. Each approach involves assumptions and approximations. The three approaches are bound together by the common goal of representing field conditions as they actually exist.

On the surface, it would seem that field observations should produce the most accurate representation of traffic flow. It is, however, difficult to produce quantitative observations of some traffic phenomena in a consistent manner that avoids subjective interpretation. There are limits to the accuracy of human observation and instrumentation of traffic flow data collection is not practical for routine field studies except for very simple parameters such as flow rate. Field data observations require a level of effort that often exceeds the available resources.

Modeling techniques have therefore been introduced as a practical, but also approximate, method of estimating the required parameters. A traffic analysis might involve a combination of all three assessment techniques. It is therefore important that the modeling techniques be based on definitions and computations that are as consistent as possible with field observations and with each other.

Vehicle trajectories have come to be recognized in the literature as the “lowest common denominator” for this purpose [1]. Vehicle trajectories represent the “ground truth” that all measurement and analysis techniques attempt to represent. Microscopic simulation models create vehicle trajectories explicitly through algorithms that apply principles of traffic flow theory to the propagation of vehicles along a highway segment. Macroscopic deterministic models do not deal with trajectories at the same level of detail, but they attempt to produce an approximation of the results that would be obtained from trajectory analyses.

With a few exceptions involving a significant research effort, field observations are not able to create complete trajectories. Instead, they attempt to establish critical points along individual trajectories. Because it does create complete trajectories, simulation modeling may be viewed as a surrogate for field data collection through which the critical points on the trajectory may be established. It is important for this purpose that the critical points be defined in a manner that promotes compatibility between the analysis techniques.

**HCM Treatment of Vehicle Trajectories**

The first issue that arises in producing comparable measurements based on vehicle trajectories is that the HCM does not deal at all in vehicle trajectories, so a direct comparison of HCM trajectories with simulation trajectories is not possible. Among other things, the perception of vehicle trajectories as the “lowest common denominator” is not entirely accurate. In fact, the only concept linking the HCM methodology and simulation models is that both approaches strive to replicate measures in the same way that they would be derived from field data. In this sense, field observations are really the lowest common denominator and we must focus on how each tool attempts to reproduce field conditions in a realistic manner.
Graphical Representation of Vehicle Trajectory

We begin by looking at how vehicle trajectories are described. Graphically, they are generally described in terms of a time-space diagram of the type shown in Exhibit 1, which depicts a classical queue accumulation and release at a signalized stop line.

There are three characteristics shown on Exhibit 1 that are not necessarily common to all time space representations of vehicle trajectories:

1. Time is shown on the vertical axis and distance is shown horizontally. The axes tend to be switched in more scientific publications in keeping with the rule of displaying the independent variable on the horizontal axis. The more pragmatic traffic engineering approach represents distance horizontally recognizing that distance is, in fact, horizontal.

2. The angular shape of the trajectory curves does not represent the acceleration and deceleration in their true forms. This shape displays an approximation of the trajectory which is appropriate for some interpretations and inappropriate for others.

3. This figure depicts a single lane of operation in which each vehicle follows its leader according to established rules. Multiple lane trajectory plots differ from single lane plots in two ways: First, the first-in-first-out (FIFO) queue discipline can be violated in multi lane situations because of overtaking. In other words, a vehicle entering a link later than its leader could leave the link earlier. Graphically, this situation is represented by trajectory lines crossing each other. Second, it is possible that some vehicles might change lanes. Lane changes can’t be represented in Exhibit 1 because distance is plotted as a one dimensional scalar quantity. Because of these complexities, multiple lane trajectories are much harder to analyze.
As another example of vehicle trajectories, Exhibit 2 shows a typical freeway situation in which queuing and shock waves are caused entirely by vehicle interactions and not by traffic control devices. Note that the plot shown in Exhibit 2 is considerably more complex and realistic than Exhibit 1, but it still does not show lane changes or overtaking. Also note that time is shown on the horizontal axis in this figure. Furthermore, some of the trajectory lines are discontinuous because of vehicles entering and exiting the lane.

![Exhibit 2: Typical freeway trajectory plot for a single lane](image)

**Mathematical Properties of Vehicle Trajectory**

While the plots shown in the two preceding figures provide a good visual insight into the operation, they do not support any quantitative assessments. To develop performance measures from vehicle trajectories, it is necessary to represent them mathematically and not just visually. A mathematical representation requires the development of a set of properties that are associated with each vehicle at specific points in time and space. Because of the time step formulation of most simulation models, it is preferable to choose time as the reference point instead of distance.

Exhibit 3 shows the trajectory of a single vehicle through a signal. At each point in time a number of properties may be determined. The trajectory for the vehicle is quantified through a list of the properties of vehicle at each point in time throughout a time range.
Properties of Vehicle $n$ at time $t$
- Vehicle ID
- Position, $p$
- Speed, $v$
- Acceleration, $a$
- Space gap, $g$
- Time headway, $h$
- Lane, $L$
- Link or analysis zone, $z$
- $D_x$ from upstream link end, $d_u$
- $D_x$ from downstream link end, $d_d$

Exhibit 3: Mathematical properties of vehicle trajectories
One important parameter in the quantification of trajectories is the time increment between sampling points, represented in Exhibit 3 as $\Delta t$. Time increments in typical simulation models range from 0.1 sec to 1.0 sec, with the smaller value gaining acceptance within the simulation community because of its ability to represent traffic flow with greater fidelity.

There are many properties that can be associated with a specific vehicle at a point in time. Some properties are required for the accurate determination of performance measures from trajectories. Others are used for different purposes such as safety analysis.

Trajectories may be analyzed either internally or externally to estimate a consistent set of performance measures. It is important to recognize the distinction between the two methods.

**External Trajectory Analysis**

External trajectory analysis is performed by postprocessing a basic set of trajectory properties for each vehicle at each time increment. The properties in the set must contain sufficient detail to support a consistent determination of all of the required performance measures without regard to the tool that produced them. The specification of the properties and file format must be such that the trajectory file can be produced by any simulation tool. The HCM must prescribe in detail what trajectory information is required, how it can be organized and how the performance measures should be determined from the trajectories.

This is the only way in which a consistent set of performance measures that are independent of the source can be obtained. It does not, however, offer a practical way for the end user to conduct highway capacity and level of service analyses. One of the principal problems with the analysis of a single trajectory is that statistically meaningful measures must be based on multiple simulation runs, which would create an intractable amount of data to be analyzed.

**Internal Trajectory Analysis**

The only practical way to apply simulation tools is through the outputs of the simulation tools themselves. This requires that internal trajectory analysis be performed by each tool in a manner that will produce the same results as external trajectory analysis. With adequate specification of the required trajectory information and computational procedures, it should be possible for any simulation tool developer to offer, at least as an option, performance measures that are compatible with other simulation tools and with the HCM procedures. This situation is analogous to the manner in which all HCM procedures are implemented. The HCM does not provide implementation software; it provides unambiguous procedures that can be implemented in a consistent manner by software developers.

**Basic Trajectory Properties**

The basic trajectory properties from which all of the required performance measures can be estimated include the following information for each vehicle within the facility boundaries and for each time step within the analysis period:

- **Vehicle ID**: Required to distinguish a specific vehicle for all other vehicles within the facility boundaries.
- **Position**: This is the most basic of all properties from which many other properties may be derived. A one dimensional position is sufficient to produce performance measures. There is still some question about a universal representation of position because different tools...
specify the position in different ways. A common reference point for position needs to be established. A reference point that indicates the relative position of the vehicle in the link would be desirable to enable developers to produce uniform measures.

- Link or segment: Required to associate performance measures with a specific link or analysis segment for reporting purposes.
- Lane: In multi-lane facilities it is important to know the lane in which the vehicle is traveling because headways, densities, etc. must be estimated by lane. It is also necessary for the identification of lane changes.

**Static Vehicle and Facility Parameters**

Some required properties can be derived from the basic properties with knowledge of certain parameters that are constant with respect to time, including:

- Vehicle length: Required to convert headways to gaps.
- Link end positions: Required to determine the position of the vehicle with respect to the upstream or downstream end of the link.

It might be expedient to repeat this static information in each record to avoid the need for an external parameter file.

**Derived Trajectory Properties**

The remainder of the required trajectory properties can be derived from the basic properties as follows:

- Instantaneous Speed: This can be determined from the relative positions of the vehicle at time \( t \) and time \( t-\Delta t \), assuming a constant acceleration during \( \Delta t \). However, since some models update vehicle positions from the speeds, it might be desirable to include speed as a basic trajectory property.

- Instantaneous Acceleration: This can be determined from the relative speeds of the vehicle at time \( t \) and time \( t-\Delta t \), assuming a constant acceleration during \( \Delta t \). However, since some models update vehicle speeds from the acceleration, it might be desirable to include acceleration as a basic trajectory property.

**Vehicle Trajectory Presentation**

To achieve a consistent trajectory analysis, a consistent method of presenting vehicle trajectory information must be specified. Dowling states in Reference 1 that

"It would be highly desirable if all microscopic analysis tools had the option of generating vehicle trajectory data in a universally readable format (for example, a generally accepted database format, such as DBASE), so as to make post-processing and comparison of results across tools possible."

A vehicle trajectory file specification now exists and is therefore a candidate for this purpose. It was developed by FHWA to support the Surrogate Safety Analysis Model (SSAM) and includes most of the required trajectory information.

The trajectory file records the location of each vehicle in a single simulation run for every time step of the simulation. Each trajectory file is expected to be named with a “.trj” extension. It utilizes a binary format to keep trajectory files from large network simulations from growing excessively large. The vehicle trajectory file is organized with a set of records summarized in
Exhibit 4. A complete description of the SSAM file format (Version 1.4) may be found in Reference 2.

### Exhibit 4: SSAM Vehicle Trajectory Record Content

<table>
<thead>
<tr>
<th>Property</th>
<th>Value Description</th>
<th>Use in Determining Performance Measures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vehicle ID</td>
<td>Unique identifier number of the vehicle</td>
<td>Used to keep track of vehicles through all time steps</td>
</tr>
<tr>
<td>Link ID</td>
<td>Unique identifier number of the link (where possible)</td>
<td>Used to select link for analysis</td>
</tr>
<tr>
<td>Lane ID</td>
<td>Unique identifier number of the lane (where possible)</td>
<td>Used to identify lanes for headway analysis</td>
</tr>
<tr>
<td>Front X</td>
<td>X coordinate of the middle front bumper of the vehicle</td>
<td>Used to identify the position of the vehicle</td>
</tr>
<tr>
<td>Front Y</td>
<td>Y coordinate of the middle front bumper of the vehicle</td>
<td>Might be used to analyze lane changing</td>
</tr>
<tr>
<td>Rear X</td>
<td>X coordinate of the middle rear bumper of the vehicle</td>
<td>Not used</td>
</tr>
<tr>
<td>Rear Y</td>
<td>Y coordinate of the middle rear bumper of the vehicle</td>
<td>Not used</td>
</tr>
<tr>
<td>Length</td>
<td>Vehicle length (front to back) in Units (feet or meters)</td>
<td>Might be required to convert headways to gaps. Also needed to determine when a vehicle has exited a queue</td>
</tr>
<tr>
<td>Width</td>
<td>Vehicle width (left to right) in Units (feet or meters)</td>
<td>Not used</td>
</tr>
<tr>
<td>Speed</td>
<td>Instantaneous forward speed (Units/sec)</td>
<td>Used to estimate delay, stops, etc.</td>
</tr>
<tr>
<td>Acceleration</td>
<td>Instantaneous forward acceleration (Units/sec²)</td>
<td>Used to determine queue conditions</td>
</tr>
</tbody>
</table>

The SSAM format was developed to support the analysis of surrogate safety measures. It contains a level of detail on the exact positioning of the vehicle that is not required for the development of performance measures. On the other hand, some additional information would be useful for this purpose. To guide future SSAM development, a “Version 2” format was proposed in an NCHRP 3-85 working paper [3]. The proposed additional information includes:

- Identification of the source model that produced the trajectory data
- A code to identify the intended movement (left, through, right, etc.) at the downstream link end
- A code to identify the vehicle type in the classification scheme used by the source model
- Upstream and downstream node ID, required because not all tools assign a unique number to each link
- Distance from the upstream and downstream link end
- Control Status at the downstream link end, indicating what the driver is seeing during the time step

The additional information would support a more refined definition and computation of control delay. The following useful measures could also be estimated:
• Startup and ending lost time
• Loss of effective green time due to queue blockages
• Signal timing parameters, including average cycle length and green time, with traffic-actuated control
• Link Capacity and v/c Ratio
• Measures of progression quality, including proportion of arrivals on the green and the HCM progression factor

It is not practical to include the recommended SSAM expansion in the 2010 HCM. However, a recommendation in the main body of this report supports the proposed expansion. A resolution from the HCQS Committee supporting this recommendation would be helpful. It should be remembered that a Committee resolution was the prime motivation for FHWA’s addition of control delay to the CORSIM performance measures report.

CORSIM Vehicle Trajectory Files
An alternative mechanism for the development of performance measures by postprocessing vehicle trajectory files is available from CORSIM. The files used to support the animated graphics displays are better suited to the initial exploration of vehicle trajectories than the SSAM format because they indicate the position of the vehicle on the link, instead of X and Y coordinates. They also indicate the driver type for each vehicle, which is necessary to establish the desired speed as a reference for delay. For purposes of this discussion, the CORSIM files will be used initially, with the intent to extend the analysis to other file formats at some point in the future.

CORSIM records and stores a substantial amount of data about each vehicle in the system for each second of simulated operation. Exhibit 5 shows a summary of the recorded data. The data elements required for plotting vehicle trajectories include:
• A unique vehicle identification for keeping track of individual vehicles through all of the time steps
• A link identifier to select links for plotting
• A lane identifier to support lane-specific plots
• The position of the vehicle on the link.

Other data elements that are not strictly required for plotting trajectories but are essential to quantitative trajectory analysis include vehicle length, instantaneous speed and instantaneous acceleration. All of the required data elements are contained in the CORSIM animated graphics files.
Vehicle Trajectory Analysis Mechanism

A common analysis mechanism is required to produce the performance measures from vehicle trajectory files. A software utility called “Vehicle Trajectory Analysis for Performance Evaluation” (VTAPE) has been developed by NCHRP project 3-85 for this purpose.

VTAPE provides very detailed step-by-step analyses with intermediate values reported for all parameters at each time step. It is a useful tool for understanding and enhancing the trajectory analysis methodology. As such, it is intended as a research tool. It should not be viewed as an end-user analysis tool. Its ultimate purpose will be to serve as the computational engine for the HCQS Simulation Subcommittee. It has been developed with that purpose in mind.

The VTAPE user interface is presented in Exhibit 6. A full description of VTAPE and instructions for its installation and operation are provided in Appendix 5 to this report. The capabilities of this utility program will be summarized here:

VTAPE Operation

With VTAPE, it is possible to select up to 8 links forming a continuous route for analysis. The data for the selected links are read from the CORSIM animated graphics files. The selected links are joined together for plotting and analysis to form a linear route. Each link is configured in terms of:

- Upstream and downstream nodes that define the link,
- Link Length,
- Free flow speed (FFS) and
- Control
VTAPE also accommodates up to three auxiliary lanes per link, to accommodate acceleration or deceleration lanes on freeways and turn bays on surface streets. The auxiliary lane properties screen is presented in Exhibit 7.

Exhibit 6: VTAPE user interface screen

Exhibit 7: VTAPE auxiliary lane properties screen
VTape performs the following functions, all of which will be demonstrated in this discussion:

1. Plotting of trajectories, either by lane or for all lanes in the link.

2. Longitudinal analysis of the trajectory of vehicles as they traverse a link. A single vehicle may be chosen for a detailed analysis over multiple links to illustrate the analysis procedure or all vehicles traversing the link in a given time period may be analyzed separately, with their performance measures included. The measures determined by this type of analysis include delay measures of various types to be explained later and stop-related measures.

3. Spatial analysis, which involves consideration of all of the vehicles on a link at a specific time step. The two principal spatial measures include density and queue lengths.

All of these functions produce results in comma delimited format for further analysis and plotting by spreadsheet software. Each function produces a summary of the MOE results and a data dump that presents intermediate values for each step to demonstrate the computational procedures.

**Process for Developing HCM Compatible Performance Measures**

An overview of the process to be used in the NCHRP 3-85/3-92 projects for developing HCM-compatible performance measures is presented in Exhibit 8.

Exhibit 8: Overview of the process for developing HCM-compatible performance measures
The Intended steps in the process are described as follows, with the numbers corresponding to those on the exhibit:

1. The simulation model produces vehicle trajectory files in the required format.
2. The files are read and analyzed by the VTAPE Utility.
3. The specifications for external analysis of vehicle trajectories are developed and demonstrated using VTAPE as a computational engine.
4. The specifications are incorporated into the HCM as guidance to simulation tool developers.
5. The HCM specifications are used by participating developers to produce an internal vehicle trajectory analysis.
6. The simulation tools produce consistent and HCM-compatible performance measures.

Limitations of Vehicle Trajectory Analysis
The process described in Exhibit 8 is intended to produce performance measures from vehicle trajectories that are based on HCM definitions of traffic parameters to promote uniformity of reporting among different simulation tools. The results should improve the ability to use simulation tools for highway capacity and level of service analysis. It must be noted, however, that the term “HCM-compatible” does not suggest that the measures produced by a simulation tool will be identical to the HCM or to those from other simulation tools. There are several factors that must be considered.

Traffic Modeling Differences
In step 1 above, the trajectory files are produced by the simulation model. Each simulation tool has its own model, which differs from those used by other tools. It is not practical or desirable for the HCM to prescribe simulation modeling details. Developers continually strive to improve the realism of their products to gain a competitive advantage in the market. The NGSIM program has had some success in developing core algorithms to be shared by simulation developers but the notion of a universal simulation model is unattainable.

Approximations in Trajectory Analysis
It was pointed out earlier that all performance measures reported by deterministic models, simulation models and field observations represent an approximate assessment of field conditions. A preliminary specification for developing consistent performance measures from trajectory analysis will be presented later in this document. The need for approximations in trajectory analysis to promote uniform reporting will become clearer at that point. One of the problems is that the HCM itself introduces approximations that can’t be replicated in simulation because of conceptual differences and model structure.

Differences that are Unrelated to Trajectory Analysis
The use of vehicle trajectories addresses some, but not all, of the sources of difference in the definition of performance measures. For example the temporal and spatial boundaries of an analysis tend to be defined differently by different tools. To promote HCM compatibility, the HCM definitions should be used in conducting simulation analyses. Applying these definitions is not always an easy task. We will expand on this idea later.
Guiding Principles for Trajectory Analysis Specifications and Interpretation

A set of principles governing the development of the HCM Chapter 7 material on interpretation of results in general and on trajectory analysis in particular must first be established. The logical starting point is the Committee resolutions on alternative tools that resulted from five motions adopted by the Committee. The first three of these motions dealt with consistent reporting of performance measures:

- **Motion 1:** The Highway Capacity Manual should include guidance to developers of traffic simulation models and other traffic analysis tools to promote consistent and accurate reporting of measures of effectiveness for highway capacity analysis. This guidance should include a set of minimum criteria that all traffic analysis tools would be encouraged to achieve.

- **Motion 2:** To promote consistency among traffic simulation models and other traffic analysis tools, the Highway Capacity Manual should include a recommended list of common measures of effectiveness (MOE’s). These MOE’s should be based on vehicle trajectories. The HCM should recommend that all traffic analysis tools include the functionality to provide those measures of effectiveness as outputs. For the purpose of this motion, vehicle trajectories shall be defined as documented in the report, Definition, Interpretation, and Calculation of Traffic Analysis Tools Measures of Effectiveness prepared by the Federal Highway Administration dated January 2007.

- **Motion 3:** The Highway Capacity Manual should discourage the use of HCM level of service threshold tables based on measures of effectiveness reported by other traffic analysis tools that are inconsistent with HCM definitions.

These motions apply specifically to the HCM Chapter 7 guidance described in this document. The process for developing HCM-compatible performance measures, as described in Exhibit 8 is entirely consistent with those motions.

The following principles are proposed to guide the development of trajectory analysis procedures. Some of the principles arise as corollaries to the motions and others are based on the objective of promoting developer participation by providing simple and unambiguous procedures that can be implemented by developers without requiring additional data and without drastically affecting their model execution times. It must be remembered that developers are under no obligation to implement the HCM recommendations on trajectory analysis. With this in mind, the following principles have been observed:

1. The trajectory analysis specifications shall be limited to the analysis of trajectories produced by the traffic flow model of each simulation tool. The specifications shall not require developers to change their traffic flow modeling logic.

2. The specifications should establish when each of the proposed measures can be adequately defined by trajectories to permit a valid comparison between the HCM and other modeling approaches. If the specifications for estimating a particular measure cannot be satisfactorily defined then the guidance should indicated that comparisons should not be made.

3. All performance measures that accrue over time and space shall be assigned to the link and time interval in which they occur. There are subtle complexities that make it impractical to do otherwise. For example, the root cause of a specific problem might not
be within the link or the immediate downstream link. In fact, the problem might be secondary to another problem at some distant location in the network and in a different time interval.

4. The guidance must state that the spatial and temporal boundaries of the analysis domain must include a period that is free of congestion on all sides. This principle is already stated in the HCM for multi-period signalized intersection analysis. To ensure that delays to vehicles that are denied entry to the system during a given period are properly recognized, it might be necessary to create fictitious links outside of the physical network to hold such vehicles.

5. Because some agencies operate under an administrative requirement to estimate level of service, an extra effort should be made to develop trajectory analysis specifications for the measures that define level of service, including density for uninterrupted flow and control delay for interrupted flow. The definitions for these measures might require additional assumptions and approximations as well as the establishment of arbitrary but consistent parameters and thresholds. Where possible, guidance should be provided on the effect of the assumptions and approximations on the validity of the comparisons.

6. The algorithms must be suitable for computation “on the fly.” They must not require information from a future time step that would complicate the data handling within the simulation process.

7. Arbitrary thresholds should be kept to a minimum because of the difficulty of obtaining acceptance throughout the user community for specific thresholds. Where arbitrary thresholds can’t be avoided they should be justified to the extent possible by definitions in the literature and, above all, they should be applied consistently for different types of analysis.

8. Computationally complex and time consuming methods should be avoided to minimize the additional load on the model. Methods should be developed to simplify situations with many special cases because of the difficulty of enumerating all special cases.

9. The same definitions, thresholds and logic should be used for determination of similar parameters in different computational algorithms for longitudinal and spatial analysis.

10. Since VTAPE is not intended to be an end-user tool, ease of understanding the logic and the ability to follow the computations should take priority over computational speed.

The supplemental alternative tool examples in Volume 4 of the 2010 HCM will be presented to illustrate the application of such tools to overcome stated limitations of the manual. Whenever possible, direct comparisons with HCM results will be avoided for measures that depend on trajectory analysis. No direct LOS comparisons will be made. Disclaimers will be added to state clearly that the available versions of the alternative tools did not include the ability to create performance measures using the trajectory based definitions of the 2010 HCM.
Trajectory Analysis Examples

As a prelude to the development of the actual procedures for producing performance measures, several examples of vehicle trajectory analysis with VTAPE have been developed to demonstrate the ability to quantify the trajectory properties. These examples will now be presented and discussed separately.

Basic Signalized Intersection

To simplify the discussion, we will start with a very basic example. The intersection configuration involves two single lane-one-way streets as shown in Exhibit 9. To simplify the situation even more, the simulation parameters will be adjusted to enforce a uniform operation. Essentially all of the randomness inherent in simulation will be removed. Simulation of uniform conditions would not normally produce useful results but this example provides a very good starting point to illustrate the nature of vehicle trajectory plots.

A trajectory plot showing two cycles of simulated operation for this example is presented in Exhibit 10. This is the classic form that appears often in the literature to support discussion related to queue accumulation and discharge. The ability to produce a plot of this nature from controlled conditions will provide a measure of confidence in the validity of future examples involving much more complicated situations.

Restoring Randomness to the Simulation

To simplify the discussion, the first example was presented with all randomness removed from the operation. Subsequent examples will be more realistic in their treatment of traffic flow. Vehicles will be generated at entry points from a Poisson distribution and CORSIM’s default parameters for randomizing driver behavior will be applied.

Exhibit 11 shows a sample trajectory plot for the same operation that was depicted in Exhibit 10. As expected, the individual trajectories follow the same pattern as the uniform case, except that some spacings and speeds are not as consistent. Since this example uses a single lane approach, the trajectory lines do not cross each other because overtaking is not possible.
Uniform Arrivals and Departures

Exhibit 10: Trajectory plot from CORSIM for uniform arrivals and departures

Random Parameters

Exhibit 11: Introducing randomness into the simulation
Vehicle Trajectories for Oversaturated Operation

Up to this point, the examples have involved v/c ratios less than 1.0, in which all vehicles arriving on a given cycle are able to clear on the same cycle. Saturation levels close to and above 1.0 present a different picture. Three cases will be presented here:

1. Cycle failure, occurring when saturation approaches 1.0 and residual queues build on one cycle but are resolved on the next cycle
2. Oversaturated operation in which queues extend throughout the approach link
3. Undersaturated operation in which queues extend to an upstream link for a part of a cycle because of closely spaced intersections.

Cycle Failure

A cycle failure example is presented in Exhibit 12. This trajectory plot shows a situation in which some vehicles arriving on Cycle 1 were unable to clear until Cycle 2. The condition is identified from the trajectory plot when the last stopped vehicle (i.e., horizontal trajectory line) was forced to stop again before reaching the stop line. The figure shows that there were four vehicles in this category. These vehicles became the first four vehicles in the queue for the next cycle. Fortunately, the arrivals on Cycle 2 were few enough that all stopped vehicles were able to clear the intersection before the beginning of the red phase. A closer inspection of Exhibit 12 shows that one more vehicle, which was not stopped, was also able to clear.

Exhibit 12: Cycle failure example
Oversaturated Operation

Oversaturated operation was produced by increasing the demand volume to the point where it exceeded the capacity of the approach. The increased demand produced a queue that extended the entire length of the link. The graphics screen capture at the right shows that the queue has, in fact, backed up beyond the link entry point.

The vehicle trajectory plot for this operation is presented in Exhibit 13. The move-up process is represented in the trajectories. Note that vehicles entering the link require up to three cycles to clear the intersection. By the computational process introduced previously, each vehicle would accrue control delay for its entire time spent on the link. It could be argued that the link travel time at free-flow speed should be subtracted, however that time would be very small compared to the delay time.

A larger question is what to do with the vehicles that are denied entry during the analysis period. The answer is that the analysis period must be long enough to include a period of uncongested operation at each end. The delay to vehicles denied entry to this link will be accounted for in upstream links during the period.
The upstream links must include a holding area outside of the system. Some tools include the delay to vehicles that are denied entry and some do not. If a tool that does not include denied entry delay is used, then fictitious links must be built into the network structure for this purpose.

**Queue Backup from a Downstream Signal**
Even when an approach is not fully saturated, queues might back up from a downstream signal for a portion of the cycle. This happens when intersections are closely spaced, for example at a diamond interchange. An example of queue backup within a cycle is shown in Exhibit 14.
The two-intersection configuration for this example is also shown in Exhibit 14. The graphics screen capture shows that vehicles that would normally pass through the upstream link are prevented from doing so by queues that extend beyond the end of the downstream link for a portion of the cycle. The question is how to treat the resulting delay.

By the definitions given to this point, the delay in the upstream link would be assigned to the upstream link, even though the signal on the downstream link was the primary cause. The important thing is to not overlook any delay and to assign all delay somewhere and in a consistent manner. With simulation modeling, the only practical place to assign delay consistently is the link on which the delay occurred. As stated previously, there are subtle complexities that make it impractical to do otherwise.

**More Complex Signal Phasing**

Up to this point we have considered only simple signal phasing. Many applications involve simulation of more complex phasing on urban streets. As an example of a more complex situation, we will examine a left turn moving on both a protected and permitted phase.

Exhibit 15 shows the trajectory plot for an eastbound left turn movement from an exclusive lane, controlled by a signal with both a protected and permitted phase. In this case, the upstream link is the eastbound approach to the intersection and the downstream link is the northbound approach to the next intersection. Since the distance on a trajectory plot is one-dimensional, the distance scale is linear, even though the actual route takes a right-angle bend.

---

**Exhibit 15: Trajectory plot for more complex signal phasing**
Even with an undersaturated operation, this trajectory plot is substantially more involved than those that we have examined previously. The following phenomena are identified on the figure:

1. Cross street traffic entering the downstream link on the NB phase: These vehicles do not appear on the upstream link because they are, in fact, on a different link. They enter the downstream link at the stop line on the red phase for the left turn movement of interest.
2. Left turns on the protected phase, shown as solid lines on the trajectory plot: The protected left turn phase takes place immediately after the red phase. The left turning vehicles begin to cross the stop line at that point.
3. Left turns on the permitted phase, shown as broken lines on the trajectory plot: The permitted left turn phase takes place immediately after the protected phase. There is a gap in the trajectory plot because the left turning vehicles must wait for the oncoming traffic to clear.
4. Left turn “sneakers:” It is not possible to identify a sneaker explicitly on the trajectory plot, however, the last left turn to clear the intersection on the permitted phase is probably a sneaker if it enters at the end of the permitted phase.
5. Left turn vehicles that enter the link in the through lane and change into the left lane somewhere along the link. These vehicles are identified by trajectories that begin in the middle of the link.
6. Through vehicles that enter the link in the left turn lane and change into the through lane somewhere along the link. These vehicles are identified by trajectories that end abruptly in the middle of the link.

The trajectory plot shown for this example is more complex than the previous plots; however, the analysis of performance can be carried out in the same way.

**Freeway Examples**

Freeway trajectories follow the same definitions as surface street trajectories but the queuing patterns are different because they are created by car following phenomena and not by traffic signals. The performance measures of interest are also different. For example, there is no notion of control delay on freeways because there is no control. The level of service on interrupted flow facilities is based on traffic density expressed in units of veh/lane/mile. In some cases, such as merging segments, the density in specific lanes is of interest.

Two cases will be examined. The first deals with a weaving segment and the second deals with merging at an entrance ramp.
Weaving Segment Example

Simulation Network Structure
The problem description, link-node structure and animated graphics view for the weaving segment example is shown in Exhibit 16. This is the same scenario used in Example Problem 1 in Chapter 12 of the 2010 HCM. There are two lanes on the freeway and on each ramp. The two ramp lanes are connected by full auxiliary lanes.

Exhibit 16: Weaving segment description and animated graphics view
Vehicle Trajectories for the Freeway Lanes

The vertical (i.e., distance) axis of the trajectory plot provides a linear one-dimensional representation of a series of connected links. The links themselves can follow any pattern as long as some of the vehicles leaving one link flow into the next link. The VTAPe software utility accommodates a maximum of 8 connected links. When multiple links are connected to a node (as is usually the case) then different combinations of links may be used to construct a multi-link trajectory analysis. The route configuration must be designed with the end product in mind. Sometimes it will be necessary to examine multiple routes to get a complete picture of the operation.

There are two entry links and two exit links to the weaving segment, giving four possible routes for analysis. We will look at two routes. The first route, which is represented in Exhibit 17, shows the traffic entering the weaving segment from the freeway and leaving to the freeway ($V_{FF}$ in Exhibit 16), represented by links (1-2-3-4).

Exhibit 17: Trajectory plot for freeway links
This is a multi-lane plot so, unlike previous plots, some of the trajectory lines might cross each other because of different speeds in different lanes. One such instance is highlighted in Exhibit 17. This figure also shows vehicles that enter and leave the weaving segment on the ramps. Because the ramps are not a part of the selected route, the ramp vehicles will appear on the trajectory plot only on the link that represents the weaving segment. Examples of ramp vehicles are identified on the figure.

The definition of link density (veh/mi) is also indicated on this figure. Density as a function of time, t, is expressed in vehicles per mile and determined by counting the number of vehicles within the link and dividing by the link length in miles. Average lane density (veh/mi/lane) on the link may then be determined by dividing the link density by the number of lanes. To obtain individual lane densities, it is necessary to perform the trajectory analysis on each lane. The analysis must also be performed on a per-lane basis to examine individual vehicle headways.

**Vehicle Trajectories for the Entrance and Exit Ramps**

By specifying the links on the route as (5-2-3-6) instead of (1-2-3-4), we can examine the trajectories for vehicles entering and leaving the weaving segment on the ramps ($V_{RR}$ in Exhibit 16). This trajectory plot is shown in Exhibit 18. This figure is very similar to Exhibit 17, except that the vehicles that do not appear outside of the weaving segment are those on the freeway links instead of the ramp links.

![Ramp Entry and Exit - All Lanes](image_url)

Exhibit 18: Trajectory plot for entrance and exit ramp links
It is also possible to construct two other routes, one for vehicles entering from the freeway and leaving to the exit ramp, $V_{FR}$, as (1-2-3-6), and for those entering from the ramp and leaving to the freeway, $V_{RF}$, as (5-2-3-4). These plots are not included here.

**Entrance ramp Merging Example**

Merging segments provide another good example of vehicle trajectory analysis on a freeway. The merging vehicles affect the freeway operation differently in each lane, so it will be necessary to examine each lane independently.

**Simulation Network Structure**

The same node structure used in the weaving segment example is used here. The lane configuration has been changed to be more representative of a merge operation. Three lanes have been assigned to the freeway and one lane to the entrance ramp. The demand volumes have been specified to provide a near-saturated operation to observe the effects of merging under these conditions. A graphic view of the operation is presented in Exhibit 19.

![Exhibit 19: Entrance ramp merging segment configuration](image)

**Trajectory Plots for all Lanes**

Exhibit 20 shows the trajectory plot for all freeway lanes combined. The operation is clearly very heterogeneous with a mixture of fast and slow speeds. Many trajectory lines cross each other and not much could be done in the way of analysis using the data from this scenario.
Trajectory Plots for Individual Lanes

It is clearly necessary to examine each lane individually. Exhibits 21, 22 and 23 show the trajectory plots for Lanes 1, 2 and 3 respectively. Because these plots represent individual lanes, the trajectory lines do not cross each other. The effect of the merging operation is quite observable (and predictable) in these three figures.

In Lane 1, the freeway speeds are very low upstream of the merge point. Merging vehicles enter the freeway slowly but they pick up speed rapidly downstream of the merge point bottleneck. The merging vehicles enter the freeway from the acceleration lane, which begins at 1000 ft on the distance scale. The merging vehicle trajectories prior to entering the freeway are not shown on this figure because those vehicles are either on a different link or a different lane.

In Lane 2, the freeway speeds are higher, but still well below the free flow speed, indicating that the merge operation affects the second lane as well. There are some vehicles entering Lane 2 in the vicinity of the acceleration lane but these are generally vehicles that have left Lane 1 to avoid the friction. Both Lane 1 and lane 2 show several discontinuous trajectories indicating lane changes. The Lane 3 operation is much more homogeneous and speeds are higher, indicating a much smaller effect of the merging operation.
Exhibit 21: Trajectory plot for freeway lane 1 (rightmost) in the merge area

Exhibit 22: Trajectory plot for freeway lane 2 (center) in the merge area

Freeway Lane 1

Freeway Lane 2
Trajectory Plots for Ramp Vehicles
To configure a trajectory route covering the entrance ramp vehicles, the ramp and acceleration lane, which were not represented in Exhibits 21-23, must be selected in place of the upstream freeway link. The acceleration lane number must first be identified from the CORSIM output. Because of CORSIM’s unique and somewhat creative lane numbering scheme, the acceleration lane will be Lane 9. So, to cover the ramp and acceleration lane, Lane 9 must be selected on the freeway link (2-3).

The trajectory plot for this route is shown in Exhibit 24. The results are not quite as anticipated. The vehicles are shown on the ramp and acceleration lane but they disappear as soon as they enter the freeway. More vehicles eventually appear towards the end of the freeway link. The vehicles disappear because Lane 9 was selected for the freeway link, so vehicles on lane 1 will not show up on the plot. The vehicles that reappear at the end of the link are those that are leaving the freeway at the downstream exit. They reappear at that point because the deceleration lane at the end of the link is also assigned as Lane 9. This is not a very useful plot but at least it confirms that the VTAPE program is working properly. It also contributes to the understanding of trajectory analysis details.
To obtain a continuous plot of ramp vehicles we must add nodes to the network at the points where the acceleration and deceleration lanes join the freeway. These nodes are shown as #7 and #8 on Exhibit 25. A continuous route may then be configured as (5-2-7-8-3-4). The trajectory plot for this route is shown in Exhibit 26.

Exhibit 24: Trajectory plot for acceleration and deceleration lanes

Exhibit 25: Addition of intermediate nodes for continuous trajectory plots
This plot shows the entering vehicles on the ramp as they pass through the acceleration lane onto the freeway. Note that there are some discontinuities in the trajectories because of the different point at which vehicles leave the acceleration lane.

**Estimation of Performance Measures from Trajectories**

The preceding section has demonstrated that it is possible to produce vehicle trajectory plots that can be interpreted and analyzed. The plots themselves represent actual data that provides a mathematical description of the lines that are plotted. The next section will address the development of the routines that compute traffic parameters and performance measures from the data.

**Performance Measures to be Estimated**

Exhibit 27 presents a table that includes all of the performance measures that are produced by the procedural chapters of the HCM 2000. The objective is to develop trajectory analysis procedures that can provide consistent estimates of these measures.
### Exhibit 27: Performance Measures Estimated by HCM Procedures

**Note:** Service Measures are indicated in **Bold**

<table>
<thead>
<tr>
<th>HCM Chapter</th>
<th>Density</th>
<th>Speed</th>
<th>v/c Ratio</th>
<th>Travel Time</th>
<th>Control Delay</th>
<th>Queue</th>
<th>Other Measures</th>
</tr>
</thead>
<tbody>
<tr>
<td>10. Freeway Facilities</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11. Basic Freeway Segments</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12. Freeway Weaving Segments</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td></td>
<td></td>
<td></td>
<td>Weaving speed Non weaving speed</td>
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<tr>
<td>13. Ramps and Ramp Junctions</td>
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<td>Yes</td>
<td>Yes</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14. Multilane Highways</td>
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<td>Yes</td>
<td>Yes</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>15. Two-Lane Highways</td>
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<td>Yes</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>% time spent following</td>
</tr>
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<td>16. Urban Street Facilities and</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td></td>
<td></td>
<td>Stop Rate Running time</td>
</tr>
<tr>
<td>17. Urban Street Segments</td>
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<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
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<td>18. Signalized Intersections</td>
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<td>Yes</td>
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<td></td>
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<td>20. AWSC Intersections,</td>
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<td>Yes</td>
<td>Yes</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>21. Roundabouts</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>22. Interchange Ramp Terminals</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Level of Service

Level of service estimates are determined by applying thresholds to specified performance measures. When level of service is estimated from performance measures obtained from an alternative tool it is essential that the performance measure be determined in the same way that the HCM determines the same measure. Alternative tools that report a performance measure with the same name as the HCM, but with a different definition or method of computation should not be used to estimate the level of service for purposes of the HCM.

The principal determinants of level of service are density for most uninterrupted flow facilities and control delay for interrupted flow facilities. At this point, no simulation tools produce control delay values using the same definitions and method of estimation as the HCM. Most
simulation tools produce density values that are very similar to the HCM definition and method of estimation but might need some refinement based on vehicle trajectory analysis. It is important to note that the HCM applies level of service thresholds to performance measures that represent the peak 15 minutes of demand (i.e., arriving vehicles) and not necessarily the 15 minute period in which the performance measure produced its maximum value.

One consideration that makes simulation more compatible with the HCM in reporting level of service is the criterion that has been adopted by the Committee for most facilities that LOS F will be assigned to any facility that operates above its capacity. So, without the need for a detailed trajectory analysis, the presence of large queues at the end of the analysis period can be taken as an indicator that LOS F has been reached. On the other hand, when the purpose of the analysis is to develop a facility design that will produce a level of service better than F, the analyst must ensure that the performance measure on which LOS is based is estimated in a manner compatible with the HCM.

**Speed and Travel Time Related Measures**

Dowling [1] suggests that the common limitations on the estimation and use of speed and travel time measures include:

- **Difficult for a decision-maker to interpret** (no value of time is obviously too high or too low without knowing more about the trip characteristics).
- **Interpretation is facility specific.** Low speed may be quite acceptable on an arterial, but not on a freeway.
- **Once all vehicles come to a stop, the mean speed conveys no further information on the severity of congestion** (speed cannot go below zero).
- **Speed is a poor indicator of how close the facility is to breakdown** (capacity).

Speed and travel time are treated together because, at least for segment values, they are closely related (i.e., Average speed = Segment length / Travel Time).

**Definitions and Thresholds**

**Target Speed**

The target speed is the speed at which a specific vehicle would prefer to drive. This parameter is used in various ways in trajectory analysis. Different tools have different definitions of target speed. Some are driver and vehicle specific, taking into account driver aggressiveness and roadway conditions. Since target speed is an element of the model’s treatment of traffic flow, we must accept the developer’s definition, especially if the target speed is different for each vehicle. For models that require a user-specified free-flow speed (FFS) the alternative tool guidance in the HCM suggests that the HCM methodology should be used to determine the free flow speed.

The examples presented here used CORSIM-generated trajectories. CORSIM applies a driver type adjustment to a user-specified FFS to determine a target speed for each vehicle. The Default CORSIM adjustment factors have been used in these examples to determine the target speed of each vehicle.
Other Speed Thresholds

Some other speed thresholds must be applied during the analysis. To minimize the need for arbitrary thresholds, the speed range was divided into three classes with breakpoint thresholds at 1/3 and 2/3 of the target speed. The justification for the 2/3 value is found in the commonly applied rule that a vehicle is experiencing congestion when its travel time is greater than 1.5 times the travel time at the target speed (i.e., the speed is below 2/3 of the target speed). The justification of the 1/3 value is much weaker, but it provides three classes with identically spaced speed ranges. The three classes can then be described as:

- Uncongested, when the speed is above 2/3 of the target speed
- Congested, when the speed is between 1/3 and 2/3 of the target speed
- Severely constrained, when the speed is below 1/3 of the target speed.

Computational Procedures

Macroscopic segment travel estimation does not require a detailed trajectory analysis. The travel time for an individual vehicle may be computed for a given segment by subtracting the time at which the vehicle entered the segment from the time at which it left the segment. The average travel time may be computed as the arithmetic mean of the individual travel times, keeping in mind that this technique is only valid for complete trips (i.e., those that have entered and left the segment).

The average speed for all vehicles within the segment during the time period may be estimated by dividing the number of vehicle miles of travel by the number of vehicle hours of travel time. The total vehicle miles and vehicle hours may be accumulated by including all of the vehicles and time steps in the analysis domain. Please see the later discussion on spatial and temporal boundaries.

Queue Related Measures

Dowling [1] suggests that the common limitations on the estimation and use of queue measures include:

- Definition of when vehicle joins a queue and when it leaves a queue is a problem.
- Interpretation is road segment and facility-specific. Queues are normal for signals, but queues that overflow turn bays or block cross streets are not desirable.
- Tallying of queued vehicles unable to enter the road segment is an issue for many tools. Many tools cannot report a queue longer than the storage capacity of the road segment or turn bay.
- Tallying of vehicles that have not been able to enter the road network during the analysis period is an issue.
- Only one simulation tool will track the buildup of queues beyond the subject link, and none of them will track congestion beyond the temporal or geographic limits of the model. With one exception, the reported queue is, by definition, never longer than the storage capacity of the turn bay or the link. Thus, the analyst cannot rely upon the reported queue length to identify queue overflow problems. The analyst must find the upstream links and review the reported queues there.
Queue measures are defined and computed by the HCM for interrupted flow facilities. They are presented in terms of the percentile maximum queue length. It is a common design practice to base the length of storage lanes on a fixed percentile queue length.

The HCM measures are somewhat primitive compared to those that could be obtained from trajectory analysis. The HCM requires an assumed vehicle length and does not consider the extra space between moving vehicles that have not left the queue. Trajectory analysis can give an accurate estimate of the position of the back of queue at all times.

In addition to increased accuracy, there is also the potential for a more useful definition of measures from trajectory analysis. For example the proportion of time that a queue is backed up to or beyond a specific point might be a better measure than the simple probability of it reaching that point.

Definitions and Thresholds

Queued State

There are two questions here:

1. What defines the entry of a vehicle into a queue? The HCM definition given in Appendix A to Chapter 16 (HCM 2000) for purposes of field observations states that:

   A vehicle is considered as having joined the queue when it approaches within one car length of a stopped vehicle and is itself about to stop. This definition is used because of the difficulty of keeping precise track of the moment when a vehicle comes to a stop.

   The HCM definition could be incorporated into trajectory analysis, with a clarification of the “one car length” issue. A specified threshold spacing approximating one car length would have to be adopted, since simulation models assign lengths to each vehicle based on the vehicle type. There is also a potential problem in which the car following logic of a particular model might prevent some vehicles from reaching the threshold spacing. The HCM defines the “average queue spacing” as the “average length between the front bumpers of two successive vehicles in a stationary queue.” No guidance is given on the appropriate value except for the statement that “Average queue spacing can be determined according to the traffic composition.”

   The threshold spacing for simulation analysis must be defined with respect to the rear bumper of the leading vehicle because the established threshold based on the front bumper (as defined in the HCM) might not be reached when the leader is a long vehicle. A value of 20 ft will be applied to the computations described in this document.

2. What defines the exit of the vehicle from the queue? The HCM definition, intended for application to field studies, is more complex here:

   Vehicles in queue are those that are included in the queue of stopping vehicles as defined above and have not yet exited the intersection. For through vehicles, exiting the intersection can be considered to occur when the rear axle of a vehicle crosses the stop line. For turning vehicles, exiting from the intersection occurs the instant a vehicle clears opposing through traffic or pedestrians to which it must
yield and begins accelerating back to free-flow speed. Note that the vehicle-in-
queue count often includes some vehicles that have regained speed but have not
yet exited the intersection.

This definition offers some interesting challenges for trajectory analysis. It presents
problems for simulation developers with respect to the development principles proposed
earlier in this discussion. It also presents some inconsistencies with the HCM procedures
for determining control delay and queue lengths. Because of their vertical stacking
nature, neither of those procedures recognizes queuing and delay that occur within the
intersection. As a practical approximation, a vehicle should be considered to have left the
queue when it has left the link in which it entered the queue. There are other conditions
that might signal the exit from a queue that will be discussed later and incorporated into
the computational procedures.

Queue Length
Queue length estimation is generally required to determine whether a queue has reached the
point where it will interfere with other traffic movements. The size of the queue can be specified
in terms of the number of vehicles in the queue or the distance of the last vehicle in the queue
from the stop line (aka back of queue or BOQ). While queuing is a phenomenon that is common
to all facilities, quantitative queue length measures are only computed in the HCM for
interrupted flow facilities. Queuing on uninterrupted flow facilities is generally the result of
oversaturation caused by excessive demand or by bottlenecks.

The probability of the BOQ reaching a specified point at which it will cause problems presents
the most interest to the analyst. The HCM computes the maximum BOQ for a range of
percentile values between 70% and 98%. Using the definition of a queued state given above,
trajectory analysis could be used to produce values that are compatible with the HCM
definitions. Queue length is one of the most promising areas for trajectory analysis.

Simulation modeling can report more accurate values of instantaneous queue length because the
BOQ is observable as a point in space at all times. Simulation models recognize the length of
each vehicle in the queue explicitly in determining the BOQ. They also recognize the increased
spacing between vehicles that occurs when a portion of a long queue is in a “move up” process.
The HCM deals in a macroscopic (and therefore more approximate) estimate of queue length.
The HCM procedure starts by computing maximum number of vehicles that will be in the queue
on an “average” cycle. It then adds an adjustment factor to account for randomness in the
number of arrivals per cycle. Finally, the queue length is converted to distance by assuming an
“average queue spacing in a stationary queue, Lₜ.”

The average spacing is a user determined quantity. A default value of 25 ft per vehicle is
provided in the HCS implementation of the HCM 2000 Chapter 16 procedure. This value
appears to be somewhat consistent with CORSIM for passenger cars. It should be noted that,
while the definitions may be compatible, the BOQ values produced by simulation modeling are
likely to be significantly different than the HCM because of differences in the manner in which
moving vehicles are propagated throughout the length of the queue.
Some simulation tools now report queue size in terms of the number of vehicles in the queue and not the BOQ position. For HCM compatibility, the BOQ position is the essential measure. More specifically, the analyst is interested in the probability that the BOQ will reach a certain point.

An instantaneous value for the BOQ may be determined at any point in time from the position of the last queued vehicle, using the queue state definition given previously. The question is how to aggregate a vector of these instantaneous values into a useful performance measure.

We must now distinguish between the probability of queue backup to a certain point and the proportion of time that the queue is backed up to or beyond that point. The HCM deals in the probability of queue backup as computed by deterministic equations. Useful estimates of the probability of queue backup by simulation require a detailed analysis of many replications. Consider, for example a 15 minute analysis period at a signalized intersection with a 120 sec cycle. This situation would cover 7.5 cycles, with the maximum BOQ determined for each cycle. Seven observations would not produce a useful measure, so a much longer analysis period would be required.

Simulation models are also able to estimate the proportion of time that a queue exceeds a specified length. This is probably a more useful measure to analysts for most purposes, but it is not HCM–compatible. The concept deserves further consideration in the guidance.

Queue length analysis by simulation must be treated differently for different conditions. There are three cases to consider:

1. **Undersaturated non-cyclical operation**, typical of the operation with isolated two-way stop control (TWSC): In this case, the queue accumulation and discharge will follow a more or less random pattern. The HCM estimates the 95\(^{th}\) percentile TWSC queue length based on a deterministic average queue length modified by a term that accounts for random arrivals. This process could be approximated by establishing a distribution of instantaneous queue length by time step. The 95\(^{th}\) percentile queue length could be determined from this distribution.

2. **Undersaturated cyclical operation**, typical of the operation at a traffic signal: In this case, a maximum BOQ will be associated with each cycle, with a reduction in the queue length indicating the beginning of a new cycle. The use of a distribution of instantaneous values would not be appropriate here because the queue accumulation and discharge is much more systematic than random. Including instantaneous queue lengths that occur when the queue is expected to be zero (i.e., at the end of the green) would underestimate the measure of interest, which is the peak queue length.

With a sufficient number of cycles a distribution of peak queue lengths with a mean value and a standard deviation could be established. The probability of queue backup to any point could then be estimated from this distribution.
3. **Oversaturated operation**: either cyclical or non-cyclical. When demand exceeds the capacity of an approach or facility, the queue will grow indefinitely. For purposes of simulation, the measure of interest is the residual BOQ at the end of the simulated interval.

The HCM suggests that traffic composition should be considered in the determination of average queue spacing. It appears that the default value of 25 ft assumes zero percent trucks. As a future task, some guidance could be developed from trajectory analysis for the determination of $L_h$ in HCM analyses to promote comparability with other tools.

**Queue Delay**

Please see the discussion of queue delay under the heading of *Delay Related Measures.*

**Computational Procedures**

Combining the definitions and thresholds specified above with other necessary criteria, the following set of conditions describes the procedure for determining when a vehicle has entered and left a queue. Note that the HCM suggests that for purposes of control delay estimation, the vehicle should be considered to remain in the queue until it leaves the link.

VTAPE experience has shown that other conditions need to be applied to supplement this main premise. The additional conditions cover situations in which, for example, a vehicle escapes a queue by changing lanes into an uncongested lane (e.g., through-vehicles caught temporarily in a turn bay overflow). In addition, vehicles may be released from a queued state on a freeway when the backward wave that caused the queue has dissipated.

**Determination of Queued State**

The computational procedure for determining whether a vehicle is in a queued state on any time step is described in Exhibit 28.

**Back of Queue Estimation**

The BOQ on any time step is determined by the position of the farthest upstream vehicle that is in the queued state. A procedure for determining the BOQ is given in Exhibit 29.
Exhibit 28: Procedure for Identifying a Queued State

Beginning of the queued state will occur when:

- The gap between a vehicle and its leader ($< \text{ or } =$) 20 ft; AND
- The vehicle speed ($> \text{ or } =$) the leader speed; AND
- The vehicle is severely constrained; i.e., speed ($< \text{ or } =$) 1/3 of the target speed.

If the link is controlled (interrupted flow case) the beginning of the queued state will also occur when:

- No leader is present on the link; AND
- The vehicle is within 20 ft of the stop line; AND
- The vehicle is decelerating OR it has stopped

End of queued state will occur when:

- The vehicle has left the link; OR
  - The vehicle has left the congested state (i.e., reached 2/3 of the target speed); AND
  - The leader speed ($> \text{ or } =$) than the vehicle speed; OR
  - The vehicle has no leader in the same link

Exhibit 29: Instantaneous Back of Queue (BOQ) Computational Procedure

(Appplies to links with traffic control at the downstream end)

Determination of queued state:
Set a “queued” flag for each vehicle when it enters the queue by the definition given previously. Reset the flag when the vehicle leaves the queue by the same set of definitions.

Loop for determination of instantaneous back of queue, BOQ(t), Initialize BOQ to zero
Start with the vehicle at the downstream end of the link and move upstream:

- If queue flag is set then BOQ (t) = Distance from the vehicle to the stop line + Vehicle length
Loop until last vehicle on the link has been processed

Increment BOQ distribution parameters
  - Sum, Sum of Squares, Sample Size
Stop Related Measures

Dowling [1] suggests that the common limitations on the estimation and use of stop-related measures include:

- **Definition of the minimum speed threshold for a stop is a stop is an issue.**
- **Since tallying of stops is normally suspended while a vehicle is moving up within a queue, the definition of a queue is an issue.**
- **Once all vehicles are queued on a road segment, further increases in congestion have no effect on stops.**

The HCM does not define or produce estimates of the number of stops, so HCM compatibility is not an issue. Most alternative tools based on both deterministic and simulation models produce an estimate of the number of stops by their own definition and most allow user specified values for the parameters that establish the beginning and end of a stop. The analysis of stops might be an issue that is best left to the alternative tool developers.

Taking a more intrepid approach, stop-related measures are of interest to analysts because of their comfort, convenience, cost and safety implications. It would therefore be useful to provide guidance to developers on standardization of stopping measures based on vehicle trajectories.

Since the number of stops is a measure of interest to the analyst, it is important to define the conditions under which the return to a stopped state constitutes another stop. No guidance of any type is provided in the HCM, and the number of stops is not generally observed in stationary field studies. Most simulation tools and moving vehicle studies define the release from a stopped state in terms of a threshold speed. Different speeds are used by different tools and some tools allow a user-specified threshold. Given the lack of guidance here, we will have to seek a consensus on the appropriate threshold.

Definitions and Thresholds

**Stopped State**

The definition of when a vehicle is stopped has the same two elements as the definition of when it is queued; i.e., when does the stop begin and when does it end? The HCM does not offer a definition for either of these conditions. The definition most consistent with the HCM and with field observations would apply the same conditions that determine when the vehicle has entered a queue. Since the queue entry definition stated in the HCM attempts to identify the point at which the vehicle stops, it should be the most suitable for this purpose.

Speed thresholds are often used to determine when a vehicle is “stopped.” The only non-arbitrary threshold for this purpose is zero. Practical considerations suggest, however that algorithms that deal with stopping would be more stable if a near zero speed was used instead. A speed of 5 mi/hr has been used in the procedural chapters of the HCM for determining when a vehicle has stopped. For consistency, the same threshold will be used here.
Release from Stopped State

There are two different modeling purposes for releasing a vehicle from the stopped state:

- To terminate the accumulation of stopped delay
- To enable the accumulation of subsequent stops.

The first is easier to deal with in the trajectory analysis. When the vehicle is no longer stopped, it should no longer accumulate stopped delay. The logical speed threshold for this condition is the same speed threshold that established the beginning of the stop.

The second is somewhat more complex and requires some discussion: The conventional approach assigns an arbitrary and sometimes user-specified threshold value to this speed. There is no basis for the HCM to choose an arbitrary speed for this purpose. On the other hand, the level of detail provided by vehicle trajectory analysis could support the development of new and useful measures.

The disutility of a stop depends heavily on the speed from which it is made. A stop from 40 mph is much worse than a stop from 15 mph, which is a common “end of stop” threshold. It is desirable that the definition of a stop should recognize the disutility. One piece of information available from the vehicle trajectory is the maximum speed attained since the last stop. One possibility would be to use this speed in determining the disutility.

Number of Stops

The degree of disutility of a subsequent stop should be based on kinetic energy loss, which is proportional to the square of the speed. A stop from the target speed should count as one full stop. A stop from a lower speed could be reduced in proportion to the square of the speed. In other words, a stop from half the target speed would count as a quarter of a stop. The stops could be accumulated over a link to provide a useful performance measure. This is an excellent example of how vehicle trajectory analysis could be used to improve performance measures in terms of both definition and accuracy. On the other hand, it might be too “far out” for the world to accept. For what it’s worth, a computational procedure for this approach will be presented.

Taking a more arbitrary and simplistic view we could revert to the three-class speed range identified earlier. Subsequent stops after the speed exceeded 1/3 of the target speed (the upper threshold of heavily constrained operation) could be assigned ½ of a stop, with a full stop being assigned after the vehicle reached 2/3 of the free flow speed into the “uncongested range.

It is worth noting that some deterministic models, such as Transyt-7F, produce estimates of the number of stops but these estimates are based on a different definition of a stop. Transyt-7F first computes the probability of stopping on a signalized approach analytically and then multiplies this probability by the approach volume. By this definition, the number of stops cannot exceed the approach volume. In other words multiple stops are not recognized. Conversely, the stop model in SIDRA recognizes the possibility of multiple stops.

Stopped Delay

Please see the discussion of stopped delay under the heading of Delay Related Measures.
Computational Procedures

The computational procedure for dealing with the proportional stop concept mentioned above is described in Exhibit 30:

Exhibit 30: Computational Procedure for Determining the Number of Stops

- Each time a vehicle speed drops below 5 mi/hr, the number of stops will be incremented by the square of (Maximum speed attained since the last stop / Target speed)
- The maximum speed since the last stop will be reset to the target speed when the speed reaches the uncongested speed range at 2/3 of the target speed.

Experience with VTAPE suggests that the target speed is slow to be attained after a stop in heavy traffic. As a practical matter, it was found that resetting the max attained speed to the target speed when it reached the uncongested state (2/3 of the target speed) produces more credible total stop estimates. Without this additional condition, it is very difficult to obtain a stop rate greater than 1.0 on congested links.

Delay Related Measures

Dowling [1] suggests that the common limitations on the estimation and use of delay measures include:

Definition of free-flow speed, against which delay is measured, is a problem. Some use the posted speed limit for the free-flow speed; others use the mean speed under very low flow conditions (can be higher or lower than the posted speed limit).

Definitions and Thresholds

Reference Speed

Delay is generally defined as the excess time spent on a road segment compared to a reference time or speed that represents a zero-delay condition. The time actually spent on the segment by a vehicle is easy to determine from its trajectory. On the other hand, the reference time is subject to a number of definitions:

- Travel time at ideal speed: usually the speed limit or free flow speed.
- Travel time at the individual vehicle’s desired speed, which is a function of prevailing roadway and traffic conditions and the driver’s characteristics.
- Travel time at 10mph below speed limit: This time is used in Florida to determine whether a trip is “on time” for travel time reliability reporting. This measure defines “on-time delay.”
- Travel time at a specified “travel time index:” The travel time index is the ratio of the actual travel time to the ideal travel time. It is used primarily for reporting congestion in the nationwide mobility monitoring project. A travel time index of 1.5 has been suggested as an indication of congestion. This measure defines “congestion delay.” It is an indicator of the need for roadway improvements.
• Travel time without traffic control: This measure defines “control delay.” Unlike the previous measures, which are applied to an entire segment, control delay is applied only to the portion of the segment in which a queue is present. So control delay is a subset of segment delay. The definition applies uniformly to signals, stop signs and roundabouts.

In all cases, a lower limit of zero must be imposed when the actual travel time is shorter than the reference time.

When the reference speed is below the ideal speed, the definitions may be applied macroscopically to the entire segment or microscopically in each time step by simulation models. The results will be different if there are locations within a segment at which the speed of a vehicle falls below the reference speed, even though the overall segment travel time is less than the reference time. The HCM accommodates only the macroscopic application. For compatibility, it would therefore appear that simulation models should also use a macroscopic application. On the other hand, the results of a microscopic application, while not strictly HCM compatible, could provide a better insight into the operation of a facility.

Aggregated Delay vs. Unit Delay

It is important to note the difference between aggregated delay, usually expressed in vehicle-hours and unit delay, usually expressed in seconds per vehicle. Aggregated delay is generally used to assess the operating costs associated with a candidate treatment, because an economic value can be assigned to a vehicle hour of delay. Unit delays are associated with driver perception of the level of service on a facility. Note that, for these two definitions to be dimensionally consistent, the unit delays must actually be expressed in \(\text{vehicle-seconds per vehicle}\). It is common practice, however, to shorten the definition to \(\text{seconds per vehicle}\) to promote public understanding.

Delay Definitions

All models, including the HCM procedures for interrupted control, produce estimates of what they call “delay” but there is some variation in their definitions. Several delay definitions are offered here in terms of vehicle trajectories, based on longitudinal trajectory analysis. In all cases, the delay is determined for each time step and accumulated over the entire time that the vehicle was in a specified link.

Time Step Delay

The delay on any time step is, by definition, the length of the time step minus the time it would have taken the vehicle to cover the distance traveled in the step at the target speed. This is easily determined.

Segment Delay

Segment delay is represented by the time actually taken to traverse a segment minus the time it would have taken to traverse the segment at the target speed. The segment delay on any step is equal to the time step delay. Segment delays accumulated over all time steps in which a vehicle is present on the segment represent the segment delay for that vehicle.
Queue Delay
The queue delay is equal to the time step delay on any step in which the vehicle is in a queued state, otherwise it is zero. Queue delays accumulated over all time steps represent the time actually taken to traverse the link minus the time it would have taken to traverse the link at the target speed while the vehicle was in a queue.

Stopped Delay
The stopped delay is equal to the time step delay on any step in which the vehicle is in a stopped state, otherwise it is zero. Since a vehicle is considered to be “stopped” if it is travelling less than 5 mph, a consistent definition of stopped delay requires that the travel time at the target speed be subtracted. Time step delays accumulated over all time steps in which the vehicle was in the stopped state represent Stopped delay. Note that earlier versions of the HCM defined stopped delay as 76% of the control delay based on empirical data.

HCM Control Delay
In keeping with the approximation of control delay given in the HCM, the control delay in any step is the length of the time step (without subtracting the travel time at the target speed) on any step in which the vehicle is in a queued state, otherwise it is zero. Control delays accumulated over all time steps represent the time actually spent in the queue. Control delay by the HCM definition is computed from trajectory analysis can produce misleading results.

Representation of Delay by Vehicle Trajectories
Exhibit 31 illustrates the various ways in which delay may be defined.

There are three points defined on this figure.
- \( T_0 \): The time at which a vehicle would have arrived at the stop line if it had been traveling at the reference speed.
- \( T_1 \): The time at which a vehicle would have arrived at the stop line if it had been traveling at the “running” speed. The running speed is generally less than the reference speed because of traffic interactions.
- \( T_2 \): The time at which a vehicle is discharged at the stop line.

The delay measures defined in terms of the time differences shown on Exhibit 31 include:
- Control delay: defined as \( T_2 - T_1 \). This is the delay definition used by the procedure for assessing level of service at controlled intersections and roundabouts.
- Segment delay, defined as \( T_2 - T_0 \). This definition is more commonly used by simulation tools. It reflects the delay experienced by each vehicle since it left the upstream node (usually another signal). Segment delay includes the control delay plus all of the other delay due to traffic interactions.
Exhibit 31: Definition of delay terms in time and space

- **Stopped Delay**
- **Queue Delay**
- **Control Delay**
- **Segment Delay**

<table>
<thead>
<tr>
<th>Time</th>
<th>Distance</th>
</tr>
</thead>
<tbody>
<tr>
<td>T₀</td>
<td></td>
</tr>
<tr>
<td>T₁</td>
<td></td>
</tr>
<tr>
<td>T₂</td>
<td></td>
</tr>
</tbody>
</table>
In addition to these two precisely defined delay terms, there are two other delay definitions shown in Exhibit 31 that are based on more complex properties of the vehicle trajectories:

- Stopped delay, which reflects the amount of time that a vehicle was actually stopped. The beginning and end of a stop is generally based on speed thresholds, which may differ among tools. In some cases the threshold speeds are user-definable.
- Queue delay, which reflects the amount of time that a vehicle spends in a queued state. The properties of the trajectory that define a queued state in different tools include speed, acceleration, spacing and number of vehicles sharing these properties.

For simulation tools that report total segment delay but do not report control delay explicitly, it is possible to produce approximate estimates of control delay by performing simulation runs with and without the control device(s) in place. The segment delay reported with no control is the delay due to geometrics and interaction between vehicles. The additional delay reported in the run with the control in place is, by definition, the control delay. For short segments with low to medium volumes, the segment delay will usually serve as an approximation of the control delay.

The development of control delay estimates by a multiple run procedure is primarily of academic interest because of the amount of effort involved. The objective at this point is to develop a specification for estimating control delay from vehicle trajectories that may be internalized by simulation model developers to produce HCM-compatible results.

**Computational Procedures**

The procedures for computing delay from vehicle trajectories involve the aggregation of all delay measures over each time step. Therefore, the results take the form of aggregated delay and not unit delay, as defined earlier. To determine unit delays, the aggregated delays must be divided by the number of vehicles involved in the aggregation. Partial trips made over a segment during the time period add some complexity to the unit delay computations.

The development of a specification for an algorithm to produce HCM-compatible control delay estimates from vehicle trajectories requires a closer look at the differences in how the HCM and typical simulation tools model the vehicle trajectories. Exhibit 31 demonstrated how various types of delays may be defined in terms of vehicle trajectories. The HCM procedures don’t deal explicitly in vehicle trajectories. Instead they use an approximate formulation represented by the area of the triangle shown superimposed on the trajectory plot shown in Exhibit 10, which assumes that all arrivals have a completely uniform spacing. The area of this triangle is equivalent to the uniform delay, $d_1$, of the HCM’s three component delay formulation. The reasons why this formulation is incompatible with trajectory analysis are illustrated in the four exhibits immediately following Exhibit 10. Exhibit 32 summarizes the incompatibilities.
Exhibit 32: Incompatibilities between the HCM delay formulation and trajectory analysis.

<table>
<thead>
<tr>
<th>Exhibit</th>
<th>Situation Depicted by Trajectory Plots</th>
<th>Incompatibility with the HCM Delay Formulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>Random arrivals</td>
<td>A different (d_i) triangle applies to each cycle</td>
</tr>
<tr>
<td>12</td>
<td>Cycle failure</td>
<td>The same vehicle appears in multiple (d_i) triangles</td>
</tr>
<tr>
<td>13</td>
<td>Oversaturation</td>
<td>No (d_i) triangle exists</td>
</tr>
<tr>
<td>14</td>
<td>Overflow from downstream link</td>
<td>Overflow vehicles are not recognized in the (d_i) triangle.</td>
</tr>
</tbody>
</table>

The HCM delay formulation introduces correction factors in other delay components that are indented to address these incompatibilities. The corrections have no relationship at all to individual vehicle trajectories, thereby making the formulation even less compatible with trajectory analysis. The point of this discussion is that, while the HCM delay formulation has been demonstrated to be a reasonable representation of field conditions, it is not possible to produce compatible estimates of control delay by analysis of simulated vehicle trajectories.

One of the problems of the HCM deterministic delay formulation is that it does not distinguish between stopped delay, queue delay and control delay. The question of stopped delay was addressed by in the 1985 HCM by introducing an adjustment factor of 0.76 to the control delay estimates, based on the results of field observations. Stopped delay has been removed from recent editions. Queue delay has never been defined mathematically by the HCM.

The computational procedures for estimating the various types of delay are presented in Exhibit 33.

Density Related Measures

Dowling [1] suggests that the common limitations on the estimation and use of density measures include:

- *Once all vehicles are queued, then further increases in congestion have no effect on density.*

Density is one of the easiest measures to compute from vehicle trajectories because it involves simply counting the vehicles in a section of roadway at a specific time. The question is how to apply density to the right section of roadway over the right period of time.

Definitions and Thresholds

Density is expressed in terms of vehicles per mile per lane and is generally recognized as an unambiguous indicator of congestion. The HCM defines level of service for uninterrupted flow in terms of density thresholds, sometimes applying the thresholds to specific lanes. Because of the importance of density as a determinant of LOS, we should try to establish trajectory analysis procedures that are compatible with the HCM so that simulated densities can be used for LOS estimation. On the other hand, trajectory analysis could produce density-based performance measures that would be more useful than the HCM by establishing the temporal and spatial characteristics of density on a facility.
Density can be determined microscopically by simulation using a simple equation that relates density to the spacing of vehicles:

\[
\text{Density (veh/mi/lane)} = \frac{5280}{\text{Spacing (ft)}}
\]

Density can also be computed macroscopically at the segment level by simply counting the number of vehicles present on the segment during a particular time step. The densities by time step may be aggregated over an analysis period by computing the arithmetic mean of the time
step densities. This method of measurement and aggregation should produce density values that are compatible with the HCM in both definition and computation, provided that the demand does not exceed the capacity. For v/c ratios >1, the density at the end of the analysis period is generally of more interest than the average density.

Density is computed on a per-lane basis by VTAPe using the Spatial Analysis feature described previously. The combined density for Lanes 1 and 2 is also computed because of its application to freeway merging situations.

**Percent Time Spent Following**

Dowling does not address the limitations on the estimation and use of percent time spent following. The HCM definition of the “following” state (headway < 3 sec) was mentioned earlier. Developers who are building two lane roadway analysis capabilities into simulation programs should be encouraged to adopt the HCM definition. Given this definition, the percent time spent following could be computed simply by determining the proportion of time steps in which a vehicle was following its leader by less than 3 seconds.
Signalized Approach Analysis Example

A simple approach to a signalized intersection (See Exhibit 9, presented earlier) was converted to a two lane approach with a length of 2000 ft. A ten minute (600 sec) analysis period was used. The cycle length was 60 sec, giving 10 cycles for inspection. The analysis period would normally be longer but ten minutes is adequate for demonstration purposes.

Trajectory Plots

The trajectory for the entire 10 cycles is shown Exhibit 34. Note that the individual trajectory lines become less visible as the analysis proceeds because of Excel’s assignment of different styles to each line to distinguish one line from another. An expanded view of a couple of cycles is shown in an inset.

Two other longitudinal analysis plots are shown in Exhibit 35. The first shows the trajectories of two vehicles where the progress of the subject vehicle is constrained by its leader. The second shows the speed and acceleration profiles for the subject vehicle.
Subject Vehicle and Leader Vehicle Trajectories

Leader

Subject vehicle

Time (sec)
Distance (ft)

Exhibit 35: Example trajectory analysis plots

Speed and Acceleration profiles

- Speed
- Acceleration
Analysis of Stops
The two main stop related measures are number of stops and stopped delay. The beginning of a stop is defined in the same way for both measures. A range of threshold speeds is in current use and most tools provide for user specified values. Elimination of user specified values is an important element of standardization. The only non-arbitrary threshold for a stop is zero speed, which is, in itself the definition of a stop. Experience with VTAPE on a few examples suggests that a speed that is nearly zero may produce a more stable result. The current version uses a threshold of mi/hr to maintain compatibility with other HCM analysis procedures.

The end of a stop is treated differently for stopped delay and number of stops. For stopped delay, the end of stop is established as soon as the vehicle starts to move. For determining the number of stops, some hysteresis is required. Most models use a speed threshold to determine the number of stops. This technique introduces an arbitrary element of the type that we are trying to avoid. The HCM offers no guidance on estimating the number of stops.

An example of the analysis of a single vehicle selected from the entire trajectory plot is shown in Exhibit 36. Note that the total stop value was 1.81 because the second stop was made from a lower speed.
Queuing Analysis
The HCM offers the following guidance on the estimation of queue length:
1. The maximum queue reach (i.e., back of queue, or BOQ) is a more useful measure than the number of vehicles in the queue, because it is the BOQ that caused blockage of lanes. As shown previously, the maximum BOQ is reached when the queue is about to dissipate (i.e., has zero vehicles).
2. A procedure is prescribed to estimate the maximum back of queue on a signalized approach at various probability levels.

Because of its macroscopic nature, the HCM queue estimation procedure cannot be applied directly to simulation. On the other hand, simulation can produce more useful measures because of its higher level of detail. We have already dealt with the first step in queue length determination by setting up the rules for determining the conditions that indicate when a vehicle is in a queue. The next step is to determine the position of the last vehicle in the queue.

The BOQ on any step is a relatively simple thing to determine. The trick is to figure out how to accumulate the individual BOQ measures over the entire period. There are several measures that can be produced.
1. The maximum BOQ at some percentile value, say, 95%
2. The maximum BOQ on any cycle at some percentile value, say, 95%
3. The historical maximum BOQ (i.e., the longest queue recorded during the period)
4. The probability that a queue will back up beyond a specified point
5. The proportion of time that the queue will be backed up beyond a specified point

It is important to distinguish between Conditions #1 and #2 above. For the #1 condition the individual observation is the BOQ on any step. So the sample size is the number of steps covered (600 in this case). For the #2 condition, the individual observation is the maximum BOQ on any cycle, so the sample size is the number of cycles (10 in this case). The HCM definition is based on the #2 condition.

Exhibit 37 illustrates the queue length per step on the signalized approach over all of the time steps in the period. Note that the ten cycles are discernable on this figure. Note also that a considerable variation in the cyclical maximum BOQ is evident.

A statistical analysis showing the per lane values of the average BOQ, the 95 percentile BOQ (based on 2 standard deviations past the average value) and the historical maximum BOQ is also presented on this figure. One important question is whether the 95% BOQ can be represented statistically based on the standard deviation, assuming a normal distribution. The BOQ histogram shown on Exhibit 38 does not support any assumed analytical distribution, however the relationship between the 95% BOQ and the historical maximum appears to be reasonable for this example.
It is also worth noting that the queue length on an isolated approach that is near saturation should have a uniform distribution (i.e., equal probability of all lengths between zero and the maximum). The standard deviation of a uniform distribution is greater than ½ of the mean, so the 95th percentile estimator (mean value plus 2 standard deviations) will be greater than the maximum value. This raises some doubt about the validity of basing the 95 percentile BOQ on the standard deviation, especially with cyclical queuing.
Delay Analysis for a Single Trajectory

A comparison of the accumulated delay by all definitions for a single vehicle trajectory is presented in Exhibit 39.

The relationships appear to be reasonable in this figure, but the concept of control delay, as defined in the HCM disintegrates at v/c ratios above 1.0. It is clear that, by the HCM definition, the control delay will approach the entire time spent in the segment and eventually become greater than the segment delay. This situation violates the concept of control delay as a subset of segment delay.
Delay Analysis for all Vehicles on the Segment

The preceding example dealt with accumulated delay of a single vehicle traversing the segment. A useful delay measure requires the accumulation of delay to all vehicles traversing the segment during the period. VTAPE is able to produce such an analysis. An example is shown in Exhibit 40. Note that, in keeping with Dowling’s recommendations, only vehicles that traversed the entire link during the period are included in this analysis. Therefore the number of vehicles analyzed (210) is lower than the number of vehicles that were actually on the link during the period (286).

286 vehicle tracks in the period.
210 vehicles entered and left the link during the period.

<table>
<thead>
<tr>
<th>Lane</th>
<th>Segment</th>
<th>Queue</th>
<th>Control</th>
<th>Stop</th>
<th>No. of Stops</th>
</tr>
</thead>
<tbody>
<tr>
<td>-</td>
<td>Delay</td>
<td>Queue</td>
<td>Control</td>
<td>Stop</td>
<td>No. of</td>
</tr>
<tr>
<td>1</td>
<td>3128</td>
<td>2562</td>
<td>2879</td>
<td>1957</td>
<td>95.408</td>
</tr>
<tr>
<td>2</td>
<td>3400</td>
<td>2793</td>
<td>3158</td>
<td>2047</td>
<td>96.158</td>
</tr>
<tr>
<td>Total</td>
<td>6529</td>
<td>5355</td>
<td>5860</td>
<td>4004</td>
<td>191.566</td>
</tr>
<tr>
<td>Average</td>
<td>31.09</td>
<td>25.50</td>
<td>27.91</td>
<td>19.07</td>
<td>0.91</td>
</tr>
</tbody>
</table>

Exhibit 40: Delay analysis for all vehicles on a segment

Unsignalized Approach Analysis Example

A supplemental example for an urban street facility was presented in Chapter 29. The original configuration involved five signalized intersections as shown in Exhibit 41. That configuration was subsequently modified to change the control at the center intersection (Intersection 3) to two way stop control (TWSC). The cross street volumes were reduced to a level at which they could be accommodated under TWSC.

Exhibit 41: Arterial street layout for the unsignalized approach example

The signal offsets at the adjacent intersections were manipulated to create three different arrival profiles on the arterial:
- Simultaneous arrival of the platoons from both directions
- Alternating arrival of the platoons from both directions
- Isolated operation, in which the adjacent signals had no effect on the arrival profiles.
The other examples presented in Chapter 29 used the native outputs of the various tools to illustrate performance measures. The TWSC example, on the other hand applied vehicle trajectory analysis using VTAPE and is therefore of interest to this discussion. The discussion in the signalized example focused on instantaneous BOQ in an effort to understand the general nature of queuing under the conditions that were examined. With knowledge of the instantaneous BOQ values available from simulation, it is possible to produce useful performance measures related to queuing. One such measure is the proportion of time that a queue would be expected to back up beyond a specified point (PTQB). This concept is different than the probability of backup to that point normally associated with deterministic tools.

The three arrival profiles created in this example were simulated with cross street demand volumes of 80, 160, 240, 320, and 400 veh/h and (PTQB) characteristics were determined by simulation for each case. The results were plotted for a specified distance of 100 ft from the stop line as shown in Exhibit 42. Each case is represented by a separate line that shows the percentage of time that the queue would be expected to back up beyond 100 ft from the stop line for each cross street entry demand volume level. The simultaneous platoon case showed the lowest PTQB levels, starting with no time with BOQ beyond 100 ft below 240 veh/h and reached a value of 80% of the time at the maximum volume of 400 veh/h. Predictably, the isolated case was the most susceptible to queue backup and the alternating platoon case fell somewhere in between.

Exhibit 42: PTQB values for three arrival profiles based on 100 ft. queue length
The preceding discussion on this example was presented in HCM Chapter 29. The remainder of the discussion is presented here to provide additional detail on the trajectory analysis results.

There are some counterintuitive results in this exhibit that require further explanation. It might be expected that the isolated case would have the smallest time with BOQ>100, followed by simultaneous platoons, then alternating platoons. The isolated case showed a greater proportion of time with BOQ>100 ft than the simultaneous case because it had a lower capacity for the TWSC movement. The higher BOQ percentages were the result of oversaturated operation with isolated control at demand volumes that could still be accommodated by simultaneous platoons.

The isolated case had approximately the same capacity as the alternating platoon case. It reached 100% PTQB for 100 ft. at lower demand volumes because of the cyclical effect of progression. The queue built up more steadily in the isolated case and when it reached 100 ft it stayed there. In the alternating case it eventually reached 100% but there existed a period of time in which the BOQ would fluctuate between >100 ft and < 100 ft. During this period, the average BOQ was probably about the same for both cases but the cyclical nature of the alternating case created brief intervals when the BOQ was less than 100 feet.

The results in Exhibit 42 deal with a fixed threshold of 100 ft. The analysis can be expanded to consider the PTQB characteristics with any assumed threshold. Exhibit 43 examines the PTQB for a range of 25 to 250 ft. The three progression cases are reflected in three separate figures:

- With simultaneous platoons, the PTQB below 75 ft was negligible at demand volumes below 320 vph. An increase was evident at higher demand levels but it only reached 100% for very short queue lengths at the highest level.
- With alternating platoons, the PTQB increased more rapidly with demand. It reached 100% for all queue lengths at the highest demand level.
- With isolated operation, the increase was more evident. The PTQB was much higher for all demand levels.

It is suggested that The PTQB provides more useful information for design purposes than the probability of the BOQ reaching a specified point. At high volume levels, the probability can be quite high, even for long queues. Based on probability a design would typically fail at a probability of 5%. On the other hand, the proportion of time that the queue exceeds specified limits might not indicate a severe problem. The probability approach is a legacy from deterministic models. The PTQB is an example of a useful performance measure that can be obtained by trajectory analysis. Very little is known about the relationship between these two approaches. Additional research would be useful in this area.
Exhibit 43: PTQB values for three arrival profiles for a range of queue lengths
Freeway Analysis Examples

A performance analysis of the freeway merge area originally shown in Exhibit 19 is presented here. A single vehicle was selected from the trajectory plot and its trajectory was analyzed. The results are shown in Exhibit 44. Note that the analysis produced segment delay and queue delay. This was a very congested segment as indicated by the trajectory plot. No stopped delay was produced because the vehicle never actually came to a stop (i.e., its speed stayed above 5 mi/hr). No control delay was produced because this was an uninterrupted flow segment.

Exhibit 44: Longitudinal analysis of delay for a selected vehicle in a merge area

A spatial analysis of the entire segment was also performed to produce the following measures by lane:

- Average Density over the segment
- Percent Slow Vehicles (i.e., traveling at less than 2/3 of the target speed)
- Percent Queued Vehicles
- Average Queue Length (measured from front of queue to back of queue)
- Average Back of Queue position
- Maximum Back of Queue position
- Percent of time steps when the queue overflowed the segment

The results are presented in Exhibit 45.
The results are presented by lane and are combined for lanes 1 and 2 for compatibility with the HCM definition of merge area density. Note that Lane 9 (rightmost column on the table) is the acceleration lane, in accordance with CORSIM’s lane numbering scheme.

**Other Analysis Examples**

Appendix 2 of this report shows a sample application to a case study that compares the macroscopic model of the HCM 2010, as implemented in FREEVAL with the microscopic simulation approach of CORSIM. Vehicle trajectory plots were used to provide insight into the simulation of an incident with an advance warning sign. They were also used to illustrate the formation of shock waves that can be created at high demand levels by adjusting the car following sensitivity parameters. An example of a backward moving shockwave is illustrated in Exhibit 46.

![Exhibit 46: Example of backward moving shock wave trajectories](image-url)
An additional example is presented in Appendix 3 of this report. It was demonstrated that trajectory analysis can be used to analyze the process by which one vehicle overtakes a slower moving vehicle on a two lane highway. Exhibit 47 shows the simulated speeds of the leading and following vehicles during a passing maneuver. It demonstrates that the follower maintains a higher speed until it must slow down to match the leader’s speed. During the passing maneuver, the follower’s speed increases and the leader’s speed drops to zero because there is no leader in the oncoming traffic lane. At the conclusion of the maneuver, the passing vehicle’s speed decreases as it acquires a new leader in the normal travel lane.

![Exhibit 47: Simulated speeds during a passing maneuver](image-url)

A trajectory based example was also presented in Appendix 1 of this report to illustrate the effect of progression quality on the movement of individual vehicles along an arterial route.

**Summary and Closure**

This discussion presents a considerable amount of “new” material that clarifies the use of vehicle trajectory analysis to promote consistent reporting of performance measures. The HCQS Committee decided by resolution that the 2010 HCM shall provide guidance on this subject. The material presented here is intended to provide the basis for that guidance, most of which now appears in HCM Chapter 24.

The discussion has gone into considerable depth in exploring the use of vehicle trajectory analysis for defining and computing performance measures from simulation tools that could be made consistent among different tools, while conforming to the definitions provided in the HCM.
Summary of Observations

- The VTAPE trajectory analysis software has demonstrated that time step trajectory files from micro simulation can be read and analyzed to produce useful results. VTAPE is a research tool and not an end-user mechanism for conducting trajectory analysis. Its main purpose is to support the development and demonstration of the computational procedures proposed for adoption by the HCQS Committee. VTAPE was developed with the intent that it could be adopted by the Simulation Subcommittee as its “official” computational engine.

- The computational procedures proposed in this document offer a reasonable approximation of the performance measures that are estimated by other techniques, including field studies and the HCM. The proposed procedures depend to a certain extent on approximations and assigned thresholds but this dependency is no greater than the other techniques and should not produce issues of compatibility.

- Software developer participation for incorporating the proposed procedures into their products is essential to the success of the HCM in promoting consistent reporting of performance measures. Therefore, the need for procedures that are unambiguous and can be implemented with a minimum of effort has been recognized throughout the development process.

- HCM compatibility was given a high priority in establishing definitions for all performance measures. On the other hand, the additional information contained in the detailed trajectory files could support the development of performance measures that are not strictly HCM compatible but could be more useful to the analyst. Standardization of these measures would be a valuable contribution of the HCM to the developer and user communities.

- It was suggested that The PTQB provides more useful information for design purposes than the probability of the BOQ reaching a specified point. The PTQB is an example of a useful performance measure that can be obtained by trajectory analysis. Very little is known about the relationship between these two approaches. Additional research would be useful in this area.

Summary of Issues

- The most practical way to report performance measures from simulation tools is to assign all measures to the segment and time interval in which they accrue. It is not practical to offer a consistent trajectory analysis methodology that seeks to associate these measures with their root cause, which might be in some other part of the network or in some other time interval. While this constraint might not be consistent with the objectives of some analysts, it eliminates several intractable problems and issues.
To ensure that all measures are fully reported, it is essential to define the analysis domain, both in time and space, such that a period of uncongested operation exists at all boundaries. It is essential that the guidance state this fact clearly.

The concept of control delay, as defined by the HCM, and the procedures by which it is computed, cannot be implemented in a consistent manner by vehicle trajectory analysis. However, a reasonable approximation of control delay is provided by the “queue delay” measure, computed as prescribed in this document.

Some deterministic tools that perform analysis on signalized arterial streets compute control delay. It is not possible to compare their estimation method with the HCM in terms of vehicle trajectories because neither the HCM nor the alternative tools make any use of vehicle trajectories in their computations. Most alternative tools use a control delay formulation that is identical, or at least very similar, to the HCM equations. They still produce different values for control delay because they model traffic flow in a more detailed (but still macroscopic) manner. To the extent that they differ, their more detailed treatment makes their delay estimates arguably more credible than the HCM.

References
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VTAPE was developed as a part of NCHRP Project 3-85 to analyze individual vehicle trajectories for evaluation of performance measures related to highway capacity and quality of service. Several VTAPE applications and examples are described in Chapter 24 of the 2010 Highway Capacity Manual (HCM) with an additional example in Chapter 29. VTAPE provides very detailed step-by-step analyses with intermediate values reported for all parameters at each time step. It is a useful tool for understanding and enhancing the trajectory analysis methodology. However, it is intended as a research tool and should not be viewed as an end-user analysis tool. Its ultimate purpose will be to serve the research community as a computational engine for continuing analysis and development of vehicle trajectory procedures. It has been developed with that purpose in mind.

VTAPE Overview

With VTAPE, it is possible to select up to 8 links forming a continuous route for analysis. The data for the selected links are read from the simulator’s animated graphics files. At this point, only CORSIM animated graphics files are recognized. Earlier versions of CORSIM used a “TSD” extension for these file names. The current version assigns TS0 for files smaller than 1 gigabyte. The TS0 notation will be used for purposes of this discussion.

The selected links are joined together for plotting and analysis to form a linear route. Each link is configured in terms of:

- Upstream and downstream nodes that define the link
- Link length
- Free flow speed (FFS)
- Control at the downstream end of the link.

VTAPE also recognizes up to three auxiliary lanes per link to accommodate acceleration or deceleration lanes on freeways and turn bays on surface streets. The auxiliary lane properties include:
• Lane number assigned by the simulation tool
• Auxiliary lane length
• FFS
• Type of lane (left turn, right turn, acceleration or deceleration).

VTAPE performs the following functions, all of which are demonstrated in this document:
1. Extraction of vehicle trajectories from the TS0 file and plotting, either by lane or for all lanes in the link.
2. Longitudinal analysis of the trajectory of vehicles as they traverse a link. A single vehicle may be chosen for a detailed analysis to illustrate the analysis procedure or all vehicles traversing the link in a given time period may be analyzed separately, with their performance measures summarized. The measures determined by this type of analysis include various types of delay and stop-related measures.
3. Spatial analysis, which involves consideration of all of the vehicles on a link at a specific time step. The two principal spatial measures are density and queue lengths.
4. Creation of a matrix of individual speeds and accelerations in the format described in Reference [1] to support emissions modeling and analysis.

Program Installation

VTAPE was written in Visual Basic Version 6 (VB6) for Windows. There is no installation disk at this stage of the program development. The program may be run by copying the VTAPE ZIP file to a computer that has VB6 installed. VB6 does not have to be running, but it must be installed to provide the required run-time support. All files must then be extracted from the zip file. The extraction process will create a folder called “VTAPE” containing the program file and two subfolders:
1. “Data:” The Data subfolder contains the CORSIM TS0 files to be read by VTAPE. It also contains the configuration files that describe the link structures for analysis.
2. “Results:” The Results subfolder contains the files produced by the various analysis functions. All files are written in comma-delimited format for direct import into spreadsheets. The following files are generated:
   • TrajectoryPlot.csv: Shows the time-space trajectories of all vehicles in the selected links.
   • TrackMOEs.CSV: Shows the results of the analysis of a single vehicle or all vehicles tracked through the selected link.
   • SpaceMOEs.csv: Shows the results for the analysis of all vehicles within a selected link
   • SpeedTable.csv: Provides a matrix of speeds and accelerations for use in the analysis of emissions.

Most of the results files also have “Dump” files associated with them. The dump files contain intermediate outputs that provide further insight into how the results were computed. The dump files are not described in detail in this document because they are primarily needed for program development.
Data Entry and Edit Features

Main Screen Features

Upon initial execution, the main screen will be displayed as shown in here. There are three frames for data entry:

1. TS0 file name selection (top left): This is the CORSIM file that will be analyzed. No file will be specified on initial execution.

2. Link Configuration (bottom left): A maximum of 8 contiguous links may be selected. The following link parameters must be specified:
   - Upstream and downstream node numbers
   - Link Length
   - Number of full lanes (not including turn bays)
   - Free-flow speed (FFS)
   - Control (check this box if the downstream node has a stop line)

   Other entries in this box will be discussed later.

3. Analysis Parameters (top right): The start time step, interval and scan rate (steps/sec) are required for each type of analysis. The individual requirements for other parameters will be discussed later.
There are also several command buttons for link configuration and analysis selection. The following buttons are associated with link configuration:

1. **Select input data file:** Upon initial execution, the first step is to select the input data file. This will display a dialog box with the sample data file. Choose this file and the main screen will reappear with the name displayed.
2. **Save configuration:** This will save your current configuration parameters (i.e., all data entry fields on the screen) to a file for later loading. You will be given a chance to specify the configuration file name.
3. **Load configuration:** This will let you browse for a configuration file that was previously saved. When you select a file, its parameters will appear in all of the data entry fields.
4. **Reset all links:** This will clear all of the link configuration parameters.

**Auxiliary Lane Features**

Auxiliary lanes include turn bays on surface streets and ramps on freeways. These lanes are given different numbers in the CORSIM lane numbering scheme. Auxiliary lane parameters are specified by clicking the *Edit* button for the associated link. When you do this a new screen will pop up as shown here.

![Auxiliary Lane Properties for Link # 1](image)

The auxiliary lane parameters include
- Lane ID: which must conform to the lane number in the TS0 file
- Length:
- Free Flow Speed (FFS)
- Lane type as defined on the screen.

At the current stage of development, only the lane ID is recognized.
Data Analysis Features

Four types of analysis features were identified earlier. Each of these features will now be described:

Extract Vehicle Trajectories for all Links

This feature generates a spreadsheet with the trajectories of all vehicles in terms of the distance from the upstream end of the link for every time step. Several trajectory plotting examples were presented in HCM Chapter 24. This figure shows a simple example for one freeway lane.

Freeway speeds in this lane are low upstream of the merge point. Merging vehicles enter the freeway slowly, but pick up speed rapidly downstream of the merge point bottleneck. The merging vehicles enter the freeway from the acceleration lane, which begins at 1,000 ft on the distance scale. The merging vehicle trajectories prior to entering the freeway are not shown in this figure because those vehicles are either on a different link or a different lane.

To perform this analysis, click the Plot trajectory button. All analysis buttons will be disabled during processing, the mouse pointer will turn into an hourglass and the Processing ... message will appear. When the processing is complete, the message will disappear and the analysis buttons will once more be enabled. At this point, click the View Results button to display the trajectory spreadsheet. The View Details button will display a spreadsheet that contains an image of the properties of each vehicle at each step of the simulation. The spreadsheet will facilitate specialized analyses that can now be performed without having to read and decode the binary information in the TS0 files. When the trajectory extraction is complete, the number of vehicles and plot records will be displayed in this frame.
Longitudinal Analysis

There are two options for longitudinal analysis:

- A single vehicle may be chosen for a detailed analysis to illustrate the analysis procedure or all vehicles traversing the selected links by specifying the “from” link “to” link.
- All vehicles in a given time period in a single link may be analyzed together, with their performance measures included. The measures determined by this type of analysis include various types of delay and stop-related measures.

If the analysis is performed on the trajectory of a single vehicle, it is necessary to specify the ID number of the vehicle. This is best accomplished by running the trajectory plot first and selecting a vehicle whose trajectory matches the desired pattern. The selected vehicle must appear in the selected links or a message will be displayed indicating that there were no track records for the vehicle in those links.

To perform this analysis, select the option you want and click the Compute track MOEs button. All analysis buttons will be disabled during processing, the mouse pointer will turn into an hourglass and the Processing ... message will appear. When the processing is complete, the message will disappear and the analysis buttons will once more be enabled. At this point, click the View Results button to display the results of this analysis.

If the analysis is performed on all vehicles in the selected links, then, the following message will be displayed, where “322” is an example value. Processing times are very long when many vehicles must be processed at once.

![Message Box]

322 Vehicles will be processed. This could take a while.

OK       Cancel

The results file “TrackMOEs.csv” contains the following fields:

- **Vehicle Position**: The distance in feet from the beginning of the route for the subject vehicle
- **Leader Position**: The distance in feet from the beginning of the route for the subject vehicle’s leader (i.e., the first vehicle ahead in the same lane)
- **Vehicles Ahead**: The number of vehicles in the link that are closer to the stop line in the same lane
- **Vehicle Speed**: The speed of the selected vehicle (ft/sec)
- **Leader Speed**: The speed of the leader (ft/sec)
- **Max Since Stop**: The maximum speed that the vehicle has reached since it stopped last. This is used to enable the identification of subsequent stops.
- **In Queue?**: A flag to indicate if the vehicle is in the queued state by the criteria specified in HCM Chapter 24
• **Stopped?**: A flag to indicate if the vehicle is in the stopped state by the criteria specified in HCM Chapter 24
• **TT**: the travel time during the last step (always the length of the step)
• **TT@FFS**: The time that the vehicle would have taken to travel the distance traveled in the last step if it has been travelling at the FFS
• **Step Delay**: By definition, TT – TT@FS
• **Link Delay**: The accumulated value of step delay since the vehicle entered the link
• **Queue Delay**: The accumulated value of step delay while in the queued state since the vehicle entered the link
• **Control Delay**: The accumulated time that the vehicle was in the queue, without subtracting the travel time at FFS. This is the definition of control delay given in the HCM. It applies as an approximation only to undersaturated operation.
• **Stop Delay**: The accumulated value of step delay while in the stopped state since the vehicle entered the link
• **Number of Stops**: A stop is declared when a vehicle’s speed drops to less than 5 mph after its speed has exceeded 1/3 of its target speed.

**Spatial analysis**

Spatial analysis encompasses all of the vehicles on a link at a specific time step. The two principal spatial measures are density and queue lengths. Since the analysis is performed on all vehicles in the link, it is not necessary to specify the ID number of the vehicle. It is still necessary to specify the link number.

To perform this analysis, click the **Compute space MOEs** button. All analysis buttons will be disabled during processing, the mouse pointer will turn into an hourglass and the **Processing ...** message will appear. When the processing is complete, the message will disappear and the analysis buttons will once more be enabled. At this point, click the **View Results** button to display the results of this analysis.

The results file “SpaceMOEs.csv” contains the following fields:

• **Time**: The number of time steps since the beginning of the simulation
• **Lane**: The lane number by the CORSIM lane numbering scheme
• **# Veh**: The number of vehicles contained on the link
• **Slow**: The number of vehicles traveling a less than 1/3 of the FFS
• **Queued**: The number of vehicles on the link in the queued state
• **FOQ**: The position of the front of the queue
• **BOQ**: The position of the back of the queue
• **MaxBOQ**: The maximum back of queue during the cycle
• **MinBOQ**: The minimum back of queue during the cycle
• **QCycles**: The number of elapsed cycles since the beginning of the period

A summary of the analysis is presented at the end of the table for each lane of operation. A sample of a summary for one lane of an approach to a two way stop controlled intersection operating within a coordinated arterial signal system is presented on the next page.
Lane 1  
Average Density 21.5  
Pct Slow Vehicles 59.0  
Pct Queued Vehicles 53.2  
Average Queue Length 49  
Average Back of Queue 55  
Maximum Back of Queue 165  
BOQ Overflows Link 0.0  
Percent of Time

Percent of time that the queue extends beyond specified points

<table>
<thead>
<tr>
<th>Feet</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>250</td>
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</tr>
<tr>
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<tr>
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<td>29</td>
</tr>
<tr>
<td>50</td>
<td>48.9</td>
</tr>
<tr>
<td>25</td>
<td>70.4</td>
</tr>
</tbody>
</table>

Mean cycle length 73  
Cycle Length Std Deviation 85.89581

For evaluating cyclical operation, VTAPE makes an attempt to identify cycles in the queue accumulation and discharge. While this works reasonably well some of the time, it has not always demonstrated credible results. More research is needed here.

**Speed – Acceleration Tables**

VTAPE Creates a matrix of individual speeds and accelerations in the format described in Reference [1] to support emissions modeling and analysis. All vehicles within the specified links are included in the results. The only required parameters are the start time step and number of steps in the interval.

To perform this analysis, click the *Generate speed–acceleration table* button. All analysis buttons will be disabled during processing, the mouse pointer will turn into an hourglass and the *Processing ...* message will appear. When the processing is complete, the message will disappear and the analysis buttons will once more be enabled. Since the output file is intended for postprocessing, there is no *View Results* button for this function.

The results will be written to a file called “SpeedTable.csv”. The output from the sample data is shown on the next page.
Number of Vehicle-Seconds Spent in Each Combination of Speed and Acceleration

CORSIM TS0 File: F:\_Data\TSIS\Ch29\IdealEB-80Sec-12Cycles.TS0

5 Links
960 Seconds simulated
77904 Vehicle-seconds processed

| Speed (mph) | -10 | -9 | -8 | -7 | -6 | -5 | -4 | -3 | -2 | -1 | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|------------|-----|----|----|----|----|----|----|----|----|----|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 - 5      | 83  | 10 | 416| 146| 55 | 61 | 37 | 71 | 47 | 134| 22524| 177| 125| 166| 240| 0 | 0 | 0 | 0 | 0 | 0 |
| 5 - 10     | 11  | 0  | 57 | 47 | 43 | 177| 87 | 213| 64 | 189| 79  | 196| 87 | 213| 58 | 313| 23 | 39 | 0 | 0 |
| 10 - 15    | 6   | 1  | 54 | 89 | 100 | 316| 157| 438| 152| 340| 200 | 276| 120| 294| 94 | 117| 113| 211| 144| 0 | 0 |
| 15 - 20    | 8   | 0  | 30 | 86 | 94 | 246| 145| 362| 198| 229| 74  | 144| 91 | 210| 210| 315| 43 | 77 | 122| 0 | 0 |
| 20 - 25    | 12  | 2  | 46 | 142| 123| 214| 147| 459| 208| 225| 70  | 143| 85 | 821 | 81 | 120 | 114| 126 | 0 | 0 |
| 25 - 30    | 4   | 0  | 38 | 112| 102| 216| 131| 388| 201| 457| 461 | 359| 82 | 718 | 19 | 313 | 0 | 0 | 0 | 0 |
| 30 - 35    | 0   | 0  | 31 | 116| 64 | 193| 97 | 272| 119| 1606| 12871| 555| 126| 890 | 23 | 286 | 0 | 0 | 0 | 0 |
| 35 - 40    | 0   | 0  | 26 | 77 | 34 | 109| 60 | 191| 180| 1498| 7893 | 458| 174 | 1066| 176| 115 | 0 | 0 | 0 | 0 |
| 40 - 45    | 0   | 0  | 6  | 28 | 14 | 31 | 30 | 102| 105| 502 | 4736 | 261| 244 | 692 | 0 | 0  | 0 | 0 | 0 | 0 |
| 45 - 50    | 0   | 0  | 2  | 9  | 11 | 28 | 38 | 130| 1373| 53  | 95  | 266 | 0 | 0  | 0 | 0 | 0 | 0 | 0 | 0 |
| 50 - 55    | 0   | 0  | 2  | 9  | 11 | 28 | 38 | 130| 1373| 53  | 95  | 266 | 0 | 0  | 0 | 0 | 0 | 0 | 0 | 0 |
| 55 - 60    | 0   | 0  | 2  | 9  | 11 | 28 | 38 | 130| 1373| 53  | 95  | 266 | 0 | 0  | 0 | 0 | 0 | 0 | 0 | 0 |
| 60 - 65    | 0   | 0  | 2  | 9  | 11 | 28 | 38 | 130| 1373| 53  | 95  | 266 | 0 | 0  | 0 | 0 | 0 | 0 | 0 | 0 |
| 65 - 70    | 0   | 0  | 2  | 9  | 11 | 28 | 38 | 130| 1373| 53  | 95  | 266 | 0 | 0  | 0 | 0 | 0 | 0 | 0 | 0 |
| 70 - 75    | 0   | 0  | 2  | 9  | 11 | 28 | 38 | 130| 1373| 53  | 95  | 266 | 0 | 0  | 0 | 0 | 0 | 0 | 0 | 0 |
| 75 - 80    | 0   | 0  | 2  | 9  | 11 | 28 | 38 | 130| 1373| 53  | 95  | 266 | 0 | 0  | 0 | 0 | 0 | 0 | 0 | 0 |
| 80 - 85    | 0   | 0  | 2  | 9  | 11 | 28 | 38 | 130| 1373| 53  | 95  | 266 | 0 | 0  | 0 | 0 | 0 | 0 | 0 | 0 |
| 85 - 90    | 0   | 0  | 2  | 9  | 11 | 28 | 38 | 130| 1373| 53  | 95  | 266 | 0 | 0  | 0 | 0 | 0 | 0 | 0 | 0 |
| 90 - 95    | 0   | 0  | 2  | 9  | 11 | 28 | 38 | 130| 1373| 53  | 95  | 266 | 0 | 0  | 0 | 0 | 0 | 0 | 0 | 0 |
| 95 - 100   | 0   | 0  | 2  | 9  | 11 | 28 | 38 | 130| 1373| 53  | 95  | 266 | 0 | 0  | 0 | 0 | 0 | 0 | 0 | 0 |
File Management

VTAPE always uses the same name for results files. Therefore each file that you want to preserve must be copied or renamed before you run another analysis. If you don’t want to preserve a file, you must still close it before running another analysis of the same type. Windows will not let you overwrite an open file. Instead, you will get a “permission denied” error.

References

Introduction

Proper application of simulation-based traffic analysis tools requires multiple simulation runs with different random number seeds to obtain valid results. The results of all runs must be averaged to produce values that reflect credible measures. Processing many runs in this manner can be very labor-intensive. The CCAP programs were developed to take the pain out of multiple run analysis tasks. This discussion assumes that you are familiar with CORSIM and the TSIS environment.

CCAP reads and summarizes multiple runs made by CORSIM using identical input data except for the random number seed. CORSIM has a scripting feature that makes a set of up to 100 such runs automatically. These runs must exist as CORSIM “.out” files before they can be summarized. Note that TSIS has a more general output processor for CORSIM that performs many of the same functions as CCAP. CCAP focuses on the MOEs required for highway capacity analysis and facilitates the accumulation of these MOEs into spreadsheets for comparison of alternatives and plotting of relationships in a more user-friendly manner.

There are two versions of CCAP:

- A single intersection processor (CCAP-I) that allows you to select any intersection in a network and process the performance measures for four approaches.
- A facility processor (CCAP-F) that allows you to select up to eight contiguous segments forming a freeway or urban street facility.

Both versions are similar in overall content and purpose but they function quite differently. The common features will be described first:

CCAP Setup

The programs are installed by the standard Windows installation process. The program files, “CCAP-I.EXE” and “CCAP-F.EXE” operate as standalone executable files that may be launched directly from the Windows Explorer or from a shortcut on your desktop or in some other folder. The default program folder is C:\program files\CCAP-I or CCAP-F. The program
folder contains the .EXE file, this help file and a folder called “Working.” All outputs are written to the working folder. All users must have read and write access to this folder.

### CORSIM Run Requirements and Limitations

The TraffEd input editor lets you select a few report options on the “Network Properties” screen. The proper report options for CCAP-I are shown at the right.

- The “card file list” must appear at the beginning of each “OUT” file. The program needs some of the input data in this list. CORSIM allows you to suppress the card file list if it isn’t needed. Do not suppress this list for CCAP-I.
- The turn-movement specific output must be requested.
- It is preferable, although not required, to suppress the run specs and network validation outputs; otherwise multiple file sets might become intractably large.

Note that these items apply to CCAP-I. CCAP-F does not need the input records or the turn-movement specific outputs.

Other CORSIM run requirements include:

- Each node may have up to 4 approach links for CCAP-I, which determines the approach direction from upstream node coordinates. If the intersection approaches are severely skewed, the directions might come out incorrectly.
- You must run your base TRF file to produce the output (OUT) file before the multiple runs may be summarized.

### Making the CORSIM Runs

The CORSIM runs are made by selecting the “Scripts” choice from CORSIM’s “Tools” drop-down menu. A list of scripts will appear. The “Multi-Run Same Case” script is the one you want. When you select this choice the screen below will appear in the working window.

```vbs
This Multi-Run script executes CORSIM multiple times for a single case file. Because CORSIM employs a Monte Carlo simulation, multiple runs with different random number seeds is recommended for obtaining accurate MOE.

This script uses three interfaces defined by the TSIS Script Tool: IOutputControl, I股指ScriptSupport, and the CORSIM Server interface. These interfaces and their functions are described in detail in the Script Tool User’s Guide.

1. Create the object used to access files.
   Set fileSystem = CreateObject( "Scripting.FileSystemObject" )

1. Pop up a file selection dialog to get the random number seed file to use.
   rnsFile = I股指ScriptSupport.SelectFile( "Select Random Number Seed File", "RNS Files (*.rns)" )
```

CORSIM Capacity Analysis Postprocessor                                                                                      Page 2
Click the green triangle at the top left of this screen. The window at the right will appear for you to choose the random number file. The window will contain a file called “random.rns.” Choose this file unless you have a better idea.

At this point another window will open to let you choose the CORSIM input file (.TRF) that you want to use for the runs. Let’s call this your “base TRF file.” When you have made your choice, you will be asked for the number of runs that you want to make. You may request a maximum of 100 runs.

Then you’ll be asked one last thing: “Do you want the logging turned on?” CCAP does not require logging, so you should answer “No” unless you want it for some other reason.

Now your files will be created. They will be placed in the same directory as your original TRF file. If your base TRF file was named “MyFile.Trf” the created files will be named “MyFile_1.Trf”, “MyFile_2.Trf”, etc. You will also have the output files for each run as “MyFile_1.Out”, “MyFile_2.Out”, etc.

If you are analyzing a multiple case situation in which one or more parameters is systematically varied, you should first make a text file with a list of the TRF file names and save the file with the “.INP” extension. Then choose the “Multi-run, many cases” option from the script tool list. If you select the INP file when prompted, all of the cases will be run as a single batch job.

Both CCAP programs can be launched as TSIS tools or by clicking the associated exe file icon or shortcut. Refer to the TSIS documentation for instructions on setting up tools. The tools should be set up to transfer the .OUT file from TSIS. To Launch CCAP programs by this method, select the “base” .OUT file (not one with a number appended as described above). Then click the tool icon that you selected as part of the tool setup.

**Closing Spreadsheet Files**

When you view a summary spreadsheet, you must remember to close it or save it under a different name before you perform another summary. Windows will not let you open a file that is already open. Instead, you will get an “Access denied” error and your program will terminate.
Running CCAP-I

When you launch CCAP-I the screen below will appear. If you have launched the program as a TSIS tool, the output file name will be displayed. Otherwise, the first step is to browse for the files that you want to summarize. Choose the output (OUT) file associated with your base TRF file. The output file will then be read to determine its contents.

Selecting the Node and Period for Analysis

The node and period are selected as follows:

- Each node will be identified and placed in the “Node” drop-down list. You have the choice of selecting only signalized nodes in the check box.
- When you select the node you want, all of the approach links will be identified.
- If the run has multiple periods you will be able to select the period of interest. Selecting a specific period will give you the values for that period. The “All periods option will give you the cumulative values for the whole run.
Specifying the Analysis Parameters

The parameters of the analysis are specified as follows:

- **Number of Runs:** This value may not exceed the number of runs that were made using the CORSIM scripting tool.
- **Start at Run:** Normally this will be run 1 unless you are doing an advanced analysis of the stochastic properties of the multiple run set.
- **Reverse Order:** This is another feature that you will only use if you are doing an advanced analysis of the stochastic properties of the multiple run set.
- **Auto Append:** If this box is checked, the results of the analysis will be automatically appended to the comma-delimited (csv) spreadsheet file.
- **Delay Definition:** This frame offers several choices for the definition of delay. Your choice here will be extracted from the CORSIM output files.
- **User Entered Parameters:** Two fields labeled Parameter 1 and Parameter 2 are provided to facilitate plotting and other analyses that require axis values. Use these fields to enter necessary parameters that are not automatically extracted from the data files.

Setting Up the Summary Files

The results of each analysis may be appended to comma-delimited (csv) summary files for subsequent report generation. These files may be opened directly by office productivity programs such as Microsoft Excel. Separate files are established for approach analysis and movement analysis. To set up a file for either purpose, just enter a name in the text box and click the “Create/Reset” button. This will open a new file with the specified name. “-App.csv” will be added to the approach file name and “-Movt.csv” will be added to the movement file name. At this point you will have a file with column headers but no data. Note that this button will destroy all existing data in the file.

Executing Summaries

When you have selected the CORSIM output file, the node and period and when you have specified all of the analysis parameters, you can execute the summary by clicking the **Summarize** button in either the “Approaches” or “Movements” frame. The approach summary gives CORSIM’s results for a maximum of 4 approaches to the selected node. The movement summary will present CORSIM’s results for the left, through and right turn movements on the approach selected by the option button on the approach screen.

Appending Data to the Summary Files

When a summary is executed, the appropriate **Append Data** button is enabled. This gives you the opportunity to review the data and decide whether or not it should be appended to the summary file. You can bypass the review step by checking the **Auto Append** box in the analysis parameter area. Each record appended to the approach summary includes the following fields:

- **File** The name of the CORSIM output file
- **Runs** The number of runs that were summarized
- **Node** The CORSIM node number
- **DelDef** The selected definition of delay (Link, queue, control or stopped)
- Parm1  A user-entered parameter
- Parm2  A user-entered parameter

Each of the four approaches contains the following fields:
- UpNode  The number of the upstream node
- Dir     The link direction
- Trips   The number of trips processed on the link
- Veh-Min The delay in vehicle-minutes
- Sec/Veh The delay in seconds per vehicle
- +95%    The upper 95% confidence limit for the delay (sec/veh)
- -95%    The lower 95% confidence limit for the delay (sec/veh)

The 95% confidence limits are based on 2 standard errors from the mean value.

**Viewing the Individual Run Details**
The summary files containing the multiple run results will be adequate for most purposes. For more advanced analysis of the stochastic properties of multiple files, a separate summary is produced containing the number of trips and delay for each approach of each run. The View Run Details button will display the results of the most recent summary. This file is overwritten each time an approach summary is executed.

**A Sample Case**
A sample case will be used to illustrate the operation of CCAP. This is a test of the basic delay model under very simple conditions involving an intersection of one-way streets. Each approach has 2 lanes and 20% turns. Because of the one-way streets, the NB approach will have right turns and the EB approach will have left turns. The input data are summarized as follows:

- Cycle Length = 60 sec
- Green time = 25 sec
- Yellow time = 4 sec
- All Red time = 1 sec
- Saturation flow rate: 1800 vphg
- Demand volumes. 800vph to 1600 vph in 200 vph increments
- Analysis period = 15 minutes

**Creating the Data**
The steps in creating the data are as follows:

1. Create a CORSIM data set with the above attributes and demand volumes of 800 vph on each approach. We named this file “CCAP-800.TRF”

2. Clone 4 more data sets changing only the demand volumes and save them with recognizable names.
3. Run each data set to produce an output file. The data in this first file will not figure into the summary but this is the file that you must select to begin the summary process.

4. Using the CORSIM scripting tool, create 30 runs from each dataset. The scripting tool numbers the runs automatically. For example, the runs for CCAP-800.TRF will be numbered as CCAP-800_1.TRF up to CCAP-800_30.TRF. You can do this manually with the “Multi run single case” option or automatically with the “Multi run many case” option.

5. Now run CCAP and browse for the output files that you have created. If you have followed our file naming scheme, the first file that you want is “CCAP-800.OUT.” Select only the “.OUT” files without the sequence numbers added by the scripting tool.

6. At this point, you would select the node and the period. Since our example had only a single period, you will not be given a choice in this case. If you specified Signalized Nodes Only before you selected the file, you will only see one node to choose from. If you left this box unchecked, you will also see the dummy nodes on both approaches. Be sure to select the signalized node for this summary.

7. Select the number of runs that you want to process, up to the number that you made with the scripting tool.

8. Enter the demand volume for the run as one of the user-specified parameters. This number will appear on one of the fields in the summary file. It will make it much easier to analyze and plot your results.

9. Select the type of delay you want to summarize. We used control delay for this example.

10. Before you perform any summaries, you should create the summary files to receive the data. Just enter a file name in the Summary File text box (no extension) and click the Create/Reset button. We called both of our files by the name Demo, causing the files Demo-App.csv and Demo-Movt.csv to be created.

11. Now you are ready to create a summary by clicking the Summarize button in either the Approach or Movement frame. The results will be displayed in these frames. If you checked the Auto Append box, the results will automatically be appended to the summary file. If not, you can now click the Append Data button for this purpose.

12. Repeat these steps for the other CORSIM files with different volumes.
Analyzing the Data
At this point, you will have two summary files, one for the approaches and one for the movements, in comma delimited format. You can inspect these files at any time by clicking the View Summary buttons. They will open automatically in your default application for CSV files. When you have added all of the data, you can rearrange the spreadsheets for analysis and plotting. Here are some plots that were obtained from this sample case. Please keep in mind that the purpose of this document is to illustrate the process of using CCAP and not to explore the basic principles of simulation.

Delay vs. Demand Volume
Here is a plot showing the classical relationship between delay and the demand volume. Note that the NB delays were higher than the EB, even though all of the input data were the same for both movements. Well, not quite all. The one way street configuration left the NB approach with a right turn and the EB approach with a left turn. Because of their lower speeds, the right turns reduced the approach capacity more than the left turns.

Approach Capacity
Capacity is not a direct output of simulation tools. The next graph shows how the approach capacity is determined by simulation. It shows how the number of trips processed tracks the input value up to a point. The point at which the number of trips drops below the demand indicates the capacity of the approach. Note that the lower capacity for the approach with the right turn was also evident in this figure.
Confidence Intervals

CCAP stores the 95% confidence interval range (+/- 2 standard errors) in the summary file. The computed confidence interval for the NB approach is plotted below. These results are based on 30 runs. The confidence range could be reduced by increasing the number of runs performed by the script tool.
Individual Run Details

A plot of the delay for the EB approach for each of the 30 runs is shown below. A curious phenomenon is apparent here. The trend line shows that the delay increases with the number of runs, indicating that a larger sample size introduces a bias as well as reducing the variability of the mean value. The only logical explanation is that the choice of random number seeds might not have been too auspicious. The most logical conclusion from a statistical perspective is that 30 runs were not enough to provide a credible result. Another observation is that basing conclusions on the first run alone would have been really bad.
Running CCAP-F

When you launch CCAP-F the screen below will appear. If you have launched the program as a TSIS tool, the output file name will be displayed. Otherwise, the first step is to browse for the files that you want to summarize.

The folder name and file name are specified separately for CCAP-F. You can simplify the folder name specification by including all files in subfolders below the program folder. Then enter “@” at the beginning of the folder name to point to the program folder. If your data files are in a subfolder called MyData then you may simply enter “@MyData.” Then enter the name of the base .OUT file in the “Input File” box.

The analysis parameters to be specified include:

- Number of runs
- Report all Runs: If you simply want average results, then do not check this box. You will want to see all runs if you are interested in the variability among runs or if you are making scatter plots of some relationships.
- Cumulative Segment Outputs: CORSIM reports all measures in a cumulative fashion (i.e., from the beginning of the simulation period). If you are interested in the period-specific segment outputs instead of cumulative outputs then leave this box unchecked and CCAP-F will produce period-specific segment outputs by subtracting the cumulative output of the previous period from the current period.
- Period length (15 or 60 min)
• Grouping by link or period: This choice affects the order in which the results are summarized in the summary spreadsheet. Different choices are suited to different plotting purposes.

• Facility Type (Freeway or Arterial): This choice will determine whether the analysis will be performed on a FRESIM or NETSIM output.

• Link Structure: It is possible to specify up to eight contiguous links for analysis by entering the node number sequence for these links.

All of the data for a particular run configuration may be saved in a configuration file. Configuration files are saved in the Working subfolder and have the extension .FCF. You may load or save any configuration file by specifying its name.

The results are also saved in the Working folder in .CSV files. Results are always appended to the file named in the Results File Name box. To start a new summary of results, specify a different file name and reset it. Resetting a file will write the header information to it. If you create results without first resetting a new file, it will not have column headings.

The Summary command button will perform a summary according to the parameters that you have specified. The results will be appended to the currently named summary file and the file will be displayed when the summary is complete. You can display the summary file again using the View command button in the Results box.
Introduction

Traffic simulation tools typically have internal emulation for traffic actuated control that responds to detector inputs from the traffic flow modeling logic and controls the right of way on each approach at every point in time. The control emulation creates a realistic simulation of traffic movement at a signalized intersection and supports the development of credible performance measures.

The CORSIM simulation package was used in NCHRP Project 3-85 to examine differences between the results from Highway Capacity Manual (HCM) procedures and a typical simulation tool and to demonstrate the use of simulation to overcome the stated limitations of the HCM. CORSIM provides emulation of a NEMA and Type 170 controller. It reports the usual performance measures (speed, delay, stops etc.) but it does not report the signal phase times timing plan that were generated by the controller. Average phase times are an important input to the HCM signalized intersection evaluation procedure, so they are required for a full comparison of the results from HCM procedures with those from alternative tools. Simulation tools do not generate direct capacity or v/c ratios. Both of those measures could be inferred from simulation if the phase times were known.

Each CORSIM run produces a data file containing information about each vehicle, including the signal display that it faces, for every second in the analysis period. These files are used by the TRAFVIEW component of TSIS to generate animated graphics displays. The TACTiming data analysis utility was developed to read the CORSIM animated graphics files and extract the signal display information to computer average G/C ratios over the simulation period. This document describes the TACTiming operation and provides an example of its use.

TACTiming Overview

With TACTiming, it is possible to select a single node from a signalized network and configure up to 4 links forming the approaches to that node. The data for the selected links are read from the simulator’s animated graphics files. At this point, only CORSIM TS0 files are recognized. The selected links represent the NB, SB, EB and WB approaches to the intersection. Each link assigned nominal splits for the through and protected left turn movements

Phase times are computed for each of the through and protected left turn movements. Phase times may be expressed either as a G/C ratio or as a percent of their nominal splits. G/C ratios may be used for comparison with C/C ratios estimated by other methods and for estimating the
capacity and v/c ratios of an approach. Percent of nominal green time is useful to normalize the results for plotting relationships with demand volume and other parameters. The TACTiming results are presented in comma-delimited text format to facilitate processing and plotting by spreadsheets.

**Program Installation**

TACTiming was written in Visual Basic Version 6 (VB6) for Windows. There is no installation disk at this stage of the program development. The program may be run by copying the TACTiming.zip file to a computer that has VB6 installed. VB6 does not have to be running, but it must be installed to provide the required run-time support. All files must then be extracted from the zip file. The extraction process will create a folder called “TACTiming” containing the program file and a subfolder called “Data”. The Data subfolder contains the CORSIM TS0 files to be read by TACTiming. It also contains the configuration files that describe the link structure, parameters for analysis and the analysis results files. There are two analysis files that will be described later.

1. *TACTimingplot.csv*: contains summary information for each run to facilitate analysis and plotting. Results accumulate in this file until it is reset.
2. *TACTiming report.csv*: This report is generated and overwritten with each run.

Both files are in comma-delimited (csv) format to be displayed by your spreadsheet program.

**Data Entry and Edit Features**

**Main Screen Features**

Upon initial execution, the main screen will be displayed as shown on the next page. There are three frames for data entry:

4. TS0 file name selection (left side): This is the CORSIM file that will be analyzed. No file will be specified on initial execution. (See the instructions at the end of this document for launching TACTiming directly from TSIS with the file name specified).
5. Nominal Splits (top right): The nominal phase times specified in the CORSIM data (seconds) are entered here for the through and protected left turn movements on each of the four approaches.
6. Plot Information (bottom right): TACTiming will usually be used to analyze multiple CORSIM runs with different parameters. The plot information frame lets you specify the parameters to be inserted in the output files to facilitate plotting of relationships. The fields in the plot frame include:
   - *Title* (make one up)
   - *Parameter 1 and 2*: These are assigned by you. For example, if you’re trying to plot phase times against volumes, you would probably specify the volume for each run in one of these fields.
   - *Units*: You may specify G/C or percent of nominal split.
   - *Import parameters from settings*: This will be discussed later.
There are also several command buttons on this screen:

- **Save settings**: As a productivity feature, all of the information entered on this screen can be saved in a file for later retrieval using the **Load settings** command.
- **Run**: This will perform the analysis and compute the phase times.
- **View the report**: A report is generated with intermediate values and diagnostics.
- **View Plot File**: Each run produces one row of data that is appended to a file to facilitate comparison and plotting. This command will display the file in your spreadsheet program.
- **Reset Plot File**: This will erase all of the data in the plot file so that you can start a new analysis. If you don’t want to lose the data in this file, you should save it under a different name. The name of the file created on reset is **TACTimingPlot.csv**.
- **Help**: Displays this document.
- **End**: Terminates the program.

Every time a run is executed, all settings are saved in a file called Lastcfg.Cf in the **data** subfolder. This saves you the problem of reentering all of the data each time you launch the program. The first time you launch it all fields will come up blank.
Data Analysis

TACTiming data analysis will be demonstrated with an example from the HCM. Example 16-1 involves an arterial route with 6 intersections numbered sequentially from left to right. The route layout is shown here.

The CORSIM node numbering scheme for node “n” is shown at the right. The numbers are for external nodes. So for Node 1 the four approach nodes would be:

- NB 101
- SB 201
- EB 301
- WB 2

The node for the WB link is not 401 because this is an internal link originating at Node 2. These are the node numbers that must be entered to select the approaches and phases that you want to analyze.

The nominal splits are EW left: 13 sec, EW through: 45 sec and NS: 42 sec.

We will analyze five CORSIM runs with demand volumes ranging from 100% to 180% of the value that was initially specified in Example 16-1. The arterial left turns all have protected (only) phasing. There is no left turn protection for the cross street approaches.

The 5 CORSIM runs were made with filenames “Prot-100.TS0” to “Prot-180.TS0” where the three digit number indicates the percent of initial demand volume. A full hour (3600 sec) was simulated for each case.
When the program is run, the first step is to select the CORSIM file. The select button will produce the following screen:

We will select the first file, Prot-100.ts0 from this list

The main screen then reappears. After entering the approach nodes for Node 1, the phase times and the Plot information, the screen should look like this.
All of the plot information must be entered manually except for Parameter 1, which contains the last three characters of the selected file name. So, by naming the files to represent the analysis cases, you can transfer the information automatically to the plot file. The units were selected as **percent of nominal splits**.

Before you make the first run, you should save the settings for future use. You should also reset the plot file to start a new analysis.

The following report file was produced by this run. The values indicate the G/C ratios for each movement. The **percent of nominal splits** units only apply to the plot file, which we will look at next.

<table>
<thead>
<tr>
<th>Approach</th>
<th>Display</th>
<th>Left</th>
<th>Through</th>
</tr>
</thead>
<tbody>
<tr>
<td>EB</td>
<td>Red</td>
<td>0.882</td>
<td>0.425</td>
</tr>
<tr>
<td>EB</td>
<td>Yellow</td>
<td>0.037</td>
<td>0.04</td>
</tr>
<tr>
<td>EB</td>
<td>Prot</td>
<td>0.081</td>
<td>0.535</td>
</tr>
<tr>
<td>EB</td>
<td>Perm</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>EB</td>
<td>None</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>EB</td>
<td>G+Y</td>
<td>0.118</td>
<td>0.575</td>
</tr>
<tr>
<td>WB</td>
<td>Red</td>
<td>0.901</td>
<td>0.444</td>
</tr>
<tr>
<td>WB</td>
<td>Yellow</td>
<td>0.036</td>
<td>0.04</td>
</tr>
<tr>
<td>WB</td>
<td>Prot</td>
<td>0.064</td>
<td>0.516</td>
</tr>
<tr>
<td>WB</td>
<td>Perm</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>WB</td>
<td>None</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>WB</td>
<td>G+Y</td>
<td>0.099</td>
<td>0.556</td>
</tr>
<tr>
<td>NB</td>
<td>Red</td>
<td>0.674</td>
<td>0.674</td>
</tr>
<tr>
<td>NB</td>
<td>Yellow</td>
<td>0</td>
<td>0.04</td>
</tr>
<tr>
<td>NB</td>
<td>Prot</td>
<td>0</td>
<td>0.286</td>
</tr>
<tr>
<td>NB</td>
<td>Perm</td>
<td>0.286</td>
<td>0</td>
</tr>
<tr>
<td>NB</td>
<td>None</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>NB</td>
<td>G+Y</td>
<td>0</td>
<td>0.326</td>
</tr>
<tr>
<td>SB</td>
<td>Red</td>
<td>0.674</td>
<td>0.674</td>
</tr>
<tr>
<td>SB</td>
<td>Yellow</td>
<td>0</td>
<td>0.04</td>
</tr>
<tr>
<td>SB</td>
<td>Prot</td>
<td>0</td>
<td>0.286</td>
</tr>
<tr>
<td>SB</td>
<td>Perm</td>
<td>0.286</td>
<td>0</td>
</tr>
<tr>
<td>SB</td>
<td>None</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>SB</td>
<td>G+Y</td>
<td>0</td>
<td>0.326</td>
</tr>
</tbody>
</table>

**Message Count:** 14400

The **message count** on the last line gives the total number of signal messages that were processed. Each approach should give one message per second of simulation. So with four approaches for 3600 seconds, the message count should be 1440 seconds, which is correct.
The plot file for the first run looks like this:

Traffic Actuated Controller Timing from CORSIM
Green + Yellow times: Ex 16-1

<table>
<thead>
<tr>
<th>Signal</th>
<th>Parm1</th>
<th>Parm2</th>
<th>Secs</th>
<th>Cycle</th>
<th>Percent</th>
<th>EBLT</th>
<th>EBTH</th>
<th>WBLT</th>
<th>WBTH</th>
<th>NBTH</th>
<th>SBTH</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>100</td>
<td>EW Prot</td>
<td>3600</td>
<td>100</td>
<td>G/Split</td>
<td>90.6</td>
<td>127.7</td>
<td>76.3</td>
<td>123.6</td>
<td>77.6</td>
<td>77.6</td>
</tr>
</tbody>
</table>

The signal (node) number, parameters, number of seconds, Units and cycle length are added automatically. The cycle length is computed from the nominal splits.

This shows the results for Node 1 with 100% demand. If we rerun the analysis using the CORSIM files representing all of the demand levels each run will add a row to the plot file which will eventually look like this. The results are plotted in the graph below.

<table>
<thead>
<tr>
<th>Signal</th>
<th>Parm1</th>
<th>Parm2</th>
<th>Secs</th>
<th>Cycle</th>
<th>Percent</th>
<th>EBLT</th>
<th>EBTH</th>
<th>WBLT</th>
<th>WBTH</th>
<th>NBTH</th>
<th>SBTH</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>100</td>
<td>EW Prot</td>
<td>3600</td>
<td>100</td>
<td>G/Split</td>
<td>90.6</td>
<td>127.7</td>
<td>76.3</td>
<td>123.6</td>
<td>77.6</td>
<td>77.6</td>
</tr>
<tr>
<td>1</td>
<td>120</td>
<td>EW Prot</td>
<td>3600</td>
<td>100</td>
<td>G/Split</td>
<td>97.4</td>
<td>115.8</td>
<td>83.5</td>
<td>111.8</td>
<td>88.2</td>
<td>88.2</td>
</tr>
<tr>
<td>1</td>
<td>140</td>
<td>EW Prot</td>
<td>3600</td>
<td>100</td>
<td>G/Split</td>
<td>99.1</td>
<td>107.7</td>
<td>90</td>
<td>105.1</td>
<td>94.8</td>
<td>94.8</td>
</tr>
<tr>
<td>1</td>
<td>160</td>
<td>EW Prot</td>
<td>3600</td>
<td>100</td>
<td>G/Split</td>
<td>95.3</td>
<td>104.1</td>
<td>89.1</td>
<td>102.3</td>
<td>98.9</td>
<td>98.9</td>
</tr>
<tr>
<td>1</td>
<td>180</td>
<td>EW Prot</td>
<td>3600</td>
<td>100</td>
<td>G/Split</td>
<td>97.6</td>
<td>103.7</td>
<td>87.2</td>
<td>100.7</td>
<td>100</td>
<td>100</td>
</tr>
</tbody>
</table>
The results are generally as anticipated. At low demand levels, the arterial through phase receives significant unused time from the actuated phases and its time exceeds the nominal split time. This effect diminishes as the demand level increases. The cross street phase time starts off well below its nominal split because of lack of demand. The time increases with demand and eventually reaches 100% of the nominal split.

This example has illustrated the use of TACTiming to analyze phase times from CORSIM. Some final comments are presented as follows:

- All of the plot information is saved when you save the settings. When you load the settings, the Import parameters from settings option lets you decide whether the plot information in the settings file should overwrite the specified settings. Sometimes you want to retain the settings that you have entered manually.
- When you view the report or plot file you must close it before doing another run. Windows will not let you open a spreadsheet that is already open. You will get a Permission Denied error from Windows.
- This program can only accumulate the green plus yellow times for each phase. There is no “all-red” indication in the CORSIM animated graphics file. This should be considered in the use of the results. There were no “all-red times specified in Example 16-1.

**Launching TACTiming from TSIS**

When TACTiming is installed in TSIS as a TSIS tool you will be able to launch TACTiming directly from TSIS, passing the name of the file that you want to analyze. Please follow the TSIS instructions for installing tools. The tool should be configured to pass TS* files. You must select an icon to represent TACTiming on the TSIS toolbar. When you highlight a TS0 file in the TSIS file list panel on the left, the icon will be enabled. Just click that icon and TACTiming will be launched with the TS0 file specified.