# Multimodal Assessment of Recurrent and Non-recurrent Conditions on Urban Streets

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## Abstract

The methodology to measure the performance of urban streets was significantly revised in the latest edition of the *Highway Capacity Manual* (HCM 2010). Urban Streets, which include urban and suburban signalized arterial highways, typically serve the four modes of transportation (auto, transit, pedestrian and bicycle) and are frequently congested. Analyzing both recurrent and non-recurrent conditions is essential. In this dissertation, the author addressed several urban streets related issues by developing an alternative method to measure recurrent multimodal conditions on urban streets; gathering feedback relating to the key elements of the developed method; and developing a probabilistic method to analyze and measure non-recurrent conditions. Real life sample applications were performed for both developed methods. The developed multimodal method addresses the following: (1) the use of level of service (LOS) step functions; (2) the comparability of LOS results across modes; (3) the impacts of modes on other modes; (4) the establishment of thresholds; (5) accuracy; and (6) user perceptions in measuring multimodal conditions on urban streets. Feedback gathered from transportation professionals through focus group meetings and surveys supported most of the features of the developed multimodal method and provided default values for method application. They were divided on the naming of condition levels and on the number of condition levels to use. Non-recurrent conditions were addressed through the development of a Markovian probabilistic method to analyze and measure the resilience of congested, signalized, arterial highways, for which availability of existing analytical tools is limited. The method results provide a plexiform of information about the rate and speed of recovery of the arterial traffic flow.

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# Chapter 1 Introduction

## 1.1 Problem Statement

Analyzing both recurrent and non-recurrent conditions is essential on urban streets, where typically all four modes (i.e., auto, pedestrian, transit, bicycles) compete for space and time within the same right of way. Since the first edition of the *Highway Capacity Manual* (HCM) in 1951, the methods (including methods for urban streets) in the various editions of the HCM have been adopted by state and local departments of transportation for analyzing recurrent conditions. HCM level of service (LOS) analysis results describe how well vehicles, transit, and non-motorized users of the system can move about. The developers of the HCM recognized the need to improve multimodal LOS measures for urban and suburban arterial highways [1], and attempts were made to do so in the urban streets chapters of the latest edition of the HCM (HCM 2010) [2]. The term "urban streets" used in the HCM encompasses both urban and suburban arterial highways. However, concerns remained with the HCM 2010 urban street methods, including their accuracy, level of complexity, use of the LOS step functions, applicability for measuring congested conditions, considerations of the modes' impact on each other and consideration of regional differences. Literature regarding these concerns will be reviewed and addressed through developing an alternative method.

The HCM does not provide methods to analyze non-recurrent events, such as incidents, the impact of which extends beyond the auto mode to the transit, pedestrian, and bicycle modes. As an example, increased delay caused by vehicular incidents can cause bus service to be off schedule, which may result in passengers missing transfer connections. The importance of effective incident management has long been recognized in the transportation industry.

Analyzing the impacts of incidents on transportation facilities and how these facilities recover from incidents, i.e., how resilient they are, is necessary for optimizing traffic flow. Tools are lacking for analyzing the impacts of incidents, particularly tools that consider the stochastic nature of traffic and thus there is a need to develop a stochastic method to analyze the resilience of urban streets.

## 1.2 Dissertation Objective

In this dissertation, the author reviewed concerns expressed in the literature with HCM 2010's urban streets methods and developed a method for assessing multimodal conditions for signalized urban/suburban arterials. The objective was to provide an alternative method to measure multimodal recurrent conditions on urban streets that addressed the shortcomings in the HCM 2010's urban streets methods. Furthermore, the Markov process was investigated and applied for developing a stochastic method using microscopic simulation data. The objective of the method is to measure and analyze the resilience of signalized, congested, arterial highways.

## 1.3 Research Approach

To develop the alternative multimodal method, five tasks were performed:

1. Conduct a literature review to identify any recommendations for improving the HCM 2010 Urban Streets methods.
2. Develop an alternative method that addresses any recommendations for improvement found in the literature review.
3. Gather feedback from practicing transportation professionals on the literature review findings and the potential usefulness of the alternative method.
4. Gather feedback from transportation professionals, working in research, academia and practice, on the scoring values to be used in a sample application.

5. Develop sample applications of the alternative method for specific corridor segments of signalized urban/suburban arterials.

To develop the stochastic method to measure and analyze resilience, three tasks were performed:

1. Conduct a literature review to identify current approaches to analyzing and measuring the resilience of arterial highways and to find examples of emerging stochastic methods that are applicable for analyzing arterial traffic conditions.
2. Develop a Markovian probabilistic method using microscopic simulation data to analyze and measure the resilience of signalized, congested, arterial highways.
3. Develop sample applications of the developed method for specific corridor segments of signalized urban/suburban arterials.

## 1.4 Dissertation Layout

In chapter 2, the author reviewed the literature to address the following topics relating to urban streets: (1) Use of LOS step functions (The term “step function” means that the LOS function is divided into constant subintervals, or steps.), (2) Comparability of LOS results across modes, (3) Impact of modes on other modes, (4) Accuracy of the HCM 2010 methods, (5) User perception, and (6) Research efforts to address HCM shortcomings. The development of an alternative method for the HCM 2010 urban streets methods, for recurrent conditions, was described in chapter 3. Concerns raised in the literature review were considered, and attempts were made to incorporate them in the method development. In chapter 4, the author described the process and results of gathering feedback from transportation professionals. In chapter 5, the author provided the results of literature review that are relevant to analyzing and measuring the resilience of arterial highways. In addition, an overview of the first order Markov chain was provided, which was then used for the development of a Markovian probabilistic method using microscopic simulation data to analyze and measure the resilience of signalized, congested, arterial highways. The author provided sample applications of both of the developed methods for two specific corridor segments in Fairfax County, Virginia, along with providing analysis of results, in chapter 6.

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# Chapter 2 Literature Review

## 2.1 Introduction

The literature regarding the HCM 2010 Urban Streets methods was identified through the use of the Transportation Research Information Service (TRIS), a search of the publications of the Transportation Research Board (TRB), and a general Internet search.

Some aspects of the urban street methodology were revised in the HCM 2010 [2] by the Urban Streets Subcommittee of TRB's Committee on Highway Capacity and Quality of Service based on research by Dowling et al. [1] and Bonneson et al. [3]. Some other aspects, however, continued being addressed as they were in the previous (2000) edition of the HCM [4]. Chapters 16 and 17 of the HCM 2010 [2] provide LOS estimation procedures and LOS thresholds for the four modes (i.e., auto, transit, pedestrian, and bicycle) of urban streets, including urban and suburban signalized arterials. Literature was limited regarding the HCM 2010 Urban Streets methods at the time of conducting this literature review. Therefore, literature addressing the HCM 2000 was reviewed for the aspects that did not change in the HCM 2010 edition.

Literature typically refers to the travelers, who are the users of the four modes, as "users." "Users", however, can also mean users of the HCM. In this paper "users" means the users of the four modes, i.e. the travelers. When "users of the HCM" is meant, it is designated as such.

## 2.2 Use of LOS Step Functions

The concept of level of service (LOS) from A through F (with *A* being the best and *F* the worst), was first established in the second edition (1965) of the HCM [5] and has been in use ever since. When Kittelson and Roess [6] evaluated the fourth, 2000 edition of the HCM 2000 [4], they stated:

> The historic mechanism of step function LOSs should be abandoned in the next full edition of the HCM in favor of multiple measures of effectiveness and numerical values from continuous relationships. The judgment implicit in LOS-specific definitions should be left to decision makers and transportation professionals.

Making decisions locally for defining conditions was addressed by Kittelson and Roess [6]: “Abandonment of the arbitrary labeling of conditions as LOSs A to F allows local jurisdictions to set their own targets for acceptability.”

Dowling, et al. [1] pointed out that “the same conditions in various regions are perceived as different levels of service, therefore the threshold should be different in different regions, according to local conditions.”

Some studies concerning the measurement of user perception have used “natural language” to gather feedback from users on transportation performance. The earliest example found was research by Sutaria and Haynes [7], who surveyed user perceptions of service quality at signalized intersections. In their study, participants were asked to rate the quality using two scales: one scale was a numerical scale from 0 to 5, and the other used “natural language” descriptions (e.g., the words *excellent, very good, good, fair, poor,* and *very poor*).

The HCM 2010, including the Urban Streets chapters, retained the use of LOS, including the key features of the LOS concept, such as having six service levels from A through F and no further distinction within LOS F. The thresholds for the various LOSs continued to be established by the creators of the HCM, i.e., TRB's Committee on Highway Capacity and Quality of Service. In addition, the thresholds continued to be the same for different regions. A new feature of method development was that travelers' perceptions were considered.

## 2.3 Comparability of LOS Results Across Modes

Dowling et al. [1] concluded that the various editions of the HCM, including the HCM 2000, did not provide comparable LOS results across modes (within HCM methods). They stated: "This is due to different definitions of level of service and different measurement scales used by the various manuals for each mode." The HCM 2010 provides elements of comparability for the pedestrian and bicycle methods, both of which were developed based on feedback from users, and uses the same conversion table to turn the scores produced by the measurement methods into LOSs. However, LOSs across the auto, transit, and non-motorized (pedestrian and bicycle) modes continued being measured differently in the HCM 2010 and continued not being comparable.

## 2.4 Impact of Modes on Other Modes

The four modes on urban streets compete within the same right of way, inevitably impacting one another. For example, higher auto volumes resulting in increased travel time is likely to reduce LOS for transit services. At the intersections all four modes are competing for right of way and time.

The HCM 2010 [2] urban streets methods include some cross-modal influences. The impact of the auto mode on the three other modes is considered along with the impact of the pedestrian mode on the transit mode. Neither the impact of the transit or bicycle mode on the other modes nor the impact of the pedestrian mode on the auto and bicycle modes is considered. Table 2-1 provides a summary of which impacts are considered and which are not.

Table 2-1. Impact of Modes on Other Modes Considered in HCM 2010 Urban Streets

| Mode | On Auto | On Transit | On Pedestrian | On Bicycle |
|---|---|---|---|---|
| Auto impact | ~~ | Yes | Yes | Yes |
| Transit impact | No | ~~ | No | No |
| Pedestrian impact | No | Yes | ~~ | No |
| Bicycle impact | No | No | No | ~~ |

## 2.5 Accuracy of the HCM 2010 Methods

Kittelson and Roess [6] questioned the accuracy of the methods in the HCM 2000 and concluded: “The point is that there is very little knowledge of the ultimate accuracies of most HCM methodologies, from input variables to the predicted measures of effectiveness.” They stated further: “If the degree of increased accuracy is insufficient to affect final investment and design choices, . . . a simpler and slightly less accurate procedure may be equally or even more effective.” They were also concerned about the increase of “black boxes” for users of the HCM methods, the validity of which is unknown to users of the methods. They also pointed out that complex models tend to be data intensive and that, the absence of quality data is an ongoing issue in transportation. The HCM 2010 [2] urban streets methods require data in addition to what was needed for the HCM 2000 [4] methods.

The HCM 2010 retained speed as the metric for the auto LOS. However, instead of average travel speed used in the HCM 2000, the HCM 2010 considers travel speed as a percentage of base free-flow speed. The base free-flow speed estimation method for urban streets in the HCM 2010 is based on the HCM 2000 [8]. The difference is the addition of procedures that were developed to improve the accuracy of the estimated running time and control delay by the HCM 2000. The new procedures estimate: delay due to turning vehicles, running time (including free-flow speed), arrival flow profile, actuated phase duration, stop rate at a signalized intersection, and capacity constraints. Bonneson, et al. [3] do not provide information on the accuracy of the HCM 2010 travel speed estimation procedure to predict field speed measurements. Speed predictions by the new method were compared with that of the HCM 2000 method, and the regression analysis resulted in an $R^2$ of 0.99, which means that the methods yield similar results. However, getting similar results does not provide information on accuracy. [1]. Travel speed estimation is based on assuming uniform arrivals and stable flow and is not applicable to congested conditions when the volume to capacity ratio is greater than 1.0 [8]. The HCM 2010 introduced significant changes in establishing auto LOS thresholds by having just one category for urban streets instead of the previous four in the HCM 2000.

When developing models for the four modes in the HCM 2010, Dowling et al. [1] showed video clips of actual street operations for the auto, pedestrian, and bicycle modes in four metropolitan areas: Chicago, Illinois; San Francisco, California; New Haven, Connecticut; and College Station, Texas. At each location, study participants rated 10 or more video clips per mode from *A* to *F*, with *"A"* representing the highest performance and *"F"* the worst. Definitions for the various LOSs were not provided. Transit data were collected through surveying passengers traveling on buses.

Based on the LOS ratings of the videos by the participants, a distribution of probabilities was provided for each letter grade of service. The researchers then used a conversion table to convert the distribution of LOS ratings into a single LOS grade. Model features were as follows:

- automobile traveler perception model: 69% fit, does not produce LOS A
- transit LOS model: 21% fit, does not produce LOS C, D, E and F
- pedestrian LOS model: 43% fit, does not produce LOS F

- bicycle LOS model: 27% fit, does not produce LOS A and B.

Of these models, the auto traveler perception model was not adopted in the HCM 2010 to calculate LOS; it was, however, adopted as an additional measure to provide a traveler perception score. The transit, pedestrian, and bicycle models were adopted in the HCM 2010 to calculate LOS.

Carter et al. [9] performed sensitivity testing to measure how the HCM 2010 multimodal LOS scores responded to changing inputs. The researchers found that: "Although many inputs performed as expected, the testing also found model responses that were of a questionable direction or magnitude." There were cases when "the results were logical but possibly contrary to what a community would expect when creating a desirable environment for walking and bicycling."

## 2.6 User Perception

Dowling, et al. [1] found that the HCM methods do not predict LOS from the traveler's perspective; instead, the methods focus only on the measurements needed for transportation professionals. This resulted in the earlier described approach to developing the HCM 2010 urban streets methods by showing video clips of actual street operations and gathering feedback from travelers.

Kikuchi and Chakroborty [10] surveyed state DOT professionals, 35% of whom believed "that fewer than six categories would be sufficient for practical applications." (The six categories are LOS A, B, C, D, E and F.) Pecheux, et al. [11] showed that users perceived only three or four levels of service and were more tolerant of delay than the HCM 2000 suggested. Fang and Pecheux [12] found that users did not distinguish between LOS A and B, but they did further differentiate within LOS F. These observations are also applicable to the HCM 2010, since it retained the traditional six LOS levels from A through F and further distinction within LOS F was not introduced [2].

Carter et al. [9] suggested that the HCM 2010 urban streets

> “scoring system does not reflect the ability of public agencies to meet user expectations” and “underestimates the benefit of changes that fall short of perfection. Fiscal, political, and physical constraints are often severe, and the measurement of performance on the basis of unconstrained user perspectives is disconnected from this reality.”

The researchers concluded that the HCM 2010 urban street method “results are not sufficient by themselves to provide a complete picture of street performance.”

## 2.7 Research Efforts to Address HCM 2000 Shortcomings

Following the publishing of the HCM 2000 various research efforts were undertaken to address its shortcomings. Again, literature review results are presented in the following topic areas: use of step function LOSs, comparability of LOS results across modes, effect of modes on other modes, accuracy of the HCM 2000 models, and users’ perceptions in measuring multimodal conditions on urban streets. An overview of the development of the HCM 2010 urban streets methods was presented earlier, as part of discussing the methods’ accuracy.

### 2.7.1 Use of Step Function LOSs

As described earlier, concerns were raised in the literature relating to the use of the LOSs and a recommendation was made to replace it with “multiple measure of effectiveness and numerical values from continuous relationships” [6]. However, this recommendation was not followed up with developing the HCM 2010 models.

Research efforts concerning the measurement of users’ perception have used natural language to gather feedback from users on transportation performance. The use of natural language, in place of the labeling LOS A through F, might support better understanding of the measures by system users. As described earlier, the earliest example found for the use of natural language was research by Sutaria and Haynes [7].

The first edition of the Transit Quality Service Manual (TQSM), published in 1999 [13], introduced an “A” to “F” classification system similar to that of the HCM 2000 [4]. The A to F scales for the various features measured are associated with numerical values. However, verbal descriptions are also provided, which can easily be turned into natural language descriptions.

### 2.7.2 Comparability of LOS Results Across Modes - Normalizing Across Modes

Measures in the HCM 2000 are calculated differently and separately for each mode**.** To determine how stakeholders “use LOS measures to make decisions and how they would prefer to do so in the future,” Winters and Tucker [14] interviewed “representatives from the Florida Department of Transportation (FDOT), various city and county governments throughout the state [of Florida], several MPOs, a number of transit agencies, and a few private citizens.” Interview results showed that “stakeholders believe that multimodal LOS measures should be used to promote a balanced multimodal transportation system by modeling all modes.” Also, “the necessity of assessing LOS equally across modes” was emphasized.

Based on expert panel input, Winters and Tucker [14] evaluated seven methods to select an alternative method that correlates the LOS for each mode with user perceptions and “keeps the current LOS methods in place but seeks to interconnect LOSs by finding the link to user needs as a common characteristic.” The basic slide rule method was selected. It was recognized, however, that this does not allow assessing LOS equally across modes. Using the basic slide rule, planners can align the LOSs of each mode by moving the bars for the LOSs of different modes to align them at the actual LOS.

### 2.7.3 Impact of Modes on Other Modes

Outside of the research efforts to develop the HCM 2010, which was described earlier, no literature was found addressing the impacts of modes on other modes.

### 2.7.4 Accuracy of the HCM Models - Speed Estimation Methods

According to Dowling et al. [1] travel speed explains 64% of the variation in LOS ratings for the auto mode in the HCM 2000 and travel speed is also a critical factor in transit, pedestrian, and bicycle LOS. A higher speed for the auto mode means higher LOS for buses mixed with traffic. The speed of motorized traffic impacts both pedestrians and bicyclists, since pedestrians are just a few feet away from the vehicles and bicyclists are mostly mixed with vehicular traffic. Higher vehicular speeds result in lower LOS for pedestrians and bicycles.

Speed can be estimated or collected in the field. Various speed estimation methods have varying levels of data needs and accuracy. Speed data collection is time-consuming and can become expensive. Since the focus of this research was to measure performance along a signalized, often congested arterial, the literature review of speed estimation also focused on how the various methodologies perform with regard to congested conditions. Attention was also given to validation issues for the methodologies. The focus on interrupted arterial highway was emphasized, since speed estimation issues for these types of highways and uninterrupted facilities are very different. Although the body of literature regarding speed estimation for uninterrupted highways (i.e., interstates) is fairly large, the literature regarding interrupted highways (i.e., signalized arterials) is more limited.

Traditional methods, applicable to interrupted highways, investigated by Dowling et al. [15] included the Bureau of Public Roads (BPR) curves, the Davidson-Akçelik formula, and the Surface Transportation Efficiency Analysis Model (STEAM). All of the investigated methods share the same basic concept for travel time estimation, which is to add delay time to free flow time. The various methods estimate free flow speed and delay different ways. Dowling et al. [15] found errors in speed estimation of these methods ranging from 26% to 39% when compared to field data.

Skabardonis and Dowling [16] compared estimated speeds by the various techniques with speeds predicted by TRANSYT-7F, a computer-based traffic analysis tool, for a range of traffic conditions on a real-world arterial. They found that the standard BPR curve predicted lower speeds for v/c < 1 and higher speeds for over-capacity conditions, which does not accurately represent conditions. The Davidson-Akçelik model overestimated delay by overestimating the effect of queueing on arterial speeds. STEAM, as the BPR model, relies mainly on v/c ratios, free flow speed and delay and has similar limitations to the BPR model in representing arterial conditions.

Lin et al. [17] proposed an alternative model for arterial travel time prediction that decomposes total delay on an arterial into link delay and intersection delay. The model's key component is a one-step transition matrix, in which the delay to a through vehicle at an intersection depends on its delay status at the adjacent upstream intersection. Thus, the model requires the delay status of each vehicle, for which field data is not available and can only be estimated from simulation results.

The HCM 2000 [4] estimates average speed along an arterial on the basis of detailed calculation of average delays at each intersection. Tarko et al. [18] questioned the practicality of this degree of detail. They raised the issue of complexity versus accuracy and undertook research to develop a simple and practical method to estimate average speeds along urban arterials. For input they require only planning level data, such as the number of lanes, the distance between signalized intersections, one-way traffic volumes, and speed limits. Their model to estimate speed was developed based on the HCM delay formula and considered only non-congested conditions.

As discussed in chapter 2.5 (Accuracy of the HCM 2010 methods), the HCM 2010 speed estimation yield similar results to the HCM 2000, i.e. speed estimation did not improve in the HCM 2010 and is still not applicable to congested conditions (when v/c ratio is >1).

In summary, traditional speed estimation methods for signalized arterial highways have significant shortcomings, including levels of inaccuracy. Most significantly, they are not applicable for congested conditions. The alternative methods by Lin et al. [17] and Tarko et al. [18 are in the early stage of development. They do attempt to overcome the shortcomings of the earlier methods. However, the method by Tarko et al. [18] shares the problem of traditional methods in not being applicable to congested conditions. By requiring simulation results, the method by Lin et al. [17] defeats one of the basic goals of speed estimation methods, which is to estimate speeds without having to go to the extent of undertaking simulation.

### 2.7.5. User Perception in Measuring Multimodal Conditions on Urban Streets

Concerns relating to HCM 2000 [4] methodologies include the extent to which LOS estimates correspond to road user perception. Pecheux et al. [11] aimed to (1) develop and test a methodology to obtain drivers' opinions with regard to urban street quality of service (QOS); (2) apply the methodology to identify the factors that affect drivers' perceptions of QOS on urban streets; and (3) provide a qualitative foundation for the development of quantitative QOS tools that are based on the perceptions of drivers.

An in-vehicle field approach was used to determine the factors that affect automobile drivers' perceptions of service quality on urban streets. While driving on a pre-selected route, 22 participants in four cities were asked to speak aloud about their driving experience and the factors that influenced their perception of service quality. Afterward, drivers also completed a written questionnaire. The drivers expressed their opinions about a wide range of issues, including simple observations, more detailed evaluations, and broad concerns related to the roadway environment. From the drivers' comments, 40 factors were identified as relevant to their perception of service quality on urban streets.

It is important to note that the participants in this study were not making time-constrained trips to work or home. If those trips were time-constrained, travel time would be of greater importance and therefore a topic of discussion. Specifically, drivers expressed a need for safety, efficient and continuous traffic flow, adequate and accurate guidance information, and a visually appealing environment.

Flannery et al. [19] tested the ability of LOS to predict drivers' perceptions of service quality. They compared drivers' assessments of the performance of urban streets with objective measures of performance, including LOS. Seventy-seven automobile drivers rated the service quality of half-mile segments of urban streets as depicted on videotaped scenes from the driver's perspective. LOS, calculated by the HCM 2000 [4] method, predicted 35% of the variance in mean driver rating. This finding suggests that LOS is significantly limited in representing drivers' assessments of performance because drivers perceive the quality of urban street segments in several dimensions, including travel efficiency, sense of safety, and aesthetics.

The authors concluded:

> As noted by the U.S. DOT Office of Operations, "Performance measures should reflect the satisfaction of the transportation service user, in addition to those concerns of the system owner or operator." The results from this study highlight "the complexity of the issues and the need for a programmatic effort to develop comprehensive, cost-effective, and practical tools that traffic engineers can use to measure drivers' assessment of quality."

## 2.8 Summary of the Literature Review

In summary, several changes were introduced for Urban Streets in the HCM 2010 to address previous research findings, such as considering user perception, the effect of modes on other modes and the comparability of LOS results across modes. Even though these issues were only partially addressed, progress was made. The accuracy of the HCM Urban Street methods, however, is lacking, procedures remained complex and data intensive, and a number of issues were not addressed, such as measuring congested conditions, fully considering the modes' impact on each other, considering regional differences and the shortcomings of the LOS step functions.

The literature review found publications that identified significant shortcomings of the HCM 2010, thus it shows the need for the development of an alternative method to assess multimodal conditions on signalized, often congested urban arterials.

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# Chapter 3 An Alternative Method for Recurrent Conditions

## 3.1 Introduction

As stated previously, an alternative method for the HCM 2010 urban streets methods was developed in this research. Key aspects of this method include using step functions in a modular framework; using deficiency indices; addressing comparability of measures across modes; incorporating the impact of modes on other modes; and determining the time period of the analysis and length of the facility analyzed. Concerns raised in the literature review were considered, and attempts were made to incorporate them in the method development.

The alternative method continues to use step functions but uses them differently than the HCM 2010. To establish step functions for measuring conditions, it is necessary to specify (1) how many condition levels are established; (2) what naming (or labeling) convention is used for the condition levels; (3) the thresholds for the condition levels (two important aspects are where thresholds are set and who determines the thresholds; a related critical issue is whether thresholds are the same nationally or determined locally); (4) what input parameters are used; and (5) what method(s) is used to process input parameters to get output.

The method presented can fit the needs of individual users and available data. It also provides for expansions should more data become available and as desired by the user.

## 3.2 Significance of the Research

The literature review revealed a number of concerns regarding the HCM's urban streets chapters that provide methods to analyze the performance of four modes (auto, transit, pedestrian and bicycle) on urban and suburban arterial highways. In addition, the literature review demonstrated that issues relating to urban streets were mostly addressed in a non-comprehensive manner. Individual issues have been researched separately, with limited success. The method developed in this chapter intended to address previously unresolved issues by answering the following questions:

- What method development approach will result in a comprehensive, systematic method to measure multimodal performance on urban and suburban arterials?
- How to address previously unresolved issues relating to user perception, use of LOS, cross modal influences, and comparability of measures across modes?

The following sections describe in detail the development of an alternative method to measure conditions on multimodal urban streets.

## 3.3 Establishing Condition Levels

### 3.3.1 Number of Condition Levels

The method includes five levels of conditions: two within the acceptable range of conditions, two within the unacceptable range of conditions, and a fifth condition is designated for extreme conditions when a mode is dysfunctional, for example, a mode is not available (for example, there is no transit service when it is needed).

### 3.3.2 Naming Convention and Thresholds for Condition Levels

In the alternative method, the expression of “condition level” instead of LOS is used for the step functions. Condition levels are described with the use of natural language, since the use of natural language might improve the understanding of the condition levels by the public and other stakeholders. Natural language might also provide for a certain degree of comparability of measures across modes.

For the purpose of further describing the concept, the naming scenario of *Good, Fair, Poor, Awful,* and *Extreme* is used. (Other naming scenarios might also be used. This naming scenario was chosen by the author for demonstration purposes.) These conditions are defined separately for the four modes, but there is an underlying unifying concept. Within acceptable conditions, which are above the traditional LOS F threshold, there are two levels of conditions: *Good* and *Fair.* Further, two intervals are created within unacceptable conditions: *Poor and Awful.* A condition can deteriorate beyond *Awful* and might be termed *Extreme.* For the auto mode, *Extreme* may occur when congested conditions deteriorate further as a result of non-recurrent incidents. It is assumed that *Extreme* conditions do not occur under recurrent conditions. In the transit, pedestrian, and bicycle modes, *Extreme* may depict conditions when use of the mode is not possible.

*Good* is not intended to be equal to LOS A in HCM 2010 (*2*), because *Good* is not ideal whereas LOS A often is. The condition levels in this concept can be related to the HCM 2010 urban streets LOSs. For example, for the auto mode, the following might be assumed: LOS A, B, and C are within *Good;* LOS D and E are within *Fair;* the upper range of LOS F is *Poor;* the lower range of LOS F is Awful. *Extreme* occurs when *Awful* deteriorates as a result of incidents for the auto mode and traffic is completely stopped.

The descriptions of the five conditions in this method may be developed to reflect differences between different locations by defining conditions and thresholds region by region or even locality by locality within a region.

## 3.4 Input Parameters

For each of the four modes, three features are measured: (1) physical features (PF); (2) operational features (OF); and (3) intermodal features (IF) (impacts by other modes). Each feature is described by a varying number of characteristics. When applying the method, decision makers and stakeholders would determine what specific features and characteristics to include. The number of characteristics included to describe a feature can be changed; i.e., any number of characteristics can be included. Examples of potential characteristics (c) to describe the three features of the four modes are shown in Table 3-1. Characteristics from the HCM 2010 were included with selected additional characteristics from Dowling et al. [1] and Kittelson & Associates, Inc. et al. [20]. Each characteristic is rated by assigning to each characteristic one of five conditions: *Good, Fair, Poor, Awful,* or *Extreme.*

Table 3-1 Characteristics (c) to Describe Features of the Four Modes

| **Mode** | **Characteristics to Describe Physical Features** | **Characteristics to Describe Operational Features** | **Characteristics to Describe Intermodal Features** |
|---|---|---|---|
| Auto | $c_1$:lane width<br>$c_2$:presence of parking<br>$c_3$:presence of median<br>$c_4$: frequency of median breaks<br>$c_5$: frequency of driveways | $c_1$:vehicle volume/capacity ratio<br>$c_2$:average travel speed<br>$c_3$:signal progression<br>$c_4$:number of vehicle stops<br>$c_5$:travel time reliability<br>$c_6$: incident recovery time | $c_1$:delay caused by transit<br>$c_2$: delay caused by pedestrians<br>$c_3$: delay caused by bicycles |
| Transit | $c_1$: percent of transit stops with shelters<br>$c_2$: percent of transit stops with benches<br>$c_3$:maintenance quality of transit stops | $c_1$:headway<br>$c_2$: transit travel time<br>$c_3$:headway variability<br>$c_4$:passenger crowding<br>$c_5$:hours of operation | $c_1$:delay caused by auto mode<br>$c_2$:accessibility by pedestrians<br>$c_3$: accessibility by bicycles |
| Pedestrian | $c_1$:existence of sidewalks<br>$c_2$:width of sidewalks<br>$c_3$: condition of sidewalks<br>$c_4$:distance from vehicular traffic<br>$c_5$:crossing conditions<br>$c_6$: ADA accessibility | $c_1$:pedestrian volume/capacity ratio<br>$c_2$:midblock crossing delay<br>$c_3$:intersection crossing delay | $c_1$:auto impact on pedestrians<br>$c_2$: transit impact on pedestrians<br>$c_3$:bicycle impact on pedestrians |
| Bicycle | $c_1$: existence of bicycle lane<br>$c_2$:width of outside through lane<br>$c_3$:travel lane pavement quality<br>$c_4$:width of shoulder<br>$c_5$:shoulder pavement quality<br>$c_6$:presence of auto parking | $c_1$:bicycle volume<br>$c_2$:intersection crossing delay<br>$c_3$:bicycle speed | $c_1$:auto impact on bicycles<br>$c_{2:}$ transit impact on bicycles<br>$c_3$:pedestrian impact on bicycles |

ADA = American's with Disabilities Act.

## 3.5 Using Deficiency Indices

Each of the five ratings is assigned a deficiency score (DS). For method development demonstration purposes, the following deficiency scores were assigned to the ratings on a scale of 0 to 5: *Good:* $DS_G = 0$; *Fair:* $DS_F = 1$; *Poor:* $DS_P = 2.5$; *Awful:* $DS_A = 4$; *Extreme:* $DS_E = 5$. *Good* conditions are not deficient by definition, so their DS is 0. The reasonableness of the assumed values was tested by gathering feedback from transportation professionals through a survey.

The impact, or weight, of characteristics in determining deficiency levels also varies. For example, when determining the deficiency level of the characteristics of the pedestrian mode, the existence (or absence) of sidewalks has a larger impact than the width of sidewalks (where they exist). To account for the differences in impact, each characteristic is assigned a weight (W) on the scale of 1 to 5 (least weight is 1, most weight is 5). For example, for the characteristic of existence of sidewalks (pedestrian mode, physical features, characteristic 1)

$$W_{p,PF,c_1} = 5$$

and for the width of sidewalks

$$W_{p,PF,c_2} = 2$$

might be appropriate since the absence of sidewalks might pose safety and connectivity issues for pedestrians whereas narrow sidewalks might pose lesser problems.

Characteristic deficiency indices (cDI) are calculated for each characteristic (c) of each feature (F) of each mode (m) by combining the deficiency score of the characteristic (cDS) with the weight of the characteristic ($W_c$). Thus a deficiency index for a given characteristic of a given feature of a given mode is $cDI_{m,F,c_n}$.

$$cDI_{m,F,c_n} = cDS_{m,F,c_n} * W_{m,F,c_n} \tag{3-1}$$

Where:

- $cDI_{m,F,c_n}$ = characteristic deficiency index for mode m, feature F, characteristic $c_n$

  $cDS_{m,F,c_n}$ = characteristic deficiency score for mode m, feature F, characteristic $c_n$

- $W_{m,F,c_n}$ = characteristic weight for mode m, feature F, characteristic c
- mode (m): a = auto, t = transit, p = pedestrians, and b = bicycles
- feature (F): PF = physical features, OF = operational features, and IF = intermodal features
- characteristic (c): characteristic of a feature.

A feature deficiency index $FDI_{m,F}$ will then be calculated for each feature (F) of each mode (m) by calculating the average of the characteristic deficiency indices of the n number of characteristics:

$$FDI_{m,F} = (\sum_{n=1}^{n} DI_{m,F,c_n})\frac{1}{n} \tag{3-2}$$

To arrive at a deficiency index ($MDI_m$) for each mode, the average of the deficiency indices of the three features is calculated:

$$MDI_m = (\sum_{F=1}^{F=3} FDI_{m,F})\frac{1}{3} \tag{3-3}$$

## 3.6 Addressing Comparability of Measures Across Modes

The described concept of condition levels (two conditions within the acceptable range and two within the unacceptable range, with the addition of *Extreme*) can contribute to some degree of comparability. Striving for a large degree of comparability might not be realistic, however. In addition to different regions possibly defining the same level of conditions differently, different users within the same region might define the same condition levels differently.

In addition, measuring each of the four modes involves some metrics that are similar or the same across modes, but mode-specific measures (that are not used across modes) are also involved. For example, vehicular speed is a metric that is relevant to all for modes, but transit service frequency applies to transit only; sidewalk availability applies to pedestrians and transit (for connectivity measures); and the presence of parallel parking impacts bicyclists the most (even though differently, but it impacts the other three modes also).

## 3.7 Determining Time Periods for Analysis and Length of Facility Analyzed

The time periods for analysis need to be identified so that all periods with less than *Good* conditions are included. Another way to express this is to state that the time period analyzed needs to start with a *Good* condition, move through deteriorated conditions, and get back to a *Good* condition.

The length of the analyzed section is determined so that it contains all spillback. (Queue spillback occurs when vehicles cannot pass through the downstream intersection. Queue spillback can extend through upstream intersections in congested conditions.) The section may include both unsignalized and (non-critical) signalized intersections. Typically, a section is formed between a critical intersection and another signalized intersection or ramp terminal or another (the next) critical intersection. Each direction is analyzed separately.

Before each characteristic is rated from *Good* to *Extreme*, uniform (reasonably uniform) sections and time periods need to be identified. If the entire section analyzed has consistent physical features for all four modes, there is no need to divide it into segments before the physical characteristics are rated. However, if the section analyzed has segments with different physical features, it needs to be separated into segments before the physical features are rated. For example, the section needs to be divided into segments if one segment has parallel parking and the others do not or one segment has sidewalks and the others do not.

The time periods analyzed are expected to be determined by operational features for the auto and transit modes.  Time periods can be divided along the travel speed periods and transit service headways.  For example, if during the morning peak period the travel speed periods are *Good, Fair, Poor, Awful, Fair,* and *Good,* each condition would become a time subperiod (these subperiods do not need to be the same length of time).  If transit service headways change during the analyzed time period, that would need to be accounted for and reconciled with the time periods that are based on the travel speed.

The deficiency index for physical features for the entire section is calculated as a proportional (by length) average of the segments' deficiency indices.  Deficiency indices for operational features and intermodal features are calculated as the proportional (by length of time of subperiods) average of subperiod deficiency indices.  Deficiency indices for the four modes are not combined into one deficiency index.

## 3.8 Conclusion for This Chapter

The alternative method to measure recurrent multimodal conditions on urban streets developed in this research addressed the shortcomings of the HCM 2010 LOS step functions by introducing step functions based on natural language with fewer steps within acceptable LOS and additional steps within unacceptable LOS.  The modular deficiency index provides for the comparability of LOS results across modes.  The alternative method fully considers the impacts of modes on other modes through considering intermodal characteristics.  The method has the flexibility to allow adjustment of the LOS thresholds and to include additional characteristics when desired by regions or localities.  In addition, weights of characteristics and deficiency scores can also be adjusted by users of the alternative method.

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# Chapter 4 Feedback From Transportation Professionals

## 4.1 Feedback on the Literature Review Findings and the Alternative Method

### 4.1.1 Methodology for Gathering Feedback

In this next step of the research, panels of practitioners were formed and meetings held to gather feedback relating to literature review findings and key elements of the alternative method presented in the previous chapters. The authors of most of the published literature are members of academia or the larger transportation research community, with limited involvement by practitioners, i.e. transportation professionals who apply performance measures in their daily work. The target audience for gathering feedback on the potential usefulness of the alternative method included practitioners.. Academics and researchers were not included. Four panels of practitioners were formed and face-to-face meetings held to gather feedback relating to literature review findings and key elements of the alternative method developed.

### 4.1.2 Description of Practitioner Panels

The panels were formed in the two most urbanized regions of Virginia, where congestion is frequent on multimodal urban and suburban arterials: Northern Virginia (NOVA) and Hampton Roads (HR). Transportation planning managers of VDOT's NOVA District, Fairfax County's Department of Transportation (DOT), Arlington County and VDOT's HR District were asked to assemble groups consisting of transportation planners and traffic engineers, including both managers and professional staff, who were familiar with the HCM 2000 and potentially the HCM 2010. Participants' familiarity with the HCM 2000 varied from basic knowledge of HCM 2000 methods to being regular users of the HCM 2000. Analyzing urban streets or reviewing an analysis of urban streets by others (for example, developers) were frequent tasks for participants. The panel meetings took place during the months of August and September of 2013. At that time only a few participants were familiar with the HCM 2010 and most have not yet used the HCM 2010 methods. The HCM 2010 became available in 2011 [2]; software to use the HCM 2010 started to become available during the year following publication, in 2012. Software availability was followed by training course offerings in 2012 and 2013. Participants explained that at the time of the panel meetings, according to VDOT guidance, they had a choice of using either the HCM 2000 or the HCM 2010. Mostly they chose working with the HCM 2000, for having familiarity with it.

No participant expressed having familiarity with how the HCM 2010 methods were developed. Analyzing urban streets or reviewing an analysis of urban streets by others (for example, developers) were frequent tasks for participants and the HCM 2000 had been an often used analytical tool. With being only recently published, the HCM 2010 has had few applications.

### 4.1.3 Activities of Practitioner Panels

Three meetings were held in NOVA (one with each panel) with transportation staff of VDOT's NOVA District (7 attendees), Fairfax County's DOT (6 attendees) and Arlington County (8 attendees). One meeting was held in HR with 9 attendees from VDOT's HR District Office and 5 from 5 different HR localities (Norfolk, City of Chesapeake, Portsmouth, City of Virginia Beach and Newport News). All four panels were a mix of professional staff (2/3 of participants) and managers (1/3 of participants), working with either in a transportation planning (4/5 of participants) or traffic engineering area (1/5 of participants). Most attendees dealt with all four modes of travel on urban streets, with various degrees of involvements.

Each meeting lasted between one and a half and two hours and had the following same activities:

1. The researcher made a short presentation about how the HCM 2010 LOS calculation methods were developed for the four modes of the urban street and the differences between the HCM 2000 and HCM 2010.
2. The researcher provided an overview of HCM literature review completed for this study.
3. The researcher administered a written questionnaire to assess participants' opinions on observations made in the literature relating to multimodal measures for urban streets in the HCM 2000 and HCM 2010. The questionnaire is provided in Appendix A.
4. The researcher presented key elements of a possible alternative method, to measure conditions on multimodal, congested urban/suburban arterials.
5. The researcher administered a second questionnaire to group participants relating to the key elements of the alternative method. The questionnaire is provided in Appendix B.

6. Open discussion. Comments during open discussion were captured by the researcher's note taking. Draft notes were then e-mailed to participants for comments and clarification, based on which notes were finalized for each of the four group meetings.

### 4.1.4 Survey Results and Open Discussion Comments Regarding to Statements in Literature

#### 4.1.4.1 Introduction

Survey results and summaries of open discussions were summarized by topic area. Tables 4-1 through 4-6 show the level of agreement by panel members with statements made in the literature that are relevant for measures of urban streets in the HCM.

#### 4.1.4.2 Use of the LOS Concept

Table 4-1 Panel Questionnaire Results Regarding to Literature Review Findings, Use of the LOS Concept, N=35

| **Use of the LOS Concept** | Strongly Disagree (%) | Disagree (%) | No Opinion (%) | Agree (%) | Strongly Agree (%) |
|---|---|---|---|---|---|
| 1. The concept of levels of service (LOSs) should be abandoned in the next full edition of the HCM. | 26 | 50 | 6 | 18 | 0 |
| 2. Multiple measures of effectiveness should replace LOS. | 6 | 44 | 9 | 37 | 5 |

Of the panel participants 76% disagreed, or strongly disagreed with the statement made in the literature that "The concept of levels of service (LOSs) should be abandoned in the next full edition of the HCM" [6]. Opinions were divided about replacing LOS with multiple measures of effectiveness, with more opposition (50%) than support (42%).

**Open Discussion.** Many participants stated that they found the first statement the hardest to respond to, because they saw both significant advantages and disadvantages of the LOS system. They expressed the following advantages of the LOS concept used in the HCM:

- Using the same HCM methods with the same LOS A-F calculations provides consistency across regions, i.e. projects in one region can be compared to projects in other regions.

- National standards (as consistent, quantitative measures) are needed for engineers.
- LOS A-F concept helps; generally people understand the grade system A-F; they all had it in school.

Disadvantages and concerns expressed include:

- The public does not realize that there are many different A-F scales.
- Distinction by the public between the different A-F scales within the HCM is not sufficient.
- There is no gradation within LOS F; gradation is needed.
- LOS A-F was developed with focus on the auto mode. The non-auto modes were added much later and are still much less developed in the HCM, than the auto mode. The HCM needs to be strengthened for the non-auto modes. In the next HCM all four modes should have equal significance/weight.
- The LOS concept can contribute to miscommunication between system users, practitioners and decision makers about interpreting results. For example, people sometimes don't understand trade-offs between modes (for example, auto delay at an intersection vs. crossing time for pedestrians – sometime people expect to improve both at the same time).
- The HCM's direction to get into users' perception of LOS was misguided. The HCM should be describing conditions. There should be science to measure quantitative data. (Also discussed later when addressing user perception related issues.)

Along with the strong support for consistent, quantitative measures, some participants expressed that translating those quantitative measure for the public with the use of natural language (good, fair, poor, etc.) might be useful in helping with understanding.

In addition to endorsing the LOS concept (with significant improvements), some participants recommended the addition of multiple measures of effectiveness, stating that having a combination of both would be best.

A concern was expressed that the HCM has been used to consider only highway expansion to solve transportation problems and to not consider well enough the other modes (transit, pedestrian and bicycle) that are typical features of urban conditions.

#### 4.1.4.3 Comparability of LOS Results Across Modes

Table 4-2 Panel Questionnaire Results Regarding to Literature Review Findings, Comparability of LOS Results Across Modes, N=35

| **Comparability of LOS Results Across Modes** | Strongly Disagree (%) | Disagree (%) | No Opinion (%) | Agree (%) | Strongly Agree (%) |
|---|---|---|---|---|---|
| 3. Current LOS calculation results are not comparable across different transportation modes in HCM methods. | 0 | 4 | 7 | 68 | 21 |
| 4. Measures (LOS or other measures) should be comparable across modes. | 2 | 33 | 15 | 35 | 14 |

Respondents mostly agreed (89% agreed or strongly agreed) with the research finding by Dowling et al. [1] that current LOS calculation results are not comparable across different transportation modes in HCM methods. However, opinions were divided whether measures should be comparable across modes (35% disagreed or strongly disagreed and 49% agreed or strongly agreed).

**Open Discussion.** Comments were made that measures being comparable across modes might not be possible. A reason for disagreeing with making measures comparable across modes was given as: factors that impact each mode are different, for example, pedestrian measures could be based on lack of sidewalks, vs. congestion (which is a potential measure for the auto mode) on sidewalks.

### 4.1.4.4 Effect of Modes on Other Modes

Table 4-3 Panel Questionnaire Results Regarding to Literature Review Findings, Effect of Modes on Other Modes, N=35

| **Effect of Modes on Other Modes** | Strongly Disagree (%) | Disagree (%) | No Opinion (%) | Agree (%) | Strongly Agree (%) |
|---|---|---|---|---|---|
| 5. More cross-modal influences should be incorporated into future Urban Streets related performance measures. | 0 | 2 | 0 | 76 | 21 |

The strongest agreement in the questionnaire related to the effects of modes on other modes: 98% of respondents agreed (76%) or strongly agreed (21%) with the statement that more cross-modal influences should be incorporated into future Urban Streets related performance measures.

**Open Discussion.** It was expressed by many participants that the four modes are competing for time and space within the same right-of-way and that the performance of a mode may hinder or support the performance of other modes. (For example, higher vehicular speeds for the auto mode might hinder bicycles and pedestrians, but support transit performance, or improved pedestrian performance might support transit services, but hinder auto performance.)

### 4.1.4.5 Establishment of Thresholds

Table 4-4 Panel Questionnaire Results Regarding to Literature Review Findings, Establishment of Thresholds, N=35

| **Establishment of Thresholds** | Strongly Disagree (%) | Disagree (%) | No Opinion (%) | Agree (%) | Strongly Agree (%) |
|---|---|---|---|---|---|
| 6. LOS thresholds should be determined by decision makers and transportation professionals (not the creators of the HCM). | 7 | 14 | 11 | 56 | 12 |
| 7. Local jurisdictions should set their own targets for various performance measures. | 17 | 18 | 3 | 52 | 10 |
| 8. Labeling of conditions as LOSs A to F should be abandoned. | 15 | 52 | 13 | 17 | 2 |
| 9. Performance measures thresholds should be different in different regions, according to local conditions. | 0 | 21 | 14 | 51 | 13 |

2/3 of participants thought that LOS thresholds should be determined by decision makers and transportation professionals and not by the TRB committees that create the HCM. Before establishing thresholds, the number of condition levels (currently there are six: LOS A, LOS B, LOS C, LOS D, LOS E and LOS F) need to be determined, along with deciding on the naming (or labeling) convention of the condition levels. A related critical issue is whether thresholds should be the same nationally or should be determined locally.

In response to the statement that local jurisdictions should set their own targets for various performance measures 62% of respondents agreed or strongly agreed, 35 % disagreed or strongly disagreed. Statement #9 addressed a similar topic and showed 64% support for establishing different thresholds in different regions, according to local conditions [1].

Regarding the naming convention of condition levels, as was found earlier, many participants favor the labeling of conditions using the grading system A through F (with making further distinction within F) and feel that it should not be abandoned: 68 % of respondents disagreed or strongly disagreed with the recommendation in the literature by Kittelson and Roess [6], that labeling conditions as LOSs A to F should be abandoned, 19% supported the abandoning of the LOS A to F labeling, and 13% had no opinion.

**Open Discussion.** Even though 68% of participants responded that the LOS A to F labeling should not be abandoned, they also made several critical observations. Comments were made that one of the reasons that the LOS A to F does not work is the missing distinction of service levels within F. A comment was also made that the HCM should add F1-F6 to further distinguish within the unacceptable LOS F.

Some participants expressed that additional measures, in addition to those provided by the HCM, would be useful to describe conditions and the additional measure could be labeled differently than A to F.

Opinions were divided relating to the question of who should be determining thresholds and whether thresholds should be different for different regions. Several participants agreed that the definition of what is “acceptable” does depend on location (region) and destination. (For example what is considered an acceptable highway level of service by a resident of Northern Virginia, may not be considered acceptable by a resident of Montana.)

One participant made a recommendation to not include value judgments in the HCM, i.e., the HCM should not establish thresholds and focus instead on describing conditions based on quantitative data.

The comment was made that the concept of defining condition levels locally needs more discussion, particularly relating to how such a concept would be implemented. While some participants saw advantages to localities being responsible for determining thresholds, they also saw associated risk, most importantly, potential for a lack of consistency across jurisdictions. If different jurisdictions identify different thresholds, comparison becomes very difficult. 35% of the respondents who disagreed or strongly disagreed were concerned about bringing additional tension into the transportation decision making process, where there is already too much difference of opinion within localities.

### 4.1.4.6 Accuracy of the HCM Methods

Table 4-5 Panel Questionnaire Results Regarding to Literature Review Findings, Accuracy of the HCM Methods, N=35

| **Accuracy of the HCM Methods** | Strongly Disagree (%) | Disagree (%) | No Opinion (%) | Agree (%) | Strongly Agree (%) |
|---|---|---|---|---|---|
| 10. HCM 2010 Urban Streets methods have an aspect of being "black boxes" for users of the HCM. | 0 | 13 | 29 | 56 | 2 |
| 11. The validity of HCM 2010 Urban Streets methods is unknown to user of the HCMs. | 0 | 13 | 13 | 58 | 15 |
| 12. Simpler procedures for HCM 2010 Urban Streets methods may be equally effective. | 0 | 6 | 27 | 64 | 2 |
| 13. Simpler procedures for HCM 2010 Urban Streets methods may be even more effective. | 2 | 6 | 27 | 60 | 5 |
| 14. HCM 2010 Urban Streets methods are data intensive. | 0 | 6 | 33 | 52 | 8 |
| 15. Absence of quality data is an on-going issue in transportation. | 0 | 8 | 19 | 46 | 26 |

The level of agreement (agree or strongly agree) regarding the accuracy of the HCM methods for the six statements (from statements #10 to #15), ranged from 58% to 74%. It was also noted that there were no or very few strong disagreements or strong agreements, except for the statement that the absence of quality data is an on-going issue in transportation (where 26% of respondents strongly agreed). However, percentages were unusually high for no opinion, ranging from 13% to 33%. 56 % of respondents agreed that the HCM 2010 Urban Streets methods have an aspect of being "black boxes" for users. 13% disagreed and 29% had no opinion.

3/4 of respondents agreed or strongly agreed with the statement that the validity of the HCM 2010 Urban Streets methods is unknown to users of the HCM.

2/3 of participants agreed that simpler procedures for the HCM 2010 Urban Streets methods might be equally or more effective.

60% of respondents agreed or strongly agreed that the HCM 2010 Urban Street methods are data intensive. There was little disagreement (6% of respondents disagreed) about the HCM 2010 Urban Streets methods being data intensive. However, 33% percent had no opinion.

**Open Discussion.** The reason some participants expressed for marking “No Opinion” was that they believed that their knowledge of the HCM methods is not deep enough, in particular the 2010 version, to express agreement or disagreement.

Some participants noted that the HCM is not used as a single reason for making a yes/no decision to recommend improvements; it is only one aspect of decision making. Still, it is a critical element in decision making and accuracy is essential. Several participants in each of the four panels were surprised by and were not aware of how significant the changes were between the HCM 2000 and HCM 2010 for Urban Streets, how the 2010 Urban Street methods were developed and what the implications were of changing from four urban street classes to one. They suggested that broader awareness in the transportation profession of these issues is necessary.

Comments were made that the HCM 2010 Urban Streets methods might seem to users as “black boxes”, because of the lack of interest (by the users of the HCM) in understanding the equations.

When learning about the model fits during the presentation about the development of the HCM 2010 methods, participants noted that the model fits (how the developed models fit the LOS of real life video clips, as described earlier) for transit, walking and biking are very low; they felt that one might as well guess LOS.

A comment was made that the auto mode method is particularly data intensive, but at the same time, it is not accurate enough.

#### 4.1.4.7 User Perception

Table 4-6 Panel Questionnaire Results Regarding to Literature Review Findings, User Perception, N=35

| **User Perception** (Users of the transportation system) | Strongly Disagree (%) | Disagree (%) | No Opinion (%) | Agree (%) | Strongly Agree (%) |
|---|---|---|---|---|---|
| 16. HCM methods do not predict LOS from the traveler's perspective. | 0 | 26 | 5 | 58 | 11 |
| 17. HCM measures are based on consensus by those who developed them. | 0 | 10 | 37 | 51 | 2 |
| 18. HCM measures are not representing accurately users' perceptions. | 0 | 23 | 25 | 45 | 7 |
| 19. Fewer than six service level categories would be sufficient for practical applications. | 2 | 37 | 6 | 37 | 18 |
| 20. Users perceive three or four levels of service. | 0 | 10 | 15 | 57 | 18 |
| 21. Users are more tolerant of delay than the HCM 2010 suggests. | 4 | 14 | 31 | 48 | 4 |
| 22. Users do not distinguish between LOS A or B. | 0 | 11 | 17 | 58 | 14 |
| 23. Users further differentiate within LOS F. | 0 | 24 | 12 | 48 | 17 |

While 69% of participants agreed or strongly agreed that the HCM methods do not predict LOS from the traveler's perspective, 26% disagreed.

37% of respondents had no opinion regarding the statement that the HCM measures are based on consensus by those who developed them (they cited unfamiliarity with this issue as a reason). 53% supported the statement.

Regarding to the accuracy of representing user perception, 53% of respondents agreed or strongly agreed with the statement that the HCM measures are not representing accurately users' perceptions. 23% disagreed and 23% had no opinion.

Even though 75% of respondents agreed (57% agreed and 18% strongly agreed) with the statement that users perceive three or four levels of service, only 57% of respondents agreed (37% agreed and 18 % strongly agreed) that fewer than six service level categories would be sufficient for practical applications.

Responses show a 72% agreement with the statement that users do not distinguish between LOS A and B. 65% of respondents agreed with the statement that users further differentiate within LOS F.

**Open Discussion.** As included in the literature review, several research projects recommended incorporating user perceptions into the HCM methods and strong emphasis was placed on doing so when developing the HCM 2010 urban streets methods. However, this assumption is not universally shared. A belief was expressed by some panel members that the HCM's direction to get into users' perceptions was unwise. A recommendation was made that the HCM should be describing conditions, based on quantitative data.

Several participants expressed that having more service levels makes project prioritization easier.

### 4.1.5 Survey Results and Open Discussion Comments Regarding the Alternative Method

#### 4.1.5.1 Introduction

Survey results and summaries of open discussions were summarized by topic area. Tables 4-7 to 4-11 include results of the questionnaire relating to the key elements of the alternative method. Each table represents a topic area. Summaries of open discussions are also provided relating to each topic.

#### 4.1.5.2 Determining the Segment Length to be Analyzed

Table 4-7 Panel Questionnaire Results Regarding to the Alternative Method, Segmentation, N=34

| **Segmentation** | Strongly Disagree (%) | Disagree (%) | No Opinion (%) | Agree (%) | Strongly Agree (%) |
|---|---|---|---|---|---|
| 1. The lengths of analyzed sections are to be determined so that they contain all spillback from the *critical* intersection. | 7 | 6 | 5 | 66 | 16 |

Regarding to what the lengths of analyzed sections are to be, 82% of respondents agreed (66%) or strongly agreed (16%) with the statement that the lengths of the analyzed sections should be determined so that they contain all spillback from the *critical* intersection. (emphasis in original questionnaire)

**Open Discussion.** Several participants commented that including all queues in the analyzed section makes sense. It was also noted that analyzing forecasted conditions may require longer sections (i.e. when queue is longer under future conditions).

### 4.1.5.3 Description of Condition Levels

Table 4-8 Panel Questionnaire Results Regarding to the Alternative Method, Description of Condition Levels, N=34

| **Description of Conditions** | Strongly Disagree (%) | Disagree (%) | No Opinion (%) | Agree (%) | Strongly Agree (%) |
|---|---|---|---|---|---|
| 2. Condition levels are to be defined locally. | 9 | 36 | 4 | 39 | 12 |
| 3. Factors impacting condition levels should be selected locally. | 3 | 35 | 4 | 45 | 13 |

Views were split regarding to the role of localities in defining condition levels and selecting factors that impact condition levels. Slightly more agreed (51%) that condition levels are to be defined locally (45% disagreed or strongly disagreed). 58% of respondents agreed or strongly agreed that factors impacting condition levels should be selected locally, 38% disagreed or strongly disagreed. There was slightly more support (7% more) for localities selecting factors, than for localities defining condition levels.

**Open Discussion.** Several members in each of the four panels disagreed with the concept of localities defining condition levels. They viewed that as having no standards any longer and stated that professionals need to have standards. They added, however, that various additional aspects that standards do not address could be evaluated through additional performance measures. Concerns were expressed with who in a locality would decide thresholds, what the decision making process would be and whether decision makers could be pressured, for example, by developers. They felt that standards should be determined in the same way nationally, but that the locality could determine which condition levels are acceptable and which are not (as is the case currently in the land development approval process in Virginia, where improvements are required at LOC C in non-congested areas, while in congested areas improvements are required at LOS D or LOS E).

### 4.1.5.4 Number of Condition Levels

Table 4-9 Panel Questionnaire Results Regarding to the Alternative Method, Number of Condition Levels, N=34

| **Number of Condition Levels** | Strongly Disagree (%) | Disagree (%) | No Opinion (%) | Agree (%) | Strongly Agree (%) |
|---|---|---|---|---|---|
| 4. Four conditions are to be used. | 5 | 29 | 37 | 26 | 3 |
| 5. Within acceptable conditions, there should be two levels of conditions. | 3 | 27 | 32 | 36 | 3 |
| 6. Within unacceptable conditions, there should be two levels. | 4 | 28 | 25 | 39 | 5 |

Opinions (agreement, disagreement and no opinion) were almost evenly divided relating to the three questions that addressed the number of condition levels to be used and how many of the condition levels to designate for describing acceptable and unacceptable conditions. Basically, there was no consensus among participants about the desirable number of condition levels.

**Open Discussion.** A participant expressed that having four condition levels seems arbitrary and slightly low. Another said, however, that the number of different conditions is less important than to ensure that they encompass all field conditions. Some participants expressed that having six service levels (from A-F, as in the current HCM) is helpful for prioritizing projects competing for funds for improvements. Comments were made that fewer than 6 service levels might be enough, but there should be degrees within LOS F and that within unacceptable conditions there should be more than two levels.

### 4.1.5.5 Natural Language Use

Table 4-10 Panel Questionnaire Results Regarding to the Alternative Method, Natural Language Use

| **Natural Language Use** | Strongly Disagree (%) | Disagree (%) | No Opinion (%) | Agree (%) | Strongly Agree (%) |
|---|---|---|---|---|---|
| 7. Natural language is helpful to describe four condition levels (if four condition levels are selected), for example: *Good*, *Fair, Poor,* and *Awful*. N=34 | 3 | 31 | 11 | 46 | 10 |
| 8. *Good* and *Fair* are appropriate word choices to describe the two acceptable conditions (if two acceptable condition levels are selected). N=33 | 3 | 21 | 14 | 60 | 3 |
| 9. *Poor* and *Awful* are appropriate word choices to describe the two unacceptable conditions (if two unacceptable condition levels are selected). N=33 | 3 | 29 | 15 | 51 | 3 |

56% of respondents agreed or strongly agreed that the use of natural language is helpful to describe four condition levels (if four condition levels are selected). 33% disagreed or strongly disagreed and 11% had no opinion. Additional questions asked for views on the use of specific words (if natural language is to be used). 2/3 of respondents supported the word choices *Good* and *Fair* to describe the two acceptable conditions. The word choices *Poor* and *Awful* were supported by only half of the participants.

**Open Discussion.** A comment was made that if the public has problems understanding letter grades, then it seems unlikely that a natural language based system will be much better. Again, views expressed earlier were repeated that LOS concept should be kept (with improvements), but multiple measures of effectiveness should be added and that best would be having a combination of both.

Participants were very interested in offering alternative natural language word choices, as shown in the following list:

- *Good, Fair, Poor, Awful* – these words are too subjective, open to interpretation.

- *Awful* isn’t an appropriate word for a technical analysis, as it is very informal and is most often used to refer to personal behavior rather than environmental conditions (maybe with the exception of the weather)
- Instead of *Awful*, use *Very Poor*
- Instead of *Awful*, use *Lousy*
- Instead of *Awful*, use *Severe*
- Prefer word choices that better illustrate conditions:
- A-> free-flow
- C-> congestions building
- F -> stop and go
- F+ - > jam
- The condition descriptors “Good, Fair, Poor and Awful” skew toward the negative. Other options to consider [that do not skew toward the negative]: “Good, Acceptable, Bad” or “Very Good, Good, Fair, Poor, Very Poor”.

#### 4.1.5.6 Deficiency Index – Modular Method

Table 4-11 Panel Questionnaire Results Regarding to the Alternative Method, Deficiency Index, N=33

| **Deficiency Index** | Strongly Disagree (%) | Disagree (%) | No Opinion (%) | Agree (%) | Strongly Agree (%) |
|---|---|---|---|---|---|
| 10. Factors impacting conditions should be considered by a deficiency index. | 0 | 8 | 20 | 68 | 4 |
| 11. The factors considered in the deficiency index should have weights (if a deficiency index is selected.) | 0 | 8 | 5 | 70 | 18 |

72% of respondents supported the deficiency index concept, 20% had no opinion and there was little disagreement (8%). Responses revealed strong support (88%) for using weights for the factors considered in the deficiency index (if a deficiency index is selected).

**Open Discussion.** Several participants made supportive comments for the concept of a modular approach in which factors impacting conditions are incorporated in a deficiency index, like a scale made up of multiple individual items. Comments were made that the name of the index is not appropriate; it is just an index; could perhaps be called condition index. Some participants expressed that this would be a very useful index. They also found the concept of applying weights helpful.

### 4.1.5.7 Summary

When considering the answers to both of the questionnaires and opinions expressed during open discussions, panel support can be summarized as follows:

- Keep the LOS system with added distinction within LOS F: F1, F2, F3, F4, F5,
- Keep the LOS system, but provide additional multiple, quantitative measures of effectiveness, i.e. do not replace the LOS system, but provide additional measures,
- Provide better measures for non-auto modes,
- Incorporate more cross-modal influences,
- Provide simpler procedures,
- Develop Deficiency Index with weights, but recommend renaming it to Condition Index, and
- Support proposed segmentation concept.

Participants were, however, divided on the following three topics:

1. Thresholds – determining locally or not – participants were divided; practical solution suggested: nationally used measurement system, without nationally determined value judgment, i.e. allow for regional and/or local determination of what is acceptable.

2. Naming convention – both LOS A through F and natural language can be misinterpreted and have subjectivity problems, i.e. there is no one naming convention that can compensate for the many sources of subjectivity.
3. Number of condition levels – even though respondents mostly agreed with the statements in the literature that system users distinguish three or four levels of service and do not distinguish between LOS A and LOS B, they were divided on reducing the number of service levels. This might relate to HCM users, who are performing analyses, having different needs than system users. Several participants expressed that having more service levels makes project prioritization easier. However, respondents did not object to using fewer condition levels in an alternative, additional method.

## 4.2 Feedback on scoring values for the alternative method

### 4.2.1 Methodology of Gathering Feedback

Feedback on the scoring values to be used in a sample application was gathered through a survey, which was distributed to transportation professionals working in research, academia, and practice. Nine VDOT district planners were asked to forward the survey to district and locality transportation staff. Three TRB committee chairs and one subcommittee chair were asked to forward the survey to their committee members and friends, including the Urban Streets Subcommittee of the Committee on Highway Capacity and Quality of Service, the Committee on Pedestrians, the Committee on Bicycle Transportation and the Committee on Transportation and Land Development. The survey was distributed and responses collected with the use of surveymonkey, an online survey service. Over a 14-day period, 125 survey responses were received. Survey responses were anonymous.

### 4.2.2 Description of Survey Respondents

A survey question asked respondents which mode they primarily work with. The answers were: All Four Modes: 55.6%, Auto Mode Only: 12.8%, Transit Mode Only: 3.4%, Pedestrian Mode Only: 3.4%, Bicycle Mode Only: 1.7, Both Pedestrian and Bicycle Modes: 12%, Non-auto Modes Only: 4% and Other (combinations): 7.1%. The distribution of the type of organizations respondents work for was as follows: Federal government: 2.6%, state government: 17.2, local government: 18%, private sector: 29.3%, university: 21.6%, MPO (Metropolitan Planning Organization or other regional organization): 9.2%, and Other (2 nonprofit, 1 retired): 2.5%.

### 4.2.3 Survey Results

Questions 1 through 12 of the survey asked respondents to do the following:

> assign a weight to each characteristic to indicate the relative impact of that characteristic on the mode's level of service. Weights are: 1 = Very Small Impact, 2 = Small Impact, 3 = Moderate Impact, 4 = Large Impact, and 5 = Very Large Impact.

In addition, opportunities to suggest additional characteristics were given to respondents. Tables 4-12 to 4-15 provide the mean and the standard deviation of the responses to Questions 1 through 12 for the four modes. Many additional characteristics were suggested, but only two were suggested by more than one respondent (each was suggested by three respondents): (1) frequency of safe crossings for pedestrians, and (2) distance of bicyclists from vehicles.

Table 4-12 Mean and Standard Deviation for Auto Mode Characteristics on a Scale of 1-5

| Features | Characteristics | Mean | Standard Deviation |
|---|---|---|---|
| Physical Features | $c_1$:lane width | 3.0 | 1.2 |
| | $c_2$:presence of parking | 3.3 | 0.9 |
| | $c_3$:presence of median | 3.1 | 1.1 |
| | $c_4$: frequency of median breaks | 3.2 | 1.0 |
| | $c_5$: frequency of driveways | 3.7 | 0.9 |
| Operational Features | $c_1$:vehicle volume/capacity ratio | 4.2 | 0.8 |
| | $c_2$:average travel speed | 3.7 | 0.9 |
| | $c_3$:signal progression | 4.1 | 0.8 |
| | $c_4$:number of vehicle stops | 4.1 | 0.8 |
| | $c_5$:travel time reliability | 3.6 | 1.0 |
| | $c_6$: incident recovery time | 3.6 | 1.1 |
| Intermodal Features | $c_1$:delay caused by transit | 2.4 | 1.1 |
| | $c_2$: delay caused by pedestrians | 2.4 | 1.1 |
| | $c_3$: delay caused by bicycles | 2.0 | 1.0 |

Table 4-13 Mean and Standard Deviation for Transit Mode Characteristics on a Scale of 1-5

| Features | Characteristics | Mean | Standard Deviation |
|---|---|---|---|
| Physical Features | $c_1$: percent of transit stops with shelters | 3.1 | 0.9 |
| | $c_2$: percent of transit stops with benches | 2.9 | 0.9 |
| | $c_3$:maintenance quality of transit stops | 3.0 | 1.1 |
| Operational Features | $c_1$:headway | 4.2 | 0.9 |
| | $c_2$: transit travel time | 4.1 | 0.8 |
| | $c_3$:headway variability | 3.7 | 0.9 |
| | $c_4$:passenger crowding | 3.4 | 1.0 |
| | $c_5$:hours of operation | 3.9 | 0.8 |
| Intermodal Features | $c_1$:delay caused by auto mode | 3.5 | 1.0 |
| | $c_2$: transit impact on pedestrians | 3.8 | 1.1 |
| | $c_3$:bicycle impact on pedestrians | 2.8 | 1.0 |

Table 4-14 Mean and Standard Deviation for Pedestrian Mode Characteristics on a Scale of 1-5

| Features | Characteristics | Mean | Standard Deviation |
|---|---|---|---|
| Physical Features | $c_1$:existence of sidewalks | 4.6 | 0.6 |
| | $c_2$:width of sidewalks | 3.6 | 0.8 |
| | $c_3$: condition of sidewalks | 3.5 | 0.9 |
| | $c_4$:distance from vehicular traffic | 3.5 | 0.9 |
| | $c_5$:crossing conditions | 4.3 | 0.8 |
| | $c_6$: ADA accessibility | 3.5 | 1.0 |
| Operational Features | $c_1$:pedestrian volume | 2.8 | 1.1 |
| | $c_2$:midblock crossing delay | 3.3 | 0.9 |
| | $c_3$:intersection crossing delay | 3.8 | 0.8 |
| Intermodal Features | $c_1$:auto impact on pedestrians | 4.1 | 0.9 |
| | $c_2$: transit impact on pedestrians | 2.8 | 1.0 |
| | $c_3$:bicycle impact on pedestrians | 2.2 | 0.9 |

ADA = Americans with Disabilities Act

Table 4-15 Mean and Standard Deviation for Bicycle Mode Characteristics on a Scale of 1-5

| Features | Characteristics | Mean | Standard Deviation |
|---|---|---|---|
| Physical Features | $c_1$: existence of bicycle lane | 4.2 | 0.9 |
| | $c_2$:width of outside through lane | 3.7 | 1.0 |
| | $c_3$:travel lane pavement quality | 3.8 | 0.9 |
| | $c_4$:width of shoulder | 3.9 | 0.8 |
| | $c_5$:shoulder pavement quality | 3.8 | 0.9 |
| | $c_4$:presence of auto parking | 3.7 | 0.8 |
| Operational Features | $c_1$:bicycle volume | 2.8 | 1.0 |
| | $c_2$:intersection crossing delay | 3.3 | 0.9 |
| | $c_3$:bicycle speed | 2.8 | 0.9 |
| Intermodal Features | $c_1$:auto impact on bicycles | 4.4 | 0.8 |
| | $c_2$: transit impact on bicycles | 2.9 | 1.0 |
| | $c_3$:pedestrian impact on bicycles | 2.2 | 0.9 |

Question 13 asked respondents to do the following:

> instead of A-F, assume that using multiple characteristics, a single mode's level of service has been rated to be in one of these 5 categories: No Deficiencies, Small Deficiencies, Medium Deficiencies, Large Deficiencies, or Total Deficiency. Assume further that each of these level of service descriptors will be given a numeric value between 0 (if No Deficiency) and 10 (if Total Deficiency). Please assign a value between 1 and 9 to each of the three remaining level of service descriptors.

The 0-10 scale, used only in this question, served the purpose of testing whether answers tended to be linear, i.e., whether differences in the values of different levels of deficiency tended to be relatively similar. The mean and standard deviation (in parentheses) values of the responses were as follows: Small Deficiencies: 2.3 (0.74); Medium Deficiencies: 5.0 (1.42); and Large Deficiencies: 7.9 (0.68). These mean values were very close to being linear, with $R^2 = 0.997$.

## 4.3 Conclusion for This Chapter

The methodology and results of gathering feedback from transportation professionals were described in this chapter. Practitioners provided feedback regarding findings and recommendations in the literature, which is produced by members of academia and the larger transportation research community, relating to the HCM urban streets methods. The feedback revealed both agreements and disagreements. Practitioners agreed with researchers' concerns about the weaknesses of the urban street methods, but disagreed with suggested course of actions recommended by researchers. For example, practitioners strongly opposed the recommendation to abandon the use of LOS altogether. Practitioners made recommendations to improve the HCM methods and supported the developed alternative method, in addition to, not instead of, the HCM urban streets methods. Being divided on three significant aspects (who should determine thresholds, naming convention, and number of condition levels) points to the critical need for further research.

Survey responses from transportation professionals working in research, academia, and practice, on the scoring values to be used in the sample application were essential, since data is currently not available based on which the scoring values could be reasonably estimated.

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# Chapter 5 Markov Method to Analyze and Measure Resilience

## 5.1 Introduction

As stated earlier, analyzing the impacts of incidents on transportation facilities and how these facilities recover from incidents, i.e., how resilient they are, is necessary for optimizing traffic flow. The resilience of a transportation facility can be described by how quickly and at what rate it recovers from the impact of incidents. Facilities recover from the impacts of incidents different ways, i.e., the speed and the rate of recovery vary.

The HCM 2010 [2] retained speed as the metric for the auto level of service (LOS). One of the key features of the HCM 2010 urban street speed estimation method, however, is that it does not apply when the volume/capacity ratio exceeds 1. This means that the HCM 2010 speed estimation method is not applicable to congested conditions, the key feature of which is that the volume/capacity ratio does exceed 1. To analyze congested, signalized arterial conditions, the HCM 2010 recommends the use of simulation models, such as CORSIM and VISSIM. Aggregate speed, delay, and travel time are typical outputs of these models. These simulation models are microscopic, but microscopic data from these models are typically not used for further analysis. Preliminary literature findings revealed very limited availability of analytical tools to measure and analyze the facilities' resilience. Such tools are essential for analyzing the impact of arterial incidents.

This chapter begins with providing resilience related literature review results. The purpose of this literature review was to identify current approaches to analyzing and measuring the resilience of arterial highways and to find examples of emerging stochastic methods that are applicable for analyzing arterial traffic conditions. Literature review results were then used for developing a Markovian stochastic method using microscopic simulation data to analyze and measure the resilience of signalized, congested, arterial highways.

## 5.2 Significance of the Research

The importance of effective incident management has long been recognized in the transportation industry. Analyzing the impacts of incidents on transportation facilities and how these facilities recover from incidents, i.e., how resilient they are, is necessary for optimizing traffic flow. Analytical tools, however, are lacking, particularly for congested conditions. A method was developed in this chapter to measure resilience by answering the following questions:

- What recently developed methods are available to measure and analyze the facilities' resilience?
- How can the probabilistic nature of traffic flow be incorporated into an analytical tool?
- How can microscopic simulation results be utilized to analyze the impact of arterial incidents?

The following sections describe in detail the development of a stochastic method to measure resilience on arterial highways.

## 5.3 Resilience Related Literature Review

The 2010 edition of the HCM included Chapter 35, titled Active Traffic Management (ATM), as a first-generation chapter, i.e., it was included in the HCM for the first time [2]. This chapter was reviewed to determine if it addressed resilience. The online *Transportation Research Record: Journal of the Transportation Research Board* and the Transportation Research Information Service were also searched to identify material that addresses the resilience of arterial highways. Examples of emerging stochastic methods that are applicable for analyzing arterial traffic conditions were also sought.

### 5.3.1 HCM 2010, Chapter 35, ATM

Chapter 35 of the HCM 2010 [2] defines *active travel management* as "a comprehensive approach to optimizing the operational performance of the roadway system" that consists of various strategies, including incident management:

> This chapter is ultimately intended to provide recommended methodologies and measures of effectiveness (MOEs) for evaluating the impacts of ATM strategies and highway and street system demand, capacity, and performance. However, at this time available information on the performance of ATM strategies has not matured sufficiently to enable the development and presentation of specific analysis methodologies.

The limitations of the HCM 2010 measures are recognized in Chapter 35 [2]:

> These HCM MOEs [in Chapter 4, Traffic Flow and Capacity Concepts; Chapter 5, Quality and Level of Service Concepts; and Chapter 7, Interpreting HCM and Alternative Tool Results] are, in essence, single point estimates of facility performance. In addition, the HCM methodologies described elsewhere in this manual are often specifically oriented to ideal or near-ideal conditions, when weather, incidents, and other factors do not adversely affect capacity.

The search of the online *Transportation Research Record: Journal of the Transportation Research Board* identified 11 publications between 2007 and 2013 that addressed topics relating to network, roadway, and speed recovery and also mentioned resilience; none measured resilience, and all addressed freeways.

### 5.3.2 Emerging Stochastic Methods to Analyze Arterial Traffic Conditions

Geroliminis and Skabardonis [21] developed an analytical model to estimate platoon dispersion on signalized arterials and queues at traffic signals. (After departing a traffic signal, traffic initially moves in tight platoons, but farther downstream this platoon tends to disperse.) The researchers modeled traffic behavior with the memoryless property of a Markov process (or Markov chain) and estimated platoon dispersion for a flow-density curve based on the HCM 2000 for undersaturated conditions. The model was applied to two arterial segments, and queue lengths were predicted by simulation and by the developed model. Results indicated the model accurately estimated queue lengths.

Adam et al. [22] estimated vehicles trapped in a dilemma zone with the use of Markovian traffic state estimation. Transition probabilities to change from any state to another were based on (1) the average and variance of the traffic volume entering the link, and (2) the car-following and lane-changing behaviors. A simulation application showed that the developed algorithm achieved reduction in trapped vehicles in the dilemma zone compared with traditional approaches, particularly at higher traffic volumes.

Microscopic (vehicle by vehicle) estimation of traffic density along signalized arterials was researched by Di et al. [23] based on the freeway MARCOM (Markov compartment) model by Davis and Kang [24]. The MARCOM model divides the road section into compartments and assumes that vehicles move between compartments according to a continuous-time, discrete-state Markov chain. The model was modified for signalized intersections by setting the nonblocking probability to 0 when the signal is red and 1 when it is green. Various flow rates from one compartment to the next are considered the various states. The researchers used detector and GPS data and used the developed model to estimate traffic density along signalized arterial highways.

These studies demonstrated that the Markov process is an applicable and valuable tool for considering the stochastic nature of traffic flow to develop a new generation of models to analyze arterial traffic operations. The studies applied first order Markov chains (or Markov processes), which are usually also referred to as *Markov chains* [25]. (The expressions “Markov process” and “Markov chain” are used interchangeably.)

## 5.4 Markovian Stochastic Method to Analyze Resilience

### 5.4.1 Introduction

As stated previously, a Markovian probabilistic method was developed in this study using microscopic simulation data to analyze and measure the resilience of signalized, congested, arterial highways.

Traffic conditions were modeled with the use of the Markov process (or Markov chain). Markov analysis looks at a sequence of events and analyzes the tendency of one event to be followed by another. Using this analysis, a new sequence of random but related events can be generated, which will look similar to the original. A Markov process is useful for analyzing dependent random events, i.e., events whose likelihood depends on what happened last.

### 5.4.2 Overview of the Markov Process

The Markov process is concerned with how a system transitions from one condition, called a state, to another. According to Minh [25], the first order Markov chain can be described as “only their present (at time *n*), not their past (at times 0, 1, 2, …., *n*-1), has any influence on their future (at time *n*+1).” In other words, the next state depends only on the last state, not on the other previous states. This property is known as the lack of memory property. A Markov chain describes at successive times the states of a system. At these times, the system may have changed from the state where it was before the observation to another state or may have stayed in the same state. These changes from one state to another state are called transitions.

A Markov chain can be expressed as probabilities to transition from state *i* to state *j*. Matrix P is called the transition matrix where each element $p_{ij}$ means the conditional probability of transitioning from state *i* to state *j*. The subscript *s* means the state space, i.e., all possible states the chain can ever reach.

$$P = \begin{bmatrix} p_{11} & p_{12} & .. & .. & p_{1s} \\ p_{21} & p_{22} & .. & .. & p_{2s} \\ .. & .. & .. & .. & .. \\ .. & .. & .. & .. & .. \\ p_{s1} & p_{s2} & .. & .. & pss \end{bmatrix} \tag{5-1}$$

The assumptions for calculating transition probabilities can be based on various approaches, such as subjective evaluation, equally likely assumption and empirical data [6].

The key elements of the Markov process include the following:

$p_{ij}^{(k)} -$ *k*–step transition probability from State *i* to State *j*

$\pi^{(0)}$ – initial condition probability vector

$\pi^{(n)}$ – absolute probability distribution vector after *n* transitions (*n* steps)

$$\pi^{(n)} = \pi^{(n-1)} P^{(n)} \tag{5-2}$$

### 5.4.3 Modeling Changes in Traffic Conditions

The earlier described stochastic Markov process (or Markov chain) was used for modeling. The Markov process describes the system transitioning probabilities from one state to another.

The Markov chain is completely characterized by the set of all states and transition probabilities. Here, the states were defined by speed ranges. (However, users of the method can determine states in various other ways. Users can choose other characteristics in addition to, or instead of, speed to describe the various states of the facilities, e.g., the number of stops by vehicles.) The option chosen here to demonstrate the method is to calculate the level of service (LOS) speed ranges, i.e., LOS thresholds, and designate each speed range as a state. The LOS thresholds are calculated based on the HCM 2010's Urban Streets' Auto Mode method [2]. This method determines LOS thresholds as ranges of travel speed as a percentage of the base free-flow speed for the facility being analyzed. The base free-flow speed for both facilities that will be used to demonstrate the method is calculated by using an equation developed by Bonneson et al.: $R^2 = 0.89$ [8]. Table 5-1 shows speed ranges, which represent the states in the Markov process, for the two facilities (Route 29 and Route 50 in Fairfax County, Virginia) that will be used for method application. These facilities are described later.

Table 5-1 Speed Ranges for States for Route 29 and Route 50 Based on HCM 2010

| **Travel Speed as a Percentage of Base Free-Flow Speed (%)** | **Level of Service** | **State** | **Route 29 Speed Intervals (Base Free-Flow Speed: 41 mph) (mph)** | **Route 50 Speed Intervals (Base Free-Flow Speed: 48 mph) (mph)** |
|---|---|---|---|---|
| >85 | A | 1 | >35 | >41 |
| >67-85 | B | 2 | >27-35 | >32-41 |
| >50-67 | C | 3 | >21-27 | >24-32 |
| >40-50 | D | 4 | >16-21 | >19-24 |
| >30-40 | E | 5 | >12-16 | >14-19 |
| ≤30 | F | 6 | ≤12 | ≤14 |

Average speed data are acquired from CORSIM simulation results, one speed data point for every second. Compared to usual practice in which average speeds of 15-minute periods are used, this provides for more detailed analysis. (The typical output interval for MOEs in CORSIM is not every second, and therefore second-by-second outputs were not readily available. Based on information from CORSIM developers, the models were reconfigured to obtain the second-by-second average speed data.) Each speed data point then is designated as being in a particular state, i.e., within a particular speed range, according to Table 5-1. For demonstrating the method, a 1-hour time period is analyzed, which means that 3,600 data points are available for analysis. The time step (a time period that is the unit of analysis) is selected to be equal to the cycle length, which is 180 seconds for both of the sample facilities.

A transition matrix is then developed for each time step based on the 180 speed data points within that particular time step. This means 20 transition matrices for the hour. The transition matrix includes all probabilities for conditions changing within this time step. The transition matrix is developed by counting how many times a particular state follows another within the 180-second time step. Table 5-2 shows an example of raw counts of states following other states in the fifth time step of the Route 29 base scenario. For example, State 3 (LOS C) occurs 35 times. Of those 35 times, State 3 (LOS C) is followed by State 2 (LOS B) 5 times, by State 3 (LOS C) 20 times (i.e., stays in the same state), by State 4 (LOS D) 8 times, and by State 5 (LOS E) 2 times. The numbers of occurrences of states in Table 5-2 are turned into probabilities of a state following another. Row by row, each number is divided by the sum of that particular row. Table 5-3 shows the results of these calculations. Thus Table 5-3 shows the transition probabilities from conditions at the beginning of the 180-second time step to conditions at the end of the time step.

Table5-2 Raw Counts of States Following Other States in Time Step 1: Route 29

| **State** | **1** | **2** | **3** | **4** | **5** | **6** | **Sum** |
|---|---|---|---|---|---|---|---|
| 1 (LOS A) | 15 | 2 | 0 | 1 | 0 | 0 | 18 |
| 2 (LOS B) | 3 | 14 | 4 | 0 | 2 | 0 | 23 |
| 3 (LOS C) | 0 | 5 | 20 | 8 | 2 | 0 | 35 |
| 4 (LOS D) | 0 | 1 | 10 | 11 | 5 | 3 | 30 |
| 5 (LOS E) | 0 | 1 | 1 | 5 | 7 | 12 | 26 |
| 6 (LOS F) | 0 | 0 | 0 | 4 | 10 | 34 | 48 |

Table 5-3 Probabilities of States Following Other States in Time Step 1: Route 29

| **State** | **1** | **2** | **3** | **4** | **5** | **6** | **Sum** |
|---|---|---|---|---|---|---|---|
| 1 (LOS A) | 0.83 | 0.11 | 0.00 | 0.06 | 0.00 | 0.00 | 1.00 |
| 2 (LOS B) | 0.13 | 0.61 | 0.17 | 0.00 | 0.09 | 0.00 | 1.00 |
| 3 (LOS C) | 0.00 | 0.14 | 0.57 | 0.23 | 0.06 | 0.00 | 1.00 |
| 4 (LOS D) | 0.00 | 0.03 | 0.33 | 0.37 | 0.17 | 0.10 | 1.00 |
| 5 (LOS E) | 0.00 | 0.04 | 0.04 | 0.19 | 0.27 | 0.46 | 1.00 |
| 6 (LOS F) | 0.00 | 0.00 | 0.00 | 0.08 | 0.21 | 0.71 | 1.00 |

To begin calculations, an initial condition vector is necessary, which describes the condition at the beginning of the first time step. In this case, the initial condition is State 3, therefore the initial condition vector is $\boldsymbol{cv_i} = \boldsymbol{0,0,1,0,0,0}$**.** Combining the initial condition vector with the transition matrix of the first time step will provide the condition vector at the end of the first time step ($\boldsymbol{cv_1}$). This vector than is combined with the transition matrix of the second time step, resulting in the condition vector at the end of the second time step ($\boldsymbol{cv_2}$). This process continues until the last time step. In the case of 20 time steps within 1 hour, 20 condition vectors would result. These condition vectors provide valuable insight into how conditions change within the hour.

## 5.5 Conclusion for This Chapter

In this chapter, the development of a novel approach was presented for analyzing the resilience of urban and suburban signalized arterial highways. The method uses Markovian traffic state estimation and previously unutilized microscopic simulation data. The current HCM LOS thresholds were used to define states for method development, which might help practitioners to interpret results. Method features are flexible, such as how states are defined, how many states are used, what thresholds are and what data are used to calculate transition probabilities.

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# Chapter 6 Sample Applications of the Developed Methods

## 6.1 Description of Sample Facilities

Sample applications were completed to demonstrate the developed methods. The methods were applied to two four-lane, arterial roadway sections, one undivided (0.8-mile-long section of Route 29 in Fairfax County, Virginia, shown in Figure 6-1), the other divided (1.3-mile-long section of Route 50 in Fairfax County, Virginia, shown in Figure 6-2). All four modes, including auto, transit, pedestrian and bicycle, use the facilities. The shared features of these facilities, i.e., that they both are signalized, four-lane, often congested, suburban arterial roadways, made them suitable for sample applications. Their differences (for example: undivided vs. divided; more vs. less frequent bus service) provide for using the method for comparing different scenarios. Traffic operations data were available from VDOT's Northern Virginia District. Bus service data were available from Fairfax County's Department of Transportation, and geometric data through field visits and Google Maps. The physical features of the facilities are summarized in Table 6-1.

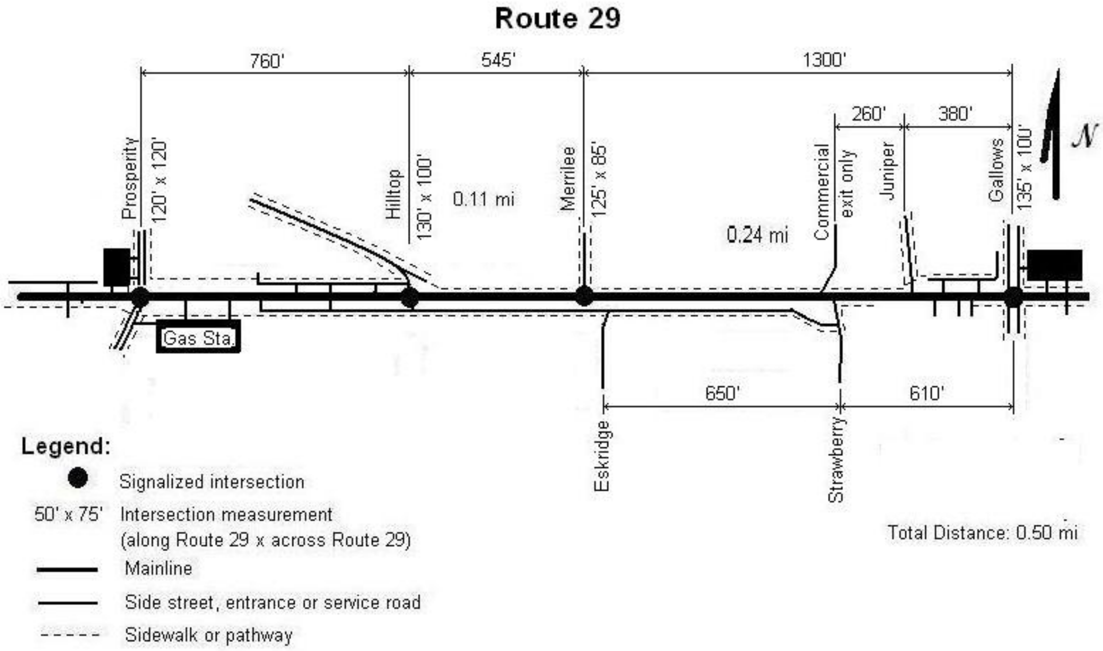

Figure 6-1 Route 29 in Fairfax County from Prosperity Avenue to Gallows

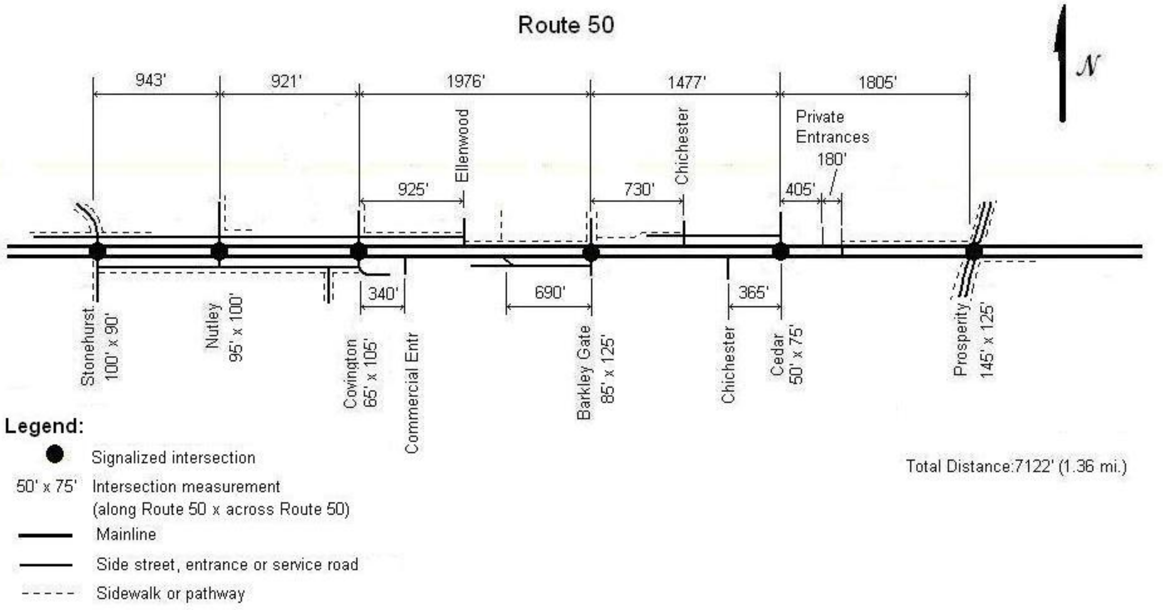

Figure 6- 2 Route 50 in Fairfax County from Stonehurst Road to Prosperity

Table 6-1. Physical Features of Undivided (Route 29) and Divided (Route 50) Arterial Facilities

| **Mode** | **Physical Feature** | **Description of 4-lane Undivided Arterial** | **Description of 4-lane Divided Arterial** |
|---|---|---|---|
| Auto | $c_1$:lane width | 12-foot lanes, 2 in each direction | 12-foot lanes, 2 in each direction |
| | $c_2$:presence of parking | No parking | No parking |
| | $c_3$:presence of median | No median | Median present |
| | $c_4$:frequency of median breaks | Substandard spacing between 3 median breaks | No substandard spacing |
| | $c_5$:frequency of driveways | 12 driveways/mile | No driveways |
| Transit | $c_1$:percent of transit stops with shelter | No shelters | No shelters |
| | $c_2$:percent of transit stops with benches | No benches | No benches |
| | $c_3$:maintenance quality of transit stops | Clean | Clean |
| Pedestrian | $c_1$:existence of sidewalks | One side only | One side only, 1/4 of length no sidewalk |
| | $c_2$:width of sidewalks | 4 feet | 4 feet |
| | $c_3$:condition of sidewalks | Good | Good |
| | $c_4$:distance from vehicular traffic | 3 feet | 3 feet |
| | $c_5$:crossing conditions | No midblock crossing, no median for refuge | No midblock crossing, median for refuge |
| | $c_6$:ADA accessibility | 80% ADA ramps | 100% ADA ramps |
| Bicycle | $c_1$:existence of bicycle lane | No bicycle lanes | No bicycle lanes |
| | $c_2$:width of outside through lane | 12 feet | 12 feet |
| | $c_3$:travel lane pavement quality | Fair | Good |
| | $c_4$:width of shoulder | No shoulder | No shoulder |
| | $c_5$:shoulder pavement quality | No shoulder | No shoulder |
| | $c_6$:presence of auto parking | No parking | No parking |

c = condition; ADA = Americans with Disabilities Act

## 6.2 Sample Application of the Alternative Multimodal Method

### 6.2.1 Steps of Alternative Multimodal Method Application

A sample application was completed to demonstrate the alternative method. The steps of method application include the following:

1. Collect peak period speed data.
2. Identify facility length and time period to be analyzed.
3. Identify characteristics to be included for each of the four modes (auto, transit, pedestrian, and bicycle) and each of the three features (physical, operational, and impact by other modes).
4. Collect data to determine each characteristic's condition level.
5. Assign deficiency scores to each of the five condition levels.
6. Determine weights to be applied to each characteristic of each mode.
7. Compute deficiency indices.

The time periods for analysis, 7 a.m. to 10 p.m., and the length of facility to be analyzed, shown on Figures 6-1 and 6-2, were determined based on data received from VDOT's Northern Virginia District and according to concepts described in chapter 3.

### 6.2.2 Condition Levels

Collected data, described earlier in this chapter, were used to determine the condition level for each characteristic according to the concept described in chapter 3; i.e., *Good* and *Fair* are within acceptable conditions (above the traditional LOS F threshold), and *Poor* and *Awful* are within unacceptable conditions (below the traditional LOS F threshold). In addition, conditions can deteriorate beyond *Awful* and might be termed *Extreme.*

When a characteristic is not constant during the analyzed period, weighted averages need to be calculated; the auto mode's characteristic relating to the average travel speed is an example. Both facilities had *Fair, Poor,* and *Awful* average travel speeds in between *Good conditions,* but in different proportions: conditions on the undivided facility (Route 29) changed from *Fair* (10%) to *Poor* (10%), then to *Awful* (50%), then to *Poor* (15%), and then to *Fair* (15%) again (in summary *Fair* [25%], *Poor* [25%], and *Awful* [50%]). Therefore, the condition level for the peak period is *Poor*. Conditions on the divided facility (Route 50) changed from *Fair* (17%) to *Awful* (33%), then to *Poor* (33%), and then to *Fair* (17%) (in summary *Fair* [34%], *Poor* [33%], and *Awful* [33%]). Therefore, the condition level for the peak period is *Poor*.

Examples for characteristics that were constant during the analyzed period are: signal progression. According to signal system engineers, the condition level for progression was *Good* for the divided facility (Route 50) and *Fair* for the undivided facility (Route 29). Bus service on the divided facility had 20 minutes headways (*Fair,* based on consulting the TCQM [20]) and the undivided facility had bus service every 15 minutes (*Good,* based on consulting the TCQM [20]).

### 6.2.3 Scoring Characteristics and Assigning Weights

Characteristics identified earlier and shown in Table 3-1 were used for the sample application. The next step was to score all characteristics within the physical, operational, and intermodal features for Route 29 and Route 50. Tables 6-2 through 6-4 show the scoring of the characteristics and calculation of the deficiency indices for Route 29 and Tables 6-5 through 6-7 for Route 50. A weight for each characteristic was based on the mean of survey responses, shown in Tables 4-12 through 4-15. Deficiency levels were assigned to each condition as follows: *Good* = No Deficiency, *Fair* = Small Deficiencies, *Poor* = Medium Deficiencies, *Awful* = Large Deficiencies, and *Extreme* = Total Deficiency. Based on the average of the answers to Question 13 in the scoring value survey (and dividing them by two to have a 0-5 scale), the following deficiency scores were used in the sample applications: *Good* = 0, *Fair* = 1.2, *Poor* = 2.5, *Awful* = 4, and *Extreme* = 5.

Table 6-2 Scoring of Physical Features and Calculation of Deficiency Indices for Route 29

| Mode | Physical Features | W | Condition | DS | DI | PDI |
|---|---|---|---|---|---|---|
| Auto | $c_1$:lane width | 3.0 | Good | 0 | 0 | 4.2 |
| | $c_2$:presence of parking | 3.3 | Good | 0 | 0 | |
| | $c_3$:presence of median | 3.1 | Poor | 2.5 | 7.8 | |
| | $c_4$: frequency of median breaks | 3.2 | Fair | 1.2 | 3.8 | |
| | $c_5$:frequency of driveways | 3.7 | Poor | 2.5 | 9.3 | |
| Transit | $c_1$:percent of transit stops with shelters | 3.1 | Good | 0 | 0 | 2.4 |
| | $c_2$: percent of transit stops with benches | 2.9 | Poor | 2.5 | 7.3 | |
| | $c_3$:maintenance quality of transit stops | 3.0 | Good | 0 | 0 | |
| Pedestrian | $c_1$:existence of sidewalks | 4.6 | Poor | 2.5 | 11.5 | 5.8 |
| | $c_2$:width of sidewalks | 3.6 | Fair | 1.2 | 4.3 | |
| | $c_3$:condition of sidewalks | 3.5 | Good | 0 | 0 | |
| | $c_4$:distance from vehicular traffic | 3.5 | Fair | 1.2 | 4.2 | |
| | $c_5$:crossing conditions | 4.3 | Poor | 2.5 | 10.8 | |
| | $c_6$:ADA accessibility | 3.5 | Fair | 1.2 | 4.2 | |
| Bicycle | $c_1$:existence of bicycle lane | 4.2 | Poor | 2.5 | 10.5 | 5.7 |
| | $c_2$:width of outside through lane | 3.7 | Poor | 2.5 | 9.3 | |
| | $c_3$:travel lane pavement quality | 3.8 | Fair | 1.2 | 4.6 | |
| | $c_4$:width of shoulder | 3.9 | Poor | 2.5 | 9.8 | |
| | $c_5$:shoulder pavement quality | 3.8 | N/A | 0 | 0 | |
| | $c_6$:presence of auto parking | 3.7 | Good | 0 | 0 | |

W = weight; DS = deficiency score; DI = deficiency index; PDI = physical feature deficiency index; c = condition; ADA = Americans with Disabilities Act.

Table 6-3 Scoring of Operational Features and Calculating Deficiency Indices for Route 29

| Mode | Operational Features | W | Condition | DS | DI | ODI |
|---|---|---|---|---|---|---|
| Auto | $c_1$:vehicle volume/capacity ratio | 4.2 | Poor | 2.5 | 10.5 | 7.3 |
| | $c_2$:average travel speed | 3.7 | Poor | 2.5 | 9.3 | |
| | $c_3$:signal progression | 4.1 | Fair | 1.2 | 4.9 | |
| | $c_4$:number of vehicle stops | 4.1 | Poor | 2.5 | 10.3 | |
| | $c_5$:travel time reliability | 3.6 | Good | 0 | 0 | |
| | $c_6$:incident recovery time | 3.6 | Poor | 2.5 | 9 | |
| Transit | $c_1$:headway | 4.2 | Good | 0 | 0 | 2.8 |
| | $c_2$: transit travel time, | 3.7 | Poor | 2.5 | 9.3 | |
| | $c_3$:headway variability | 4.1 | Fair | 1.2 | 4.9 | |
| | $c_4$:passenger crowding | 3.4 | Good | 0 | 0 | |
| | $c_5$:hours of operation | 3.9 | Good | 0 | 0 | |
| Pedestrian | $c_1$:pedestrian volume/capacity ratio | 2.8 | Good | 0 | 0 | 2.8 |
| | $c_2$: midblock crossing delay | 3.3 | Poor | 2.5 | 8.3 | |
| | $c_3$:intersection crossing delay | 3.8 | Good | 0 | 0 | |
| Bicycle | $c_1$:bicycle volume | 2.8 | Good | 0 | 0 | 1.1 |
| | $c_2$:intersection crossing delay | 3.3 | Good | 0 | 0 | |
| | $c_3$:bicycle speed | 2.8 | Fair | 1.2 | 3.4 | |

W = weight; DS = deficiency score; DI = deficiency index; ODI = operational feature deficiency index; and c = condition.

Table 6-4 Scoring of Intermodal Features and Calculation of Deficiency Indices for Route 29

| Mode | Impact by Other Modes | W | Condition | DS | DI | IDI |
|---|---|---|---|---|---|---|
| Auto | $c_1$:delay caused by transit | 2.4 | Good | 0 | 0 | 0 |
| | $c_2$:delay caused by pedestrians | 2.4 | Good | 0 | 0 | |
| | $c_3$:delay caused by bicycles | 2.0 | Good | 0 | 0 | |
| Transit | $c_1$:delay caused by auto mode | 3.5 | Poor | 2.5 | 8.8 | 5.6 |
| | $c_2$:accessibility by pedestrians | 3.8 | Fair | 1.2 | 4.6 | |
| | $c_3$:accessibility by bicycle | 2.8 | Fair | 1.2 | 3.4 | |
| Pedestrian | $c_1$:auto impact on pedestrians | 4.1 | Fair | 1.2 | 4.9 | 1.6 |
| | $c_2$:transit impact on pedestrians | 2.8 | Good | 0 | 0 | |
| | $c_3$:bicycle impact on pedestrians | 2.2 | Good | 0 | 0 | |
| Bicycle | $c_1$:auto impact on bicycles | 4.4 | Awful | 4 | 17.6 | 7.0 |
| | $c_2$:transit impact on bicycles | 2.9 | Fair | 1.2 | 3.5 | |
| | $c_3$:pedestrian impact on bicycles | 2.2 | Good | 0 | | |

W = weight; DS = deficiency score; DI = deficiency index; IDI = intermodal deficiency index; c = condition.

Table 6-5 Scoring of the Physical Features and Calculation of Deficiency Indices for Route 50

| Mode | Physical Features | W | Condition | DS | DI | PDI |
|---|---|---|---|---|---|---|
| Auto | $c_1$:lane width | 3.0 | Good | 0 | 0 | 0 |
| | $c_2$:presence of parking | 3.3 | Good | 0 | 0 | |
| | $c_3$:presence of median | 3.1 | Good | 0 | 0 | |
| | $c_4$: frequency of median breaks | 3.2 | Good | 0 | 0 | |
| | $c_5$:frequency of driveways | 3.7 | Good | 0 | 0 | |
| Transit | $c_1$:percent of transit stops with shelters | 3.1 | Poor | 2.5 | 7.8 | 5.0 |
| | $c_2$: percent of transit stops with benches | 2.9 | Poor | 2.5 | 7.3 | |
| | $c_3$:maintenance quality of transit stops | 3.0 | Good | 0 | 0 | |
| Pedestrian | $c_1$:existence of sidewalks | 4.6 | Awful | 4 | 18.4 | 6.3 |
| | $c_2$:width of sidewalks | 3.6 | Fair | 1.2 | 4.3 | |
| | $c_3$:condition of sidewalks | 3.5 | Good | 0 | 0 | |
| | $c_4$:distance from vehicular traffic | 3.5 | Fair | 1.2 | 4.2 | |
| | $c_5$:crossing conditions | 4.3 | Poor | 2.5 | 10.8 | |
| | $c_6$:ADA accessibility | 3.5 | Good | 0 | 0 | |
| Bicycle | $c_1$:existence of bicycle lane | 4.2 | Poor | 2.5 | 10.5 | 4.9 |
| | $c_2$:width of outside through lane | 3.7 | Poor | 2.5 | 9.3 | |
| | $c_3$:travel lane pavement quality | 3.8 | Good | 0 | 0 | |
| | $c_4$:width of shoulder | 3.9 | Poor | 2.5 | 9.8 | |
| | $c_5$:shoulder pavement quality | 3.8 | N/A | 0 | 0 | |
| | $c_6$:presence of auto parking | 3.7 | Good | 0 | 0 | |

W = weight; DS = deficiency score; DI = deficiency index; PDI = physical feature deficiency index; c = condition; ADA = Americans with Disabilities Act.

Table 6-6. Scoring of the Operational Features and Calculation of Deficiency Indices for Route 50

| Mode | Operational Features | W | Condition | DS | DI | ODI |
|---|---|---|---|---|---|---|
| Auto | $c_1$:vehicle volume/capacity ratio | 4.2 | Poor | 2.5 | 10.5 | 5.0 |
| | $c_2$:average travel speed | 3.7 | Poor | 2.5 | 9.3 | |
| | $c_3$:signal progression | 4.1 | Good | 0 | 0 | |
| | $c_4$:number of vehicle stops | 4.1 | Poor | 2.5 | 10.3 | |
| | $c_5$:travel time reliability | 3.6 | Good | 0 | 0 | |
| | $c_6$:incident recovery time | 3.6 | Good | 0 | 0 | |
| Transit | $c_1$:headway | 4.2 | Fair | 1.2 | 5.0 | 3.8 |
| | $c_2$: transit travel time, | 3.7 | Poor | 2.5 | 9.3 | |
| | $c_3$:headway variability | 4.1 | Fair | 1.2 | 4.9 | |
| | $c_4$:passenger crowding | 3.4 | Good | 0 | 0 | |
| | $c_5$:hours of operation | 3.9 | Good | 0 | 0 | |
| Pedestrian | $c_1$:pedestrian volume/capacity ratio | 2.8 | Good | 0 | 0 | 2.8 |
| | $c_2$: midblock crossing delay | 3.3 | Poor | 2.5 | 8.3 | |
| | $c_3$:intersection crossing delay | 3.8 | Good | 0 | 0 | |
| Bicycle | $c_1$:bicycle volume | 2.8 | Good | 0 | 0 | 1.1 |
| | $c_2$:intersection crossing delay | 3.3 | Good | 0 | 0 | |
| | $c_3$:bicycle speed | 2.8 | Fair | 1.2 | 3.4 | |

W = weight; DS = deficiency score; DI = deficiency index; PDI = physical feature deficiency index; c = condition.

Table 6-7. Scoring of Intermodal Features and Calculation of Deficiency Indices for Route 50

| Mode | Impact by Other Modes | W | Condition | DS | DI | IDI |
|---|---|---|---|---|---|---|
| Auto | $c_1$:delay caused by transit | 2.4 | Good | 0 | 0 | 0 |
| | $c_2$:delay caused by pedestrians | 2.4 | Good | 0 | 0 | |
| | $c_3$:delay caused by bicycles | 2.0 | Good | 0 | 0 | |
| Transit | $c_1$:delay caused by auto mode | 3.5 | Poor | 2.5 | 8.8 | 7.2 |
| | $c_2$:accessibility by pedestrians | 3.8 | Poor | 2.5 | 9.5 | |
| | $c_3$:accessibility by bicycle | 2.8 | Fair | 1.2 | 3.4 | |
| Pedestrian | $c_1$:auto impact on pedestrians | 4.1 | Fair | 1.2 | 4.9 | 1.6 |
| | $c_2$:transit impact on pedestrians | 2.8 | Good | 0 | 0 | |
| | $c_3$:bicycle impact on pedestrians | 2.2 | Good | 0 | 0 | |
| Bicycle | $c_1$:auto impact on bicycles | 4.4 | Awful | 4 | 17.6 | 7.0 |
| | $c_2$:transit impact on bicycles | 2.9 | Fair | 1.2 | 3.5 | |
| | $c_3$:pedestrian impact on bicycles | 2.2 | Good | 0 | | |

W = weight; DS = deficiency score; DI = deficiency index; PDI = physical feature deficiency index; c = condition.

### 6.2.4 Analysis of Results

Deficiency indices for both facilities and all four modes were summarized and are shown in Table 6-8.

Table 6-8 Summary of Deficiency Indices (DI) for Undivided and Divided Arterials

| **Mode** | **Physical Features DI** | | **Operational Features DI** | | **Intermodal Features DI** | | **Section DI** | |
|---|---|---|---|---|---|---|---|---|
| | **Undivided** | **Divided** | **Undivided** | **Divided** | **Undivided** | **Divided** | **Undivided** | **Divided** |
| Auto | 4.2 | 0 | 7.3 | 5.0 | 0 | 0 | 3.8 | 1.7 |
| Transit | 2.4 | 5.0 | 2.8 | 3.8 | 5.6 | 7.2 | 3.6 | 5.3 |
| Pedestrian | 5.8 | 6.3 | 2.8 | 2.8 | 1.6 | 1.6 | 3.4 | 3.6 |
| Bicycle | 5.7 | 4.9 | 1.1 | 1.1 | 7.0 | 7.0 | 4.6 | 4.3 |

Results of method applications in Table 6-8 show that the undivided arterial highway is more deficient (*DI* = 3.8) than the divided facility ((*DI* = 1.7) for the auto mode. The transit mode's *DI*, however, is higher for the divided arterial (*DI* = 5.3), since it has lower transit headways than the undivided facility, where more frequent transit service results in a lower deficiency index (*DI* = 3.6). The pedestrian mode's *DI*s are similar for the two facilities (*DI* = 3.4 for the undivided and *DI* = 3.6 the divided). Some of the deficiencies, however, are different. The divided arterial does not have continuous sidewalks on either side. The undivided arterial has continuous sidewalks, at least on one side. The divided arterial, however, offers median refuge for crossing pedestrians, and 100% Americans with Disabilities Act ramps (vs. 80% on the undivided facility). Both facilities have similar bicycle deficiency indices (*DI* = 4.6 for the undivided and *DI* = 4.3 for the divided), with the undivided facility being more deficient as a result of pavement quality problems.

## 6.3 Sample Application of the Markovian Resilience Method

### 6.3.1 Steps of Markovian Method Application

Sample applications were completed to demonstrate the developed Markovian resilience method. The method was designed to be applied in practice. A user-friendly MS-Excel pivot application was created to process microscopic data gathered from CORSIM, making it easy to enter input variables, based on which condition vectors and related graphs are provided. The steps of method application include:

1. Prepare master CORSIM files (prepare network and initial data files, verify files with actual network, and calibrate files using field data).
2. Prepare and run scenarios (with different volumes, incidents, durations, signal timings, etc.; create CORSIM files for and run these scenarios).
3. Perform Markov analysis (enter CORSIM results into MS-Excel pivot table and analyze resulting condition vector tables and graphs).

Method features, such as definition of states, number of condition levels, thresholds for condition levels, data used, and cycle length can be adjusted in the MS-Excel pivot application. Data can come from various sources, such as smart traffic centers, real time, archives, simulation, etc. The developed method can be modified for other applications, e.g., for evaluating signal timing strategies, work zone road closures, and variable speed limits. In addition to the arterial application included in this study, the method is applicable to freeways and networks.

### 6.3.2 Scenarios for Method Application

Master CORSIM files were prepared for the earlier described facilities (Route 29 and Route 50) for base conditions and also for an additional CORSIM scenario for each facility with blocking the right through lane for 20 minutes, starting in the second time step. Traffic operations data were available from the Virginia Department of Transportation's (VDOT) Northern Virginia District, and geometric data through field visits and Google Maps.

The shared features of the sample facilities, i.e., that they both are signalized, four-lane, often congested, suburban arterial roadways, made them suitable for sample applications. Their differences provide for using the developed method for comparing the results of applying the method to different scenarios.

The differences include the following:

- Route 29 is undivided, and Route 50 is divided.
- Route 29's speed limit is 35 mph, and Route 50's is 45 mph.
- Route 29 has curb and gutter, and Route 50 does not.
- Route 29 has more access points per mile than does Route 50.

### 6.3.3 Method Application

The states for method application are based on Table 5-1 for the two sample facilities. The differences between the two sample facilities resulted in the different thresholds for the six states, since the equation developed by Bonneson et al. [8] to calculate base free-flow speed is dependent on these differences (presence of median, posted speed limit, presence of curb, and access point density). The only additional variable for the base free-flow speed equation is the number of through lanes, which is the same (two in each direction) for the two sample facilities. Second-by-second average speed (total vehicle miles divided by total travel time) data from 1 hour of morning peak period (7:15-8:15) of CORSIM runs (3,600 data points) for each of the four scenarios were inserted into an MS-Excel pivot table. Based on these data, MS-Excel calculated transition matrices and condition vectors.

As a reference, analysis results using the HCM urban streets method would be as shown in Table 6-9. As can be seen for both facilities, the LOS levels do not change between the base and lane block scenarios and the average speeds change very little from one 15-minute period to the next; i.e., minimal information is gained about traffic conditions. As it will be demonstrated, the application of the developed Markov method results in details that previously were not available about the tendencies and characteristics of the traffic conditions.

Table 6-9 15-Minute LOSs During Morning Peak Hour

| **Scenario** | **7:15 -7:30** | **7:30-7:45** | **7:45-8:00** | **8:00-8:15** |
|---|---|---|---|---|
| Route 29 base | LOS D (19.3) | LOS D (19.3) | LOS D (18.9) | LOS D (18.9) |
| Route 29 lane block | LOS D (16.3) | LOS D (15.5) | LOS D (16.7) | LOS D (17.1) |
| Route 50 base | LOS E (15.6) | LOS E (15.4) | LOS E (14.9) | LOS E (14.6) |
| Route 50 lane block | LOS E (15.3) | LOS E (14.6) | LOS E (14.8) | LOS E (14.7) |

Speeds in miles per hour are shown in parentheses.

Table 6-10 includes condition vectors for the 1-hour base conditions on Route 29, and Table 6-11 for the lane block scenario on Route 29. Table 6-12 provides condition vectors for the 1-hour base conditions on Route 50, and Table 6-13 for the lane block scenario on Route 50.

Table 6-10 Condition Vectors Within a 1-Hour Period: Route 29 Base Conditions

| **Condition Vector** | **State 1 (LOS A)** | **State 2 (LOS B)** | **State 3 (LOS C)** | **State 4 (LOS D)** | **State 5 (LOS E)** | **State 6 (LOS F)** |
|---|---|---|---|---|---|---|
| $cv_1$ | 0.11 | 0.21 | 0.25 | 0.15 | 0.12 | 0.16 |
| $cv_2$ | 0.1 | 0.2 | 0.26 | 0.15 | 0.11 | 0.18 |
| $cv_3$ | 0.11 | 0.2 | 0.25 | 0.14 | 0.09 | 0.21 |
| $cv_4$ | 0.09 | 0.26 | 0.16 | 0.18 | 0.1 | 0.21 |
| $cv_5$ | 0.12 | 0.19 | 0.22 | 0.13 | 0.12 | 0.22 |
| $cv_6$ | 0.11 | 0.21 | 0.19 | 0.14 | 0.11 | 0.24 |
| $cv_7$ | 0.11 | 0.2 | 0.21 | 0.11 | 0.11 | 0.26 |
| $cv_8$ | 0.11 | 0.2 | 0.2 | 0.12 | 0.12 | 0.25 |
| $cv_9$ | 0.11 | 0.18 | 0.23 | 0.08 | 0.16 | 0.24 |
| $cv_{10}$ | 0.1 | 0.2 | 0.18 | 0.16 | 0.11 | 0.25 |
| $cv_{11}$ | 0.12 | 0.19 | 0.17 | 0.15 | 0.1 | 0.27 |
| $cv_{12}$ | 0.1 | 0.19 | 0.22 | 0.1 | 0.1 | 0.29 |
| $cv_{13}$ | 0.06 | 0.24 | 0.21 | 0.09 | 0.11 | 0.29 |
| $cv_{14}$ | 0.05 | 0.24 | 0.2 | 0.12 | 0.09 | 0.3 |
| $cv_{15}$ | 0.09 | 0.19 | 0.19 | 0.13 | 0.11 | 0.29 |
| $cv_{16}$ | 0.07 | 0.19 | 0.22 | 0.11 | 0.12 | 0.29 |
| $cv_{17}$ | 0.08 | 0.18 | 0.2 | 0.14 | 0.09 | 0.31 |
| $cv_{18}$ | 0.09 | 0.17 | 0.19 | 0.16 | 0.08 | 0.31 |
| $cv_{19}$ | 0.09 | 0.18 | 0.18 | 0.14 | 0.1 | 0.31 |
| $cv_{20}$ | 0.05 | 0.21 | 0.19 | 0.11 | 0.14 | 0.3 |

Table 6-11 Condition Vectors Within a 1-Hour Period: Route 29 Lane Block

| **Condition Vector** | **State 1 (LOS A)** | **State 2 (LOS B)** | **State 3 (LOS C)** | **State 4 (LOS D)** | **State 5 (LOS E)** | **State 6 (LOS F)** |
|---|---|---|---|---|---|---|
| $cv_1$ | 0.05 | 0.26 | 0.23 | 0.23 | 0.05 | 0.18 |
| $cv_2$ | 0.01 | 0.27 | 0.2 | 0.18 | 0.13 | 0.21 |
| $cv_3$ | 0 | 0.27 | 0.19 | 0.21 | 0.1 | 0.23 |
| $cv_4$ | 0.02 | 0.26 | 0.17 | 0.23 | 0.08 | 0.24 |
| $cv_5$ | 0.01 | 0.25 | 0.18 | 0.22 | 0.09 | 0.25 |
| $cv_6$ | 0.01 | 0.18 | 0.23 | 0.22 | 0.1 | 0.26 |
| $cv_7$ | 0.01 | 0.17 | 0.23 | 0.2 | 0.09 | 0.3 |
| $cv_8$ | 0.01 | 0.17 | 0.2 | 0.21 | 0.11 | 0.3 |
| $cv_9$ | 0.02 | 0.17 | 0.18 | 0.22 | 0.1 | 0.31 |
| $cv_{10}$ | 0.06 | 0.13 | 0.19 | 0.19 | 0.1 | 0.33 |
| $cv_{11}$ | 0.05 | 0.15 | 0.22 | 0.15 | 0.08 | 0.35 |
| $cv_{12}$ | 0.02 | 0.2 | 0.15 | 0.2 | 0.05 | 0.38 |
| $cv_{13}$ | 0.03 | 0.21 | 0.14 | 0.13 | 0.12 | 0.37 |
| $cv_{14}$ | 0.01 | 0.21 | 0.15 | 0.15 | 0.09 | 0.39 |
| $cv_{15}$ | 0.04 | 0.18 | 0.15 | 0.15 | 0.09 | 0.39 |
| $cv_{16}$ | 0.03 | 0.19 | 0.14 | 0.16 | 0.08 | 0.4 |
| $cv_{17}$ | 0.04 | 0.18 | 0.14 | 0.15 | 0.09 | 0.4 |
| $cv_{18}$ | 0.06 | 0.17 | 0.13 | 0.16 | 0.07 | 0.41 |
| $cv_{19}$ | 0.06 | 0.17 | 0.12 | 0.16 | 0.08 | 0.41 |
| $cv_{20}$ | 0.06 | 0.18 | 0.12 | 0.15 | 0.1 | 0.39 |

Table 6-12 Condition Vectors Within a 1-Hour Period: Route 50 Base Conditions

| **Condition Vector** | **State 1 (LOS A)** | **State 2 (LOS B)** | **State 3 (LOS C)** | **State 4 (LOS D)** | **State 5 (LOS E)** | **State 6 (LOS F)** |
|---|---|---|---|---|---|---|
| $cv_1$ | 0 | 0 | 0 | 0.53 | 0.31 | 0.16 |
| $cv_2$ | 0 | 0 | 0 | 0.49 | 0.34 | 0.17 |
| $cv_3$ | 0 | 0 | 0 | 0.5 | 0.3 | 0.2 |
| $cv_4$ | 0 | 0 | 0 | 0.4 | 0.37 | 0.23 |
| $cv_5$ | 0 | 0 | 0 | 0.36 | 0.34 | 0.3 |
| $cv_6$ | 0 | 0 | 0 | 0.39 | 0.29 | 0.32 |
| $cv_7$ | 0 | 0 | 0 | 0.4 | 0.31 | 0.29 |
| $cv_8$ | 0 | 0 | 0 | 0.4 | 0.31 | 0.29 |
| $cv_9$ | 0 | 0 | 0.01 | 0.37 | 0.32 | 0.3 |
| $cv_{10}$ | 0 | 0 | 0 | 0.33 | 0.35 | 0.32 |
| $cv_{11}$ | 0 | 0 | 0 | 0.36 | 0.26 | 0.38 |
| $cv_{12}$ | 0 | 0 | 0 | 0.36 | 0.29 | 0.35 |
| $cv_{13}$ | 0 | 0 | 0 | 0.36 | 0.33 | 0.31 |
| $cv_{14}$ | 0 | 0 | 0 | 0.35 | 0.33 | 0.32 |
| $cv_{15}$ | 0 | 0 | 0 | 0.29 | 0.38 | 0.33 |
| $cv_{16}$ | 0 | 0 | 0 | 0.28 | 0.34 | 0.38 |
| $cv_{17}$ | 0 | 0 | 0 | 0.32 | 0.29 | 0.39 |
| $cv_{18}$ | 0 | 0 | 0 | 0.27 | 0.39 | 0.34 |
| $cv_{19}$ | 0 | 0 | 0 | 0.31 | 0.34 | 0.35 |
| $cv_{20}$ | 0 | 0 | 0 | 0.32 | 0.31 | 0.37 |

Table 6-13 Condition Vectors Within a 1-Hour Period: Route 50 Lane Block

| **Condition Vector** | **State 1 (LOS A)** | **State 2 (LOS B)** | **State 3 (LOS C)** | **State 4 (LOS D)** | **State 5 (LOS E)** | **State 6 (LOS F)** |
|---|---|---|---|---|---|---|
| $cv_1$ | 0 | 0 | 0 | 0.51 | 0.32 | 0.17 |
| $cv_2$ | 0 | 0 | 0 | 0.5 | 0.32 | 0.18 |
| $cv_3$ | 0 | 0 | 0 | 0.44 | 0.36 | 0.2 |
| $cv_4$ | 0 | 0 | 0 | 0.29 | 0.4 | 0.31 |
| $cv_5$ | 0 | 0 | 0 | 0.28 | 0.39 | 0.33 |
| $cv_6$ | 0 | 0 | 0 | 0.3 | 0.33 | 0.37 |
| $cv_7$ | 0 | 0 | 0 | 0.27 | 0.41 | 0.32 |
| $cv_8$ | 0 | 0 | 0 | 0.27 | 0.35 | 0.38 |
| $cv_9$ | 0 | 0 | 0 | 0.27 | 0.35 | 0.38 |
| $cv_{10}$ | 0 | 0 | 0 | 0.26 | 0.34 | 0.4 |
| $cv_{11}$ | 0 | 0 | 0 | 0.3 | 0.27 | 0.43 |
| $cv_{12}$ | 0 | 0 | 0 | 0.3 | 0.3 | 0.4 |
| $cv_{13}$ | 0 | 0 | 0 | 0.3 | 0.35 | 0.35 |
| $cv_{14}$ | 0 | 0 | 0 | 0.34 | 0.31 | 0.35 |
| $cv_{15}$ | 0 | 0 | 0 | 0.22 | 0.39 | 0.39 |
| $cv_{16}$ | 0 | 0 | 0 | 0.23 | 0.37 | 0.4 |
| $cv_{17}$ | 0 | 0 | 0 | 0.24 | 0.36 | 0.4 |
| $cv_{18}$ | 0 | 0 | 0 | 0.26 | 0.38 | 0.36 |
| $cv_{19}$ | 0 | 0 | 0 | 0.26 | 0.4 | 0.34 |
| $cv_{20}$ | 0 | 0 | 0 | 0.27 | 0.36 | 0.37 |

### 6.3.4 Analysis of Results

An initial observation revealed that even though there is only one service level difference between the two facilities, conditions differ a great deal as States 1, 2, and 3 (LOS A, B, and C) do not occur for the time period sampled on Route 50 and all six states are present on Route 29. The 20 condition vectors were plotted for each of the four scenarios in three dimensions, shown in Figure 6-3, providing a visual representation of how conditions change within the hour. The trend of change (improving, deteriorating, or not changing) and the speed of change (how quickly the change is taking place) for each of the six states are discernible. The blocked scenario of Route 29 shows the reduced proportions of States 1 and 2 (LOS A and B) and the increased proportions of States 5 and 6 (LOS E and F). The blocked scenario of Route 50 shows the increased proportions of States 5 and 6 (LOS E and F) and no change in the absence of States 1, 2, and 3 (LOS A, B, and C).

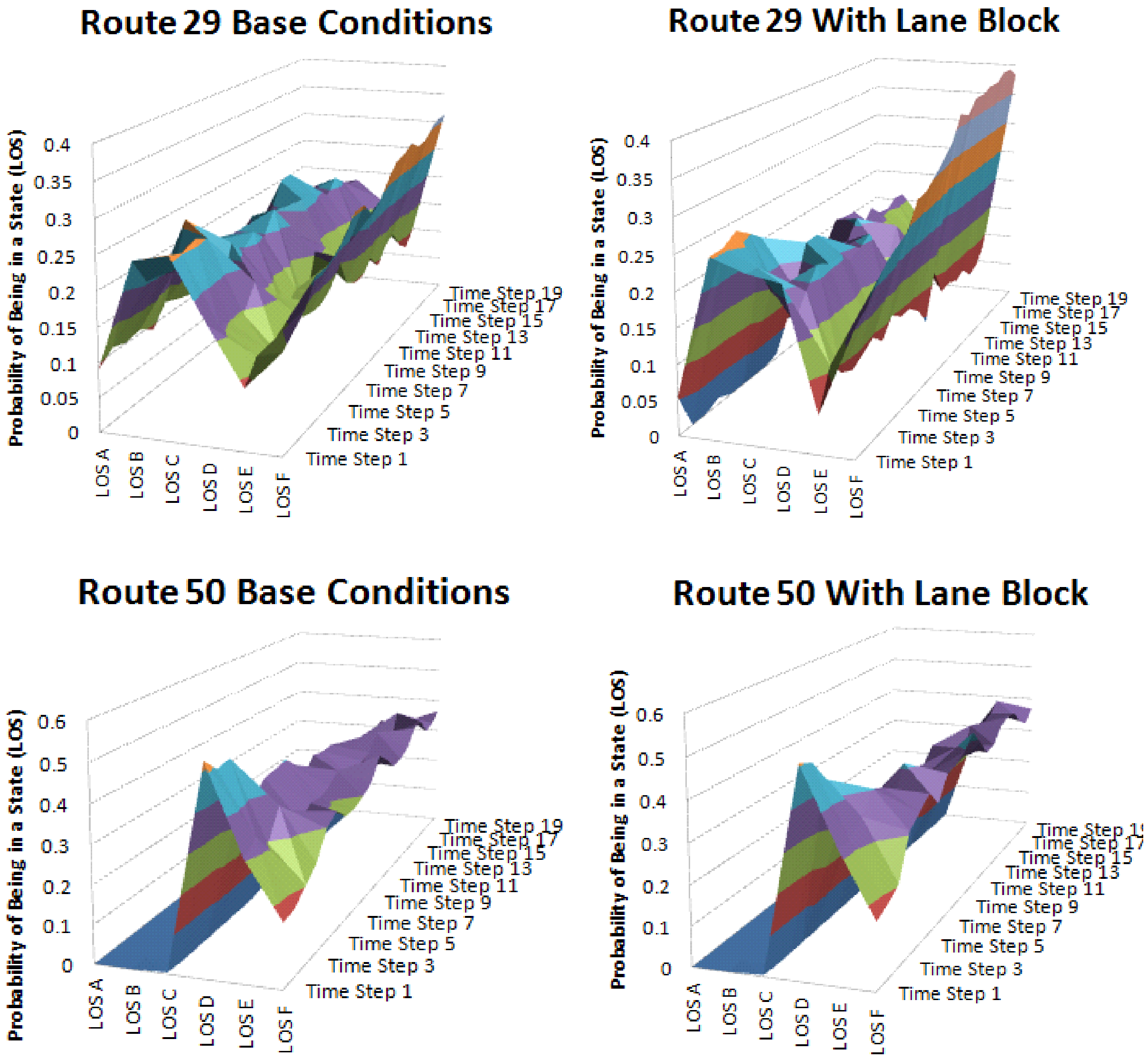

Figure 6-3 Graphs of condition vectors of four scenarios

Line diagrams of the four scenarios are provided in Figure 6-4. Plotting all six states, which are essentially condition levels, would result in overcrowded graphs, but combining them into three could reveal meaningful trends. A reduction in condition levels is also suggested in the literature. As described earlier, Pecheux et al. [11] showed that users perceived three or four levels of service, and Fang and Pecheux [12] found that users did not distinguish between LOS A and B. Probabilities of being in States 1, 2, and 3 (LOS A, B, and C) were added up to create one condition level; the sum of States 4 and 5 (LOS D and E) resulted in the second level; and State 6 (LOS F) became the third level.

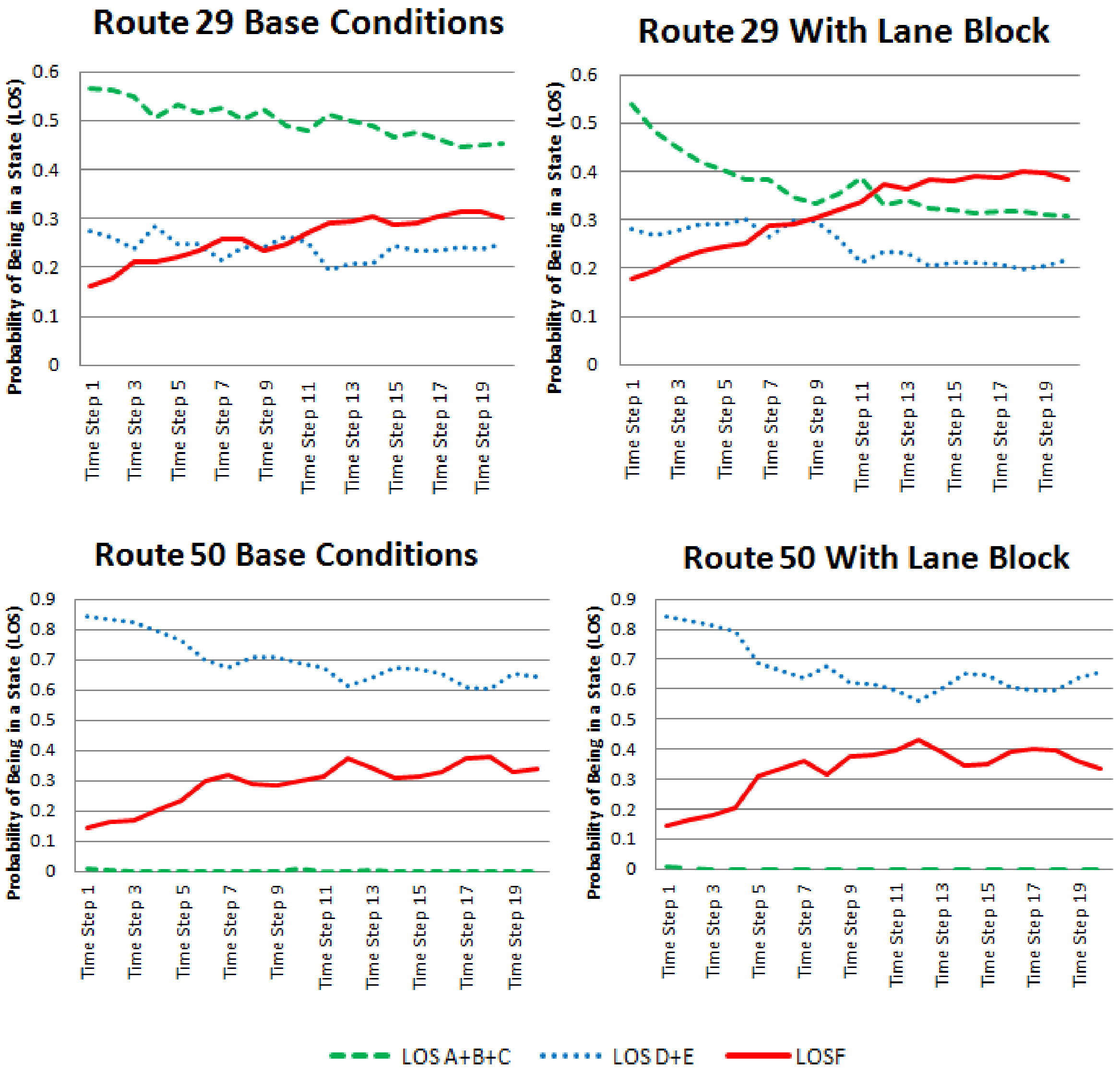

Figure 6-4 Four scenarios, three condition levels

In the Route 29 base scenario, the proportion of LOS F steadily increases and reaches 30% proportion at the14th time step. Under the blocked scenario, the proportion of LOS reaches 30% at the 7th time step, 21 minutes earlier than under the base scenario. Moreover, the proportion of

LOS F keeps on increasing under the blocked scenario and does not recover to the base condition level during the 1-hour period analyzed.

In the Route 50 base scenario, the proportion of LOS F steadily increases and reaches 38% proportion at the 11th time step. Under the blocked scenario, the proportion of LOS F reaches 38% at the 8th time step, 9 minutes earlier than under the base scenario. After that, the proportion of LOS F is larger than under the base scenario for 5 more time steps (15 minutes), but at that time it recovers to the level of the base case scenario.

These observations can be used to measure the resilience, i.e., the ability to recover from a negative impact on traffic conditions, of the two facilities. In this case, Route 50 shows more resilience than Route 29.

## 6.4 Conclusion for This Chapter

In this chapter, sample applications were completed to demonstrate the developed methods, which were designed to be applied in practice. Specific steps that are necessary for method application were provided for both methods. Method application results showed that the results of applying the methods were meaningful for assessing recurrent and non-recurrent conditions. Both methods provided results that current methods do not provide.

# Conclusions and Future Research

The author addressed several aspects of recurrent and non-recurrent conditions on multimodal urban streets (i.e. urban and suburban signalized arterial highways). Recurrent conditions were addressed by developing a multimodal method that is an alternative to the HCM 2010 urban streets methods. The Markov process, that can consider the stochastic nature of traffic, was investigated to address non-recurrent conditions and a Markovian method was developed to measure and analyze the resilience of urban streets, which include urban and suburban signalized arterial highways.

A review of selected literature revealed that a number of issues regarding the HCM’s urban streets methods that were not addressed in previous editions of the HCM were also not addressed in the HCM 2010. The developed alternative multimodal method provides measures for the four modes (i.e. auto, transit, pedestrian and bicycle) on urban streets and addresses the shortcomings in the HCM 2010’s urban streets methods. The shortcomings of the HCM 2010 LOS step functions were addressed in the developed method by introducing step functions based on natural language with fewer steps within acceptable LOS and additional steps within unacceptable LOS. The modular deficiency index provides for the comparability of LOS results across modes. The alternative method fully considers the impacts of modes on other modes through considering intermodal characteristics. The method has the flexibility to allow adjustment of the LOS thresholds and to include additional characteristics when desired by regions or localities. Weights of characteristics and deficiency scores can also be adjusted by users of the alternative method.

In addition to addressing previously unresolved issues, the multimodal method represents a comprehensive, systematic approach, which overcomes the problem of addressing various issues separately, without considering their interdependence.

Feedback from transportation professionals revealed that practitioners agreed with researchers' concerns about the weaknesses of the urban street methods, but disagreed with suggested course of actions recommended by some researchers. Practitioners also had disagreements within themselves, which points to the critical need for further research. Survey responses from transportation professionals working in research, academia, and practice, on the scoring values to be used in the sample application were essential, since data, based on which the scoring values could be reasonably estimated, are currently very limited.

*Future research regarding multimodal assessment of recurrent conditions on urban streets.* Future research can enhance the specifics of the method, such as what other characteristics to include; what naming convention to use for the condition levels; how to determine thresholds for the condition levels; who determines the thresholds; and what the weights and deficiency scores should be. A related critical issue is whether thresholds should be the same nationally or determined locally. Once deficiency scores and weights are refined by further research, they could be considered as default values for the method, which could then be changed regionally or locally according to input from stakeholders. The method could be further refined through pilot applications with involvement by users, i.e. stakeholders, including citizens, elected representatives and others, of multimodal urban streets.

A review of selected literature found that analytical tools are lacking, particularly for congested conditions to assess the impact of incidents, particularly how facilities recover from incident, i.e., how resilient they are. Studies demonstrated that the Markov process is an applicable and valuable tool for considering the stochastic nature of traffic flow to develop a new generation of models to analyze arterial traffic operations.

The author developed a method for analyzing the resilience of urban and suburban signalized arterial highways using Markovian traffic state estimation and previously unutilized microscopic simulation data.  Method results provide a plexiform of information that no other methods provide, about the rate and speed of recovery of the arterial traffic flow.  Sample applications of the developed method for two four-lane, congested arterial sections, Route 29 and Route 50, in Fairfax County, Virginia, demonstrated the practicality and usefulness of the developed method. Method features are flexible, such as how states are defined, how many states are used, what thresholds are and what data are used to calculate transition probabilities.

Data can come from various sources, such as smart traffic centers, real time, archives, simulation, etc.  The developed method can be modified for applications other then resilience.  In addition to the arterial application which is developed and demonstrated in this study, the method is applicable to freeways and networks.

*Future research regarding the Markovian method.* Future research can further explore what can be learned from the outputs of method application (condition vectors and transition matrices). Applying the developed method (or a modified version of it) to freeways and networks is a promising research direction.  Researching how data from other sources could be used for method application might find data sources which would negate the need to simulate the analyzed highway section.  Research could be undertaken to use the method, or the underlying concepts, for other applications, for example, evaluating signal timing strategies, work zone road closures, variable speed limits and other traffic operational strategies.

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## APPENDIX A

## Questionnaire

## Measures for Multimodal Urban Arterials

Responses to the questionnaire are confidential, and results will only be summarized in aggregate form. No individual respondents will be identified in questionnaire summaries. Your participation is truly appreciated. Participants will receive questionnaire summary results.

## HCM Evaluation Results in Literature

Transportation researchers and professionals have differing views on how future editions of the Highway Capacity Manual (HCM) should address Urban Streets. The following statements were made by transportation researchers and professionals and can be found in published literature. Please mark your answer for each question reflecting the degree of your agreement or disagreement with the statements.

### Use of LOS

1. The concept of levels of service (LOSs) should be abandoned in the next full edition of the HCM.

|__Strongly Disagree |__Disagree |__No opinion |__Agree |__Strongly Agree

2. Multiple measures of effectiveness should replace LOS.

|__Strongly Disagree |__Disagree |__No opinion |__Agree |__Strongly Agree

### Comparability of LOS Results Across Modes

3. Current LOS calculation results are not comparable across different transportation modes (within HCM methods).

|__Strongly Disagree |__Disagree |__No opinion |__Agree |__Strongly Agree

4. Measures (LOS or other measures) should be comparable across modes.

|__Strongly Disagree |__Disagree |__No opinion |__Agree |__Strongly Agree

**Effect of Modes on Other Modes**

5. More cross-modal influences should be incorporated into future Urban Streets related performance measures.

|__Strongly Disagree |__Disagree |__No opinion |__Agree |__Strongly Agree

**Establishment of Thresholds**

6. LOS thresholds should be determined by decision makers and transportation professionals (not the creators of the HCM methods).

|__Strongly Disagree |__Disagree |__No opinion |__Agree |__Strongly Agree

7. Local jurisdictions should set their own targets for various performance measures.

|__Strongly Disagree |__Disagree |__No opinion |__Agree |__Strongly Agree

8. Labeling of conditions as LOSs A to F should be abandoned.

|__Strongly Disagree |__Disagree |__No opinion |__Agree |__Strongly Agree

9. Performance measures thresholds should be different in different regions, according to local conditions.

|__Strongly Disagree |__Disagree |__No opinion |__Agree |__Strongly Agree

**Accuracy of the HCM Models**

10. HCM 2010 Urban Streets methods have an aspect of being "black boxes" for users.

|__Strongly Disagree |__Disagree |__No opinion |__Agree |__Strongly Agree

11. The validity of HCM 2010 Urban Streets methods is unknown to users.

|__Strongly Disagree |__Disagree |__No opinion |__Agree |__Strongly Agree

12. Simpler procedures for HCM 2010 Urban Streets methods may be equally effective.

|__Strongly Disagree |__Disagree |__No opinion |__Agree |__Strongly Agree

13. Simpler procedures for HCM 2010 Urban Streets methods may be even more effective.

|__Strongly Disagree |__Disagree |__No opinion |__Agree |__Strongly Agree

14. HCM 2010 Urban Streets methods are data intensive.

|__Strongly Disagree |__Disagree |__No opinion |__Agree |__Strongly Agree

15. Absence of quality data is an on-going issue in transportation.

|__Strongly Disagree |__Disagree |__No opinion |__Agree |__Strongly Agree

### User Perception

16. HCM methods do not predict LOS from the traveler's perspective.

|__Strongly Disagree |__Disagree |__No opinion |__Agree |__Strongly Agree

17. HCM measures are based on consensus by those who developed them.

|__Strongly Disagree |__Disagree |__No opinion |__Agree |__Strongly Agree

18. HCM measures are not representing accurately users' perceptions.

|__Strongly Disagree |__Disagree |__No opinion |__Agree |__Strongly Agree

19. Fewer than six service level categories would be sufficient for practical applications.

|__Strongly Disagree |__Disagree |__No opinion |__Agree |__Strongly Agree

20. Users perceive three or four levels of service.

|__Strongly Disagree |__Disagree |__No opinion |__Agree |__Strongly Agree

21. Users are more tolerant of delay than the HCM 2010 suggests.

|__Strongly Disagree |__Disagree |__No opinion |__Agree |__Strongly Agree

22. Users do not distinguish between LOS A or B.

|__Strongly Disagree |__Disagree |__No opinion |__Agree |__Strongly Agree

23. Users further differentiate within LOS F.

|__Strongly Disagree |__Disagree |__No opinion |__Agree |__Strongly Agree

**Follow-Up Questions**

1. How would you describe your role in your organization?

    a. Professional staff
    b. Mid-level management (team leader)
    c. High-level management (leads several teams)
    d. Other: (Please write in.)

2. If you would like to receive survey results, please provide your e-mail address:

    E-mail:

3. If you are available for follow-up questions, please provide your name:

    Name:

# APPENDIX B

## Questionnaire

## Alternative Urban Street Method Concept

Responses to the questionnaire are confidential, and results will only be summarized in aggregate form. No individual respondents will be identified in questionnaire summaries. Your participation is truly appreciated. Participants will receive questionnaire summary results.

### Segmentation

1. The lengths of analyzed sections are to be determined so that they contain all spillback from the *critical* intersection.

|__Strongly Disagree |__Disagree |__No opinion |__Agree |__Strongly Agree

### Description of Conditions

2. Condition levels are to be defined locally.

|__Strongly Disagree |__Disagree |__No opinion |__Agree |__Strongly Agree

3. Factors impacting condition levels should be selected locally.

|__Strongly Disagree |__Disagree |__No opinion |__Agree |__Strongly Agree

4. Four conditions are to be used.

|__Strongly Disagree |__Disagree |__No opinion |__Agree |__Strongly Agree

5. Within acceptable conditions, there should be two levels of conditions.

|__Strongly Disagree |__Disagree |__No opinion |__Agree |__Strongly Agree

6. Within unacceptable conditions, there should be two levels.

|__Strongly Disagree |__Disagree |__No opinion |__Agree |__Strongly Agree

7. Natural language is helpful to describe four condition levels (if four condition levels are selected), for example: *Good, Fair, Poor,* and *Awful*.

|__Strongly Disagree |__Disagree |__No opinion |__Agree |__Strongly Agree

8. *Good* and *Fair* are appropriate word choices to describe the two acceptable conditions (if two acceptable condition levels are selected).

|__Strongly Disagree |__Disagree |__No opinion |__Agree |__Strongly Agree

9. *Poor* and *Awful* are appropriate word choices to describe the two unacceptable conditions (if two unacceptable condition levels are selected).

|__Strongly Disagree |__Disagree |__No opinion |__Agree |__Strongly Agree

10. Factors impacting conditions should be considered by a deficiency index.

|__Strongly Disagree |__Disagree |__No opinion |__Agree |__Strongly Agree

11. The factors considered in the deficiency index should have weights (if a deficiency index is selected.

|__Strongly Disagree |__Disagree |__No opinion |__Agree |__Strongly Agree