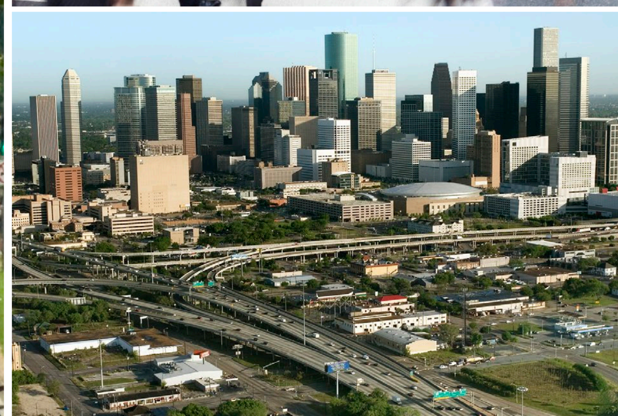
Active Transportation and Demand Management

Analytical Methods for Urban Streets


U.S. Department of Transportation
Federal Highway Administration

Foreword

Welcome to the Federal Highway Administration (FHWA) Active Transportation and Demand Management (ATDM) Analytical Methods for Urban Streets. Practice-ready analytical methods are needed to encourage broader deployment and adoption of ATDM strategies. This document describes a preliminary investigation of urban street ATDM analysis within a highway capacity analysis context. For this initial investigation, the research team and its stakeholders selected a short list of high-priority ATDM methods. Results of the study will be of interest to practitioners and researchers concerned with dynamic and reversible lane use along signalized arterials.
The technical approach taken within this project was to make use of existing data sources and methodologies to the greatest extent possible. The existing methods were then supplemented by original research aimed at determining conditions under which ATDM strategies are beneficial, and developing suggested analysis procedures. The suggested procedures are compatible with the *Highway Capacity Manual's* annual reliability and special event analysis framework for urban streets.

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Technical Report Documentation Page

<table>
<tr><td>1. Report No.
FHWA-HOP-16-088</td><td>2. Government Accession No.</td><td colspan="2">3. Recipient's Catalog No.</td></tr>
<tr><td colspan="2" rowspan="2">4. Title and Subtitle
Active Transportation and Demand Management Analytical Methods for Urban Streets</td><td colspan="2">5. Report Date
February 2017</td></tr>
<tr><td colspan="2">6. Performing Organizations Code</td></tr>
<tr><td colspan="2">7. Authors
David Hale, Hani Mahmassani, Archak Mittal</td><td colspan="2">8. Performing Organization Report No.</td></tr>
<tr><td colspan="2" rowspan="2">9. Performing Organization Name and Address
Leidos, Inc.
11251 Roger Bacon Drive
Reston, VA 20190</td><td colspan="2">10. Work Unit No. (TRAIS)</td></tr>
<tr><td colspan="2">11. Contract or Grant No.
Contract No.
DTFH61-12-D-00050</td></tr>
<tr><td colspan="2" rowspan="2">12. Sponsoring Agency Name and Address
United States Department of Transportation Federal Highway Administration Office of Operations
1200 New Jersey Avenue, SE
Washington, DC 20590</td><td colspan="2">13. Type of Report and Period Covered
Research Report
September 2015 – December 2016</td></tr>
<tr><td colspan="2">14. Sponsoring Agency Code
HOP-1</td></tr>
<tr><td colspan="4">15. Supplementary Notes
The Contracting Officer's Representative was John Halkias, HOP-1.</td></tr>
<tr><td colspan="4">16. Abstract
This report describes an investigation of analytical, Highway Capacity Manual (HCM)-compatible evaluation methods for urban street active transportation and demand management (ATDM). ATDM strategies have been successfully deployed in the United States, but the lack of available analytical methods may be reducing their successful adoption by more cities. To achieve the full benefits of ATDM, it is essential that the user community of traffic engineers and planners, and the policy decision makers they support, have ready tools to evaluate the benefits and operational impacts of specific projects. Accordingly, the HCM provides an ideal vehicle to disseminate these capabilities at a level of analysis that most engineers and planners are familiar and comfortable with. Due to the scarcity of field data, conclusions developed during this project were based on software experiments. This effort produced a detailed set of ranges and conditions under which dynamic lane grouping (DLG) could be effective. Additionally, this effort illustrated the potential benefits of three ATDM strategies, and demonstrated HCM implementation of two ATDM strategies. It was originally believed that the ATDM strategies could be effectively modeled via capacity adjustment factors, similar to what was accomplished during the freeway ATDM project. However, it was later discovered that the capacity adjustment paradigm would be unsuitable for arterials, and that the HCM reliability framework would offer a preferable solution. Specifically, the alternative lane use configurations could be modeled as special event datasets, along with re-optimized timing plans for the new lane uses. Case studies then demonstrated this concept.</td></tr>
<tr><td colspan="2">17. Key Words
ATDM, adaptive signals, dynamic lane grouping, reversible lanes, Highway Capacity Manual, HCM</td><td colspan="2">18. Distribution Statement
No restrictions.</td></tr>
<tr><td>19. Security Classif. (of this report)
Unclassified</td><td>20. Security Classif. (of this page)
Unclassified</td><td>21. No of Pages
100</td><td>22. Price
N/A</td></tr>
</table>

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized.

SI* (MODERN METRIC) CONVERSION

FACTORS APPROXIMATE CONVERSIONS TO SI UNITS				
SYMBOL	**WHEN YOU KNOW**	**MULTIPLY BY**	**TO FIND**	**SYMBOL**
LENGTH				
In.	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
AREA				
in.^{2}	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
VOLUME				
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: volumes greater than 1,000 L shall be shown in m^3				
MASS				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
TEMPERATURE (exact degrees)				
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
ILLUMINATION				
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
FORCE and PRESSURE or STRESS				
lbf	poundforce	4.45	newtons	N
lbf/in.^{2}	poundforce per square inch	6.89	kilopascals	kPa

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

SI* (MODERN METRIC) CONVERSION (continued)

APPROXIMATE CONVERSIONS TO SI UNITS				
SYMBOL	**WHEN YOU KNOW**	**MULTIPLY BY**	**TO FIND**	**SYMBOL**
LENGTH				
mm	millimeters	0.039	inches	in.
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
AREA				
mm^2	square millimeters	0.0016	square inches	$in.^2$
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
VOLUME				
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
MASS				
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
TEMPERATURE (exact degrees)				
°C	Celsius	1.8C+32	Fahrenheit	°F
ILLUMINATION				
lx	lux	0.0929	foot-candles	fc
cd/m^2	$candela/m^2$	0.2919	foot-lamberts	fl
FORCE and PRESSURE or STRESS				
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

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List of Acronyms

AMS	analysis, modeling, and simulation
APM	active parking management
ASCT	adaptive signal control technology
ATDM	active transportation and demand management
ATM	active transportation management
BBS	bus bypass shoulders
DDI	diverging diamond interchange
DLG	dynamic lane grouping
FDOT	Florida Department of Transportation
FHWA	Federal Highway Administration
HCM	*Highway Capacity Manual*
HCQSC	Highway Capacity and Quality of Service Committee
ICM	integrated corridor management
NCHRP	National Cooperative Highway Research Program
OD	origin-destination
OPAC	optimized policies for adaptive control
PTI	planning time index
RCL	reversible center lanes
RHODES	Real Time Hierarchical Optimized Distributed Effective System
RTOR	right-turns-on-red
SCATS	Sydney Coordinated Adaptive Traffic System
SCOOT	split cycle offset optimization technique
SHRP	Strategic Highway Research Program
TAZ	traffic analysis zones
TRB	Transportation Research Board
TSP	transit signal priority
TTI	travel time index
TTPM	travel time per mile
VDOT	Virginia Department of Transportation
USDOT	United States Department of Transportation
VHD	vehicle-hours delay
VHT	vehicle-hours traveled

CHAPTER 1. INTRODUCTION

BACKGROUND AND UNDERSTANDING

The *Highway Capacity Manual* (HCM) is one of the most widely-used transportation documents for evaluating the performance of transportation facilities. It has been developed and maintained by the Highway Capacity and Quality of Service Committee (HCQSC) of the Transportation Research Board (TRB), with funding provided by state and federal highway agencies. The HCM contains analytical and computational procedures for evaluating operational efficiency of various highway facilities (e.g., signalized intersections, urban street segments, interchange ramp terminals, freeway facilities, ramp junctions, unsignalized intersections, two-lane rural highways, multilane highways, freeway weaving sections, and basic freeway segments). Recent surveys for the National Cooperative Highway Research Program (NCHRP) Project 03-115 (Kittelson and Associates, 2013) confirmed that the signalized analysis procedures are the most heavily utilized procedures in the HCM. HCM procedures are implemented within several commercial software packages (e.g., HCS 2010™, Synchro™, Vistro™, and Transmodeler™), and likely used by thousands of traffic engineers and planners across the United States.

HCM guidelines and software tools are a vital resource for these engineers and planners. They provide a practical platform for evaluating and predicting traffic operational performance. They complement the traffic simulation tools; which are powerful enough to analyze advanced technologies, unique configurations, and larger networks. Simulation tools are not necessary for all types of traffic analyses. Their use requires more time, expertise, and resources than the HCM methods, which often provide sufficiently robust assessments and conclusions. Any traffic facilities, technologies, or control strategies not "covered" by the HCM, or that deviate substantially from cases considered in the HCM, must be analyzed through simulation or other alternative tools.

By continuously developing new guidelines and updated procedures to address new facilities and technologies, the HCQSC hopes to support congestion mitigation in a time of population growth and limited resources. One example of HCM evolution is the diverging diamond interchange (DDI); whose construction has increased significantly since the year 2010, but can only be analyzed through simulation or other tools. The DDIs have been a revelation in this country. They have substantially reduced both congestion and accidents at a relatively low cost, within existing right-of-ways. The recently published HCM 6th Edition provides new procedures for DDI analysis. Given that the HCM methods and software tools are accessible to a wide audience of engineers and planners, the recent inclusion of DDI procedures will hopefully facilitate the adoption of these congestion-fighting facilities.

The DDI example shows that the HCQSC is incentivized to develop HCM methods in a way that considers new technologies and control strategies. Recent editions of the HCM have added brand-new qualitative and quantitative content related to active transportation and demand management (ATDM) strategies, which mitigate congestion in creative and innovative ways. As stated in the HCM, "ATDM strategies are essentially real-time changes in geometry, lane assignment, or traffic control that are implemented in the timeframe of a few seconds." Sample ATDM strategies include adaptive signals, dynamic merge control, dynamic lane grouping, and speed harmonization. The recent release of HCM-based ATDM analysis procedures is an important element of the U.S. Department of Transportation's (USDOT) technology transfer mandate; in that it enables these new technologies and control strategies to be intelligently analyzed and adopted by more cities, and by the broader professional practice community.

The HCM-based ATDM analysis methods available to date remain limited in terms of scope and applicability, as only freeway facilities can be analyzed. Furthermore, new and improved variants on the ATDM applications' algorithms and parameters are being developed through both virtual and field deployments. However, as previously noted, the signalized analysis procedures are the most heavily utilized in the Manual; yet none of the computational procedures for interrupted flow facilities contain support for ATDM strategy evaluation. The latest HCM (Transportation Research Board of the National Academies, 2016) states "there is relatively little research on the demand, capacity, speed, and delay effects of urban street ATDM strategies." Therefore new research is needed to develop HCM-compliant macroscopic relationships, targeted at urban street ATDM analysis.

To achieve the full benefits of ATDM, it is essential that the user community of traffic engineers and planners, and the policy decision makers they support, have ready tools to evaluate the benefits and operational impacts of specific projects in the locations where they are considered. Through development of Analysis, Modeling and Simulation (AMS) testbeds, the Federal Highway Administration (FHWA) is producing the research and capability for in-depth assessment of different ATDM bundles under specific operational conditions. However, application to AMS tools is often beyond the capability and resources of communities that do not maintain state-of-the-art network simulation tools. Accordingly, the HCM provides an ideal vehicle to disseminate these capabilities at a level of analysis that most engineers and planners are familiar and comfortable with.

WORK ORDER OBJECTIVE

Building on recent studies and research inside and outside the HCQSC, this project provided new urban street ATDM methodologies, data sets, and content for the HCM. This content may subsequently be incorporated within other chapters throughout the HCM. To the extent possible the measures and data used in this work were based upon existing sources, methodologies, and projects. In other words, major new data collection was not performed for this project.

TECHNICAL APPROACH

The objective of this project was to develop user-friendly, practice-accessible procedures that enable local engineers and planners to assess the potential impact on facility and system capacity of ATDM actions. Accomplishing these objectives entails several challenges, which arise primarily from the fundamental nature of ATDM actions. As its name indicates, ATDM is about moving system operations from a static, partially-informed, supply-driven approach to the fundamental concept of taking a dynamic, informed approach that targets both supply-side actions and demand-oriented measures to optimize performance. ATDM seeks to dynamically monitor, control, and influence travel, traffic, and facility demand of the entire transportation system and over a traveler's entire trip chain. The dynamic, data-driven nature of these interventions, and the fact that their target may extend beyond the local facility level, raises several challenges for this work. These challenges include:

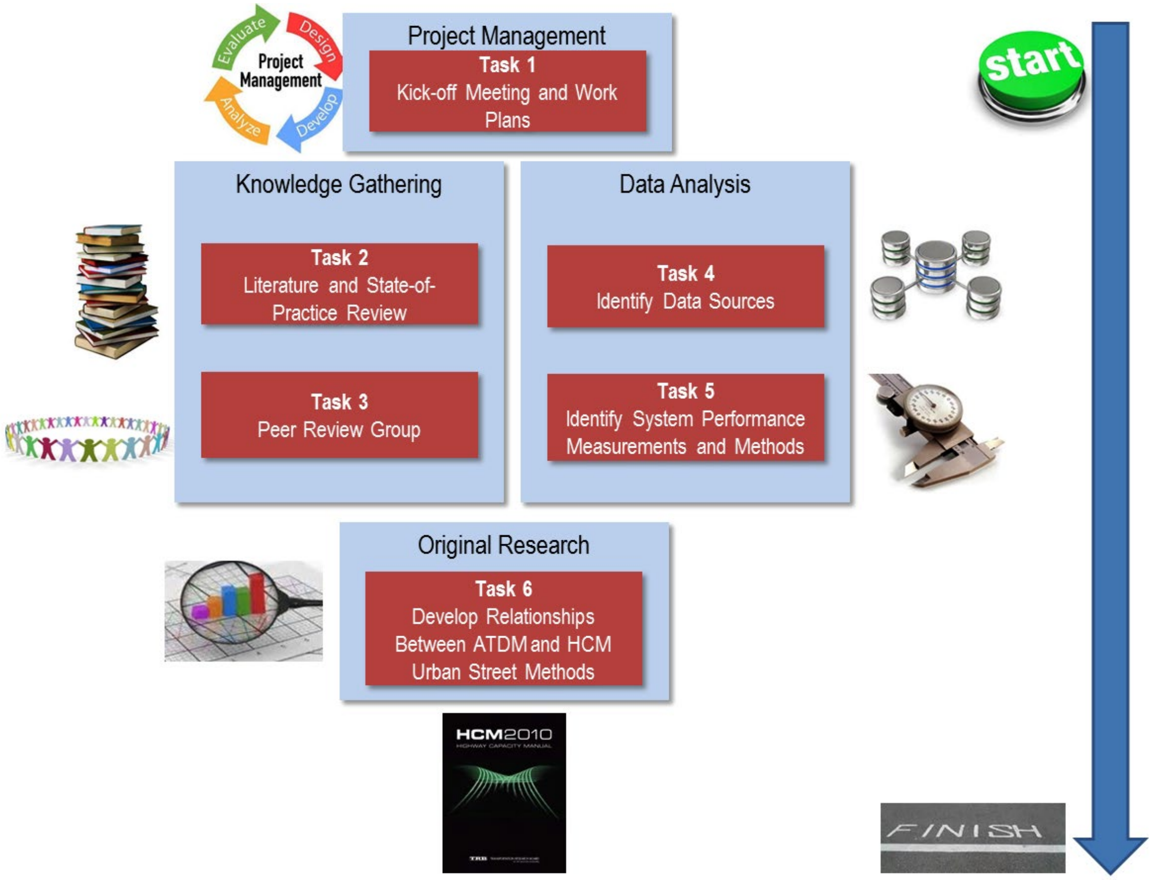
1. Variability in impacts (throughput, delay) of applying the same strategy at different times: Even when applied at the same location, with the same parameter settings, a range of outcomes are possible depending on actual realizations of stochastic factors.

2. System effects: because some ATDM strategies target individual traveler decisions, their impact may extend beyond the immediate location where they are applied; these interactions in the context of network interconnections make it difficult, in some situations, to limit or localize the impacts to specific facilities.

3. Context specificity and lack of transferability/scalability: the observed or simulated impacts of applying certain strategies may be dependent on unique characteristics of these locations. For instance, weather-related ATDM actions examined in the Chicago testbed may not transfer especially well to a city like Atlanta, where drivers are not accustomed to snow occurrences.

The research team planned to address these challenges by articulating a framework that recognizes the above factors, and providing practical ranges of possible outcomes instead of a single mean value. The framework would be developed through analysis of existing results developed in the five AMS testbeds (with particular focus on Chicago and Phoenix testbeds which are explicitly considering arterial-related strategies), actual field deployments (especially from the integrated corridor management (ICM) sites with applicable strategies), and stakeholder input. The framework would then be applied in conjunction with a scenario-based approach, similar to that developed in SHRP-2 L04 project to produce travel time reliability outputs using simulation models (Kim, Mahmassani, Vovsha, Stogios, & Dong, 2013) (Mahmassani, Kim, Stogios, Currie, & Vovsha, 2013).

Figure 1 summarizes the team's approach to the work order. For Task 1, the team began the project by finalizing the project work plan following an initial kickoff meeting. Then for Task 2, the team conducted a literature and state-of-the-practice review of relevant methodologies defined in the HCM. For Task 3 the team assembled a peer group of HCM and ATDM experts, who could continuously provide guidance throughout the project. Task 4 documented existing data sources, which could facilitate efficient execution of HCM-centric ATDM research. Task 5 identified candidate system performance measures and methods for assessing urban street ATDM effectiveness. In Task 6 the team conducted original research, based on insights gained from the other five tasks.



Source: Federal Highway Administration

Figure 1. Diagram. The research team's technical approach.

PEER REVIEW GROUP

The peer review group represented a unique project task, and will be mentioned throughout this report. In parallel with Task 2 – Review of Existing Methodologies, Task 3 of the project required establishment of a peer review group to provide input on development of the methodologies. Members of the group were drawn from the HCQSC, the HCQSC Task Force on ATDM, the FHWA, and other interested individuals. The peer group met periodically throughout the project's period of performance via web conference. The peer review group provided input on which urban street ATDM strategies should be implemented in the HCM, how best to conduct the original research, and how to meet overall project objectives.

CHAPTER 2. EXISTING METHODOLOGIES

Following Task 1 – Project Management, Task 2 of the project involved a literature review and state-of-practice review of all relevant methodologies defined in the *Highway Capacity Manual* (HCM), to identify if they were applicable to this work effort. To fulfill this task, it was first necessary to define the scope of the work effort, in terms of the most appropriate active transportation and demand management (ATDM) strategies for HCM implementation. To define the scope of the work effort, the research team conducted a review of prior HCM-based ATDM research on freeways, plus a review of urban street ATDM strategies. Results of this review were documented in a detailed technical memorandum in December 2015, and are repeated here in this chapter.

Based on stakeholder (i.e., peer review group) feedback, the team's knowledge of HCM methods, the review of HCM-based freeway ATDM research, and the review of urban street ATDM strategies, the research scope was narrowed to three specific ATDM strategies: ***adaptive signal control, reversible center lanes***, and ***dynamic lane grouping***. The research team believes there would be significant national interest in developing the ability to analyze impacts of these strategies in an HCM context, and without requiring micro-simulation. This chapter summarizes the information and thought process that led to the selection of the specific three strategies listed above.

ACTIVE TRANSPORTATION AND DEMAND MANAGEMENT ON FREEWAYS

When beginning the effort to incorporate ATDM concepts into the HCM, the Federal Highway Administration (FHWA) and Highway Capacity and Quality of Service Committee (HCQSC) focused solely on freeways for their initial implementations. This is likely due to the fact that ATDM strategy implementation is more common at the freeway level, and because arterial modeling is generally more complex than freeway modeling. The original freeway ATDM implementation effort for the HCM was documented and published in 2013 (Dowling, Margiotta, Cohen, & Skabardonis, 2013). The report points out an important concept, namely the lack of insight on how ATDM strategies will perform when implemented in the United States. The report encourages transportation analysts to choose any traffic analysis tool responsive to ATDM, and to consult the FHWA traffic analysis tool guidance documents. The report also emphasizes data requirements. In cases where sufficient amounts of data (e.g., 6-12 months of collected or observed data) are not available, alternatives and approximations are suggested. One key difference between this FHWA methodology and the current HCM is that the latter is limited to individual facilities, and does not assess system-wide performance.

The report summarizes freeway-level ATDM strategies, divided into three categories:

1. Active demand management.
2. Active traffic management.
3. Active parking management.

The freeway ATDM report then describes the details of numeric performance measures. Conventional measures are said to perhaps not be sufficient, as they overlook the benefits of ATDM. The report then recommends the following measures:

1. **Vehicles-Miles Traveled (VMT)-Demand:** Summation of the products of origin-destination (OD) trip table numbers, and shortest path distances for each OD.
2. **VMT-Served:** Summation of the products of link lengths and vehicle volumes on the link.
3. **Vehicle-Hours Traveled (VHT):** Summation of the products of total link volumes and average link travel times. This accounts for any delays to vehicles prevented from entering the facility either by controls (such as ramp metering) or by congestion.
4. **Vehicle-Hours Delay (VHD):** Difference between VHT (including vehicle-entry delay) and theoretical VHT if all links could be traversed at the free-flow speed with no entry delays [VHT (FF)].

$$VHD=VHT-VHT\ (FF)$$

Figure 2. Equation. Vehicle-hours delay (VHD).

5. **Average System Speed:** The sum of (VMT-Served /VHT) for each scenario.
6. **Average delay per vehicle:** The sum of VHDs for all scenarios divided by the sum of total vehicle trips for all scenarios.
7. **80th percentile Travel Time Index ($TTI_{80\%}$):** TTI provides a measure of travel time reliability.

$$TTI_{80\%} = \frac{[VHT_{80\%} / VMT_{80\%}]}{[VHT_{free\text{-}flow} / VMT_{free\text{-}flow}]}$$

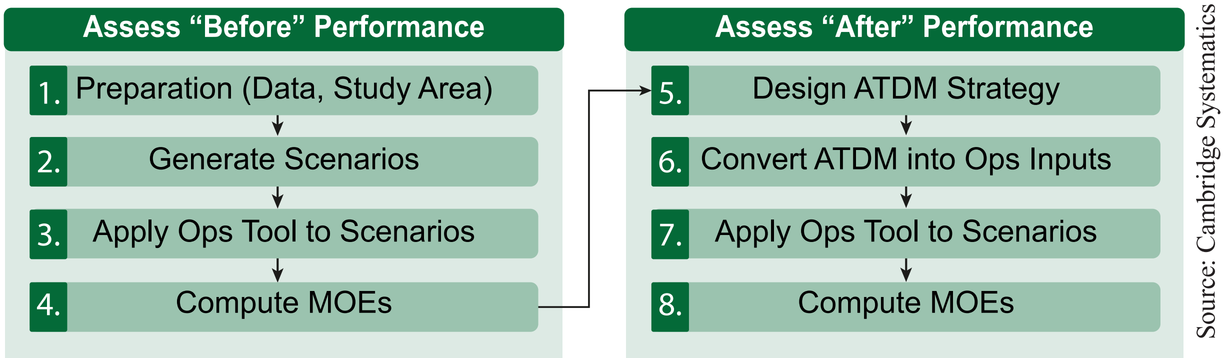
Figure 3. Equation. 80th percentile travel time index.

VHT and VMT in the numerator are the 80th percentile quantities. The report states that 80th percentile relates better to mean speed than 90th, 95th or 99th percentile quantities.

8. **Planning Time Index (PTI):** This is another measure of travel time reliability. It is computed using the equation with 95th percentile values substituted for the 80th percentile values. For example, a PTI of 1.50 means that the traveler must allow 50 percent extra time over free-flow travel time to get to their destination on-time. Put another way, a commuter will arrive late one day per month (1 of out 20 weekdays) if they plan their trip at the PTI.

The report recommends assessing ATDM strategies for peak hours (same as HCM), but over all weekdays rather than a single weekday (different from HCM). The rationale behind this is that an agency would aim to operate a facility at levels that are annually optimal. If the aim is to cater to another time period and demand, then the assessment should be applied to the period of interest. Section 3.5 of the report provides performance measures for several United States facilities using actual field-measured data.

After defining and illustrating performance measures, Section 4 of the freeway ATDM report discusses assessment of ATDM strategies deployed in the field. The recommended analysis procedure shown in Figure 4 is performed before and after ATDM implementation. Furthermore, the "after" implementation is divided into "opening day" and "equilibrium" (i.e., 3-6 months after implementation) categories.



MOE = measures of effectiveness, ATDM = active transportation and demand management

Figure 4. Chart. Flowchart of the active traffic demand and management analysis process.

The "before" conditions are analyzed using historic data. These conditions are used to calibrate and error-check the strategy through analysis tools. The "after" conditions are analyzed to determine ATDM strategy effectiveness. As mentioned earlier, the analyst is free to choose any analysis tool that is sensitive to ATDM (e.g., HCM, micro-simulation, meso-simulation).

Details of the steps are as follows:

1. **Preparatory Steps:** Set the scope and purpose of the analysis, define a target study area, and collect data.
2. **Generate Scenarios:** Set "before" condition using historic data on demand, incidents, and weather. Demand and capacity scenarios are generated to evaluate existing conditions, and to test the new ATDM strategy.
3. **Apply Selected Operations Analysis Tool to Scenarios:** The appropriate operations analysis tool (e.g., HCM, simulation) is used to evaluate facility operations for each scenario.
4. **Compute MOEs (Performance Measures):** The results from step 3 are combined to yield throughput, delay, and travel time reliability measures for the "before" condition.
5. **Design ATDM Strategy:** Based on an assessment of the "before" conditions and an identification of the relative contribution of weather, demand, incidents, and work zones to the undesirable performance of the facility or system, the analyst selects and designs an ATDM strategy that he or she wishes to test. If ATDM is already in place for the before condition, then the analyst identifies changes in the existing ATDM strategy to be tested.
6. **Convert ATDM Strategy into Operations Analysis Tool Inputs:** This is a translation of ATDM strategies into the appropriate demands, capacities, and control inputs required by the operations analysis tool for each specific scenario.
7. **Apply Selected Operations Analysis Tool to Scenarios (Opening Day):** Opening day demands are held essentially constant. Drivers are assumed to cooperate with the new controls in effect (wait for ramp meters, obey new speed limits, etc.) and take advantage of any new capacity provided (simple lane shifts, however no route, time-of-day, or mode shifts).
8. **Compute MOEs (Opening Day):** Results output by the operations analysis tool for Opening Day are combined to yield the desired MOEs. "After" results are assessed by the analyst to determine if the ATDM strategy should be fine-tuned and reevaluated.

The same analysis tool is applied to the before, opening day, and long-term demand analysis conditions for each scenario. For longer term forecasts of ATDM investment benefits (e.g., 20 years or more), the three stages of analysis (i.e., before, opening day, long term) are repeated with 20-year forecasts of demand as the base condition. The opening day analysis is used to estimate ATDM operational effects in the future. Equilibrium analysis is then used to estimate the demand changes that would occur under ATDM.

Complete explanations for the above steps are provided in section 5 of the report. Section 6 illustrates an application of freeway ATDM strategies to estimate annual facility performance. The report walks through each of the 8 steps mentioned above with real data. In this section, the first strategy to be applied is "Convert high-occupancy vehicle (HOV) to high-occupancy toll (HOT) Lane." "Dynamic Ramp Metering" is then added, for an analysis of combined effects. Finally, "Traffic Incident Management" is analyzed in a stand-alone manner.

Step 6 ("Convert ATDM Strategy into Operations Analysis Tool Inputs") was a key factor in determining ATDM strategy impacts in an HCM context. For example, the freeway ATDM research team increased ramp merge section capacities by 3 percent to capture the capacity increasing effects of ramp metering. The team selected the value of 3 percent based on their review of recent research, but further recommended that this important value should be "determined by the user." Similarly, the team assumed HOV and HOT lane capacities of 1350 and 1500 vehicles per lane per hour, respectively, to capture before-and-after ATDM strategy impacts. Finally, in cases of traffic incident management, the team assumed a 10 percent decrease in traffic volume demand. Therefore, from the freeway ATDM research, reported ATDM strategy benefits from the before-and-after HCM reliability experiments were highly dependent on these key assumptions (e.g., 3 percent capacity increase, 10 percent demand decrease) within Step 6. As such, a key question for the arterial ATDM research team revolved around whether a similar framework would be viable for urban streets; and if so, what key assumptions would be made in step 6.

The following sub-sections address existing ATDM methodologies in the context of arterial/urban streets. There is a substantial amount of literature available on ATDM, however, this review focuses on strategies potentially related to urban streets.

ACTIVE TRANSPORTATION AND DEMAND MANAGEMENT ON ARTERIALS

As shown in Table 1, most ATDM strategies can be classified within 4 categories. A brief description of each strategy (Kuhn, Gopalakrishna, & Schreffler, 2013) is provided in the Appendix.

Table 1. Classification of active transportation and demand management strategies.

Active Demand Management	Active Traffic Management	Active Parking Management	Weather Related Strategies
Dynamic Ridesharing	Dynamic Lane Use Control	Dynamically Priced Parking	Snow Emergency Parking Management
On-Demand Transit	Dynamic Speed Limits	Dynamic Parking Reservation	Traffic Signal Preemption for Winter Maintenance Vehicles
Dynamic Pricing	Queue Warning	Dynamic Way-Finding	Snowplow Routing
Predictive Traveler Information	Adaptive Ramp Metering	Dynamic Parking Capacity	Anti-icing and Deicing Operations

Active demand management (ADM) is a characteristic of the market. Planners must conduct a sensitivity analysis to estimate the feasibility and success of ADM strategies. The International Technology Scanning Program accesses and evaluates innovative foreign technologies and practices that have the potential to benefit the U.S. highway transportation systems. This approach allows for advanced technology to be efficiently adapted and put into practice, without spending scarce research funds to re-create advances already developed by other countries. Since 1990, around 70 such studies have been conducted on various aspects of transportation that also includes ATDM (Mirshahi, et al., 2007). Most of the cases are from European countries like the Netherlands, Germany, England, etc. Active traffic management (ATM) strategies aim to move traffic more efficiently, albeit in ways that do not involve demand management. They manage traffic using real-time data. Figure 5 (adapted from the FHWA) provides potential benefits of ATM.

Active traffic management strategy	POTENTIAL BENEFITS											
	Increased throughput	Increased capacity	Decrease in primary incidents	Decrease in secondary incidents	Decrease in incident severity	More uniform speeds	More uniform driver behavior	Increased trip reliability	Delay onset of freeway breakdown	Reduction in traffic noise	Reduction in emissions	Reduction in fuel consumption
Speed harmonization	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Temporary shoulder use	✓	✓						✓	✓			
Queue warning			✓	✓	✓	✓	✓	✓		✓	✓	✓
Dynamic merge control	✓	✓	✓			✓	✓	✓	✓	✓	✓	✓
Dynamic lane markings	✓	✓						✓				
Construction site management	✓	✓						✓		✓	✓	✓
Dynamic truck restrictions	✓	✓				✓	✓	✓			✓	✓
Dynamic rerouting and traveler information	✓		✓	✓			✓	✓			✓	✓
Automated speed enforcement			✓		✓	✓	✓	✓			✓	✓

Source: Federal Highway Administration, Guide for Highway Capacity and Operations Analysis of Active Transportation and Demand Management Strategies, FHWA-HOP-13-042 (Washington, DC: June 2013).

Figure 5. Chart. Active traffic management strategies and potential benefits.

Next is a discussion of ATDM strategies that have potential use on arterial streets.

Dynamic Speed Limits

Speed harmonization (or variable/dynamic speed limit control) is an active traffic management strategy that adjusts and coordinates maximum appropriate speed limits on the basis of prevailing traffic conditions, road surface conditions, and weather condition information. Such strategies are used to deal with congestion, incidents, or special events. They maximize traffic throughput by delaying breakdown formation, and by minimizing incident-related hazards (PB Americas, Inc., 2007).

When a facility is operating near capacity, shock waves may appear and propagate because of frequent lane changing-merging maneuvers, or sudden decelerations. The shock wave propagation may eventually produce traffic flow breakdowns with a corresponding increase in travel delay, decreased throughput, and potentially unsafe driving situations. Speed harmonization aims at avoiding shock wave formation, dampening its propagation, and minimizing incident-related hazards by controlling vehicular speeds, and creating a more uniform traffic flow. A successful and efficient implementation of speed harmonization depends highly on the sensor coverage of intelligent transportation systems, selection of efficient enforcement strategies (to increase driver compliance with posted speed limits), implementation of effective control strategies for speed limit selection, and selection of road segments for implementing the corresponding logic (Waller, Ng, Ferguson, Nezamuddin, & Sun, 2009). This strategy can be implemented in conjunction with other strategies, but with some tweaks. It has two key elements: minimum duration between the speed limit change, and upstream location where speed limit is changed. Before implementing the strategy, one must find optimal values for these two elements.

Speed harmonization has been found beneficial in reducing collisions, reducing travel times, increasing facility reliability, and reducing incidents. Its success also depends on driver compliance. Speed harmonization was introduced in European countries (e.g., Netherlands, Germany, UK, Spain, Greece, Finland), and was then adopted by the United States (e.g., Washington, Michigan). In the United States it is used on freeways and in work zones. In the literature, speed harmonization was only found to be deployed on freeways. The consensus of most researchers seems to be that it may not be significantly beneficial without advanced vehicle technologies (Hale, et al., 2016). However when combined with other strategies, or with advanced vehicle technologies, it may improve facility level of service.

Dynamic Lane Use Control

Dynamic lane use involves the dynamic closing or opening of individual traffic lanes, to better align roadway capacities with time-varying traffic demands. Advance warning of the closure(s) (typically through dynamic lane control signs) is needed to safely merge traffic into adjoining lanes. Dynamic lane use has been implemented on arterial roads in Greece. For example, bus-only lanes are operated on weekdays from 6 a.m. to 9 p.m., and on Saturdays from 6 a.m. to 4 p.m. Secondly, Olympic lanes for exclusive use by Olympic athletes, VIPs, accredited media, sponsors, technical officials, public transport buses carrying spectators, and Olympic-accredited vehicles were operated from 6:30 a.m. to midnight during the 17-day Olympic Games (Mirshahi, et al., 2007). In Minneapolis, bus bypass shoulders (BBS) have proven to be both safe and effective. Their criteria to implement BBS are that average speeds must drop below 35 mph during the peak period, or intersection approaches must suffer continuous queues. Other criteria include congestion delays that occur at least once a week, six or more transit buses using the shoulder per week, delay savings greater than 8 minutes per mile per week, and the shoulder must be at least 10 ft wide. To ensure safety, maximum bus speeds are restricted to 35 mph, and buses may not drive more than 15 mph faster than main traffic.

Reversible Center Lanes

Reversible lanes provide a mechanism to better utilize roadway right-of-way when directional asymmetries exist. Under ATDM, the direction of travel could be reversed when certain conditions are realized; because of the potential for collisions when geometric features change unexpectedly, most real-world implementations follow predictable schedules. However, under certain extreme or unusual surge conditions, triggering reversible lane operations in real-time could be an effective strategy. Specific examples of dynamically operated reversible lanes are very limited, and do not cover a wide range of conditions. In Washington, DC, despite some safety issues, it has shown potential of improving traffic conditions (Dey, Ma, & Aden, 2011). Another study conducted in Utah detailed the benefits (Avenue Consultants, 2013). These benefits include increased peak-direction throughput during the peak hours. In the opposite direction, throughput is found to be either increased or remains the same. Simulation studies have been published to integrate reversible lanes on arterial roads (Zhao, Ma, Liu, & Yang, 2014).

Adaptive Traffic Signal Control

This strategy consists of continuous monitoring of arterial traffic conditions, and of queuing at intersections. It also requires dynamic adjustment of signal timings to optimize one or more operational objectives (e.g., minimize overall delays). Congestion and delays may originate from poor traffic signal timings. Signal controls that are responsive to changing traffic can ease traffic congestion, and reduce the associated delays. Benefits of adaptive traffic signal control (ATSC) are as follows (Federal Highway Administration, 2016) (Mladenovic, Stevanovic, Kosonen, & Glavic, 2015):

1. Continuously distribute green light time equitably for all traffic movements.
2. Improve travel time reliability by progressively moving vehicles through green lights.
3. Reduce congestion by creating smoother flow.
4. Prolong the effectiveness of traffic signal timing.
5. Fast and effective in addressing fluctuating demands, special events, and queue spillback.
6. Capability to handle short-term communication, provide priority for Public Transport vehicles.
7. Environmentally friendly; can reduce emissions by improving traffic flow.

More than 20 different ATSCs have been developed during the last 30 years. However, only about a dozen of them have been applied in the real world with more than one field implementation (Fehon, 2004). Available adaptive signal control products include:

- Split Cycle Offset Optimization Technique (SCOOT.)
- Sydney Coordinated Adaptive Traffic System (SCATS).
- Real Time Hierarchical Optimized Distributed Effective System (RHODES).
- Optimized Policies for Adaptive Control (OPAC).
- FHWA's ACS-Lite.
- InSync.
- LA ATCS.
- SPOT / UTOPIA – Urban Traffic Optimization by Integrated Automation.
- MOTION (Method for the Optimization of Traffic Signals in On-line controlled Networks).
- BALANCE+.
- ATCS (Adaptive Traffic Control System)+.
- ITACA+.
- RTACL+.
- Streetwise (new adaptive module)+.
- QuicTrac+.

Note: + indicates systems known to be operational but not widely used (Fehon, 2004).

National Cooperative Highway Research Program (NCHRP) Synthesis 403 provided surveys of ATSC performance (Stevanovic, 2010). In the surveys, 45 agencies participated including 34 in North America, and 11 in other countries (Table 2). Most interviewed agencies (80 percent) deployed ATCSs in the network with speed limits between 30 and 45 mph. Survey results also showed that 42 percent of agencies deployed ATCSs on arterial networks, 10 percent were deployed on grid networks, and 33 percent were deployed on a combination of the two network types.

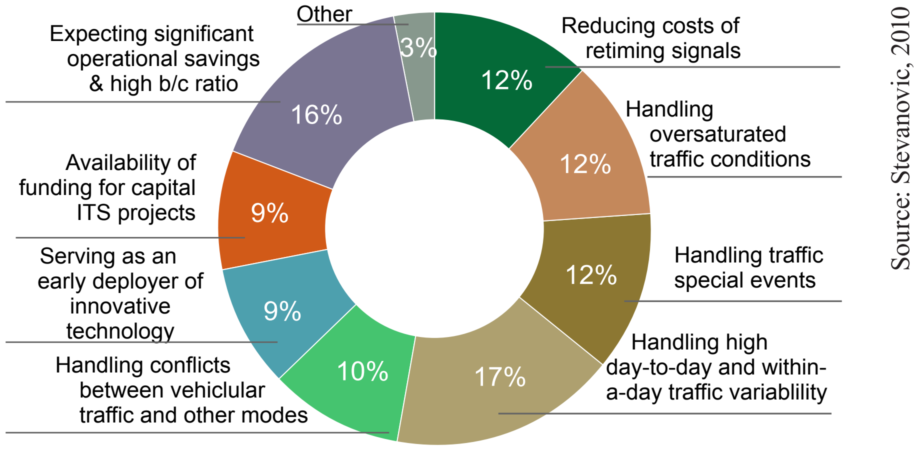


Figure 6. Chart. Pie chart of reasons for implementing adaptive signal systems.

Figure 6 shows the leading reasons for implementing an ATSC. The figure reveals that ATSC is typically chosen for its capability to handle high day-to-day and within-a-day traffic variability. In the survey, most agencies used SCOOT, SCATS and OPAC. However more recently, InSync, ASC-Lite and LA ATCS received more attention.

Table 2. International survey of adaptive signal deployments.

Agency	System	Agency	System
U.S. Deployments		**International Deployments**	
City of Longview Texas	ACS Lite	Econolite Canada Inc., Canada	RHODES
W.E. Stilson Consulting Group, LLC, Columbus, Ohio	ACS Lite	Dublin City Council, Ireland	SCATS
City of Little Rock, Arizona	InSync	New Zealand Transport Agency, Auckland, New Zealand	SCATS
California Department of Transportation-District 7, California	LA ATCS	Roads & Traffic Authority, New South Wales, Sydney, Australia	SCATS
Culver City, California	LA ATCS	Unidad Operativa de Control de Tránsito, Concepcion, Chile	SCATS
Los Angeles Department of Transportation, California	LA ATCS	VicRoads, Victoria, Australia	SCATS
City of Chesapeake, Virginia	OPAC	City of Blackpool Council, United Kingdom	SCOOT
Town of Cary, North Carolina	OPAC	City of Red Deer, Canada	SCOOT
Virginia Department of Transportation, Virginia	OPAC	City of Southhampton, United Kingdom	SCOOT
Pinellas County, Florida	OPAC, RHODES	CIty of Toronoto	SCOOT
City of Tucson, Arizona	RHODES	Derby City Council, United Kingdom	SCOOT
Washington State Department of Transportation, Washington	RHODES	Greater Manchester Urban Traffic Control Unit	SCOOTS

2

EXISTING METHODOLOGIES

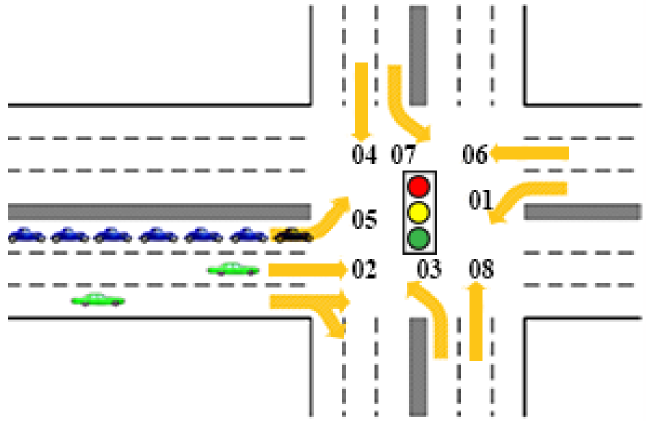
Table 2. International survey of adaptive signal deployments. (continued)

Agency	System	Agency	System
U.S. Deployments		**International Deployments**	
City of Chula Vista, California	SCATS	Halifax Regional Municipality	SCOOTS
City of Gresham, Oregon	SCATS	Hampshire County Council, United Kingdom	SCOOTS
Cit of Menlo Park, California	SCATS	IMoTS Siemans Ltd, Beijing, China	SCOOTS
City of Santa Rosa, California	SCATS		
City of Sunnyvale, California	SCATS		
Cobb County, Georgia	SCATS		
Delaware Department of Transportation, Delaware	SCATS		
Florida DOT District 4, Florida	SCATS		
Minnesota Department of Transportation, Minnesota	SCATS		
Pasco County, Florida	SCATS		
Road Commission for Oakland County, Michigan	SCATS		
Utah Department of Transportation, Utah	SCATS		
City of Anaheim, California	SCOOT		
City of Ann Arbor, Michigan	SCOOT		
Collier County, Florida	SCOOT		
Orange County, Florida	SCOOT		
Reedy Creek Improvement District, Florida	SCOOT		
Short Elliot Hendrickson Inc., Minnesota	SCOOT		

The Virginia Department of Transportation (VDOT) conducted a comprehensive review of ATSCs (Fontaine, Ma, & Hu, 2015). VDOT reviewed 13 ATSC corridors in Virginia, using Bluetooth and INRIX data, for multiple days. The results showed that mainline traffic operations generally improved if (1) the corridor was not oversaturated; (2) the corridor did not have characteristics that encourage platoon dispersion; and (3) the corridor did not already function well. Side street delays generally increased, although net benefits in overall corridor travel time were usually still observed.

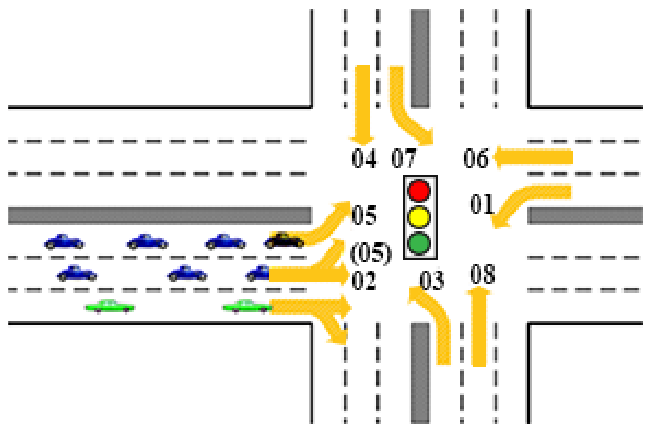
Dynamic Lane Grouping

Dynamic lane grouping (DLG) involves the dynamic changing of allowable turning movements in each lane; also known as lane assignments, or lane channelization (Su, Jiang, Jagannathan, & Hale, 2015). For example, consider an intersection approach with three through lanes and one left-turn lane. When the intersection experiences heavy left-turn demands with relatively low through demand, dynamically converting a through lane into a left-turn lane would better align capacity supply and traffic demand across all lanes, leading to an overall reduction in delay. Indeed, multiple studies found that volume demands at intersections vary greatly across weekdays (Levinson, Sullivan, & Bryson, 2006), having significant operational effects (Hellinga & Abdy, 2007), similar to those caused site-to-site variation (Tarko & Perez-Cartagena, 2005). This allows a better alignment of roadway capacities with time-varying traffic demands. Figure 7 and Figure 8 illustrate an example of left-turn congestion before DLG, and improved left-turn flow after DLG.



Source: Su, Jiang, Jagannathan, & Hale, 2015

Figure 7. Image. Left-turn congestion prior to dynamic lane grouping.



Source: Su, Jiang, Jagannathan, & Hale, 2015

Figure 8. Image. Improved left-turn flow after dynamic lane grouping.

Queue Warning

This ATDM strategy involves real-time display of warning messages along a roadway; typically on dynamic message signs, and possibly coupled with flashing lights. It alerts motorists that queues or significant slowdowns are ahead; thus reducing rear-end crashes, and improving safety.

Transit Signal Priority

Transit signal priority (TSP) is an ATDM strategy involving the management of traffic signals to detect when a bus is approaching an intersection. Sensors and/or probe vehicle technology can be used to turn the signals green sooner, or to extend the green phase, thereby allowing a bus to pass through more quickly.

ESTABLISHMENT OF PROJECT SCOPE

As stated at the beginning of the chapter, Task 2 of the project involved a literature review and state-of-practice review of relevant HCM methodologies, to determine if they were applicable to this work effort. Given the team's prior knowledge of HCM methodologies, it became necessary to first define the scope of the work effort, in terms of the most appropriate ATDM strategies for HCM implementation. To define the scope of the work effort, the research team conducted a review of prior HCM-based ATDM research on freeways, plus a review of urban street ATDM strategies. Results of this review were repeated earlier in this chapter. Concurrent with this review, the research team and peer review group were asked to choose top-priority ATDM strategies for HCM implementation from the following list:

- Variable Speed Limits.
- Dynamic Turn Restriction.
- Dynamic Lane Closure.

- Dynamic Lane Grouping.
- Congestion Pricing.
- Queue Warning.
- Reversible Center Lanes.
- Dynamic Speed Control.
- Adaptive Signal Control.
- Dynamic Route Guidance.
- Dynamic Parking.
- Transit Signal Priority.

Because the prior research team for HCM-based freeway ATDM had chosen three strategies for their study, and due to resource constraints in the urban street ATDM project, it was decided that a maximum of three strategies could be chosen. The following micro-decisions were also made:

- Adaptive Signal Control quickly became a top priority due to its pre-existing popularity on U.S. arterials, although many expressed concerns about the large number of products and algorithms.
- Some strategies (e.g., Dynamic Route Guidance, Congestion Pricing) were deemed difficult to integrate into the HCM urban streets framework, due to their network-wide dynamic modeling requirements.
- Due to the operational emphasis of the HCM, safety-based strategies (e.g., Queue Warning) were not suitable.
- Some strategies (e.g., Dynamic Parking, Dynamic Turn Restriction, Dynamic Lane Closure, Variable Speed Limits) were assigned low priorities due to a lack of popularity on arterials, and/or lack of available relevant data on arterials.
- Dynamic Lane Grouping and Reversible Center Lanes were considered top candidates due to their existing and successful U.S. implementations, despite the lack of before-and-after data.

Based on stakeholder feedback, the team's knowledge of HCM methods, the review of HCM-based freeway ATDM research, and the review of urban street ATDM strategies, the research scope was narrowed to three specific ATDM strategies: ***adaptive signal control, reversible center lanes,*** and ***dynamic lane grouping***. The research team believes there would be significant national interest in developing the ability to analyze impacts of these strategies in an HCM context, and without requiring micro-simulation. Furthermore, these strategies could be classified as ATM strategies as opposed to ATDM strategies, because they aim to move traffic more efficiently and without demand management. It is this focus that perhaps led to their current popularity in the United States, and their potential suitability for HCM implementation.

Beyond the selection of three strategies, the project scope involving was further refined during the Original Research phase of the project. This additional project scope refinement will be discussed in the subsequent chapters.

CONCLUSIONS AND NEXT STEPS

The objective of this task (Task 2) was to identify HCM methodologies applicable to this work effort. At the conclusion of Task 2, it was believed that the three chosen urban street ATM strategies could be effectively modeled via capacity adjustment factors, similar to what was accomplished during the freeway ATDM project. However, it was later discovered (during Task 6 – Original Research) that the capacity adjustment paradigm would be unsuitable for arterials, and that the HCM reliability framework would offer a preferable solution. Specifically, the alternative lane use configurations could be modeled as special event datasets within the HCM reliability framework, along with re-optimized timing plans for the new lane uses. The inadequacy of the capacity adjustment paradigm will be discussed more thoroughly in an upcoming chapter.

Regarding the adaptive signal control strategy, the HCM reliability framework would not accurately capture these effects or impacts. As such, this report will present potential benefits of adaptive signals under various conditions, both from field data and from simulations, but will not suggest a new HCM method for adaptive signal analysis. Conversely, for reversible center lanes and dynamic lane grouping, this report will provide not just potential benefits under various conditions, but will also demonstrate analysis of these strategies via the HCM reliability framework.

The peer review group identified the ARTPLAN software tool, developed by the Florida Department of Transportation (FDOT) and described in FDOT's Q/LOS Handbook (Florida Department of Transportation, 2013), as a relevant existing HCM methodology for analyzing reversible center lane operations. A relevant testimonial paragraph from the Handbook is shown below.

> *Conceptual planning is best suited for obtaining a more precise determination of the LOS of a facility. Examples of conceptual planning applications are determining the design concept and scope for a facility (e.g., four through lanes with a raised median and bicycle lane), conducting alternatives analyses (e.g., four through lanes undivided versus two through lanes with a two-way left turn lane), and determining needs when a generalized planning approach provides insufficient detail. Florida's LOS planning software (LOSPLAN), which includes ARTPLAN, FREEPLAN, and HIGHPLAN, is the easy to use tool for conducting these types of evaluations.*

CHAPTER 3. EXISTING DATA SOURCES

As discussed in the Introduction chapter, Task 3 of the project required establishment of a peer review group to provide input on development of the methodologies. The peer review group provided input on which urban street active transportation and demand management (ATDM) strategies should be implemented in the *Highway Capacity Manual* (HCM), how best to conduct the original research, and how to meet overall project objectives. The final list of peer group members was submitted to the Federal Highway Administration (FHWA) in January 2016. Due to the special nature of Task 3, a dedicated chapter is not needed for the peer review group. However, the peer group's influence on other tasks will be noted when applicable. For example, members of the peer review group were helpful in assembling the data sources for urban street ATDM. The available data sources were the focus of Task 4, as described in this chapter.

Task 4 of the project required identification of available data sources, typically in the form of before-and-after-ATDM-implementation field studies around the country, which might help to develop models for predicting ATDM strategy impacts. However, existing data sources could also include testbeds of research data, simulation platforms, or existing simulation results, which could further provide a basis for ATDM model development. Ultimately, existing data were only obtained for the same three ATDM strategies chosen to be the top priorities of this project, namely: **adaptive signal control, reversible center lanes, and dynamic lane grouping.** Moreover, only adaptive signal control had a sufficient quantity of existing data studies to support model development. Results of this data review were documented in a detailed technical memorandum in January 2016, and are repeated here in this chapter.

AVAILABLE TESTBEDS

Due to a lack of widespread ATDM implementation on arterial roads, simulation studies would be needed to supplement the field data studies. Existing simulation datasets and testbeds were identified and considered to the greatest extent possible. For example, the Analysis Modeling and Simulation (AMS) testbeds[1] have been identified as good candidates for evaluating ATDM applications and strategies. In addition the Saxton Traffic Operations Laboratory, located at the Turner-Fairbank Highway Research Center, contains a certain number of simulation datasets and resources. Datasets generated by a prior Saxton Lab study on dynamic lane grouping were collected and reviewed for this project.

ADAPTIVE SIGNAL CONTROL (FIELD STUDIES AND SIMULATION STUDIES)

Evaluation of the Virginia Department of Transportation Adaptive Signal Control Technology Pilot Project

- Conclusions are based on testing of the InSync system (Fontaine, Ma, & Hu, 2015).

1 See Federal Highway Administration, Analysis, Modeling, and Simulation (AMS) Testbed Initial Screening Report, FHWA-JPO-13-094 (Washington, DC: 2013) at: http://ntl.bts.gov/lib/51000/51000/51002/DF3F1F7.pdf.

- Adaptive signal control (ASCT) generally improves mainline operations if the corridor (1) is not over capacity (2) does not have traffic or geometric characteristics that impair progressive flow, or (3) does not already operate at a good level of service.
- Side street delays generally increase when ASCT technology is deployed, although there is usually a net reduction in overall corridor delay.

Cornell Road InSync Evaluation

- InSync improved corridor travel times, but overall average delays increased at the intersections (Hathaway, Urbanik, & Tsoi, 2012).

Adaptive Signal Testing for Recurring and Non-Recurring Conditions

- InSync outperformed other signal timing plans on the intersection, corridor and network-wide levels (Stevanovic, Zlatkovic, & Dakic, 2015).
- The advantages of adaptive traffic control systems were more significant for non-recurring traffic conditions.

SCATS Evaluations

- Overall minor positive effect (Hathaway, Tsoi, & Urbanik, 2012) (Hathaway, Tsoi, & Urbanik, 2012) (Hathaway & Urbanik, 2012).
- SCATS benefited high-volume intersections.
- Low-volume intersections performed worse under SCATS.
- Positive effect on travel times.
- Minor improvement in intersection-wide delays.
- SCATS appears best for high-volume corridors that prioritize through traffic, and low-volume movements can tolerate larger delays.

Palm Beach Traffic Management Center Active Arterial Traffic Management Program

- Signal timing control for incident management (Palm Beach County, 2015).

REVERSIBLE CENTER LANES (BEFORE-AND-AFTER FIELD STUDY)

- Significant operational benefits found in Salt Lake City "Flex Lanes" (Avenue Consultants, 2013).

DYNAMIC LANE GROUPING (BEFORE-AND-AFTER SIMULATION STUDY)

- This testbed consists of two signalized corridors in Northern Virginia (Su, Jiang, Jagannathan, & Hale, 2015).
- Most simulation experiments in this study involved two intersections flagged as good candidates for dynamic lane grouping (DLG) treatment. Significant benefits were measured at these two intersections, in terms of average vehicle delay. However, the study identified a total of five intersections that were potentially good candidates for DLG treatment.

CONCLUSIONS AND NEXT STEPS

As shown in this chapter, existing data were only obtained for the same three ATDM strategies chosen to be the top priorities of this project, namely: ***adaptive signal control, reversible center lanes***, and ***dynamic lane grouping***. Moreover, only adaptive signal control had a sufficient quantity of existing data studies to support model development. As such, HCM-compatible models for reversible and/or dynamic lanes would be heavily dependent on simulation studies, to be conducted during Task 6 – Original Research. And although the quantity of adaptive signal data was sufficient to support model development, additional data was still desired for better confidence. The model development effort is described in the upcoming chapters on Task 6 – Original Research. However the next step in the project (Task 5 – Performance Measures) was a review of appropriate system performance measures, which could be effective in assessing ATDM strategy impacts.

CHAPTER 4. SYSTEM PERFORMANCE MEASUREMENT

This chapter presents the potential traffic performance measures for evaluating active transportation and demand management (ATDM) impacts. Results of the Task 5 – System Performance Measures review were documented in a detailed technical memorandum in February 2016, and are repeated here in this chapter. The first section of the chapter summarizes the available performance measures from existing and known data sources, collected during Task 4, which focused on before-and-after assessment of ATDM strategies. The second section summarizes the "Performance Measures (Measures of Effectiveness) for ATDM Analysis" section of the 2013 Federal Highway Administration (FHWA) report, entitled: "Guide for Highway Capacity and Operations Analysis of Active transportation and demand management Strategies" (Dowling, Margiotta, Cohen, & Skabardonis, 2013). The 2013 study focused primarily on freeways, but many of the performance measures suggested by that study could ultimately benefit the urban streets ATDM study. In the third section, additional performance measures used in the current Analysis, Modeling and Simulation testbed project are listed. Some of these performance measures would be generated by the simulation experiments in Task 6. The fourth section summarizes performance measures that can be generated by two of the available software platforms for *Highway Capacity Manua*l (HCM) urban street reliability analysis: Streetval-Java, and HCS-Streets. If the macroscopic before-and-after ATDM impacts found during Task 6 can be successfully coded into one or both of these platforms, it could become possible to assess ATDM impacts in terms of annual reliability and other advanced measures.

ADAPTIVE SIGNAL PERFORMANCE MEASURES

Virginia Department of Transportation Study (InSync)

Crow Canyon Road and Bollinger Canyon Road in San Ramon, California:

- Fifty percent decrease in **average travel time** during the PM peak, in the major-street direction.
- Unspecified increase in **travel time** and **approach delay** PM peak, off-peak direction.
- Seventy-five percent decrease in **average major approach delay** during the PM peak.
- **Average delay** along minor streets increased by approximately 3 seconds per vehicle.

10th Street Corridor in Greeley, Colorado:

- Nine percent decrease in **travel times.**
- Thirteen percent decrease in **stopped delay**.
- Eleven percent increase in **average speed**.
- Six percent decrease in **fuel consumption and emissions**.
- Forty-five percent decrease in **stops**.
- **Side street delays increased** on some approaches.

Original Research:

- **No benefits when conditions are oversaturated.**
- Twenty percent reduction in **stops**.
- Seven percent increase in **average speed**.
- Seven percent decrease in **travel time**.
- **Side street delays** increase by 5-10 sec/veh.
- Adaptive signal control (ASCT) most effective at sites with **variable traffic demands** (e.g., seasonal variations, school schedules, incidents, special events).
- ASCT not effective on routes with **high truck volumes**.
- **Long signal spacing** will reduce ASCT effectiveness.
- ASCT improves mainline operations if the corridor does not have traffic or geometric characteristics that impair **progressive flow**.
- ASCT improves mainline operations if corridor does not already operate at a **good level of service (LOS)**.

Based on these VDOT study results, the team concluded that sensitivity analysis in the ATDM project should examine: degree of saturation, variable traffic demands, percent trucks, signal spacing, progression quality, non-recurring events (e.g., weather, incidents), and cycle lengths.

Cornell Road Study (InSync)

- Fourteen percent decrease in **travel times.**
- No improvement in **average delay**.
- Ten to twenty second increase in **cycle lengths**.

Non-Recurring Conditions VISSIM Study (InSync)

- ASCT technology advantages are more significant for **nonrecurring traffic conditions** (e.g., weather, incidents, rail pre-emption).
- Sixteen percent decrease in network-wide **average delay** (no non-recurring events).
- Nine percent decrease in network-wide **stops** (no non-recurring events).
- Seven percent decrease in network-wide **travel time** (no non-recurring events).
- Twenty-four percent decrease in network-wide **average delay** (with non-recurring events).
- Twelve percent decrease in network-wide **stops** (with non-recurring events).
- Twelve percent decrease in network-wide **travel time** (with non-recurring events).

Powell Road Study (SCATS)

- One percent decrease in **24-hour travel times**.
- Seven percent decrease in **midday travel times** (9 am – 2:30 pm).
- Two percent increase in **pm peak travel times** (2:30 pm – 7:00 pm).
- Six percent increase in **overnight travel times** (12:00 am – 5:30 am).
- No change in **am peak travel times** (5:30 am – 9:00 am).
- No change in **evening travel times** (8:00 pm – 12:00 am).

Redmond Road Study (SCATS)

- Twelve percent decrease in **major-street travel times**.
- Twenty-six percent decrease in **major-street travel times during the county fair**.
- Five to twenty second increase in **cycle lengths**.
- No change in the **buffer index**.
- Two-second decrease in **average delay per vehicle**.
- Fifteen-second decrease in **average delay per vehicle during the county fair**.

Tualatin-Sherwood Road Study (SCATS)

- No change in the **buffer index**.
- Ten to fifteen 1 second increase in **cycle lengths**.
- Fifty-second decrease in **travel times** (over 1.3 miles) during high-demand periods.
- Ten-second increase in **travel times** (over 1.3 miles) during low-demand periods.

REVERSIBLE CENTER LANE PERFORMANCE MEASURES

Salt Lake City Flex Lanes

Vehicle trips and travel times were measured in the field.

Intersection delays were computed by an un-named traffic model.

- During the PM peak period, westbound (peak direction) **travel times** were reduced by 50 seconds and eastbound (non-peak direction) were reduced by 20 seconds.
- During the AM peak period, eastbound (peak direction) **travel times** were reduced by 45 seconds, but increased in the westbound direction (non-peak direction) by 65 seconds.
- The benefits of the travel time savings in both the AM and PM peak directions (which have significantly higher traffic volumes) outweigh the detriments of the increased travel time in the AM non-peak direction.
- **Traffic volumes** on 5400 South increased during Flex Lane operations (AM and PM peak periods) in the peak direction.

- At one of the two data collection locations, traffic volumes decreased during Flex Lane operations (AM and PM peak periods) in the non-peak direction. The other data collection location showed an increase in PM traffic volumes while AM traffic volumes remained the same.
- The Flex Lanes currently save a total of $792,000 in **user costs per year** (based on travel time savings).
- The Flex Lanes currently reduce **idle emissions** by 1.24 tons per year.

DYNAMIC LANE GROUPING PERFORMANCE MEASURES

Bottleneck Project (Saxton Transportation Operations Laboratory Task Order 6) Study

Synchro ™ datasets were provided by Randy Dittberger (VDOT) for two signalized corridors in Northern Virginia.

These datasets are used "to store signal timings," but were not calibrated for local conditions. Intersection delays were computed by SimTraffic™.

Out of 17 intersections, three were identified as top candidates for dynamic lane grouping (DLG):

- Colts Neck Road and Sunrise Valley Drive, with a 32 percent reduction in intersection-wide **average delay per vehicle.**
- Nutley Street SW and Lee Highway, with a 23 percent reduction in intersection-wide **average delay per vehicle**.
- Reston Parkway and Sunrise Valley Drive, with a 10 percent reduction in intersection-wide **average delay per vehicle**.

The third intersection derived benefits from DLG treatment at Colts Neck, due to its close proximity; specifically, queue spillback was reduced. Due to the lack of sufficient field data, HCM-compatible models for DLG would be heavily dependent on software modeling, to be performed during the Original Research task. Although some researchers developed mathematical programming models for optimizing the effects of DLG (Zhang & Wu, 2012) (Zhao J., Ma, Zhang, & Yang, 2013), these models were not developed with HCM compatibility in mind.

SUMMARY OF TASK 4 PERFORMANCE MEASURES

Figure 9 summarizes a set of nine performance measures from available data sources. These performance measures were relevant to the three chosen active traffic management (ATM) strategies for this project. The amount of available data in Figure 9 leads to the conclusion that more data would be needed, to confidently development HCM models. However the available data succeed in demonstrating *potentia*l benefits of the strategies, and provide a benchmark for the simulation studies in Task 6 – Original Research.

Source	ASCT	Reversible	DLG	Time Period	Spatial	Travel Time	Delay	Emissions	Stops	Speed	Volumes	Cycle Length	Buffer Index	User Costs
California	InSync			pm peak	major-street	-50%	-75%							
California	InSync			pm peak	minor-street		+3%							
Colorado	InSync			pm peak	major-street		-13%							
Colorado	InSync			pm peak	minor-street		+3%							
VDOT	InSync					-7%								
VDOT	InSync				minor-street		+7 s/veh							
VDOT	InSync			oversaturated conditions		no benefits	no benefits	no benefits	no benefits	no benefits	n/a	n/a	no benefits	no benefits
VDOT	InSync			high truck volumes		no benefits	no benefits	no benefits	no benefits	no benefits	n/a	n/a	no benefits	no benefits
VDOT	InSync			long signal spacing		no benefits	no benefits	no benefits	no benefits	no benefits	n/a	n/a	no benefits	no benefits
VDOT	InSync			little progressive flow		no benefits	no benefits	no benefits	no benefits	no benefits	n/a	n/a	no benefits	no benefits
VDOT	InSync			LOS A-B		no benefits	no benefits	no benefits	no benefits	no benefits	n/a	n/a	no benefits	no benefits
VDOT	InSync			stable traffic demands		no benefits	no benefits	no benefits	no benefits	no benefits	n/a	n/a	no benefits	no benefits
Cornell Rd	InSync					-14%	no benefits					+10-20 sec		
FAU-VISSIM	InSync			baseline	network-wide	-7%	-16%		-9%					
FAU-VISSIM	InSync			during events	network-wide	-12%	-24%		-12%					
Powell Rd	SCATS			24-hour		-1%								
Powell Rd	SCATS			9:00a-2:30pm		-7%								
Powell Rd	SCATS			2:30 p-7:00pm		+2%								
Powell Rd	SCATS			12:00a-5:30a		+6%								
Powell Rd	SCATS			5:30a-9:00a		no change								
Powell Rd	SCATS			8:00p-12:00a		no change								
Redmond Rd	SCATS			pm peak	major-street	-12%	-2 s/veh					+5-20 sec	no change	
Redmond Rd	SCATS			county fair	major-street	-26%	-15 s/veh							
Tualantin Rd	SCATS			high demand	1.3 miles	-50 sec						+10-15 sec	no change	
Tualantin Rd	SCATS			low demand	1.3 miles	-10 sec						+10-15 sec	no change	
Utah		■		pm peak	peak direction	-50 sec								
Utah		■		pm peak	off-peak dir	-20 sec								
Utah		■		am peak	peak direction	-45 sec								
Utah		■		am peak	off-peak dir	+65 sec								
Utah		■		both peaks	peak direction						increase			
Utah		■						-1.24 tons/yr						-$800K/yr
Virginia			■	pm peak	overall		-32%							
Virginia			■	pm peak	overall		-23%							

ASCT = adaptive signal control technology. SCATS = Sydney Coordinated Adaptive Traffic System.
VDOT = Virginia Department of Transportation.

Source: Federal Highway Administration

Figure 9. Chart. Summary of nine performance measures from existing data sources.

PERFORMANCE MEASURES FROM THE FREEWAY ACTIVE TRANSPORTATION AND DEMAND MANAGEMENT PROJECT

This section summarizes the "Performance Measures (Measures of Effectiveness) for ATDM Analysis" section of the 2013 FHWA report, entitled: "Guide for Highway Capacity and Operations Analysis of Active Transportation and Demand Management Strategies" (Dowling, Margiotta, Cohen, & Skabardonis, 2013). The 2013 study focused primarily on freeways, but many of the performance measures suggested by that study could ultimately benefit the urban streets ATDM study.

1. **Vehicle-Miles Traveled (VMT)-Demand:** The sum of the product of origin-destination (OD) trip table numbers and shortest path distances for each OD.

   Note: This would only be meaningful for demand management strategies.

2. **VMT-Served:** The sum of the products of link lengths and vehicle volumes on a link.
   Note: same as above.

3. **Vehicle-Hours Traveled (VHT):** Summation of the products of total link volumes and average link travel times. VHT also accounts for any delays to vehicles prevented from entering the facility either by controls (such as ramp metering) or by congestion.

   Note: There is no difficulty extracting this from simulation results; however because overall demand patterns will be assumed to be the same with and without ATDM treatments, this is not a very useful PM for this project.

4. **Vehicle-Hours Delay (VHD):** The difference between VHT (including vehicle-entry delay) and theoretical VHT if all links could be traversed at the free-flow speed with no entry delays [VHT (FF)] (the equation for this calculation can be found in Figure 2 on page 6). Shortest path is chosen for these computations. VHD is used in economic cost and benefit analysis of ATDM measures.

5. **Average System Speed:** The sum of (VMT-Served / VHT) for each scenario. This is a measure of average system-wide efficiency.

6. **Average Delay Per Vehicle:** The sum of VHDs for all scenarios divided by the sum of total vehicle trips for all scenarios.

7. **80th percentile Travel Time Index ($TTI_{80\%}$):** This is a measure of travel time reliability on the facility (the equation for this calculation can be found in Figure 3 on page 6). In this equation, VHT and VMT in the numerator is the 80th percentile qualities. The report states that 80th percentile relates better to mean speed than 90th, 95th or 99th percentile.

8. **Planning Time Index (PTI): Another measure of travel time reliability on the facility.**

$$PTI = \frac{[VHT_{estimated} / VMT_{estimated}]}{[VHT_{free\text{-}flow} / VMT_{free\text{-}flow}]}$$

Figure 10. Equation. Planning Time Index.

Note: Both of the above measures of reliability are more appropriate for freeway-oriented corridor travel. For arterials and control-side targeted interventions, other measures from the travel time distribution may be preferable. In particular, extracting the ***standard deviation of the travel time distribution*** *along paths or subpaths would be more meaningful in this project.*

The report recommends assessing ATDM strategies for peak hours (same as HCM) but over all of the weekdays rather than a single weekday (different from HCM). In most available network models, demand data are not available for an entire week, but rather for representative operational conditions.

ANALYSIS, MODELING, AND SIMULATION TESTBED PERFORMANCE MEASURES

The following performance measures were considered candidates for collection during the Task 6 simulation experiments.

For all strategies: **Standard deviation of the travel time distribution** along paths or subpaths.

For adaptive signal control strategies:

- **Stopped Time** along links and subpaths.
- **Travel Time** along links and subpaths.

For reversible lanes:

- **Corridor Speed.**
- **Corridor Travel Time.**

Additional performance indicators specifically address travel time reliability. Figure 11 presents a list of available reliability measures, categorized on the basis of their applicability to different levels of travel time distributions and associated reliability analysis, namely network-level, OD-level, and path/segment/link-level. For the network-level, travel times experienced by vehicles are not directly comparable because distances traveled by vehicles may be significantly different. In this case, measures that are normalized by the trip distance can be used. Each vehicle's travel time can be converted into the distance-normalized travel time, i.e., travel time per mile (TTPM) and various statistics can be extracted from the distribution of TTPMs as presented in Type A measures in Figure 11. For the OD-level, travel times experienced by vehicles are comparable, although actual trip distances could be different depending on the route followed by each vehicle. OD-level travel times are not limited to travel times between actual traffic analysis zones (TAZ). Travel time distributions between any two points can be included in this category. Reliability measures that can be used when travel times are comparable include many conventional metrics such as the mean and standard deviation of travel times, percentiles, buffer index, etc., as presented in Type B in Figure 11. For OD-level analysis, therefore, both Type A and B measures can be used. At the path/segment/link-level, not only are travel times for different vehicles comparable but also trip distances are the same. This allows the calculation of unique free-flow travel times for a given path and, therefore, and allows the use of additional measures that require the free-flow travel time. Such measures include Travel Time Index, Planning Time Index, Misery Index and Frequency of Congestion as shown in Type C in Figure 11. As such, any Type A, B and C measures for the path/segment/link-level can be used for travel time reliability analysis. For arterial analysis, Types B and C measures would be applicable measures for the path/segment/link-level travel time reliability analysis. For arterial analysis, Type B and C measures would be applicable.

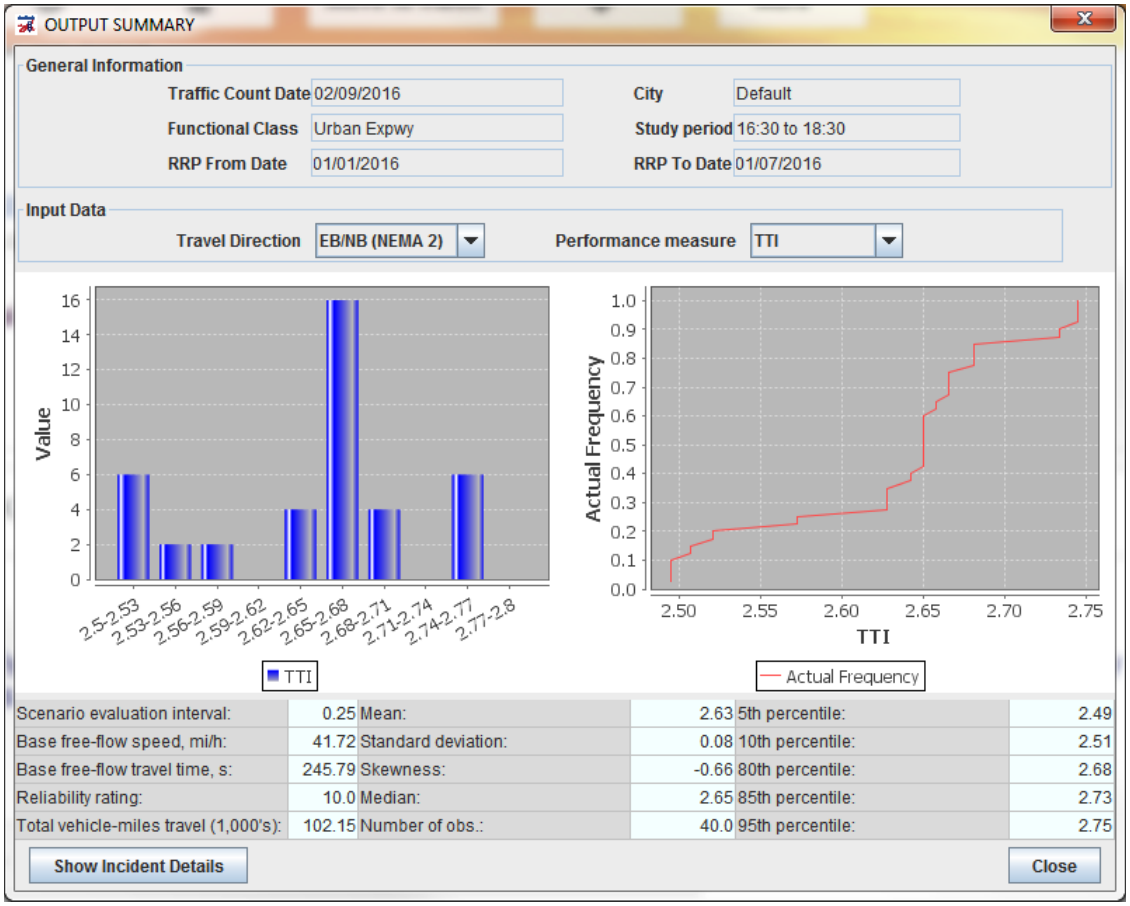
	Analysis Level		
	Network-level	00-level	Path/Segment/Link-level
Distance-normalized Measures (Type A)	• Average of Travel Time Per Mile (TTPMs) • Std. Dev. of TTPMs • 95th/90th/80th Percentile TTPM		
Measures for comparable travel times (Type B)		• Average Travel Time • Std. Dev of Travel times • Coefficient of Variation *std. dev. of travel times/mean travel time* • 95th/90th/80th Percentile Travel Time • Buffer Index *(95th percentile travel time-mean travel time/mean travel time)* • Skew Index *(95th percentile travel time-median travel time)/median travel time - 10th percentile travel time)* • Percentile On-time Arrival *percent of travel times < 1.1* median travel time*	
Measures for the same travel distance (Type C)			• TTI (Travel time Index) *mean travel time/free flow travel time* • PTI (Planning Time Index) *95th percentile travel time/free flow travel time* • Misery Index *mean of the highest 5% of travel times/ free flow travel time* • Frequency of Congestion *percent of travel times>2* free-flow travel time*

Source: Federal Highway Administration

Figure 11. Chart. Reliability measures for different analysis types.

PERFORMANCE MEASURES FROM HIGHWAY CAPACITY MANUAL-BASED COMPUTATIONAL ENGINES

HCM-based computational engines could further assess the models developed by this project. The available HCM-based computational engines for urban streets are believed to be Streetval-Java (from the Institute for Transportation Research and Education (ITRE) at North Carolina State University) and HCS-Streets (from McTrans at the University of Florida). These two platforms have the necessary architecture needed for executing HCM-compliant annual reliability analyses, and generating advanced performance measures. The availability of these platforms for modification during this project's period of performance, and the effort level for incorporating this project's models into these platforms, was uncertain. However, the developers of both platforms expressed a willingness to assist on the urban streets ATDM project. Streetval-Java and HCS-Streets have different advantages, disadvantages, and sample datasets, which may affect the choice of platform (if any) to be used on this project. Streetval-Java is described first. Figure 12 illustrates a screenshot of reliability performance measures reported by Streetval. Currently, this screen shows travel time index (TTI)-related performance measure statistics at the bottom of the screen. The Streetval software also reports travel time, travel speed, stop rate, running time, through delay and total delay.



Source: ITRE, NC State University.

Figure 12. Screenshot. Performance measures available from Streetval-Java.

According to McTrans' *Urban Streets Reliability Users Guide* (from the HCS-Streets software package), there are two reports available to the user: the formatted report and the text report. The formatted report provides an overview of the results in a table. There are four sections in the table: base dataset analysis, reliability input summary, reliability performance measure results, and travel time results for each replication. Base dataset analysis provides general information that can be found in the base dataset. Reliability input summary provides general information on the reliability analysis and the random seed summary. The random seed numbers displayed on this report are for the first replication. Random seed numbers for each replication can be found in the text report. The formatted report is illustrated in Figure 13 and Figure 14.

Highway Capacity Software 2010 Urban Streets Reliability Results Summary

Base Dataset Analysis					
Base Dataset File	Chap17Streets.xus	Data Collection Date	9/7/2011 12:00:00 AM	Analyst	
Start Time	07:00	End Time	08:00	Period Duration	01:00
Number of Periods	4	Intersections	2	Segments	1
Comments	HCS Export				

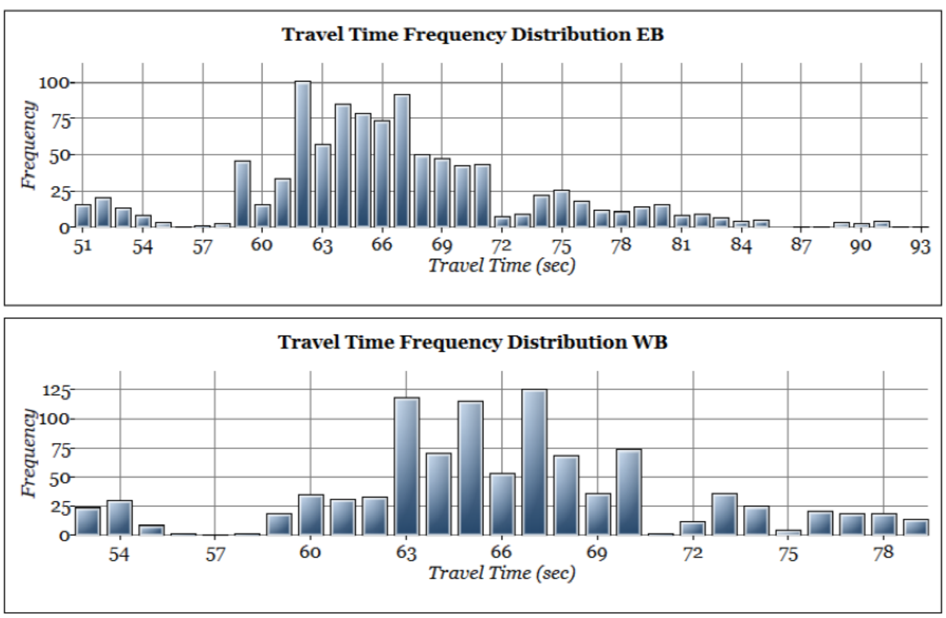
Reliability Input Summary							
Reporting Start Date	1/1/2011	Reporting End Date	1/1/2012	**Random Seed Summary**			
Analysis Days	260	Weather Location	LINCOLN, NE		Weather	Demand	Incident
Urban Street Class	UrbanPrincipal	Base Demand Ratio	0.011	Include	Y	Y	Y
Shoulder Presence	Yes	Number of Replications	5	Seed	82	11	63

Reliability Performance Measure Results	East Bound	West Bound
Vehicle miles traveled (veh-m)	80761	80750
Number of Scenarios	1040	1040
Base free-flow travel time (s)	30.095	30.095
Mean TTI	2.222	2.22
80th percentile TTI	2.36	2.32
95th percentile TTI (PTI)	2.657	2.581
Reliability rating (%)	85.692	89.674
Total delay (veh-h)	18.367	

Replication	Average TT	95th Percentile TT	Average TT	95th Percentile TT
1	67.044	80.034	66.855	77.208
2	66.515	79.69	66.767	76.64
3	66.721	79.761	67.019	77.724
4	66.976	79.46	66.416	77.276
5	67.051	81.374	67.066	78.342
Average	66.861	80.064	66.825	77.438
Standard deviation	94.501	113.109	94.465	109.597
95th% Confidence Interval	55.989 - 77.733	64.702 - 95.426	56.117 - 77.533	63.042 - 91.834
	±16.261%	±19.187%	±16.024%	±18.591%

Source: McTrans Center, University of Florida

Figure 13. Screenshot. Reliability output summary report from Highway Capacity Software-Streets.



Source: McTrans Center, University of Florida

Figure 14. Screenshot. Travel time frequency from Highway Capacity Software-Streets.

The formatted report section on "Reliability Performance Measure Results" provides information on the following performance measures for each major street direction: vehicle miles traveled (veh-m), number of scenarios, base free-flow travel time(s), mean TTI, 80th percentile TTI, 95th percentile TTI (PTI), reliability rating (percent), and total delay (veh-h). The last section of the table includes information on travel time for each replication. The average travel time and 95th percentile travel time are provided in the formatted report. However the text report provides more detailed results, as shown in Figure 15.

Performance Measure	EASTBOUND VALUES
Vehicle Miles Travelled (veh-mi)	80761
Base Free-Flow Speed (mi/h)	40.78
Base Free-Flow Travel Time (s)	30.095
Reliability Rating	85.692
Number of Scenarios	1040

Replication 1 :

Random Number Seeds	Weather	Demand	Incident
	82	11	63

	Travel Time (s)	Travel Speed (mi/h)	Stop Rate (stops/veh)	Running Time (s)	Through Delay (s/veh)	Total Delay (veh-hr)
Average	67.044	18.605	2.413	33.488	33.556	18.586
Standard Deviation	11.307	2.095	0.367	0.721	10.888	8.394
Skewness	9.494	-0.499	4.394	7.452	9.761	10.88
Median	65.781	18.657	2.413	33.376	32.381	17.194
5th Percentile	53.716	15.334	1.748	33.087	20.602	11.898
10th Percentile	59.056	16.185	2.079	33.2	25.847	14.229
80th Percentile	71.007	19.781	2.608	33.538	37.531	20.157
85th Percentile	74.052	20.207	2.711	33.585	40.331	22.218
95th Percentile	80.034	22.848	2.877	33.803	46.039	27.34

Replication 2 :

Random Number Seeds	Weather	Demand	Incident
	83	12	64

	Travel Time (s)	Travel Speed (mi/h)	Stop Rate (stops/veh)	Running Time (s)	Through Delay (s/veh)	Total Delay (veh-hr)
Average	66.515	18.659	2.399	33.452	33.063	18.245
Standard Deviation	7.296	1.948	0.291	0.652	6.947	5.564
Skewness	1.409	0.196	-0.268	10.547	1.111	5.936
Median	66.078	18.573	2.421	33.377	32.684	17.269
5th Percentile	53.696	15.401	1.756	33.087	20.617	11.885
10th Percentile	59.065	16.23	2.08	33.197	25.859	14.219

Source: McTrans Center, University of Florida

Figure 15. Screenshot. Detailed reliability outputs report from Highway Capacity Software-Streets.

Results for the major street forward direction are displayed first, and then results for the other major street direction are displayed. The following performance measures are displayed for each major street direction: vehicle miles traveled (veh-mi), base free-flow speed (mi/h), base free-flow travel time (s), reliability rating, and number of scenarios. Following these results, information for each are replications. Each replication displays the random number of seeds for weather, demand, and incident. Then the average, standard deviation, skewness, median, 5th percentile, 10th percentile, 80th percentile, 85th percentile, and 95th percentile are displayed for travel time (s), travel speed (mi/h), stop rate (stops/veh), running time (s), through delay (s/veh), and total delay (veh-hr).

CONCLUSIONS AND NEXT STEPS

The dilemma revealed by this chapter is that desired reliability-based performance measures, such as travel time index and planning time index, were generally not collected during the available field studies. Instead, the available field studies (whose results were summarized earlier in Figure 9) focused on travel times and delays. Thus, the only way to integrate these results with Task 6 simulation results would be to collect travel times and delays during Task 6. Having said this, the amount of available data for reversible/dynamic lanes was extremely limited, and the amount of available data for adaptive signals was insufficient for developing a reliable model. As such, the performance measures from available data sources (Task 4) would not be considered a constraint on the remainder of the project (Tasks 5 and 6), and project outcomes would be heavily dependent upon the original research in Task 6. Moreover, the HCM-compatible computational engines could provide an effective vehicle for obtaining most desired performance measures, if the urban street ATM methods could be successfully implemented within them.

CHAPTER 5. RESEARCH METHODOLOGY

As the research team began to work on Task 6 – Original Research in March 2016, the project scope had already been narrowed to three specific active transportation and demand management (ATDM) strategies: ***adaptive signal control, reversible center lanes***, and ***dynamic lane grouping***. These fall into the category of active traffic management (ATM) strategies, which aim to move traffic more efficiently but without demand management. The key objective of Task 6 – Original Research was to conduct simulation-based studies of all three relevant ATM strategies, to determine their impacts under a wide variety of real-world conditions. Ideally it would then be possible to apply this data towards developing *Highway Capacity Manual* (HCM)-compatible analytical models, for predicting ATM strategy impacts under a wide variety of conditions.

A preliminary step in the simulation-based studies was to define a set of key experimental parameters, to be customized for each individual ATM strategy. Proper choice of experimental parameters would facilitate development of robust and reliable models. Improper choice of experimental parameters would interfere with the team's ability to meet project objectives. Therefore throughout the month of March, the team held discussions about what might be the optimal choice of experimental parameters. The experimental parameters fell into three categories: input parameters, output parameters, and experimental scope.

INPUT PARAMETERS

With regard to the input parameters, it was important to identify those that would have maximum impacts on ATM strategy benefits. For example, it is generally known that adaptive signals produce minimal benefits when traffic congestion is either too heavy or too light. Instead, adaptive signals produce maximum benefits under "medium" levels of congestion. Although many literature sources would likely concur, the Virginia Department of Transportation (VDOT) study (Fontaine, Ma, & Hu, 2015) cited in Chapter 1 is one source that mentions this concept. Because adaptive signal benefits are closely associated with traffic congestion levels, it stands to reason that "Degree of Saturation" (also known as volume-to-capacity ratio), which could be varied by adjusting traffic volume demands, would be a key input parameter in these experiments. In fact, Degree of Saturation was considered by the team to be a key input parameter for all three ATM strategy experiments. However, it would be important to further differentiate between Degree of Saturation on the major street, on the minor street, and on specific turn movements.

Table 3 presents the list of chosen experimental input parameters at the end of the Task 6 planning phase (end of March 2016). For adaptive signals and reversible lanes, benefits were expected to depend heavily on the level of major- and minor-street congestion. For dynamic lane grouping, benefits were expected to depend heavily on through and adjacent turn movement congestion. Most adaptive signal input parameters were consistent with those recommended by the VDOT study. Reversible lane input parameters were consistent with the macroscopic, corridor-wide benefits of changing the number of through lanes on the major street. Dynamic lane grouping input parameters were consistent with detailed elements of signal operations. The team used judgment in deciding that Driver Compliance would not be a significant factor in predicting dynamic or reversible lane benefits, based on past observations of full reversible lane utilization in Chicago and Washington, DC.

Table 3. Experimental input parameters.

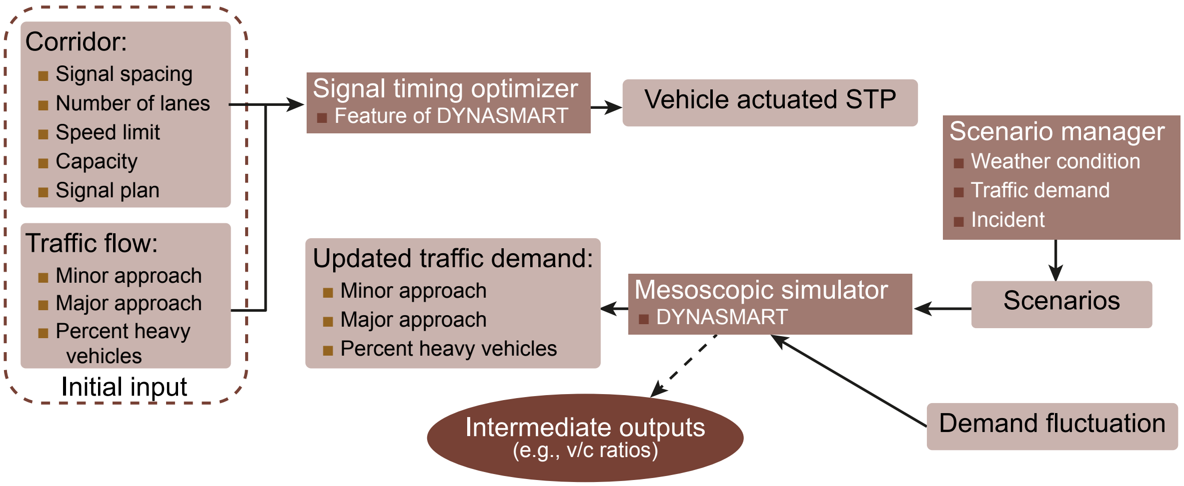
	Adaptive Signals	Reversible Lanes	Dynamic Grouping
Deg. of saturation (major street)	■	■	
Deg. of saturation (minor street)	■	■	
Deg. of saturation (turn mvt.)			■
Arterial progression quality	■	■	■
Percentage of heavy vehicles	■		
Signal spacing	■	■	
Number of lanes (major street)		■	■
Length of corridor	■	■	
Demand variability	■		
Driver compliance			
Green ratio (major street)			■
Left-turn protection			■
Shared turn lanes			■

OUTPUT PARAMETERS

With regard to the output parameters, it was important to identify those that would best reflect ATM strategy benefits. A comprehensive set of such output measures was provided earlier in Chapter 3, based on the findings from Task 5 – Performance Measurement. For example, it is generally known that adaptive signals produce maximum benefits when progression quality is mediocre, but has the potential to improve significantly with better signal timings. Although many literature sources would likely concur, the VDOT study (Fontaine, Ma, & Hu, 2015) cited in Chapter 1 is a source that mentions this. Because adaptive signal benefits are correlated with platoon progression, performance measures related to travel time would be key output parameters in these experiments. Travel time measures would also be an excellent indicator of reversible center lane benefits. By contrast, it was believed that dynamic lane grouping benefits would be more easily observed at the intersection level.

Towards the end of the Task 6 planning phase (end of March 2016), a new decision was made. It was decided that capacity adjustment models should be developed for each ATM strategy. This would be consistent with some of the assumptions made during the freeway ATDM project, and with many of the capacity adjustment factors that already exist in the HCM. Capacity adjustment models would offer tremendous flexibility in terms of output parameters: they would facilitate the analysis of any performance measure within the HCM urban streets procedure. Without capacity adjustment models, it was believed that only a small fraction of output parameters could be analyzed. The plans towards developing capacity adjustment models are illustrated in Figure 16 and Figure 17. The goal was to adjust the capacity aspect of volume-to-capacity ratios, which are intermediate outputs in the urban streets procedure. These would then ripple through the procedure to produce accurate final performance measures (e.g., delay, travel time index).

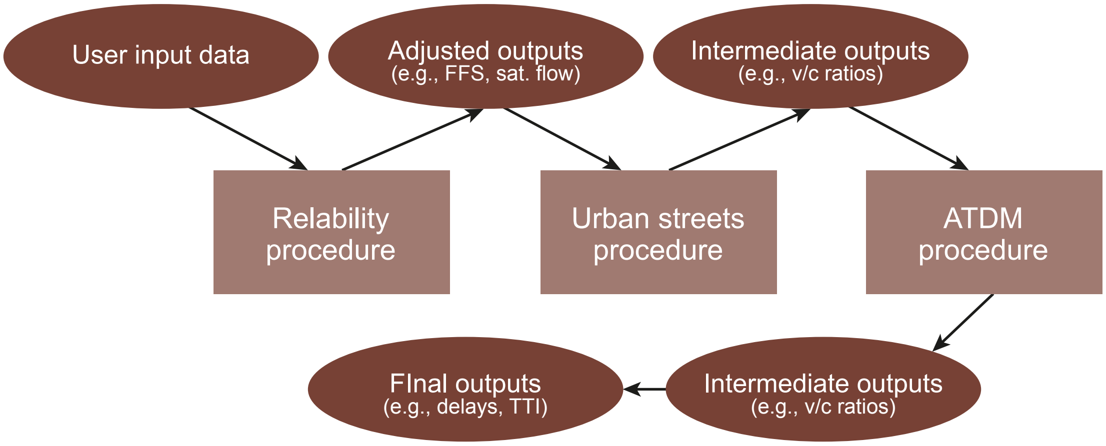
Note: STP = signal timing plan. v/c = volume/capacity.



Source: Federal Highway Administration

Figure 16. Flowchart. Proposed method for development of *Highway Capacity Manual* adaptive signal model.

Note: ATDM = active transportation and demand management. FFS = free flow speed. TTI = travel time index. v/c = volume/capacity.



Source: Federal Highway Administration

Figure 17. Flowchart. Proposed method for modeling dynamic lane groups in the *Highway Capacity Manual*.

SCOPE

Given the time constraints of the project, it was desirable to define a narrow scope in which the HCM models for adaptive signal control, reversible center lanes, and dynamic lane grouping would be developed. For example, although the benefits of these three ATM strategies would be very different for coordinated and uncoordinated traffic signals, the experimental scope was limited to ***coordinated signals***. This was largely due to the scope of the urban streets procedure, but also because data collection for both coordinated and uncoordinated signals might not fit within the project's time frame. Similarly, the team would focus on ***actuated coordination*** as opposed to pre-timed signals, for the reversible and dynamic lane strategies.

Regarding the ***temporal scope*** of these experiments, it was desirable to treat the three chosen strategies differently. For example, adaptive signals are known to produce some of their most significant benefits during the "shoulders" of the peak traffic periods. This ties back to the concept of adaptive signals producing maximum benefits under "medium" levels of congestion, as discussed earlier in this chapter. Therefore, an ideal adaptive signal experiment would capture the shoulder periods and/or medium congestion periods. Conversely, the reversible and dynamic lane treatments would tend to produce maximum benefits during the "second highest" peak period. In other words, these two strategies tend to work well when the default lane configuration works best during the most congested peak period (e.g., PM Peak), but is much less efficient during the next most congested peak period (e.g., AM Peak). Therefore, ideal experiments for reversible lanes and dynamic lane grouping would examine their benefits during the second highest peak period.

Regarding the ***spatial scope*** of these experiments, it was desirable to examine benefits across an entire corridor. However for dynamic lane grouping, whose impacts are highly dependent on the performance of physically adjacent movements, it was decided that extensive experiments should be performed at the single-intersection level, while still retaining the coordinated-actuated operations. The team also briefly discussed scenarios in which the number of major-street through lanes would be dynamically increased. Ultimately these scenarios were not considered during the Task 6 experiments, because the necessary number of downstream lanes would typically not exist. By contrast, it is much more common to have the necessary number of downstream lanes for a left-turn movement, or a right-turn movement, if a second turn lane could be dynamically added. Naturally, at intersections where the necessary number of downstream lanes for a left- or right-turn movement would not exist, the dynamic lane grouping strategy could not be implemented or considered. Indeed, "safe turning geometry" was defined as a pre-requisite to dynamic lane grouping implementation in (Su, Jiang, Jagannathan, & Hale, 2015).

Regarding ***signal timing optimization***, this would be an important consideration for all three chosen ATM strategies, albeit in slightly different ways. For adaptive signal before-and-after studies, the "before" scenario would ideally have optimized, coordinated-actuated timing plans. For the reversible and dynamic lane treatments, both the "before" and "after" scenarios should have optimized timing plans. In other words, when the lane configuration of an intersection or arterial is changed, any prior signal timing plan would no longer be suitable for the new geometry. This implies that any realistic before-and-after study of reversible or dynamic lanes should involve at least two signal timing optimization efforts (i.e., one for "before", one for "after") for each data point, observation, or comparison.

Regarding ***integration of field data***, it was desired at the outset of the project to develop robust models based on existing field data, while using simulated data to fill in the gaps. However due to the scarcity of field data located during Task 4 – Existing Data Sources, it became clear that any models developed during this project would need to be based on simulated data, with field data used for validity checks at best.

Finally, it was decided that the dynamic lane grouping experiments need not account for ***permissive left-turn movements***. This is because the dynamic increase from one to two exclusive left-turn lanes would tend to make permissive left-turn movements unsafe, and would tend to be needed at traffic congestion levels not compatible with permissive left-turn movements. This does not mean that no permissive left-turn could ever safely benefit from dynamic lane grouping. It simply means that permissive left-turn movements were a relatively low priority in the context of this project, and were thus excluded from the experimental scope. Regarding permissive right-turn movements, also known as right-turns-on-red (RTOR), these were included in the experimental scope of dynamic lane grouping. This is because it is not uncommon for the inside right-turn lane of a dual right-turn lane group to have RTOR allowed.

TESTBEDS

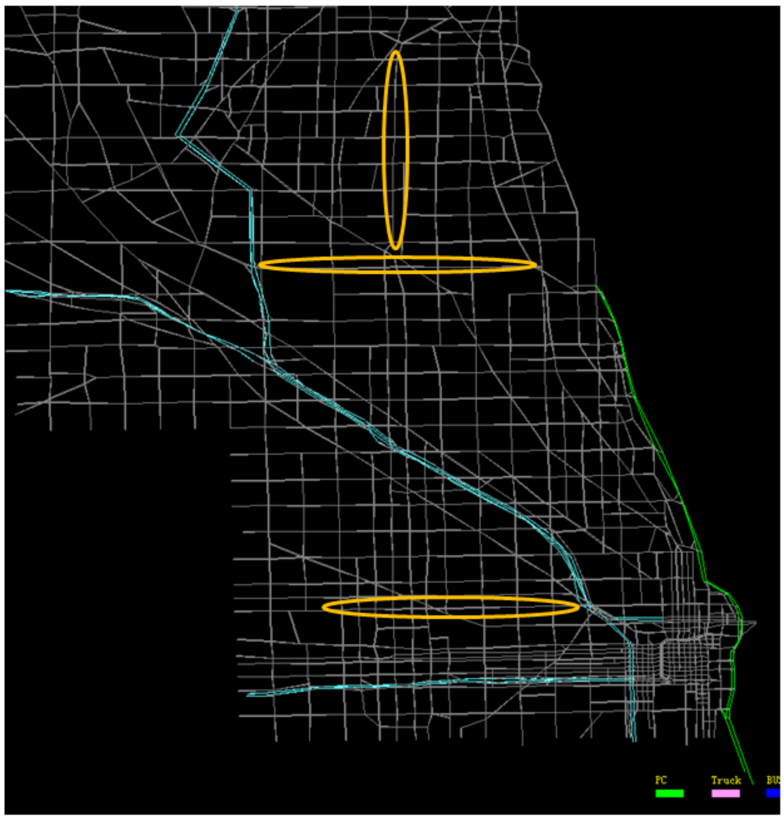
After establishing the fundamental research parameters, it was time to develop virtual testbeds for the simulation experiments. The goal was to devise urban street intersection and/or corridor conditions that would clearly reveal ATM strategy impacts. For adaptive signals and reversible lanes, the need to measure corridor-level impacts led to the simulation of three representative corridors in Chicago. For dynamic lane grouping, the need to measure intersection-level impacts led to a simple intersection design. This simplified intersection and experimental design treated the dynamic lane grouping approach as one entity, and combined all other intersection approaches into a second entity, to simplify the analysis of interdependent traffic movements. The Chicago testbeds are described first, followed by the simplified intersection testbed.

Chicago Corridors

The team selected West Peterson Avenue, West Chicago Avenue, and McCormick Boulevard as appropriate environments for ATM impact analysis. Analysis of multiple locations would add robustness to the final conclusions. The fundamental characteristics of these corridors are summarized in Table 4. These corridors had been previously modeled in virtual software platforms (i.e., DYNASMART™ and Synchro™). Thus, they were ideal choices for a project whose objective was to exploit existing data sources. Additionally, the corridor lengths, number of intersections, and signal spacings were considered excellent conditions for analyzing typical urban street operations. Figure 18 illustrates all three corridors, as depicted within the DYNASMART™ simulation platform.

Table 4. Characteristics of the Chicago Testbed corridors.

	W Peterson Ave	W Chicago Ave	McCormick Blvd
Length (miles)	4	4	4
Number of Signalized Intersections	8	11	9
Intersection Spacing Range (miles)	0.17 - 1.0	0.13 - 0.62	0.24 - 0.52
Average Intersection Spacing (miles)	0.56	0.35	0.45
Other Comments	Connects to I-94	Connects to I-90	None



Source: Federal Highway Administration

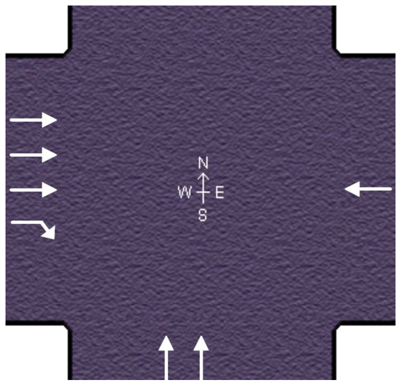
Figure 18. Screenshot. Testbed corridors for simulation of active traffic management strategy impacts.

Simplified Intersection

For dynamic lane grouping, the need to measure intersection-level impacts led to a simple intersection design. This simplified intersection and experimental design treated the dynamic lane grouping (DLG) approach as one entity, and combined all other intersection approaches into a second entity, to simplify the analysis of interdependent traffic movements.

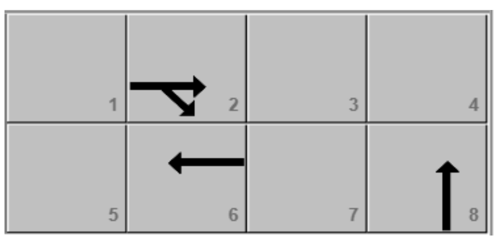
The experimental design called for analyzing DLG benefits under various combinations of through movement degree of saturation (v/c), through movement green ratio (g/C), adjacent turn movement v/c, and adjacent turn movement g/C. All other movements were served by the side-street signal phase. This helped to simplify the analysis of relative congestion levels in the following manner:

to decrease congestion levels on the DLG approach relative to the rest of the intersection, it was only necessary to increase traffic volume demand on one side-street movement. This helped to isolate and analyze DLG impacts with minimal experimental noise. It also increased the number of combinations of v/c and g/C for both left- and right-turn scenarios, and major-street scenarios with two or three exclusive through lanes, that could be analyzed. Figure 19, Figure 20, and Figure 21 illustrate the lane geometry, signal phasing, and signal timing of one sample scenario. To conserve project resources, no data were collected for major streets having four exclusive through lanes, which was considered a low-priority scenario.



Source: McTrans Center, University of Florida

Figure 19. Screenshot. Sample testbed geometry for dynamic lane grouping.



Source: McTrans Center, University of Florida

Figure 20. Screenshot. Sample testbed signal phasing for dynamic lane grouping.

Green	37.0	108.0
Yellow	4.0	4.0
Red	1.0	1.0

Source: McTrans Center, University of Florida

Figure 21. Screenshot. Sample testbed signal timing for dynamic lane grouping.

The experimental design called for analyzing hundreds of intersection scenarios, and required signal timing optimization both before and after DLG. For example, after optimizing signal timings for the "before" scenario in Figure 18, it would then be necessary to add a second exclusive right-turn lane, subtract an exclusive through lane, and re-optimize the timings.

Moreover, optimized timings in the "before" scenario had to match certain levels of v/c and g/C on the DLG approach, sometimes requiring numerous trial-and-error optimizations. Note that the need for matching certain levels of v/c and g/C on the DLG approach will become clearer when experimental results are presented in the next chapter. To efficiently meet these experimental requirements, the Highway Capacity Software ™ (HCS 2010 ™) was chosen as the analysis platform. This choice of traffic analysis tool would allow hundreds of signal timing optimizations to be performed within a reasonable time frame, because the HCS intersection evaluations offer much smaller computer run times than comparable simulation-based evaluations.

CONCLUSIONS AND NEXT STEPS

The team's planned methodology for Task 6 – Original Research was essentially finalized by the beginning of April 2016. This methodology consisted of a set of key experimental parameters and testbeds, to be customized for each individual ATM strategy. Proper choice of experimental parameters would help towards developing robust and reliable models. Improper choice of experimental parameters would interfere with the team's ability to meet project objectives. Therefore throughout the month of March, the team held discussions about what might be the optimal choice of experimental parameters. The experimental parameters fell into three categories: input parameters, output parameters, and experimental scope. While determining the output parameters, it was decided that capacity adjustment models should be developed for each ATM strategy. If successful, this would facilitate the analysis of any performance measure within the HCM urban streets procedure. Thus in April 2016, following much planning and discussion over what experimental parameters would be best for the project, the simulation-based experiments would finally begin. These experiments are described next in Chapter 6.

CHAPTER 6. SIMULATION EXPERIMENTS

At the outset of the project it was desired to develop a robust active transportation and demand management (ATDM) analytical models based on existing field data, while using simulated data to fill in the gaps. However due to the scarcity of urban street ATDM before-and-after studies located during Task 4 – Existing Data Sources, it became clear that any models developed during this project would need to be based on simulated data, with field data used for validity checks at best. Following the choice of key experimental parameters and testbeds for each active traffic management (ATM) strategy, it was then possible to actually generate the simulated data through simulation experiments. This chapter presents the results of those simulation experiments, which were conducted to meet the requirements of Task 6 – Original Research.

Towards the end of the Task 6 planning phase (end of March 2016), it was decided that the simulation experiments should be geared towards developing capacity adjustment models for each ATM strategy. This would be consistent with some of the assumptions made during the freeway ATDM project, and consistent with capacity adjustment factors that already exist in the *Highway Capacity Manual* (HCM). Capacity adjustment models would offer tremendous flexibility in terms of output parameters: they would facilitate the analysis of any performance measure within the HCM urban streets procedure.

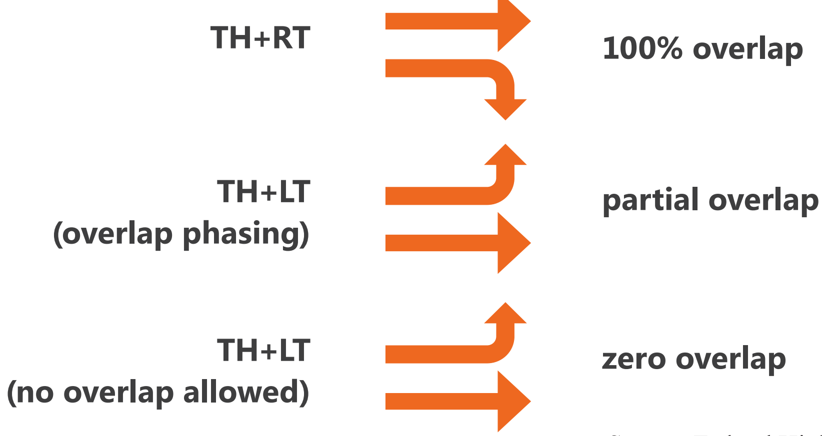
DYNAMIC LANE GROUPING CAPACITY ADJUSTMENTS

Due to the nature of the dynamic lane grouping (DLG) experimental conditions, the DLG simulation experiments were conducted in the HCS 2010 platform, which is not considered a simulation-based platform, despite containing limited amounts of macroscopic simulation. It is instead primarily an analytical modeling platform, designed to execute the analytical HCM procedures. This platform facilitated the execution of hundreds of signal timing optimizations within a reasonable time frame, as discussed in the previous chapter.

Figure 22 illustrates three of the basic scenarios originally considered for DLG. It was expected that one model would be developed for each scenario. The models could later potentially be unified into a single model with appropriate parameters, if they had enough in common. Because through and right-turn movements on the same intersection approach typically move during the same signal phases, right-turn DLG scenarios were called “100 percent overlap” scenarios. Because through and left-turn movements on the same approach typically move during some but not all of the same signal phases, actuated left-turn scenarios were called “partial overlap” scenarios.

Pre-timed through and left-turn scenarios, in which opposing left-turn phases would terminate simultaneously, were called “zero overlap” scenarios, because the through and left-turn movements would never receive green simultaneously. Although traffic analysis tools in the 1990’s offered the ability to model simultaneous termination of opposing left-turn phases at actuated signals, the HCM 2010 procedure did not recognize or support this type of analysis. As such, the “zero overlap” scenarios were considered a low priority, and were omitted from Task 6 experiments to conserve project resources.

Note: TH+RT = through and right turn movements. TH+LT = through and left turn movements.



Source: Federal Highway Administration

Figure 22. Diagram. Phasing scenarios for dynamic lane grouping.

Figure 22 illustrates initial data collection efforts for the "partial overlap" model. The "Before" tab of the spreadsheet summarized key input and output parameter values, before DLG was implemented. The "After" tab of the spreadsheet summarized the same values after DLG was implemented. The "Diff" tab automatically computed the ratio of "Before" and "After" results from each cell. "Diff" results were then mapped back to the "Before" tab, to compare DLG impacts against combinations of degree of saturation (v/c) and green ratio (g/C). Similar experiments were conducted for "full overlap" scenarios, and with three exclusive through lanes on the major street. A total of four spreadsheets were created to handle the four combinations of phasing and laneage. These results were then plotted in charts, as shown in Figure 24 and Figure 25.

Blank rows in Figure 23 were the results of scenarios in which intersection delays increased as a result of DLG treatment. Before the Task 6 experiments, it was generally understood that DLG would only be effective in cases where a turning movement was relatively congested, and the adjacent through movement was relatively uncongested. However, the precise ranges where DLG would cease to be effective were unknown. Scenarios where DLG proved ineffective were removed from the charts shown in Figure 24 and Figure 25, in order to make the capacity adjustment results more predictable and stable. It was expected that this would also facilitate development of more accurate capacity adjustment models, later on in Task 6. The plan was to develop "pre-requisite" guidelines for the intersection conditions under which DLG could be effective, and under which the capacity adjustment models would be valid. No models would be needed for predicting DLG impacts under conditions in which DLG was clearly known to be ineffective. These pre-requisite guidelines, based on the data collection results, are presented later in the chapter.

Figure 23 illustrates several of the relevant input and output parameters identified during the experimental planning phase, as described earlier in Chapter 4. Reading from left to right, these include v/c, g/C, capacity (c), and control delay for the through movement; v/c, g/C, capacity (c), and control delay for the left-turn movement; intersection-wide delay; and cycle length. Column K contains the percentage increase in left-turn movement capacity, which resulted from adding a second left-turn lane and re-optimizing the timings. Column F contains the percentage decrease in through movement capacity, which resulted from removing a through lane and re-optimizing the timings.

			TH					LT					INT		delay							
case	lanes	v/c	g/c	c	delay	lanes	v/c	g/c	c	delay	act	delay	PHF	cycle	diff							
1	2	0.35	0.6	2167	7.6	1	0.93	0.39	700	35.2	semi	24.8	0.92	70	0.722	35	17.57	60		53.71	58	93
2	2	0.38	0.6	2201	10	1	0.95	0.42	755	42.8	semi	32.5	0.92	95	0.705	38	14.3	60		51.66	57	95
3																						
4	2	0.47	0.6	2201	10.9	1	0.95	0.42	755	42.8	semi	31.3	0.92	95	0.923	47	13.51	60		50.66	48	95
5	2	0.32	0.6	2166	6.3	1	0.91	0.36	643	30.6	semi	20.5	0.92	60	0.756	32	19.44	60		53.46	59	91
17	2	0.13	0.6	2166	5.3	1	0.91	0.36	643	30.6	semi	23.8	0.92	60	0.66	13	19.44	60		53.46	78	91
9	2	0.23	0.6	2166	5.8	1	0.91	0.36	643	30.6	semi	30.6	0.92	60	0.497	23	19.44	60		53.46	68	91
25																						
6																						
10	2	0.4	0.48	1730	18.3	1	1	0.34	587	66.9	semi	40.2	0.92	105	0.659	40	20.61	48		54.39	60	100
11	2	0.5	0.48	1730	19.9	1	1	0.34	587	66.9	semi	39.3	0.92	105	0.934	50	18.4	48		49.88	50	100
12	2	0.3	0.48	1730	17.2	1	1	0.34	587	66.9	semi	41.3	0.92	105	0.586	30	20.61	48		54.39	70	100
18	2	0.2	0.48	1730	16.1	1	1	0.34	587	66.9	semi	42.8	0.92	105	0.556	20	20.61	48		54.39	80	100
19	2	0.1	0.48	1730	15.1	1	1	0.34	587	66.9	semi	44.6	0.92	105	0.545	10	20.61	48		54.34	90	100
26																						
7																						
8																						
13																						
14	2	0.42	0.36	1302	42	1	1.3	0.26	451	215	semi	83.3	0.92	170	0.521	42	45.9	36		51.84	88	130
15	2	0.31	0.36	1310	40.7	1	1.28	0.26	460	205.3	semi	84.8	0.92	175	0.485	31	42.61	36		52.21	97	128
16	2	0.08	0.36	1320	34.4	1	1.26	0.27	465	196.1	semi	86.7	0.92	165	0.456	8	41.94	36		52.12	118	126
20	2	0.12	0.24	886	59.1	1	1.55	0.16	280	349	semi	129.8	0.92	200	0.653	12	38.57	24		54.85	143	155
21	2	0.25	0.24	886	61.3	1	1.55	0.16	280	349	semi	127.8	0.92	200	0.663	25	36.43	24		54.63	130	155
22	2	0.37	0.24	886	63.8	1	1.55	0.16	280	349	semi	126.1	0.92	200	0.677	37	39.29	24		54.74	118	155
23	2	0.49	0.24	886	66.7	1	1.55	0.16	280	349	semi	124.7	0.92	200	0.732	49	58.57	24		49.21	106	155
24	2	0.5	0.24	872	59.3	1	1.04	0.12	210	124.5	semi	49.4	0.92	175	0.899	50	30	24		51.38	54	104
27																						

Source: Federal Highway Administration

Figure 23. Chart. Data collection results (partial overlap, two exclusive through lanes).

Figure 24 through Figure 27 reflect the original objective of developing capacity adjustment models for both turn movements and through movements, under various congestion levels. These charts were created using the data collected and recorded within spreadsheets, similar to the one shown in Figure 23. The desire to simplify and group results under common g/C values required a trial-and-error signal timing optimization process, as discussed in the previous chapter. Figures 24 and 26 represent the scenarios with three exclusive through lanes on the major street, prior to the removal of a through lane. Figure 25 and 27 represent the scenarios with two exclusive through lanes on the major street. Although these four charts were created for the partial overlap (i.e., left-turn) scenarios, similar charts were created for the full overlap (i.e., right-turn) scenarios.

During this data collection, it was believed capacity adjustment factors or models could soon be developed. This would be similar to what was attempted during the freeway ATDM project. In areas where the data looked unstable, such as in Figure 25, it was hoped that additional data collection would clarify and stabilize those relationships. However, at this point it was realized that even if the capacity adjustment models were perfect, they would nonetheless be unsuitable for arterials. The inadequacy of the capacity adjustment paradigm will now be discussed.

Under the DLG treatment, an exclusive through lane can be temporarily re-channelized as an exclusive left-turn (or right-turn, if needed) lane, to better accommodate fluctuating demands. If that were to happen on the eastbound approach in Figure 28, for example, capacity adjustment models would attempt to predict and re-compute capacities for the eastbound movements. However under actuated or adaptive signal control, this would further affect green times and progression quality for the eastbound left turn, because now its green phase would terminate sooner. It would also re-distribute green time for other movements throughout the signal cycle, possibly altering their capacities and progression quality. If turn pocket queue spillover were alleviated, from a

Note: g/C = green time. LT = left turn. TH = through movement. v/c = volume to capacity ratio.

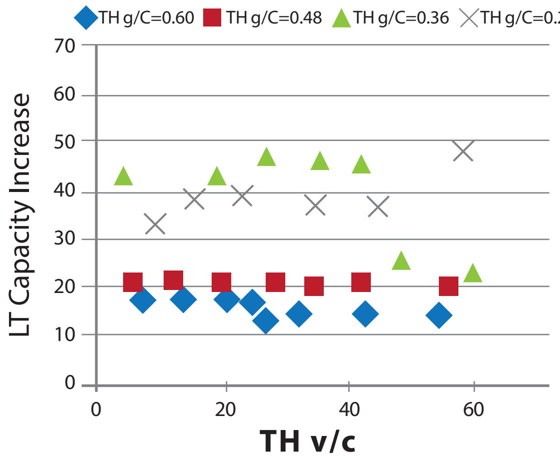


Figure 24. Chart. Left-turn capacity increase (three exclusive through lanes)

Source: Federal Highway Administration

Note: g/C = green time. LT = left turn. TH = through movement. v/c = volume to capacity ratio.

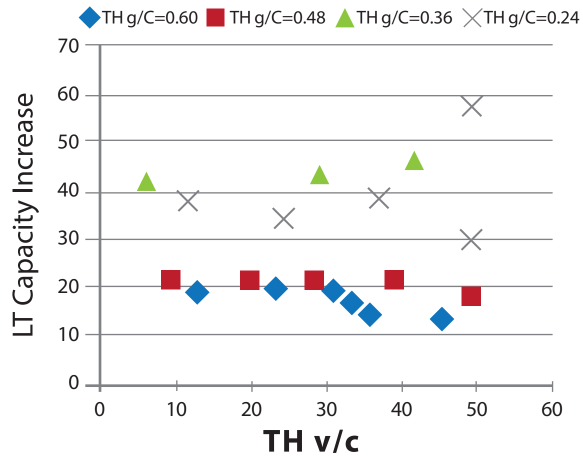


Figure 25. Chart. Left-turn capacity increase (two exclusive through lanes).

Source: Federal Highway Administration

Note: g/C = green time. LT = left turn. TH = through movement. v/c = volume to capacity ratio.

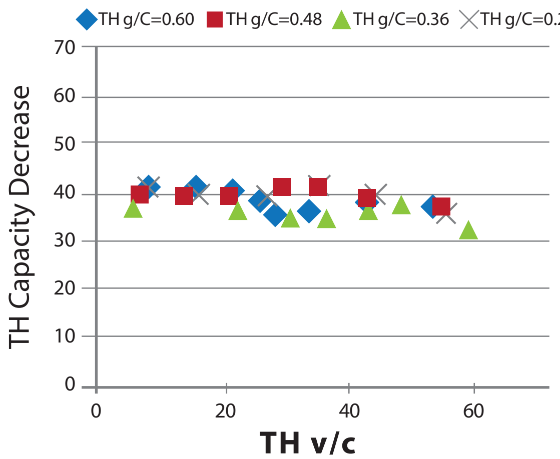


Figure 26. Chart. Through capacity decrease (three exclusive through lanes).

Source: Federal Highway Administration

Note: g/C = green time. LT = left turn. TH = through movement. v/c = volume to capacity ratio.

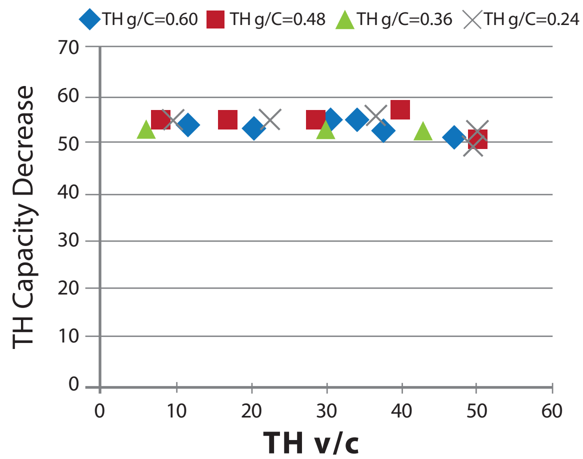


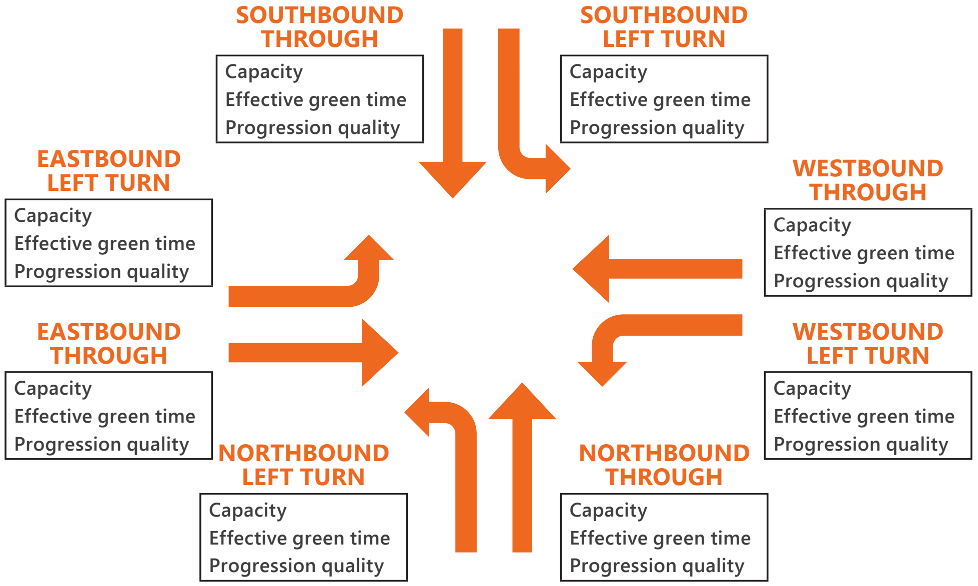
Figure 27. Chart. Through capacity decrease (two exclusive through lanes).

Source: Federal Highway Administration

left-turn pocket into an adjacent through lane, multiple movements would again be affected. And as stated both in the previous chapter and in this chapter, signal timings should be re-optimized whenever lane channelizations change, which would affect movements on all approaches regardless of actuation. The bottom line is that the vehicle flows and green times of all traffic movements at a signalized intersection are highly interdependent, and that prediction of capacity adjustments for one or two movements is not nearly enough to know how the intersection will ultimately operate. In fact, this same concept would hold true for the other relevant ATM strategies in this project, reversible lanes and adaptive signals. Upon this realization, Task 6 efforts were refocused to address the following questions:

- What overall benefits of the ATM strategies are possible under various conditions?
- How can the ATM strategies be implemented within an HCM framework?

These questions will be addressed in the upcoming sub-sections of this chapter.



Source: Federal Highway Administration

Figure 28. Diagram. Circular dependency of turn movement operations at a traffic signal.

ADAPTIVE SIGNAL BENEFITS

To examine the potential benefits of adaptive signals, the team used the methodology discussed in Chapter 4 (Figure 16) to simulate the three Chicago corridors described in Chapter 4 (Figure 18). The peer review group had expressed concerns about what would be the exact definition of "adaptive signals", and the wide variety of adaptive signal products on the market. The experiment emulated the net result of what an adaptive logic might accomplish, but without using specific commercial adaptive control logic. It was believed that depending on the timing parameters, particularly in terms of creating progression as an "emergent" property, one might obtain very different performance for actuated control. In other words, there is no standard benchmark for actuated control; whereas for pre-timed control, the team used optimized Synchro plans as a baseline. Table 5, Table 6, and Table 7 illustrate the 24-hour impacts of adaptive signals on all three corridors. Although these tables demonstrate consistently positive impacts according to a wide range of performance measures, the magnitudes of these benefits were less consistent (e.g., delay reductions between 3 percent and 24 percent; TTI reductions between 3 percent and 13 percent). The team also simulated the reliability of traffic under rain and snow conditions as follows:

1. Randomly select 20 percent of the vehicles traversing any section of the selected locations.
2. Perturb their departure time between -5 and +5 minutes.
3. Simulate and get the MOEs with and without the strategy.

4. Repeat step 1-3 for 20 times using different random seed each time.
5. Compute mean and variance of the measures of effectiveness (MOEs).

Table 5. Adaptive signal impacts on West Peterson Avenue (percent change).

Direction	Travel Time Index	Planning Time Index	Misery Index	Moving Speed	Tour Speed	Delay	Stop Time	Stopped Vehicles
East	-1.5	1.0	2.7	0.7	5.4	-5.9	-5.7	-0.6
West	-33.2	-31.9	-62.5	-0.4	4.9	-42.9	-34.9	-1.3
Major	-8.6	-4.2	-4.2	0.2	5.3	-13.2	-12.5	-0.9
Minor	-3.0	-2.8	-0.2	1.6	5.1	-6.8	-8.0	-0.6
All	**-3.4**	**-2.3**	**-0.5**	**0.7**	**5.4**	**-5.9**	**-5.7**	**-0.6**

Table 6. Adaptive signal impacts on West Chicago Avenue (percent change).

Direction	Travel Time Index	Planning Time Index	Misery Index	Moving Speed	Tour Speed	Delay	Stop Time	Stopped Vehicles
East	-17.0	-18.0	-11.7	11.9	22.4	-32.7	-28.1	-1.2
West	-2.7	-5.8	-1.2	0.9	1.3	-6.0	-3.4	-1.1
Major	-16.2	-17.9	-12.8	8.0	13.5	-28.8	-24.5	-1.0
Minor	-11.9	-8.4	-15.4	1.8	5.4	-21.7	-25.0	-0.6
All	**-12.7**	**-9.3**	**-13.5**	**2.9**	**7.0**	**-23.6**	**-24.8**	**-0.7**

Table 7. Adaptive signal impacts on McCormick Boulevard (percent change).

Direction	Travel Time Index	Planning Time Index	Misery Index	Moving Speed	Tour Speed	Delay	Stop Time	Stopped Vehicles
East	-2.4	-4.7	-3.1	0.9	1.0	-10.4	-7.7	3.4
West	-43.5	-47.7	-34.3	26.3	20.7	-30.6	-20.4	-2.7
Major	-37.8	-54.1	-38.9	16.0	12.0	-29.5	-19.3	-0.9
Minor	-2.4	-3.5	-1.3	0.1	1.2	-1.5	-1.9	-0.5
All	**-4.7**	**-6.7**	**-1.8**	**1.1**	**2.1**	**-3.0**	**-2.7**	**-0.5**

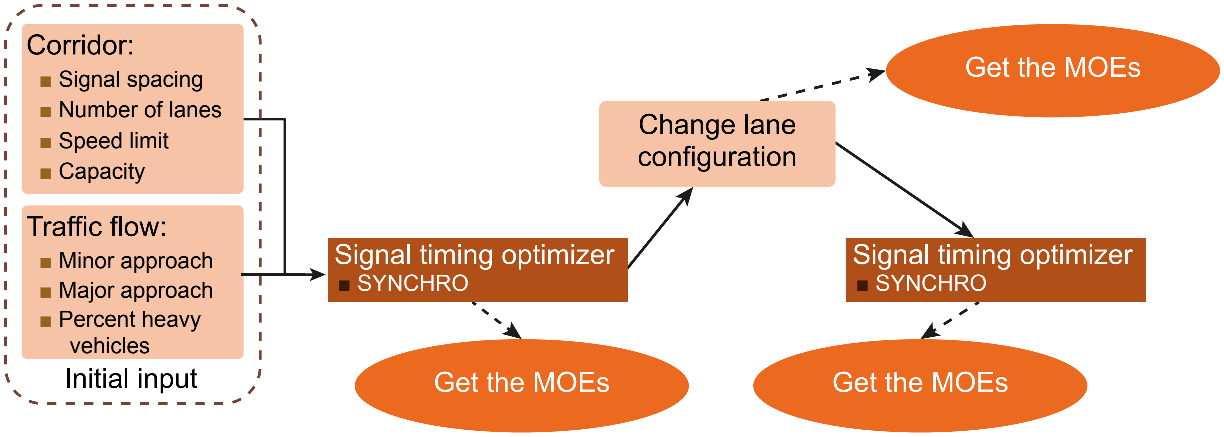
Experimental conditions corresponded to actually-occurring weather days in Chicago, based on historical records. These experiments indicated that adaptive signal benefits were often more significant under rainy conditions, a finding consistent with (Stevanovic, Zlatkovic, & Dakic, 2015). Rain was found to exhibit the most variability in performance (across the repetitions). By contrast, snow conditions produced a much tighter distribution of performance indicators across repetitions, because speeds were generally very low for all vehicles. Therefore, although adaptive control did not improve ***average performance*** under severe weather conditions, it did improve ***performance reliability*** under these conditions.

Together with the field study results obtained for Task 4, these simulation results provide the type of data that could potentially be used to develop analytical models for the HCM. However, a number of obstacles still remain. For example, the simulation results demonstrated potential benefits in comparison to an optimized pre-timed plan. Therefore, potential benefits in comparison to an optimized semi-actuated plan are still unknown. Moreover, even if overall benefits compared to semi-actuated control were known, the impact of high-priority input parameters (i.e., Table 3 from Chapter 4) would not be known. In summary, although it should be possible to develop case studies demonstrating the impacts observed during this project, there is still no clear path to developing a generalized adaptive signal model for the HCM, which would accurately handle a wide range of real-world conditions.

REVERSIBLE CENTER LANE BENEFITS

To examine the potential benefits of reversible center lanes (RCL), the team used the methodology illustrated in Figure 29 to analyze hypothetical RCL benefits along the Peterson Avenue corridor described in Chapter 4 (Figure 18). The current operation of Peterson Avenue does not include reversible lanes. In the hypothetical RCL configuration, three lanes were assigned to eastbound traffic, while only one lane was assigned to westbound traffic. Accordingly, the majority of traffic demand was in the eastbound direction. Four different directional demand splits were tested (i.e., 40-60, 30-70, 20-80, and 10-90 percentage split). For example, a 40-60 split implies that 40 percent of traffic flow was in the westbound direction, and 60 percent was in the eastbound direction.

Note: MOE = measure of effectiveness



Source: Federal Highway Administration

Figure 29. Flowchart. Proposed method for assessing reversible center lane benefits.

As discussed in Chapter 5, degree of saturation was believed to be a critical variable in determining ATM strategy benefits. Thus for each directional split, two demand levels were tested: the original demand level measured in Chicago, and a higher demand level that doubled the original demand. These experimental demand scenarios are shown in Table 8.

Table 8. Demand scenarios for evaluating reversible center lane benefits.

Demand Level (vehicles/hr)			High	Regular
Total Volume			6704	3352
Volume Directional Split	40-60	West bound	2682	1341
		East bound	4022	2011
	30-70	West bound	2011	1006
		East bound	4693	2346
	20-80	West bound	1341	670
		East bound	5363	2682
	10-90	West bound	670	335
		East bound	6034	3017

The experimental results are illustrated through bar charts as shown in Figure 29 and Figure 30. The blue bar represents performance under the base case conditions. The orange bar represents performance under RCL conditions, but before signal timings have been re-optimized. The green bar represents performance under RCL conditions, after signal timings have been re-optimized.

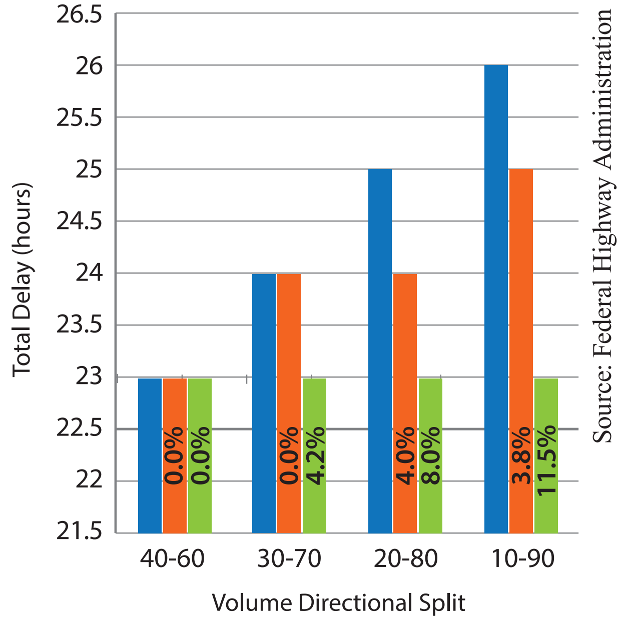


Figure 30. Chart. Reversible center lane delay reductions under original demand levels.

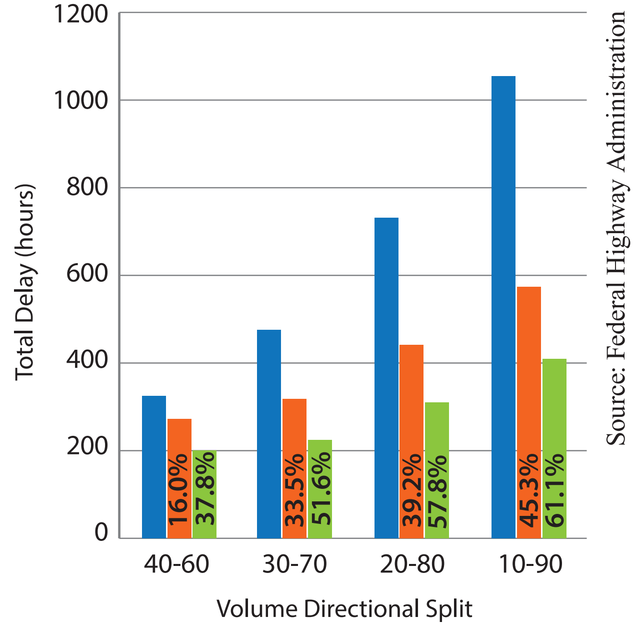


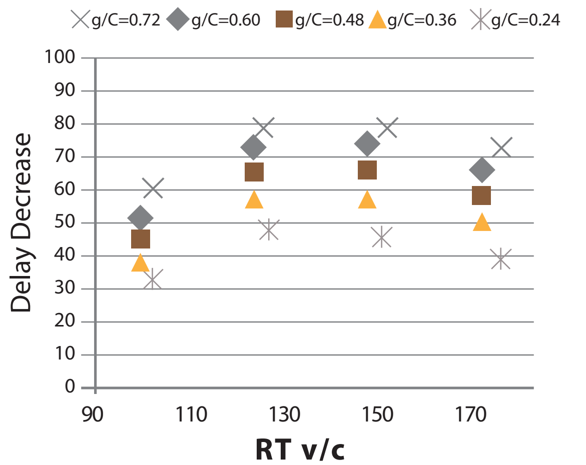
Figure 31. Chart. Reversible center lane delay reductions under heavy demand levels.

Similar benefits were observed through other performance measures such as vehicle stops, speeds, and travel times. Through these results, it can be concluded that RCL benefits are generally maximized when degrees of saturation and directional splits are both maximized. However the tipping point at which RCL benefits are viewed as significant may depend on a large number of additional factors affecting urban street operations. These could include signal spacing, progression quality, distribution of major/minor-street demands, and corridor reliability. As such, HCM reliability analysis could be an effective method of predicting RCL benefits for a wide variety of urban street conditions. An example HCM reliability analysis of before-and-after-RCL conditions is shown in the next chapter.

DYNAMIC LANE GROUPING BENEFITS

During the initial DLG experiments, it was realized that the interdependent vehicle flows and green times of all signalized traffic movements would make capacity adjustment models impractical. At that time, Task 6 efforts were refocused to address the overall benefits of the ATM strategies under various conditions, and how ATM strategies could be implemented within an HCM framework. As such, new charts were developed from the original DLG data collection efforts described earlier in this chapter. Although the capacity adjustment data collected during those experiments would no longer be useful, the delay reduction data collected during those experiments would now become useful. Figures 32 through 40 illustrate the intersection-wide delay reductions due to DLG, under various conditions.

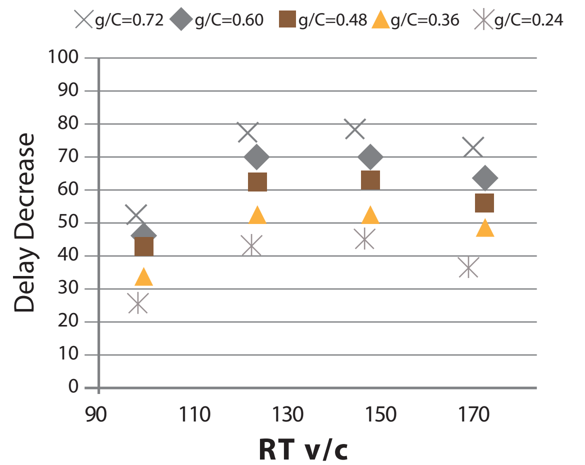
Note: g/C = green time. RT = right turn.
v/c = volume to capacity ratio



Source: Federal Highway Administration

Figure 32. Chart. Intersection percentage delay reductions under dynamic lane grouping (right turns, three through lanes, 35 percent degree of saturation for the adjacent through movement).

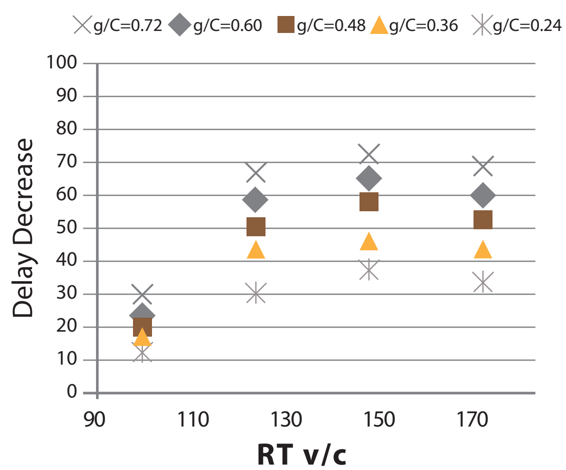
Note: g/C = green time. RT = right turn.
v/c = volume to capacity ratio



Source: Federal Highway Administration

Figure 33. Chart. Intersection percentage delay reductions under dynamic lane grouping (right turns, three through lanes, 47 percent degree of saturation for the adjacent through movement).

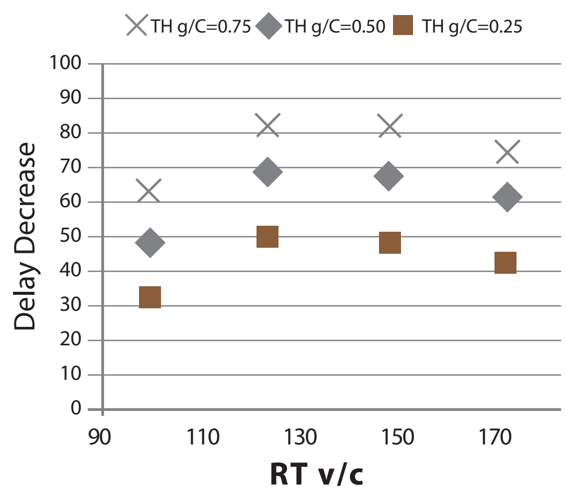
Note: g/C = green time. RT = right turn.
v/c = volume to capacity ratio



Source: Federal Highway Administration

Figure 34. Chart. Intersection percentage delay reductions under dynamic lane grouping (right turns, three through lanes, 59 percent degree of saturation for the adjacent through movement).

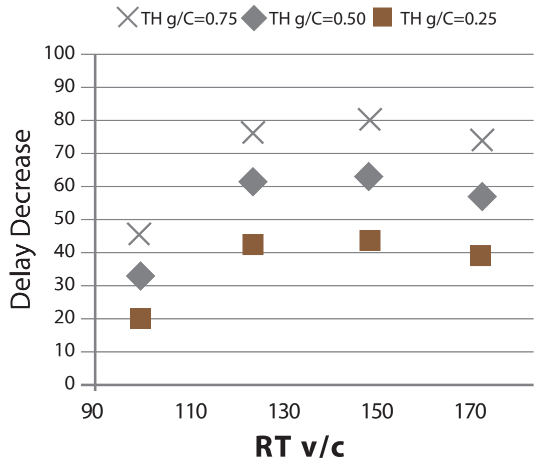
Note: g/C = green time. RT = right turn.
TH=total hours. v/c = volume to capacity ratio.



Source: Federal Highway Administration

Figure 35. Chart. Intersection percentage delay reductions under dynamic lane grouping (right turns, two through lanes, 30 percent degree of saturation for the adjacent through movement).

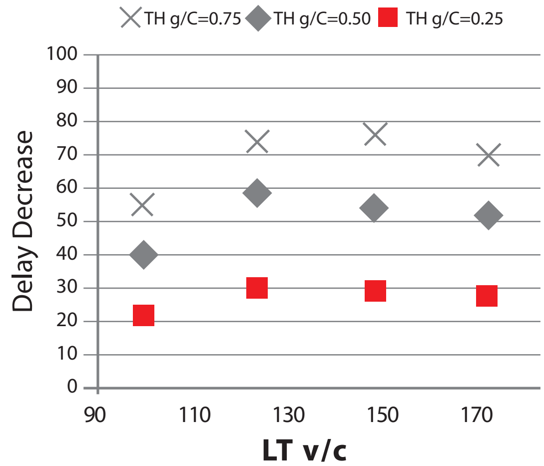
Note: g/C = green time. RT = right turn.
TH=total hours. v/c = volume to capacity ratio.



Source: Federal Highway Administration

Figure 36. Chart. Intersection percentage delay reductions under dynamic lane grouping (right turns, two through lanes, 42 percent degree of saturation for the adjacent through movement).

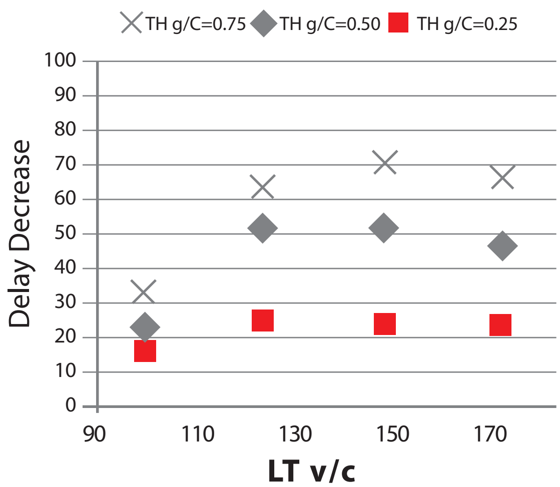
Note: g/C = green time. RT = right turn.
TH=total hours. v/c = volume to capacity ratio.



Source: Federal Highway Administration

Figure 37. Chart. Intersection Percentage Delay Reductions under dynamic lane grouping (left turns, three through lanes, 44 percent degree of saturation for the adjacent through movement).

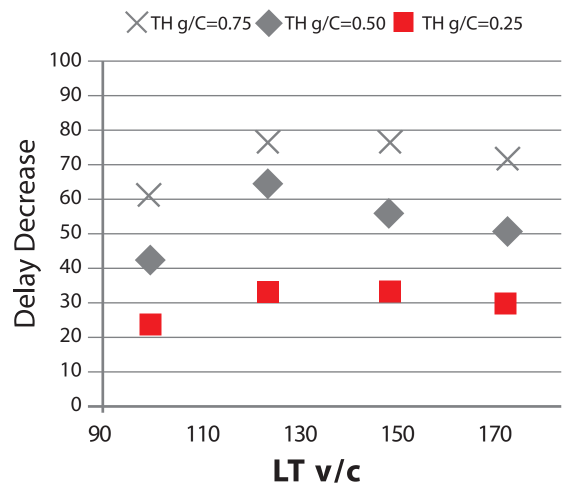
Note: g/C = green time. RT = right turn.
TH=total hours. v/c = volume to capacity ratio.



Source: Federal Highway Administration

Figure 38. Chart. Intersection percentage delay reductions under dynamic lane grouping (left turns, three through lanes, 59 percent degree of saturation for the adjacent through movement).

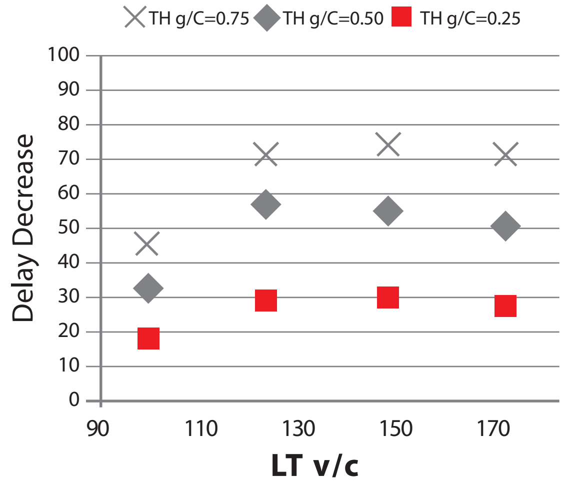
Note: g/C = green time. RT = right turn.
TH=total hours. v/c = volume to capacity ratio.



Source: Federal Highway Administration

Figure 39. Chart. Intersection percentage delay reductions under dynamic lane grouping (left turns, two through lanes, 30 percent degree of saturation for the adjacent through movement).

Note: g/C = green time. RT = right turn.
TH=total hours. v/c = volume to capacity ratio.



Source: Federal Highway Administration

Figure 40. Chart. Intersection percentage delay reductions under dynamic lane grouping (left turns, two through lanes, 42 percent degree of saturation for the adjacent through movement).

A small number of additional experiments were performed with shared lane scenarios, and with right-turns-or-red (RTOR) allowed. In a shared lane scenario, lane channelization can be dynamically changed from shared to exclusive, or vice-versa. Also, it is not uncommon for the inside right-turn lane of a dual right-turn lane group to have RTOR allowed. These experiments found that shared lane DLG produces no significant benefits for right turns unless RTOR is allowed, and produces no significant benefits for left turns. However in shared lane RTOR cases where DLG produces significant benefits, those benefits would be very hard to predict by a simple method or chart, due to the sheer number of independent variables (e.g., conflicting through demand (TH), opposing left turn (LT) demand, existence of shielded right turn (RT) phase, v/c of multiple movements, g/C of multiple movements).

Following the production of these delay reduction charts, the following observations became possible:

- Significant benefits only occur when turn movement degree of saturation (v/c) exceeds 95 percent; and when adjacent through movement degree of saturation is at least 5 percent lower than (N-1)/N, where N is the number of exclusive through lanes prior to DLG.
- Benefits are much higher when g/C is high on the DLG approach prior to DLG (in other words, when DLG movements receive green during most of the cycle prior to DLG)
- Benefits are increased when turn movement degree of saturation is in the mid-100-percent range, prior to DLG (in other words, when adding a new turn lane allows the turn movement to go from significantly oversaturated to undersaturated).
- Benefits are increased when cycle lengths can be re-optimized to accommodate the new lane grouping (may not be effective with other congested intersections in the urban street, which may govern the background cycle length).

- Similar benefits are observed for left turns versus right turns, and for two exclusive through lanes versus three exclusive through lanes (however, the pre-requisite listed in the first bullet may be harder to satisfy with only two exclusive through lanes).
- Benefits increase when there is good progression quality on the DLG approach, prior to DLG (observed in bonus experiments where "arrival types" were modified in HCS 2010)
- If it were possible to automatically detect v/c and g/C of various turn movements, it might become more effective to implement DLG in real time than by fixed time-of-day.

CONCLUSIONS AND NEXT STEPS

An initial set of simulation experiments was geared towards the development of capacity adjustment models for three ATM strategies. After a few weeks of these experiments, it became apparent that vehicle flows and green times of all traffic movements at a signalized intersection are highly interdependent, and that capacity adjustment for one or two movements could not accurately predict intersection operations. In fact, this same concept would hold true for all relevant ATM strategies in this project. Upon this realization, Task 6 efforts were refocused to address the following questions:

- What overall benefits of the ATM strategies are possible under various conditions?
- How can the ATM strategies be implemented within an HCM framework?

Potential overall benefits under various conditions were partially addressed by experimental results presented in the second and third sub-sections of this chapter. However the next step, and a crucial component of this project, would be the issue of how ATM strategies could be implemented in an HCM framework. The next chapter will address this issue by demonstrating how some ATM strategies can be implemented within an HCM framework. These implementations can also further address the first bulleted question, regarding potential ATM strategy benefits. In fact, these HCM implementations may make it easier to determine ATM strategy benefits under various conditions, without requiring simulation studies. This was an original and primary goal of the project.

CHAPTER 7. HIGHWAY CAPACITY MANUAL FRAMEWORK IMPLEMENTATION

In the early stages of the project, it was believed that the three chosen urban street active traffic management (ATM) strategies could be effectively modeled via capacity adjustment factors, similar to what was accomplished during the freeway active transportation and demand management (ATDM) project. However, it was later discovered that the capacity adjustment paradigm would be unsuitable for arterials, and that the *Highway Capacity Manual* (HCM) reliability framework would offer a preferable solution. Specifically, the alternative lane use configurations could be modeled as special event datasets within the HCM reliability framework, along with re-optimized timing plans for the new lane uses. The inadequacy of the capacity adjustment paradigm was detailed in the previous chapter.

The research team was always aware of the ability to model alternative lane use configurations as special event datasets within the HCM reliability framework. However, the team had hoped that capacity adjustment models might provide another modeling option. Capacity adjustment models (or factors) would have made it possible for engineers to analyze ATM strategy impacts without having to develop alternative datasets, and without having to develop alternative optimized timing plans. Access to both modeling options would have provided great flexibility for the analyst, just as simulation and the HCM provide alternate modeling options for many facility types. Thus when the capacity adjustment option was deemed inadequate, the HCM reliability framework quickly became the best and only option for ATM strategy.

RELIABILITY FRAMEWORK FUNDAMENTALS

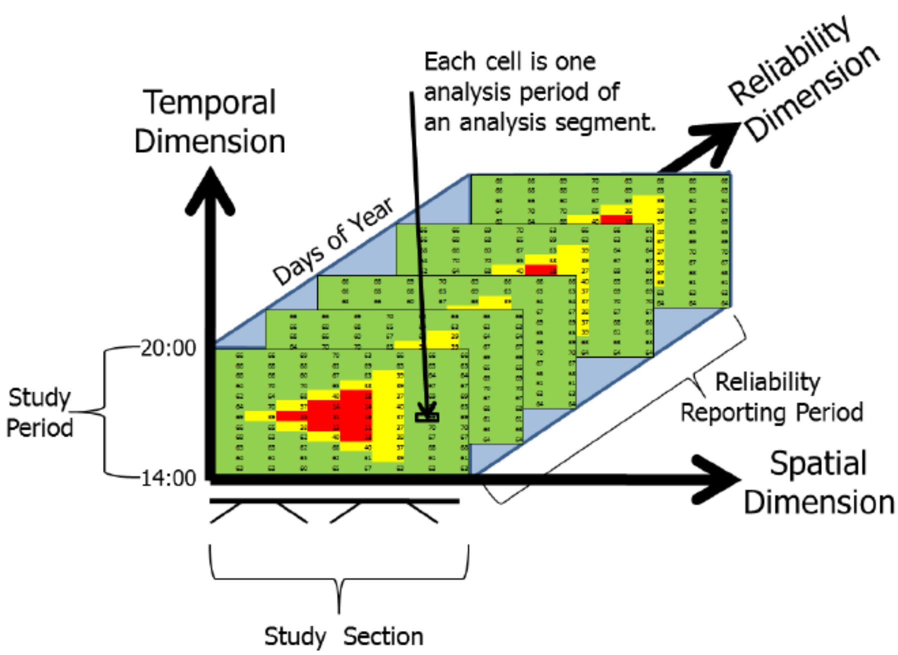
The HCM reliability framework is largely based on the product of a second Strategic Highway Research Program (SHRP 2) project (Zegeer, et al., 2014). At its core, the reliability methodology consists of hundreds of repetitions of the HCM urban streets methodology. In contrast to the urban streets methodology, where inputs represent average values for a defined analysis period, the reliability methodology varies the demand, capacity, geometry, and traffic control inputs to the facility methodology with each repetition (i.e., scenario). Chapter 17 of the recently published HCM 6th Edition provides the following additional description:

> *The full range of HCM performance measures output by the facility methodology are assembled for each scenario and used to describe the facility's performance over the course of a year (or other user-defined reliability reporting period). Performance can be described on the basis of a percentile result (e.g., the 80th or 95th percentile travel time) or the probability of achieving a particular level of service (e.g., the facility operates at LOS D during X percent of weekday hours during the year). Many other variability and reliability performance measures can be developed from the facility's travel time distribution.*

The reliability methodology is sensitive to the main sources of variability that lead to travel time unreliability. These sources are identified in the following list.

- *Temporal variability in traffic demand—both regular variations by hour of the day, day of the week, and month or season of the year and random variations between hours and days.*
- *Incidents that block travel lanes or that otherwise affect traffic operations and thus capacity.*
- *Weather events that affect capacity and possibly demand.*
- *Work zones that close or restrict travel lanes, thus affecting capacity.*
- *Special events that produce atypical traffic demands that may require management by special traffic control measures.*

Figure 41 further illustrates the reliability framework described above. The analyst must define their desired study period and study section in advance. Within the resulting "analysis box," a certain proportion of "cells" could potentially benefit from ATM strategies, depending on their traffic operational conditions. In this case, the occurrence of an ATM strategy activation could be considered a special event, and could be modeled accordingly.



Source: Transportation Research Board of the National Academies, 2010

Figure 41. Image. Reliability Analysis Box.

RELIABILITY FRAMEWORK DATASETS

The input data needed to evaluate an HCM urban street for one analysis period can be referred to as a "dataset." However for evaluations involving special events or work zones, the reliability framework requires more than one HCM dataset. The "base" dataset describes base conditions when work zones and special events are not present, and can represent average conditions. As implied earlier, the reliability framework essentially generates hundreds of copies of the base dataset. This allows these hundreds of scenario datasets to have their inputs adjusted to reflect varying demands, weather, incidents, and other time-varying conditions throughout the year.

Although the HCM reliability framework contains procedures for intelligently adjusting traffic volume, saturation flow rate, free-flow speed, capacity, and other inputs to reflect time-varying conditions throughout the year, some time-varying conditions are too complex or unpredictable for the procedure to handle on its own. "Alternative" datasets are needed to describe conditions when a specific work zone is present, or when a special event occurs. For example, if a large sporting event affects 3 percent of cells within the annual analysis, an alternative dataset reflecting those conditions would be applied to generate the results for those cells. This alternative dataset may have lane geometries, signal timings, free-flow speeds, and saturation flow rates that deviate significantly from the base dataset, such that only an engineer familiar with local conditions could accurately specify them.

ACTIVE TRAFFIC MANAGEMENT STRATEGY IMPLICATIONS

The paradigm of alternative datasets within the HCM reliability framework is the way in which ATM strategies can be modeled. For example, an alternative dataset for the dynamic lane grouping (DLG) strategy might have two exclusive right-turn lanes instead of one, two exclusive through lanes instead of three, and signal timings re-optimized to accommodate the new lane use. Similarly, an alternative dataset for reversible center lanes might have an additional exclusive through lane at all intersections in the westbound direction, one fewer exclusive through lane at all intersections in the eastbound direction, and signal timings re-optimized to accommodate the new lane uses. In this manner, as long as the alternative datasets were applied during the proper time periods, the overall reliability model could be accurate and effective. For DLG, the pre-requisite criteria developed in the previous chapter provide possible guidance in selecting time periods in which DLG could be effective. For reversible lanes, a simpler analysis of directional demands (e.g., through the ARTPLAN tool) could reveal optimum time periods for implementation. The potential for modeling adaptive signals in this manner is less clear. Alternate lane groupings and center lane reversals are typically in effect throughout multiple 15-minute time periods before reverting to the original lane geometries, which is consistent with typical HCM modeling. By contrast, adaptive signals produce significant signal timing changes as frequently as every minute, or every two minutes. Furthermore, adaptive signals are known to produce significant inefficiencies during their "transition" periods (Pohlmann & Friedrich, 2014), and the HCM framework might not capture these transition effects. Transition effects also exist for alternate lane groupings and center lane reversals; but because these transitions occur with so much less frequency, their impacts on yearly, daily, and perhaps even hourly overall results, are negligible.

HIGHWAY CAPACITY MANUAL FRAMEWORK CASE STUDIES

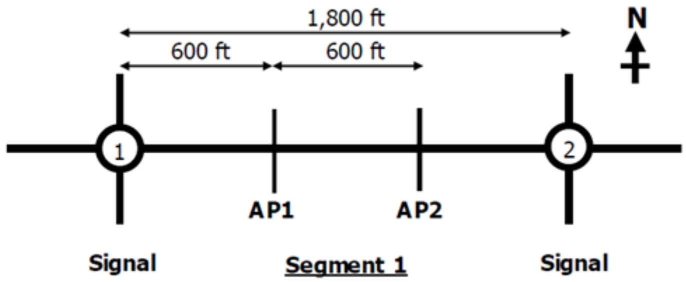
Chapter 3 introduced the available software platforms for HCM urban street reliability analysis: Streetval-Java and HCS-Streets. If special event modeling (via alternate datasets) can be successfully implemented within one or both of these platforms, it would then become possible to assess ATM impacts in terms of annual reliability and other advanced measures. Although efforts are underway to implement special event modeling within these platforms, this functionality is not yet ready for testing. Therefore, the only current way to assess ATM impacts in the reliability framework is by testing two different base datasets: one base dataset with the ATM treatment, and one base dataset without the ATM treatment. Because of this limitation, the reliability analysis box will be limited to the time periods where ATM treatments are effective. Note that this may cause the benefits to appear exaggerated. If it were possible to test these ATM strategies through special event modeling, the annual benefits would be more modest, because many time periods do not require ATM treatments.

In this project, dynamic lane grouping and reversible center lanes were tested within the HCM reliability framework. This testing was performed within the HCS-Streets platform. Results from these two case studies are presented in the following sub-sections. To reiterate, the reliability analysis box will be limited to time periods in which ATM treatments are effective, which may cause the benefits to appear exaggerated.

The purpose of these case studies is to provide a proof-of-concept, which demonstrates how certain ATM strategies can be implemented within the HCM reliability framework. Although some ATM strategies (e.g., adaptive signals) may not fit within the framework without additional research and development, other strategies are modeled more readily through modification of HCM datasets. An ideal case study would clearly demonstrate ATM strategy benefits for typical urban street conditions.

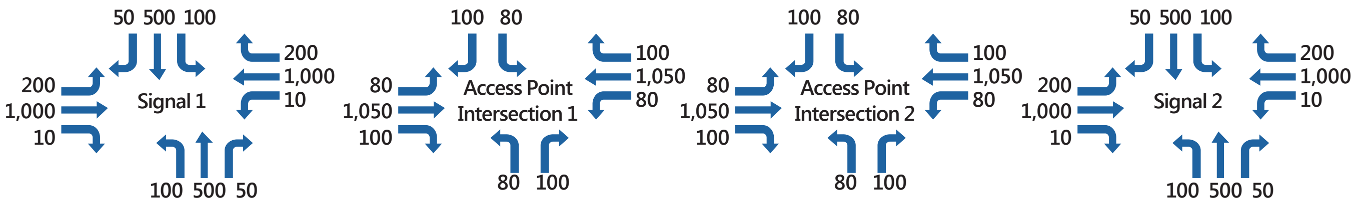
To establish such typical conditions, an example dataset from HCM 6th Edition Chapter 30 (Urban Street Segments: Supplemental) was used as a baseline. This urban street has two exclusive through lanes on the major street, but only one on the minor street. Baseline intersection spacings are illustrated in Figure 42. Baseline volume demands are illustrated in Figure 43. The fundamental characteristics (e.g., traffic volume demands, lane channelizations, signal timings) of this dataset provide a good starting point for analysis of typical conditions, but several important adjustments were still needed. Specifically, there was a need to introduce:

- Typical intersection spacings that would benefit from signal timing coordination.
- Time-varying demands across multiple time periods.
- Oversaturation within the “middle” time periods.
- Directional splits (i.e., significantly heavier volume demands on one of the two major-street directions).
- Turn movement demands that would reflect a need for ATM interventions, while simultaneously falling within the umbrella of typical urban street conditions.
- Signal timings re-optimized to best accommodate all of these changes.



Source: Transportation Research Board of the National Academies, 2010

Figure 42. Diagram. Baseline intersection spacing.



Source: Transportation Research Board of the Research Board of National Academics, 2010

Figure 43. Diagram. Baseline traffic volumes.

CASE STUDY #1: DYNAMIC LANE GROUPING

The case studies for DLG and reversible center lanes will each describe a customization of input conditions, summary of output results, and interpretation of output results.

Intersection Spacings

In the example dataset from HCM Chapter 30 there are two signalized intersections, and two mid-block access points. The distance between the signalized intersections is 1800 feet. At this distance, platoon progression benefits are minimal, and signal coordination benefits are minimal. To create case study conditions more sensitive to platoon progression and signal coordination, the distance between signals was reduced to 500 feet, and the access points were eliminated. It was believed that the 500-foot spacing with no access points would help to reveal DLG impacts more clearly.

Time-Varying Demands

In typical real-world conditions, traffic volume demands continuously fluctuate throughout each hour. The HCM recommends 15-minute time periods for capturing the impacts of these changes. The Manual further recommends that when analyzing oversaturated conditions, both the first and final time periods should be undersaturated, so that residual queuing can be fully addressed within the "middle" time periods. This is why the congested red area is fully contained within the analysis box, as shown in Figure 41 earlier. Since analysis of oversaturated traffic conditions is believed to be a top national priority, the case study dataset was split up into four 15-minute time periods, with degrees of saturation exceeding 100 percent for some turn movements during time period #2. Specific volume demand modifications are listed below:

- Time period #1: turn movement volumes unchanged at both intersections.
- Time period #2: turn movement volumes increased by 20% at both intersections.

- Time period #3: turn movement volumes decreased by 10% at both intersections.
- Time period #4: turn movement volumes decreased by 10% at both intersections.

This creation of time-varying demands causes residual queues to form during time period #2, dissipate during time period #3, and further dissipate during time period #4. Despite time periods #3 and #4 having the same traffic volume demands, delays and queue lengths are actually lighter in time period #4 relative to time period #3, because the congestion from time period #2 has had more time to dissipate. This is believed to be more representative of the typical congested conditions that need to be addressed in developed nations. If DLG and other ATM strategies can effectively mitigate such conditions, then these strategies will be valuable.

Directional Splits

In typical real-world conditions, directional traffic demands are significantly unbalanced during peak time periods. In the AM peak period, the vast majority of commuters travel into or towards some sort of city center, or central business district. In the PM peak, most drivers travel in the opposite direction. It is this commuting demand that places the greatest strain upon transportation networks, and creates a need for ATM strategies.

In the example dataset from HCM Chapter 30, baseline traffic volume demands are illustrated in Figure 43. It can be seen that traffic demands are identical along both major-street (eastbound and westbound) directions. As such, the baseline demands are not representative of top-priority traffic congestion problems that need to be solved, and do not reflect typical peak period conditions. To remedy this, the following directional volume adjustments were made:

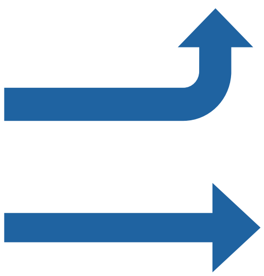
- Eastbound turn movement volumes increased by 10 percent at both intersections during all time periods.
- Westbound turn movement volumes decreased by 10 percent at both intersections during all time periods.

This created a 20 percent directional split (i.e., 60:40) along the major-street direction. Benefits were then analyzed for DLG in the heaviest (i.e., 60 percent) direction of traffic. According to the Chapter 5 findings, benefits increase when there is good progression quality on the DLG approach, prior to DLG treatment. This would not preclude DLG from ever being beneficial in the lightest direction of travel, although in those cases benefits could be less significant

Demands Requiring Active Traffic Management Intervention

Following the adjustments for time-varying demands and directional splits, additional demand adjustments were needed to assess potential ATM benefits. This is because, as shown in Figure 43 earlier, through movement demands greatly exceed their adjacent turn movement demands, as is typical on urban streets. Although this distribution of turn movement demands is typical, a sharp increase in right-turn (or left-turn) demands during certain time periods is not uncommon. This could be caused by a special attractor, such as a post office that drivers must visit on their way home, or a church that receives heavy traffic on weekends. Regardless of the reason for heavy turn movement demands in certain time periods, the DLG treatment is designed to accommodate those sharply changing demands.

Referring to Figure 42 and Figure 43 earlier, eastbound through and left-turn volumes were changed at intersection #2 for this experiment. Specifically, eastbound left-turn volumes were increased by 100 vehicles per hour (veh/hr) in all time periods at intersection #2. At the same time, eastbound through volumes were decreased by 100 vehicles per hour (veh/hr) in all time periods at intersection #2. Figure 44 illustrates these changes. Despite the left-turn demands never exceeding their adjacent through movement demands in any time period, the restrictive nature of left-turn signal phases caused left-turn degrees of saturation to greatly exceed their adjacent through movement demands in every time period, even when signal timings were optimized. These are the pre-requisite conditions for DLG effectiveness, as discussed in the prior chapters.



	Before	After
Time Period #1	55	155
Time Period #2	66	166
Time Period #3	50	150
Time Period #4	50	150
Time Period #1	275	175
Time Period #2	330	230
Time Period #3	250	150
Time Period #4	250	150

(all volumes in units of vehicles per hour)

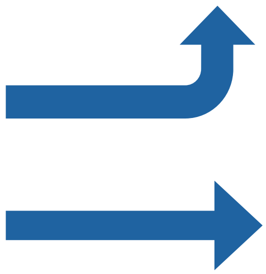
Source: Federal Highway Administration

Figure 44. Diagram. Creation of demands requiring dynamic lane grouping treatment.

Re-Optimized Signal Timings

Following the aforementioned changes involving signal spacings and demand volumes, it was appropriate to re-optimize signal timings (i.e., cycle length, green splits, offsets) for both intersections. Phasing sequence optimization was omitted from this process, but phasing sequence was unlikely to have a significant impact under these conditions. This re-optimization effort was appropriate because in practice, local engineers would often not allow obsolete signal timings to remain in effect after a fundamental change in lane groupings.

In the HCS 2010 platform, signal timings are optimized via genetic algorithm (Hale, Park, Stevanovic, Su, & Ma, 2015) (Park, 1998) (Agbolosu-Amison, Park, & Yun, 2009). In this case study, “Overall Delay” was chosen as the optimization objective function. Figure 45 illustrates the time-period specific degrees of saturation at intersection #2, before and after the eastbound flows were increased (left turns) and decreased (through movements) to warrant DLG treatment. Figure 45 degrees of saturation in the “after” column also reflect the re-optimized signal timings. Without the re-optimization effort, degrees of saturation would have been much higher in the “after” column. Another impact of the re-optimization effort was that the urban street cycle length increased from 117 seconds to 127 seconds, in order to accommodate the increased congestion.

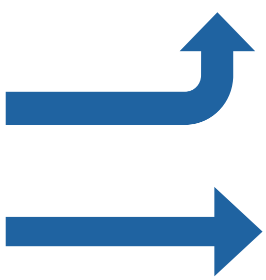


	Before	After
Time Period #1	86%	129%
Time Period #2	86%	159%
Time Period #3	85%	104%
Time Period #4	85%	104%
Time Period #1	76%	47%
Time Period #2	99%	76%
Time Period #3	62%	36%
Time Period #4	62%	36%

Source: Federal Highway Administration

Figure 45. Diagram. Degrees of saturation before and after eastbound volume changes.

Given the sharp contrasts between left-turn and through movement degrees of saturation, conditions were now ripe to perform a before-and-after analysis, in which the "after" analysis would convert the leftmost through lane into a second exclusive left-turn lane. Figure 46 illustrates the time-period specific degrees of saturation at intersection #2, before and after DLG treatment. Figure 46 degrees of saturation in the "after" column also reflect yet another re-optimization of signal timings, in which the background cycle length decreased from 127 seconds to 120 seconds. These results show that through movement operations were being compromised to relieve left-turn movement congestion, in a way that substantially lowers overall intersection delays. The intersection-wide and corridor-wide benefits will be illustrated later.



	Before	After
Time Period #1	129%	89%
Time Period #2	159%	97%
Time Period #3	104%	86%
Time Period #4	104%	87%
Time Period #1	47%	91%
Time Period #2	76%	133%
Time Period #3	36%	70%
Time Period #4	36%	70%

Source: Federal Highway Administration

Figure 46. Diagram. Degrees of saturation before and after dynamic lane grouping.

Reliability Analysis

In order to perform the before-and-after reliability analysis, it was necessary to first define the reliability analysis box within HCS 2010. Spatial limits were already defined within the base dataset. Regarding temporal limits of the analysis, these limits were defined as January 1st 2015 through January 1st 2016. However, only Tuesdays, Wednesdays, and Thursdays would be included in the analysis. This produced a total of 157 analysis days. Given that there were four time periods in the base dataset, this led to the creation of 157*4 = 628 total scenarios. Weather impacts were automatically imported from the Washington DC area. Default hourly, weekly, and monthly demand volume distributions within the software were accepted. It was assumed that the corridor would experience no traffic accidents.

The overall results are illustrated in Figure 47 and Figure 48. These results show that DLG decreased total delay by 39 percent (i.e., from 32.7 to 19.9 vehicle-hours), which accounts for all approaches at both intersections. However the results also show that corridor travel time more than doubled (i.e., from 35 to 75 seconds), reflecting sacrifices made by the through movements. This implies that decisions over whether to implement DLG should depend on local priorities, and to what extent through vehicles should receive preferential treatment over turning vehicles. Finally, reliability measures such as TTI and PTI are also provided by HCS 2010.

This case study showed that DLG could be explicitly analyzed within the HCM reliability framework, and could provide significant operational benefits. The exercise also demonstrates that perhaps not all time periods need to satisfy the pre-requisite criteria suggested in Chapter 5. There it was stated that significant benefits only occur when adjacent through movement degree of saturation is at least 5 percent lower than (N-1)/N (where N is the number of exclusive through lanes), prior to DLG treatment. However DLG was highly beneficial here, despite time period #2 clearly violating this pre-requisite. Finally, when considering the impressive 39 percent delay reduction, it should be remembered that benefits may be exaggerated by a reliability analysis box confined to ATM-friendly time periods, as mentioned earlier in the chapter.

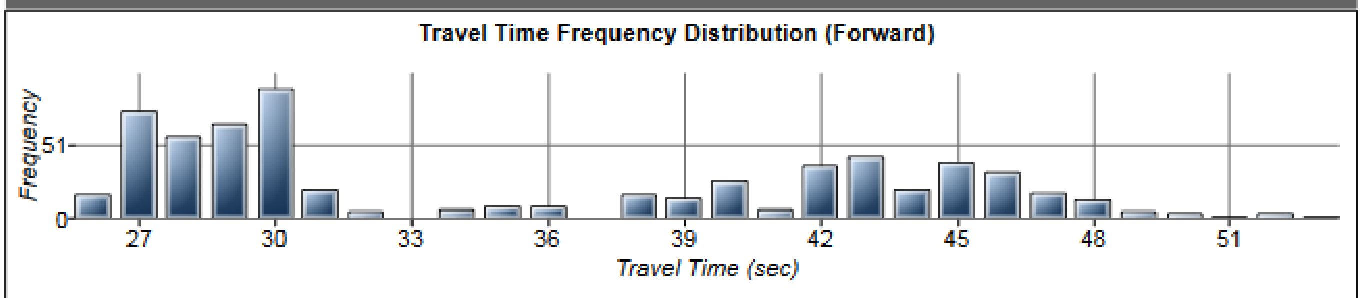
HCS 2010 Urban Streets Reliability Results Summary

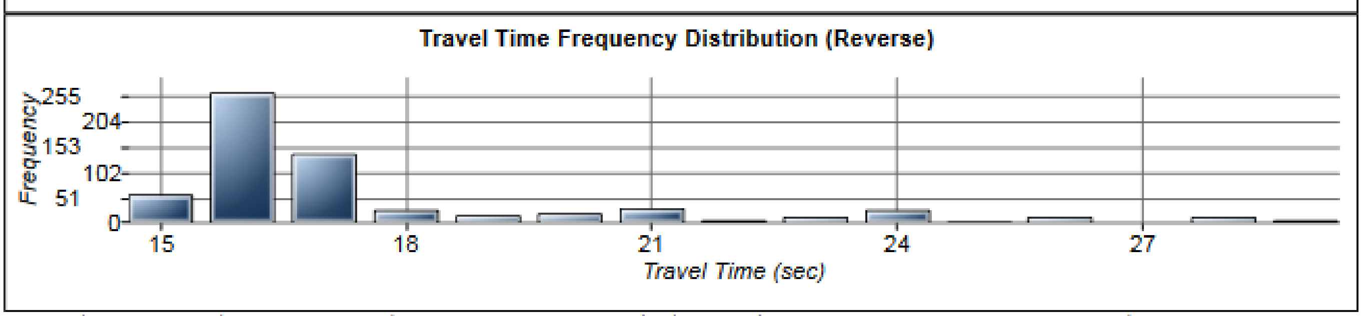
Base Dataset Analysis					
Base Dataset File	DLG Base Case 3.xus	Data Collection Date	9/7/2015 12:00:00 AM	Analyst	
Start Time	07:00	End Time	08:00	Period Duration	01:00
Number of Periods	4	Intersections	2	Segments	1
Comments	HCS Export				

Reliability Input Summary							
Reporting Start Date	1/1/2015	Reporting End Date	1/1/2016	**Random Seed Summary**			
Analysis Days	157	Weather Location	WASHINGTON NAT'L AP, D.C.		Weather	Demand	Incident
Urban Street Class	Urban Principal	Base Demand Ratio	0.076	Include	Y	Y	Y
Shoulder Presence	Yes	Number of Replications	1	Seed	82	11	63

Reliability Performance Measure Results	East Bound	West Bound
Vehicle miles traveled (veh-m)	9147	11607
Number of Scenarios	628	628
Base free-flow travel time (s)	8.957	8.957
Mean TTI	3.967	2.02
80th percentile TTI	4.929	2.214
95th percentile TTI (PTI)	5.291	3.076
Reliability rating (%)	0	84.897
Total delay (veh-h)	32.684	

Replication	Average TT	95th Percentile TT	Average TT	95th Percentile TT
1	35.532	47.395	18.091	27.554
Average	35.532	47.395	18.091	27.554
Standard deviation	0	0	0	0
95th% Confidence Interval	35.532 - 35.532	47.395 - 47.395	18.091 - 18.091	27.554 - 27.554
	±0%	±0%	±0%	±0%





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Source: McTrans Center, University of Florida

Figure 47. Image. Reliability analysis results before dynamic lane grouping.

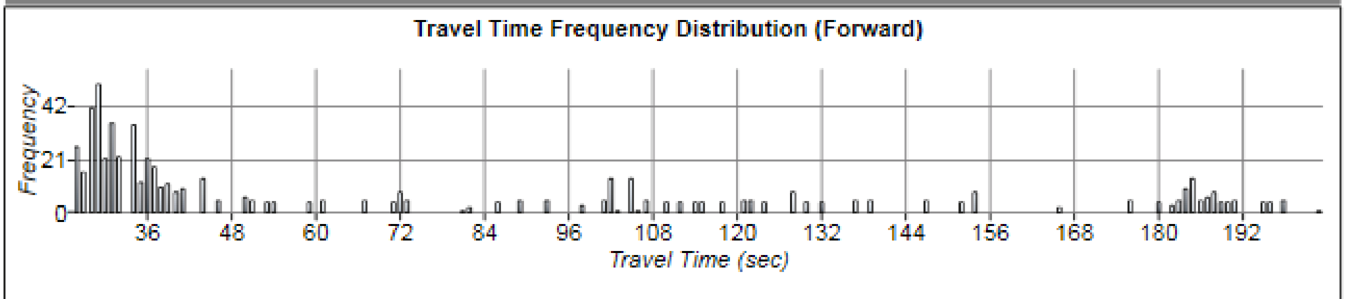
HCS 2010 Urban Streets Reliability Results Summary

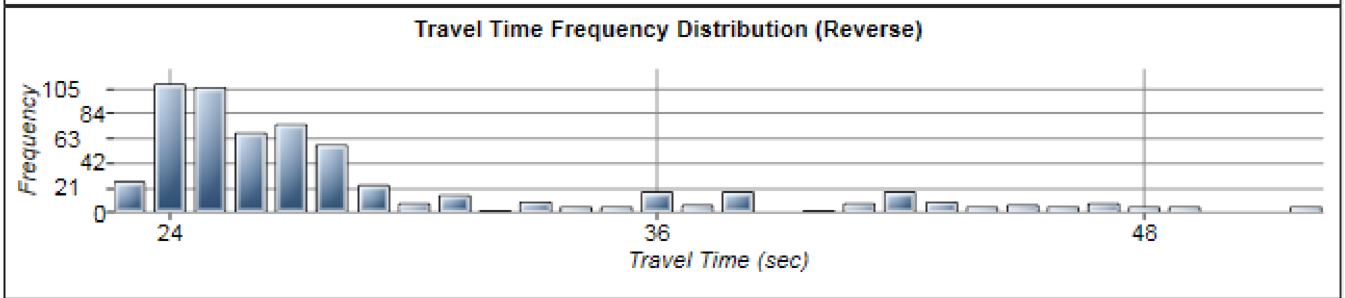
Base Dataset Analysis					
Base Dataset File	DLG Base Case 3a.xus	Data Collection Date	9/7/2015 12:00:00 AM	Analyst	
Start Time	07:00	End Time	08:00	Period Duration	01:00
Number of Periods	4	Intersections	2	Segments	1
Comments	HCS Export				

Reliability Input Summary				**Random Seed Summary**			
Reporting Start Date	1/1/2015	Reporting End Date	1/1/2016		Weather	Demand	Incident
Analysis Days	157	Weather Location	WASHINGTON NAT'L AP, D.C.				
Urban Street Class	Urban Principal	Base Demand Ratio	0.076	Include	Y	Y	Y
Shoulder Presence	Yes	Number of Replications	1	Seed	82	11	63

Reliability Performance Measure Results	East Bound	West Bound
Vehicle miles traveled (veh-m)	9068	11954
Number of Scenarios	628	628
Base free-flow travel time (s)	9.91	8.957
Mean TTI	7.617	3.331
80th percentile TTI	13.017	3.989
95th percentile TTI (PTI)	18.978	5.199
Reliability rating (%)	0	0
Total delay (veh-h)	19.934	

Replication	Average TT	95th Percentile TT	Average TT	95th Percentile TT
1	35.532	47.395	18.091	27.554
1	75.492	188.074	29.834	46.564
Average	75.492	188.074	29.834	46.564
Standard deviation	0	0	0	0
95th% Confidence Interval	75.492 - 75.492	188.074 - 188.074	29.834 - 29.834	46.564 - 46.564
	±0%	±0%	±0%	±0%





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Source: McTrans Center, University of Florida

Figure 48. Image. Reliability analysis results after dynamic lane grouping.

CASE STUDY #2: REVERSIBLE CENTER LANES

Similar to the prior case study for DLG, case study #2 for reversible center lanes (RCL) will describe a customization of input conditions, summary of output results, and interpretation of output results.

Corridor Geometry

For reasons discussed in the prior case study, the distance between signals was reduced to 500 feet, and the access points were eliminated. However to simplify the analysis, left- and right-turn movements were eliminated at all intersections. This was because major-street left turns are often prohibited along RCL corridors, and because minor-street demands could be easily modified without introducing flow-balancing discrepancies along the major street. Left-turn volume demands were added and combined into the through movement demands. Right-turn volume demands were deleted from the analysis.

Time-Varying Demands

For reasons discussed in the prior case study, the RCL case study dataset was split up into four 15-minute time periods, with eastbound degrees of saturation exceeding 100 percent during time period #2. Specific volume demand modifications are listed below:

- Time period #1: volumes decreased by 20 percent at both intersections.
- Time period #2: volumes unchanged at both intersections.
- Time period #3: turn movement volumes decreased by 25 percent at both intersections.
- Time period #4: turn movement volumes decreased by 25 percent at both intersections.

Due to the absorption of left-turn demands into the through movement, significant new congestion was created. As such, volumes were not increased as much during this stage as they were during the parallel DLG stage. As with the prior case study, this creation of time-varying demands caused residual queues to form during time period #2, dissipate during time period #3, and further dissipate during time period #4. Despite time periods #3 and #4 having the same traffic volume demands, delays and queue lengths were again lighter in time period #4 relative to time period #3, because the congestion from time period #2 had more time to dissipate. This is believed to be more representative of typical congested conditions, and any ATM strategy capable of mitigating such conditions would be valuable.

Directional Splits Requiring Active Traffic Management Intervention

Efficient handling of significant directional splits provides the impetus behind the RCL strategy. As discussed in the prior case study, directional traffic demands are typically very unbalanced during peak time periods, due to typical commuting patterns. In the example dataset from HCM Chapter 30, baseline traffic volume demands were illustrated in Figure 43. It can be seen that traffic demands are identical along both major-street (eastbound and westbound) directions. These baseline demands are not representative of top-priority traffic congestion problems, and do not reflect typical peak period conditions. To remedy this, the following directional volume adjustment was made:

- Westbound volumes decreased by 20 percent at both intersections during all time periods.

This created a 20 percent directional split (i.e., 60:40) along the major-street direction. The case study would then attempt to assess RCL benefits for this 60:40 split. Benefits of RCL would potentially be greater for 70:30 and 80:20 directional splits, which are not uncommon. In the "before" scenario, only one exclusive through lane would serve the critical eastbound direction. This reflects a typical scenario in which lane use was designed to accommodate the highest daily demand direction (e.g., PM peak), but then is much less efficient during the second highest demand direction (e.g., AM peak). In the "after" scenario, one exclusive through lane would be donated from the westbound direction to the eastbound direction.

Re-Optimized Signal Timings

Following the above changes, it was appropriate to re-optimize signal timings (i.e., cycle length, green splits, offsets) for both intersections. Phasing sequence optimization was again omitted from the process, and "Overall Delay" was again chosen as the objective function. This re-optimization effort was appropriate because local engineers would typically not allow obsolete signal timings to remain in effect, after a change in lane use. Given the sharp contrast in the number of exclusive through lanes available to each major-street direction, conditions were now ripe to perform a before-and-after analysis in which the "after" analysis would convert one westbound through lane into an eastbound through lane. Figure 49 illustrates the time-period-specific degrees of saturation before and after RCL treatment. Figure 49 degrees of saturation in the "after" column reflect yet another re-optimization of signal timings, in which the background cycle length decreased from 103 seconds to 70 seconds. These results show that westbound operations were being compromised to relieve eastbound congestion, in a way that substantially lowered overall corridor travel times. The corridor-wide benefits will be illustrated later.

		Before	After
→	Time Period #1	90%	51%
	Time Period #2	100%	54%
	Time Period #3	77%	44%
	Time Period #4	77%	44%
←	Time Period #1	38%	78%
	Time Period #2	50%	109%
	Time Period #3	32%	65%
	Time Period #4	32%	65%

Source: Federal Highway Administration

Figure 49. Diagram. Degrees of saturation before and after reversing center lanes.

Reliability Analysis

In order to perform the before-and-after reliability analysis, it was necessary to first define the reliability analysis box within HCS 2010. These reliability parameters were the same as those used during the DLG case study. Spatial limits were defined in the base dataset. Temporal limits were again defined as January 1st 2015 through January 1st 2016. Only Tuesdays, Wednesdays, and Thursdays were included in the analysis. This produced a total of 157 analysis days and 157*4 = 628 total scenarios. Weather impacts were imported from the Washington DC area. Default hourly, weekly, and monthly demand volume distributions within the software were accepted. It was assumed that the corridor would experience no traffic accidents.

The overall results are illustrated in Figure 50 and Figure 51. These results show that RCL decreased total delay by 30 percent (i.e., from 8.1 to 5.6 vehicle-hours), which accounts for all approaches at both intersections. However the results also show that corridor travel time increased slightly, from 18.5 to 20.1 seconds. This is likely due to the "Overall Delay" objective function, which often mitigates side-street delays at the expense of arterial progression. Finally, reliability measures such as TTI and PTI also reflect slightly higher travel times when RCL is in effect. This again probably has more to do with the optimization objective function than with the RCL treatment itself. In fact, when "Travel Time" and/or "Arterial Delay" were tried as the objective functions in subsequent test optimizations, the result both times was a five-minute cycle length, and only five seconds of green time on the minor street, producing overwhelming amounts of delay on the side street. Therefore, the original 30 percent delay reduction achieved by the "Overall Delay" objective function was probably the best attainable result in this software platform, despite the modest increase in major-street travel times.

This case study showed that RCL could be explicitly analyzed within the HCM reliability framework, and could provide significant operational benefits. The exercise also demonstrated the difficulty in reconciling conflicting objectives such as minimizing overall delays, and minimizing major-street travel times. Finally, when considering the 30 percent delay reduction, it should be remembered that benefits may be exaggerated by a reliability analysis box confined to ATM-friendly time periods, as mentioned earlier in the chapter.

CONCLUSIONS

In the early stages of the project, it was believed that the chosen urban street ATM strategies could be effectively modeled via capacity adjustment factors. However, it was discovered that this would be unsuitable for arterials, and that the HCM reliability framework would offer a preferable solution. At that point, the HCM reliability framework quickly became the best and only option for ATM strategy implementation. Two case studies performed in the HCS 2010 reliability engine, for dynamic lane grouping and reversible center lanes, provided a proof-of-concept for ATM strategies implementation within the HCM reliability framework. It is not clear whether adaptive signals or other advanced ATDM strategies could be accurately analyzed in this manner.

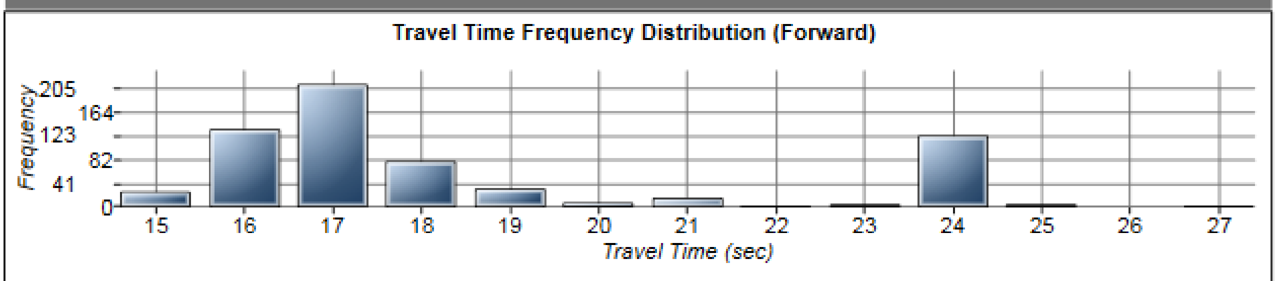
HCS 2010 Urban Streets Reliability Results Summary

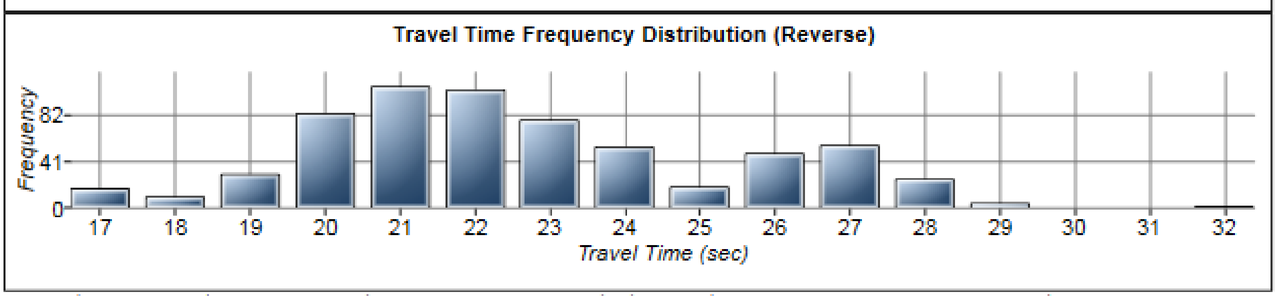
Base Dataset Analysis					
Base Dataset File	REV Base Case.xus	Data Collection Date	9/7/2015 12:00:00 AM	Analyst	
Start Time	07:00	End Time	08:00	Period Duration	01:00
Number of Periods	4	Intersections	2	Segments	1
Comments	HCS Export				

Reliability Input Summary							
Reporting Start Date	1/1/2015	Reporting End Date	1/1/2016	Random Seed Summary			
Analysis Days	157	Weather Location	WASHINGTON NAT'L AP, D.C.		Weather	Demand	Incident
Urban Street Class	Urban Principal	Base Demand Ratio	0.076	Include	Y	Y	Y
Shoulder Presence	Yes	Number of Replications	1	Seed	82	11	63

Reliability Performance Measure Results	East Bound	West Bound
Vehicle miles traveled (veh-m)	13544	11101
Number of Scenarios	628	628
Base free-flow travel time (s)	9.91	8.957
Mean TTI	1.872	2.527
80th percentile TTI	2.379	2.896
95th percentile TTI (PTI)	2.441	3.066
Reliability rating (%)	99.668	45.897
Total delay (veh-h)	8.068	

Replication	Average TT	95th Percentile TT	Average TT	95th Percentile TT
1	18.549	24.19	22.633	27.459
1	18.549	24.19	22.633	27.459
Average	18.549	24.19	22.633	27.459
Standard deviation	0	0	0	0
95th% Confidence Interval	18.549 - 18.549	24.19 - 24.19	22.633 - 22.633	27.459 - 27.459
	±0%	±0%	±0%	±0%





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Source: McTrans Center, University of Florida

Figure 50. Image. Reliability analysis results before reversing center lanes.

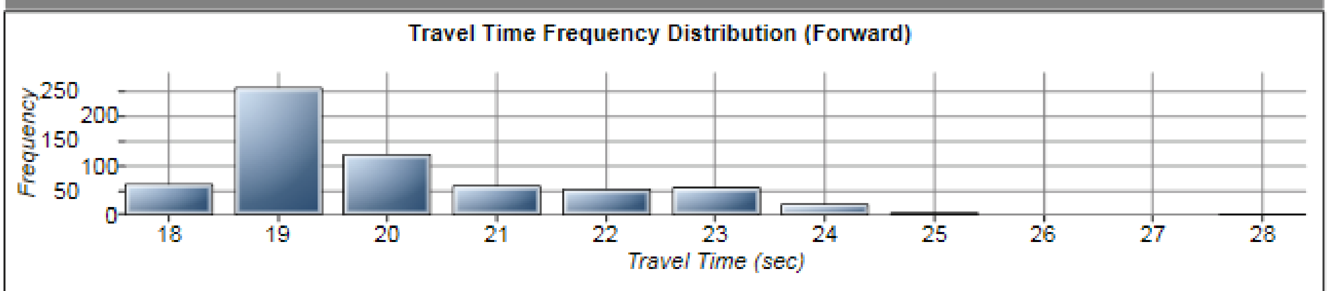
HCS 2010 Urban Streets Reliability Results Summary

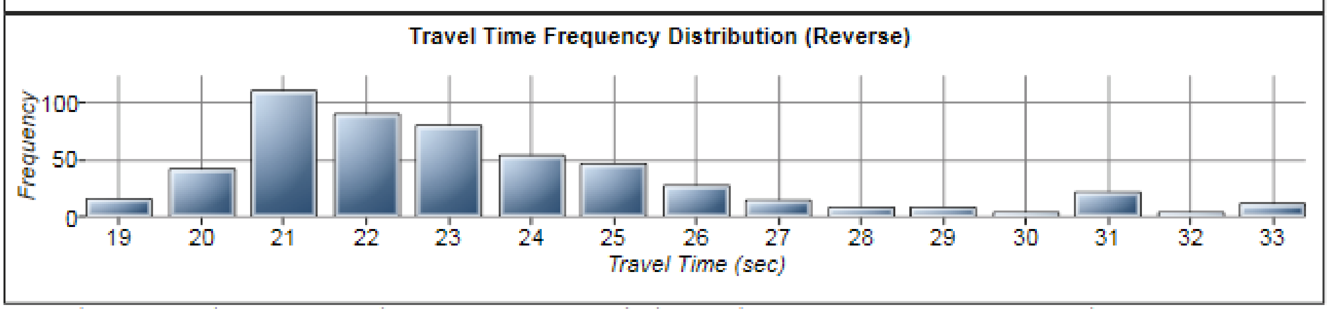
Base Dataset Analysis					
Base Dataset File	REV Base Case a.xus	Data Collection Date	9/7/2015 12:00:00 AM	Analyst	
Start Time	07:00	End Time	08:00	Period Duration	01:00
Number of Periods	4	Intersections	2	Segments	1
Comments	HCS Export				

Reliability Input Summary							
Reporting Start Date	1/1/2015	Reporting End Date	1/1/2016	**Random Seed Summary**			
Analysis Days	157	Weather Location	WASHINGTON NAT'L AP, D.C.		Weather	Demand	Incident
Urban Street Class	Urban Principal	Base Demand Ratio	0.076	Include	Y	Y	Y
Shoulder Presence	Yes	Number of Replications	1	Seed	82	11	63

Reliability Performance Measure Results	East Bound	West Bound
Vehicle miles traveled (veh-m)	13889	10989
Number of Scenarios	628	628
Base free-flow travel time (s)	8.957	9.91
Mean TTI	2.245	2.546
80th percentile TTI	2.427	3.062
95th percentile TTI (PTI)	2.609	3.665
Reliability rating (%)	82.483	59.887
Total delay (veh-h)	5.614	

Replication	Average TT	95th Percentile TT	Average TT	95th Percentile TT
1	20.108	23.365	25.229	36.326
1	20.108	23.365	25.229	36.326
Average	20.108	23.365	25.229	36.326
Standard deviation	0	0	0	0
95th% Confidence Interval	20.108 - 20.108	23.365 - 23.365	25.229 - 25.229	36.326 - 36.326
	±0%	±0%	±0%	±0%





 HCS 2010™ Streets Reliability Version 6.90 Generated: 6/26/2016 5:50:09 PM

Source: McTrans Center, University of Florida

Figure 51. Image. Reliability analysis results after reversing center lanes.

CHAPTER 8. PROJECT CONCLUSIONS AND RECOMMENDATIONS

Building on recent studies and research inside and outside the Highway Capacity and Quality of Service Committee (HCQSC), this project provided new urban street active transportation and demand management (ATDM) methodologies, data sets, and content for the *Highway Capacity Manual* (HCM). This content may subsequently be incorporated within other chapters throughout the HCM. To the extent possible the measures and data used in this work were based upon existing sources, methodologies, and projects. In other words, major new data collection was not performed for this project.

The HCM is one of the most widely-used transportation documents, and the signalized analysis procedures are the most heavily utilized procedures in the Manual. The HCM complements traffic simulation tools; which require more time, expertise, and resources. By continuously developing new guidelines and updated procedures to address new facilities and technologies, the HCQSC hopes to support congestion mitigation in a time of population growth and limited resources. The recent release of HCM-based ATDM analysis procedures is an important element of the U.S. Department of Transportation's technology transfer mandate; in that it enables these new technologies and control strategies to be intelligently analyzed and adopted by more cities, and by the broader professional practice community. The HCM provides an ideal vehicle to disseminate these capabilities at a level of analysis that most engineers and planners are familiar and comfortable with. However new research is needed to develop HCM-compliant macroscopic relationships, targeted at urban street ATDM analysis.

Many urban street ATDM strategies were described in Chapter 1. Based on stakeholder (i.e., peer review group) feedback, the team's knowledge of HCM methods, the review of HCM-based freeway ATDM research, and the review of urban street ATDM strategies, the research scope was narrowed to three specific ATDM strategies: ***adaptive signal control, reversible center lanes,*** and ***dynamic lane grouping***. The research team believes there would be significant national interest in developing the ability to analyze impacts of these strategies in an HCM context, and without requiring micro-simulation. These strategies could be classified as active transportation management (ATM) strategies as opposed to ATDM strategies, because they aim to move traffic more efficiently but without demand management.

It was desired at the outset of the project to develop robust models based on existing field data, while using simulated data to fill in the gaps. However due to the scarcity of field data located during Task 4 – Existing Data Sources, it became clear that any models developed during this project would need to be based on simulated data, with field data used for validity checks at best. Existing data were only found for the same three ATM strategies chosen to be the top priorities of this project. Moreover, only adaptive signal control had a sufficient quantity of existing data studies to support model development. As such, HCM-compatible models for reversible and/or dynamic lanes would be heavily dependent on simulation studies, to be conducted during Task 6 – Original Research. The original simulation studies from this project provided a detailed set of ranges and conditions under which the dynamic lane grouping strategy could be effective. It also provided an extensive set of potential benefits from dynamic lane grouping and adaptive signals.

In the early stages of the project, it was believed that the three chosen ATM strategies could be effectively modeled via capacity adjustment factors, similar to what was accomplished during the freeway ATDM project. However, it was later discovered that the capacity adjustment paradigm would be unsuitable for arterials, and that the HCM reliability framework would offer a preferable solution. Specifically, the alternative lane use configurations could be modeled as special event datasets within the HCM reliability framework, along with re-optimized timing plans for the new lane uses. The inadequacy of the capacity adjustment paradigm was detailed in Chapter 5.

Although capacity adjustment data collected during the dynamic lane grouping (DLG) experiments was not ultimately useful, delay reduction data collected during those same experiments produced the following observations:

1. Significant DLG benefits only occur when turn movement degree of saturation (volume to capacity, or v/c) exceeds 95 percent; and when adjacent through movement degree of saturation is at least 5 percent lower than (N-1)/N, where N is the number of exclusive through lanes prior to DLG treatment.
2. Benefits are much higher when g/C is high on the DLG approach and/or movement prior to DLG treatment (in other words, when DLG movements receive green during most of the cycle prior to DLG treatment).
3. Benefits are increased when turn movement degree of saturation is in the mid 100 percent range, prior to DLG treatment (in other words, when adding a new turn lane allows the turn movement to go from significantly oversaturated to undersaturated).
4. Benefits are increased when cycle lengths can be re-optimized to accommodate the new lane grouping (may not be effective with other congested intersections in the urban street, which may govern the background cycle length).
5. Similar benefits are observed for left turns versus right turns, and for two exclusive through lanes versus three exclusive through lanes.
6. Benefits are increased when there is good progression quality on the DLG approach, prior to DLG treatment.
7. Shared lane DLG produces no significant benefits for right turns unless RTOR is allowed, and produces no significant benefits for left turns.
8. If it were possible to automatically detect v/c and green time to cycle length (g/C) of various turn movements, it might become more effective to implement DLG in real time than by fixed time-of-day.

The adaptive signal simulation experiments produced the following observations:

- Together with the field study results obtained for Task 4, these simulations provided the type of data that could potentially be used to develop analytical models for the HCM.
- Although adaptive control produced consistently positive impacts according to a wide range of performance measures, the magnitudes of these benefits were less consistent.
- Adaptive signal benefits were often more significant under rainy conditions, a finding consistent with prior separate studies.

- Although adaptive control did not improve ***average performance*** under snow conditions, because speeds were generally very low for all vehicles, it did improve ***performance reliability*** under these conditions.
- Potential benefits in comparison to an optimized semi-actuated plan are still unknown.
- The impacts of high-priority input parameters (i.e., Table 3 from Chapter 4) are still unknown.
- Although it would be possible to develop case studies demonstrating the impacts observed during this project, there is still no clear path to developing a generalized adaptive signal model for the HCM, which would accurately handle a wide range of real-world conditions.

The reversible center lane (RCL) experiments produced the following observations:

- RCL benefits are generally maximized when degrees of saturation and directional splits are both maximized.
- The tipping point at which RCL benefits are viewed as significant may depend on a large number of additional factors affecting urban street operations (e.g., signal spacing, progression quality, distribution of major/minor-street demands, corridor reliability).
- HCM reliability analysis could be an effective method of predicting RCL benefits for a wide variety of urban street conditions.

Case studies for dynamic lane grouping and reversible center lanes provided a proof-of-concept for ATM strategy analysis within the HCM reliability framework. It is not clear whether adaptive signals or other advanced ATDM strategies could be accurately analyzed in this manner. DLG case study results also implied that in an oversaturated, multi-period model, not all time periods need to satisfy the pre-requisite criterion suggested in list item #1 on the previous page.

Follow-on studies should perform a more comprehensive set of ATM strategy experiments in the HCM reliability framework. HCM computational engines should have their special event modeling capabilities updated, so that ATM strategies can be modeled in a 24-hour manner when desired. Other ATM strategies based on relatively simple geometric concepts, similar to dynamic lane grouping and reversible center lanes, should be analyzed via the special event dataset method. A more extensive research effort might be needed for bringing adaptive signals into the HCM framework, although the secrecy of adaptive signal algorithms may continue to be an obstacle. Additional research would also be needed for bringing demand management strategies (e.g., congestion pricing) into the HCM framework; although this might require additional progress in the surface-freeway HCM integration effort, or in using HCM methods to model complex grid networks.

APPENDIX. SUMMARY OF URBAN STREET ACTIVE TRANSPORTATION AND DEMAND STRATEGIES

1. Active Demand Management

It consists of the strategies that aim to redistribute drivers. This occurs either by incentivizing them to use a facility during off-peak hours, or by discouraging them from using a facility by charging a fee during peak hours. The following is a list of active demand management (ADM) strategies:

- *Dynamic Ridesharing: e.g., carpooling, vanpooling.*
- *Shared use mobility: e.g., car-share, bike-share.*
- *On-Demand Transit.*
- *Transit connection protection.*
- *Dynamic Pricing.*
- *Predictive Traveler Information.*

2. Active Traffic Management

Active traffic management (ATM) strategies aim to move traffic more efficiently. They manage traffic on a facility using real-time data. ATM strategies include the following:

- ***Dynamic Lane Use Control:*** The dynamic closing or opening of individual traffic lanes as warranted, and providing advance warning of the closure(s) (typically through dynamic lane control signs) to safely merge traffic into adjoining lanes.
- ***Reversible Lanes:*** The reversal (i.e., contraflow treatment) of lanes in order to dynamically allocate the capacity of congested roads, thereby allowing capacity to better match traffic demand throughout the day.
- ***Dynamic Junction Control:*** Dynamic allocation of mainline and ramp lanes access in interchange areas where high traffic volumes are present. To be warranted, significant traffic congestion must be caused by ramp weaving activity.
- ***Dynamic Lane Grouping:*** Dynamic assignment of lane channelization (i.e., allowed turning movements in each lane) at signalized intersections. To be warranted, significant traffic congestion on left-turn or right-turn movements must occur simultaneously with little or no congestion on the adjacent through lanes, during certain times of the day.
- ***Adaptive Traffic Signal Control:*** The continuous monitoring of arterial traffic conditions and intersections queuing, plus dynamic adjustment of signal timings to optimize one or more operational objectives (e.g., minimize overall delays).

- ***Dynamic Merge Control:*** Also known as dynamic late merge or dynamic early merge, this strategy consists of dynamically managing the entry of vehicles into merge areas with a series of advisory messages (e.g., displayed on a dynamic message sign or lane control sign). These advisory messages prepare motorists for an upcoming merge, encouraging or directing a consistent merging behavior.
- ***Dynamic Speed Limits:*** Adjustment of speed limits based on real-time traffic, roadway, and/or weather conditions.
- ***Queue Warning:*** Real-time display of warning messages (typically on dynamic message signs (DMS) and possibly coupled with flashing lights) along a roadway to alert motorists that queues or significant slowdowns are ahead, thus reducing rear-end crashes and improving safety.
- ***Adaptive Ramp Metering:*** Deployment of traffic signal(s) on ramps, to dynamically control the rate at which vehicles enter a freeway facility.
- ***Transit Signal Priority:*** Management of traffic signals by using sensors or probe vehicle technology, to detect when a bus nears a signal-controlled intersection. Returning the traffic signals to green sooner, or extending the green phase, can allow buses to pass through more quickly.

3. Active Parking Management

As the name suggests, active parking management (APM) is designed to manage parking facility demands using the following strategies:

- *Dynamically Priced Parking.*
- *Dynamic Parking Reservation.*
- *Dynamic Way-Finding.*
- *Dynamic Parking Capacity.*

4. Weather Related Strategies

Due to its very dynamic and responsive nature to the current conditions, another dimension is added to ATDM. That's where weather related strategies come in. These strategies include:

- *Snow Emergency Parking Management.*
- *Traffic Signal Preemption for Winter Maintenance Vehicles.*
- *Snowplow Routing.*
- *Anti-Icing and Deicing Operations.*

BIBLIOGRAPHY

Agbolosu-Amison, S., Park, B., & Yun, I. (2009). Comparative evaluation of heuristic optimization methods in urban arterial network optimization. *IEEE ITSC*. St. Louis: IEEE.

Avenue Consultants. (2013). *5400 South Flex Lanes Before/After Evaluation*. Salt Lake City: Utah Department of Transportation.

Dey, S., Ma, J., & Aden, Y. (2011). Reversible Lane Operation for Arterial Roadways: The Washington, DC, USA Experience. *ITE Journal*, 26-35.

Dowling, R., Margiotta, R., Cohen, H., & Skabardonis, A. (2013). *Guide for Highway Capacity and Operations Analysis of Active Transportation and Demand Management Strategies*. Federal Highway Administration Office of Operations.

Federal Highway Administration. (2016, January 20). *Adaptive Signal Control Technology*. Retrieved June 20, 2016, from Every Day Counts: https://www.fhwa.dot.gov/innovation/everydaycounts/edc-1/asct.cfm.

Fehon, K. (2004). Adaptive Traffic Signals: Are we missing the boat? *ITE District 6 Annual Meeting*. Institute of Transportation Engineers.

Florida Department of Transportation. (2013). *2013 Quality/Level of Service Handbook*. Florida Department of Transportation.

Fontaine, M., Ma, J., & Hu, J. (2015). *Evaluation of the Virginia Department of Transportation Adaptive Signal Control Technology Pilot Project*. Richmond: Virginia Department of Transportation.

Hale, D., Park, B., Stevanovic, A., Su, P., & Ma, J. (2015). *Optimality Versus Run Time for Isolated Signalized Intersections. Transportation Research Part C: Emerging Technologies*, 191-202.

Hale, D., Phillips, T., Raboy, K., Ma, J., Su, P., Lu, X., et al. (2016). *Introduction of Cooperative Vehicle-to-Infrastructure Systems to Improve Speed Harmonization*. Washington DC: FHWA.

Hathaway, E., & Urbanik, T. (2012). *Task 8 – Tualatin-Sherwood Road SCATS Evaluation*. Portland: Kittelson & Associates, Inc.

Hathaway, E., Tsoi, S., & Urbanik, T. (2012). *Bend/Redmond SCATS System Evaluation*. Portland: Kittelson & Associates, Inc.

Hathaway, E., Tsoi, S., & Urbanik, T. (2012). *Powell Boulevard SCATS System Evaluation*. Portland: Kittelson & Associates, Inc.

Hathaway, E., Urbanik, T., & Tsoi, S. (2012). *Cornell Road InSync System Evaluation*. Portland: Kittelson & Associates, Inc.

Hellinga, B., & Abdy, Z. (2007). Impact of Day-to-Day Variability of Peak-Hour Volumes on Signalized Intersection Performance. *Transportation Research Board 85th Annual Meeting Compendium of Papers*, (pp. paper 07-0608). Washington DC.

Kim, J., Mahmassani, H., Vovsha, P., Stogios, Y., & Dong, J. (2013). Scenario-Based Approach to Travel Time Reliability Analysis Using Traffic Simulation Models. *Transportation Research Record* 2391, 56-68.

Kuhn, B., Gopalakrishna, D., & Schreffler, E. (2013). *The Active Transportation and Demand Management Program (ATDM): Lessons Learned*. Federal Highway Administration Office of Operations.

Levinson, H., Sullivan, D., & Bryson, R. (2006). Effects of Urban Traffic Volume Variations on Service Levels. *Transportation Research Board 85th Annual Meeting Compendium of Papers*, (pp. paper 06-2381). Washington DC.

Mahmassani, H., Kim, J., Stogios, Y., Currie, K., & Vovsha, P. (2013). *Incorporating Reliability Performance Measures in Operations and Planning Modeling Tools*. SHRP2 Project L04 Final Report.

Mirshahi, M., Obenberger, J., Fuhs, C., Howard, C. K., Kuhn, B., Mayhew, R., et al. (2007). *Active traffic management: The next step in congestion management*. Federal Highway Administration Office of Policy.

Mladenovic, M., Stevanovic, A., Kosonen, I., & Glavic, D. (2015). Adaptive Traffic Control Systems: Guidelines for Development of Functional Requirements. *Mobil.TUM 2015 – International Scientific Conference on Mobility and Transport*. Munich.

Palm Beach County. (2015). *Palm Beach Transportation Management Center Active Arterial Traffic Management Program*. Florida Department of Transportation.

Park, B. B. (1998). *Development of genetic algorithm-based signal optimization program for oversaturated intersections*. College Station: Texas A&M University.

PB Americas, Inc. (2007). *Active Traffic Management (ATM) Feasibility Study*. Seattle: Washington State Department of Transportation.

Pohlmann, T., & Friedrich, B. (2014). Traffic Signal Transition in Coordinated Meshed Networks. *Transportation Research Record: Journal of the Transportation Research Board*, http://dx.doi.org/10.3141/2192-09.

Stevanovic, A. (2010). *NCHRP SYNTHESIS 403: Adaptive Traffic Control Systems Domestic and Foreign State of Practice*. National Cooperative Highway Research Program.

Stevanovic, A., Zlatkovic, M., & Dakic, I. (2015). Comparison of adaptive traffic control benefits for recurring and nonrecurring traffic conditions. *22nd ITS World Congress*. Bordeaux, France.

Su, P., Jiang, X., Jagannathan, R., & Hale, D. (2015). Dynamic Lane Grouping at Signalized Intersections: Selecting the Candidates and Evaluating Performance. *ITE Journal Volume 85 No. 11*, 43-47.

Tarko, A., & Perez-Cartagena, R. (2005). Variability of Peak Hour Factor at Intersections. *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 1920, 125–130.

Transportation Research Board of the National Academies. (2010). *Highway Capacity Manual 2010*. Washington DC.

Transportation Research Board of the National Academies. (2016). *Highway Capacity Manual 6th Edition: A Guide for Multimodal Mobility Analysis*. Washington D.C.

Waller, T., Ng, M., Ferguson, E., Nezamuddin, N., & Sun, D. (2009). *Speed harmonization and peak-period shoulder use to manage urban freeway congestion*.

Zegeer, J., Bonneson, J., Dowling, R., Ryus, P., Vandehey, M., Kittelson, W., et al. (2014). *Incorporating Travel Time Reliability in the Highway Capacity Manual. SHRP 2 Report S2-L08-RW-1*. Washington DC: Transportation Research Board.

Zhang, L., & Wu, G. (2012). Dynamic Lane Grouping at Isolated Intersections: Problem Formulation and Performance Analysis. *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 2311, 152–166.

Zhao, J., Ma, W., Liu, Y., & Yang, X. (2014). Integrated design and operation of urban arterials with reversible lanes. *Transportmetrica B: Transport Dynamics*, 130-150.

Zhao, J., Ma, W., Zhang, H., & Yang, X. (2013). Two-Step Optimization Model for Dynamic Lane Assignment at Isolated Signalized Intersections. *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 2355, 39–48.

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February 2017

FHWA-HOP-16-088