Guidelines on the Use of Auxiliary Through Lanes at Signalized Intersections

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AUTHORS

Nagui Rouphail; Brandon Nevers; Jim Bonneson; Bastian Schroeder; Hermanus Steyn; Yuri Mereszczak; Zach Clark; Joe Hummer; Zach Bugg; Danica Rhodes; Transportation Research Board

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NCHRP REPORT 707

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Brandon Nevers
Hermanus Steyn
Yuri Mereszczak
Zach Clark
KITTELSON & ASSOCIATES, INC.
Reston, VA

IN ASSOCIATION WITH

Nagui Rouphail
Joe Hummer
Bastian Schroeder
Zach Bugg
NORTH CAROLINA STATE UNIVERSITY
INSTITUTE FOR TRANSPORTATION RESEARCH AND EDUCATION
Raleigh, NC

Jim Bonneson
TEXAS TRANSPORTATION INSTITUTE
College Station, TX

Danica Rhodes
WRITE RHETORIC
Boise, ID

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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AUTHOR ACKNOWLEDGMENTS

These guidelines were prepared as part of NCHRP Project 3-98, "Guidelines on the Use of Auxiliary Through Lanes at Signalized Intersections." The research team consisted of Brandon Nevers (principal investigator), Hermanus Steyn, Michael Houston, Yuri Mereszczak, Zach Clark, and Mark Vandehey (Kittelson & Associates, Inc.); Nagui Rouphail (co-principal investigator), Joe Hummer, Bastian Schroeder, and Zach Bugg (North Carolina State University Institute of Transportation Research and Education); Jim Bonneson (Texas Transportation Institute), Danica Rhodes (Write Rhetoric), and data collection staff from Quality Counts.

Several additional individuals contributed to the project. Mike Alston and Brendan Lehan of North Carolina State University provided key contributions to the development of the operations and safety assessments. Séverine Maréchal and Diego Franca of Kittelson & Associates, Inc. assisted with the survey and interim report. Ralph Bentley and Jon Sommerville assisted with exhibits and production of the guidelines. Brian Ray, Lee Rodegerdts, and Paul Ryus of Kittelson & Associates, Inc. provided review and input in the development of the guidelines.

The research team thanks each of the panel members for the valuable input, guidance, and support provided throughout the project. Their contributions significantly enhanced the research products.

The research team also appreciates the input provided by each of the survey respondents. This information provided the basis for the identification and selection of study ATL approaches that are the foundation for the guidelines produced from this project. The research team also thanks Jay Ring at the University of Buffalo for supplying data collected at ATL sites in Buffalo, New York.

FOREWORD

By Nanda Srinivasan
Staff Officer
Transportation Research Board

Lanes for through movements that begin upstream of a signalized intersection and end downstream of the intersection—auxiliary through lanes (ATLs)—are recognized as a moderate-cost approach to increase intersection and overall corridor capacity. *NCHRP Report 707* provides guidelines to use for justification, design, and analysis of ATLs at signalized intersections. The report is aimed to assist transportation professionals in the effective and safe use of intersection auxiliary through lanes.

Auxiliary through lanes (ATLs) at signalized intersections have been used throughout the United States. An ATL is a limited-length through lane added upstream and downstream of an intersection. Prior studies suggest that the length of auxiliary lanes beyond the intersection is a significant factor affecting upstream lane usage and, therefore, the intersection capacity. However, the conditions for their effective use and their affect on operations, safety, and the site location were yet to be documented. This research provides a technical assessment for their use, documents their affect on operations and safety, and provides guidelines including design criteria and placement.

The research was performed by Kittelson & Associates, Inc., in association with the Institute for Transportation Research and Education (ITRE), Texas Transportation Institute (TTI), Write Rhetoric, and Quality Counts. Information was gathered via literature review and interviews with practitioners to inform the framework of the study. Data were collected from 22 ATL approaches across the United States. Statistical models were developed using field data to predict the amount of traffic expected to use the ATL. A safety study was conducted by examining 16 ATL approaches from eight intersections across the United States using a calibrated VISSIM model with FHWA's Surrogate Safety Assessment Model (SSAM).

The guidelines are accompanied by a final report posted on the TRB website as *NCHRP Web-Only Document 178: Assessment of Auxiliary Through Lanes at Signalized Intersections* along with a spreadsheet-based computational engine posted on the project web page (http://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=2492).

CONTENTS

Note: Many of the photographs, figures, and tables in this report have been converted from color to grayscale for printing. The electronic version of the report (posted on the Web at www.trb.org) retains the color versions.

1. INTRODUCTION

An auxiliary through lane (ATL) is a limited length through lane added upstream and downstream of an intersection, as shown in Exhibit 1-1.

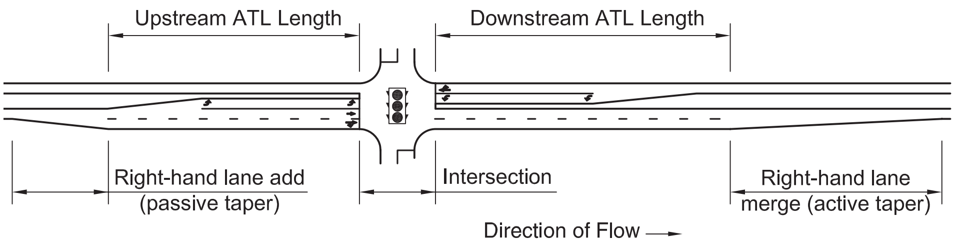


Exhibit 1-1
Typical Auxiliary Through Lane Configuration

ATLs are typically applied as an intermediate-cost treatment to reduce recurring bottlenecks at signalized intersections. They can be applied to either the major-street or minor-street approach. When an ATL is present, through traffic is allowed to disperse across an additional through lane at the signalized intersection, which increases the stop-bar capacity of the approach. This increase capacity reduces delay and queuing for through vehicles. An ATL also reduces the time required for the green light phase to serve the through demand on the approach, meaning the extra time can then be allocated to other movements at the intersection.

ATLs are typically applied at locations where additional through capacity is desired but construction of a continuous through lane (CTL) is not feasible. ATLs can also be applied as an interim improvement until a CTL improvement is made or can be justified. In summary, an ATL achieves a portion of the capacity benefits of a CTL for a portion of its cost and right-of-way/environmental impact.

Field data and observations were collected at 22 ATL approaches across the United States to analyze ATL performance and the relationship between the traffic operations, safety, and design characteristics of ATLs. Results from this data collection effort indicate that during the peak period an average of 24 percent of through traffic used the ATL on approaches with one continuous through lane. Despite the relatively low utilization, ATLs provide significant benefits in terms of reduced vehicle delay. Analysis of the field data shows that the presence of the ATL reduced delay by an average of 100 seconds per vehicle compared to the case with no ATL in place during the observational periods (assuming all other factors remain equal). This delay reduction is because many of those approaches would have operated in an oversaturated state without the ATL in place. Similar conclusions were reached for ATLs with two CTLs. Thus, while ATLs do not achieve the full operational benefit of a CTL, their operational benefits are nonetheless substantial.

ATLs are most effective under congested conditions when the demand-to-capacity ratio for the through movement approaches 1.0 without the ATL in place. If congestion levels are too low there is limited incentive for drivers to use the ATL. As congestion increases, the risk that a driver will not clear the intersection within the current cycle increases, along with the delay savings achieved by using the ATL, making it more likely that a driver will choose to use the ATL. This research found a strong correlation between congestion level and use of the ATL.

This document presents guidelines that are a culmination of information gathered via a literature review, a survey of transportation practitioners, and an analysis of field data regarding ATLs, along with the research team's experience in the operation and design of signalized intersections. These guidelines are intended to be applied by transportation practitioners as a decision support tool and are intended to supplement national guidance documents and local agency policies and practices on intersection design.

SCOPE OF THE GUIDELINES

These guidelines apply to auxiliary lanes for through movements that begin upstream of a signalized intersection and end downstream of the intersection. It focuses on ATLs that begin with a right-hand add lane upstream of the signal and end with a right-hand merge downstream of the signal.

The operational models presented in these guidelines assume that both the continuous and auxiliary through lanes are free from impedances from left-turn movements and downstream activity.

These guidelines provide practitioners with the tools and guidance needed to answer the following questions:

- What factors affect the use of ATLs?
- How much traffic is likely to use an ATL?
- What is the safety performance of ATLs?
- What tools are available to evaluate operational and safety performance of ATLs?
- What minimum length is needed for the upstream and downstream components of the ATL?
- What signs and pavement markings should be applied on ATLs?
- How can simulation be used to supplement a deterministic analysis of ATLs?

LIMITATIONS OF THE GUIDELINES

The ATL guidelines do not address the following conditions:

- Non-signalized intersections
- Intersections that serve as transitions from either four-lane to two-lane roadways or six-lane to four-lane roadways
- Left- or right-turn lanes with an upstream addition and downstream drop
- Approaches that have more than two CTLs
- Approaches that include shared left–through lanes or downstream facilities where queues extend into the ATL

- Approaches that experience blockage due to downstream conditions
- Approaches that operate within a well-coordinated signal system such that the majority of vehicles arrive during the green phase of the traffic signal

In addition, the guidelines do not provide statistical or analytical models to predict the number of crashes or conflicts on an ATL. Rather, a summary of crash data obtained for ATL approaches is provided.

Lastly, these guidelines do not provide guidance for applying ATLs relative to other capacity-enhancing intersection treatments.

ORGANIZATION OF GUIDELINES

These guidelines are organized to follow a typical analysis and design process for ATLs as shown in Exhibit 1-2. Also included is the corresponding chapter that documents the information and procedures needed to carry out the appropriate step in the process.

The title and content for all chapters and appendices are described below:

- **Chapter 2: ATL Characteristics.** Describes the operational, safety, and design characteristics of ATLs, as well as needs and considerations for potential ATL user types.
- **Chapter 3: Operational Analysis.** Presents a statistical model for predicting the amount of traffic that will use an ATL for approaches with one or two CTLs.
- **Chapter 4: Safety.** Documents the results from an evaluation of field crash data and discusses geometric and operational factors expected to impact the safety performance of an ATL.
- **Chapter 5: Geometric and Traffic Design**. Describes an approach for preparing a functional design plan for an ATL, provides a method for determining the minimum upstream and downstream ATL length, and presents guidance on signing and pavement markings for ATLs.
- **Chapter 6: Sample Application.** Demonstrates how to apply the operations, safety and design tools, methods, and guidelines to a practical example.
- **Appendix A.** Describes how analysts can use traffic simulation models to estimate the operational performance and, to a limited extent, the safety performance of ATL designs.
- **Appendix B.** Describes the computational engine that carries out the deterministic operational analysis procedure described in Chapter 3.
- **Appendix C.** Describes the method and equations for calculating the minimum required upstream and downstream ATL lengths.

Exhibit 1-2
Guidelines Organization

Assess Multimodal Needs

- Identify facility needs for pedestrians, bicyclists, and transit riders (Chapter 2)

Evaluate Traffic Operations

- HCM analysis using statistical model to predict ATL use (Chapter 3 & Appendix B)
- Microsimulation (Appendix A)

Assess Safety Effects

- Qualitative evaluation (Chapter 4)
- Conflict prediction (Appendix A)

Calculate Design Elements

- Upstream Passive Taper
- Upstream ATL Length
- Downstream ATL Length
- Downstream Active Taper

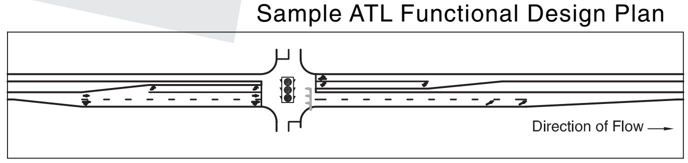
(Chapter 5)

Lay Out Individual Segments

- Approaching ATL
- Approaching Signal
- Departing Intersection
- Merge at End of ATL

(Chapter 5)

Sample ATL Functional Design Plan



NOTES

- No additional data required beyond traditional intersection analysis
- Applicable to approaches with one or two continuous through lanes and an exclusive or shared right-turn lane

RECOMMENDED RESOURCE DOCUMENTS

There are many other resources regarding the operations, design, and safety of intersection treatments that contain information relevant to the analysis and design of ATLs. The following resource documents should be used in the analysis and design of ATLs along with these guidelines, and in addition to relevant local agency resources:

- *A Policy on Geometric Design of Highways and Streets* (AASHTO Green Book) (*1*);
- *Highway Capacity Manual 2010* (HCM) (*2*);
- *Manual on Uniform Traffic Control Devices* (MUTCD) (*3*); and
- *Highway Safety Manual* (HSM) (*4*).

2. ATL CHARACTERISTICS

In many ways, ATLs at signalized intersections are similar to CTLs. Both have the same physical footprint at the intersection and both carry through traffic. As a result, many aspects of the analysis and design process are the same for an ATL and a CTL.

However, there are some unique characteristics of ATLs that require special attention. These relate to the lane-change maneuver required to enter the ATL upstream of the signalized intersection and merge back into the CTL downstream of the intersection. These lane-change maneuvers influence traffic operations and safety performance as well as design elements such as lane length, signing, and pavement markings.

The purpose of this chapter is to (1) identify and define key terms used to describe ATLs, and (2) draw attention to characteristics and user needs that are unique for ATLs compared to CTLs.

These guidelines do not attempt to duplicate fundamental guidance related to the traffic operations, safety, and design characteristics of through lanes at signalized intersections as described in the resource documents identified in Chapter 1. Rather, these guidelines focus on practices and procedures that are unique to the analysis and design of ATLs.

TERMINOLOGY

The following list includes key terms and definitions used throughout these guidelines to describe ATLs.

Auxiliary Through Lane (ATL): A limited-length through lane added upstream and downstream of an intersection.

Shared ATL: An ATL that accommodates right-turning movements in addition to through movements.

Exclusive ATL: An ATL that does not include turn movements.

Continuous Through Lane (CTL): An approach through lane that is adjacent to the ATL and continuous at least one-half mile upstream and downstream of the intersection.

Upstream ATL Length: The available queue storage on the approach measured between the end of taper and the stop bar at the intersection. The upstream ATL length should be sufficient to ensure the ATL is accessible throughout the cycle.

Downstream ATL Length: The downstream length of the ATL measured from the stop bar for the opposing direction and the beginning of taper. The downstream length of the ATL should be sufficient to ensure that vehicles in the ATL are able to merge adequately at the desired prevailing speed.

Prevailing Speed: The majority of drivers feel comfortable traveling at this speed on a given road section, regardless of the posted speed.

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Passive Taper: The ATL taper upstream of the intersection that allows vehicles to enter the ATL.

Active Taper: The ATL taper downstream of the intersection that requires vehicles to merge.

X_T: The demand-to-capacity ratio for the through movement assuming the ATL is not in place.

APPLICATION

Similar to CTLs, ATLs are implemented to increase the stop-bar capacity on approaches at signalized intersections that represent a "choke point" along an arterial street. They can be applied in urban, suburban, or rural environments on either the major-street or minor-street approach.

ATLs are often applied in lieu of a CTL when:

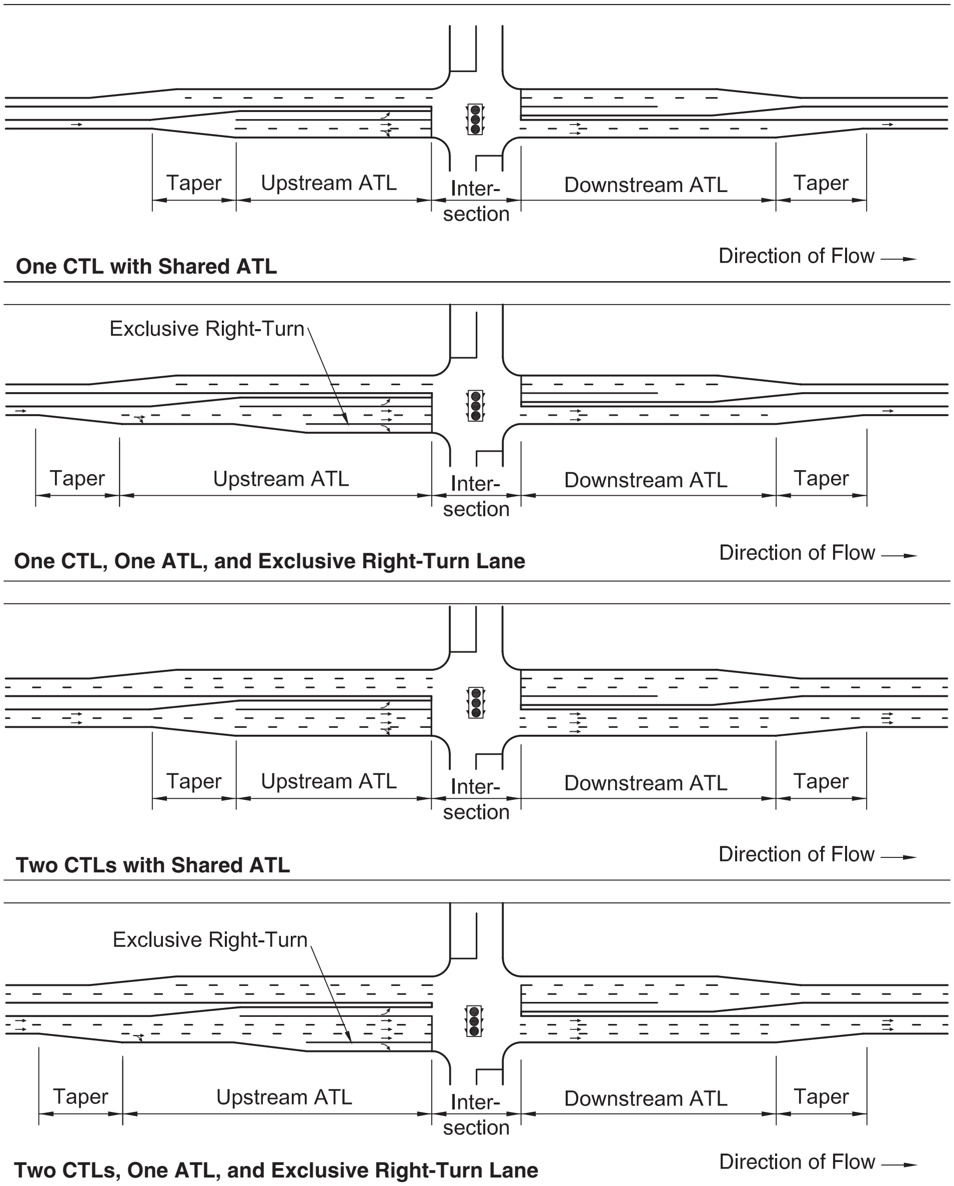
- Construction of a CTL is not feasible;
- The capacity added by the ATL adequately accommodates current or projected traffic demand through the intersection bottleneck; and
- Sufficient length is available to accommodate upstream storage and downstream merge activity.

CONFIGURATION TYPES

These guidelines address four types of ATL configurations as shown in Exhibit 2-1:

- One CTL with a shared ATL
- One CTL, one ATL, and an exclusive right-turn lane
- Two CTLs with a shared ATL
- Two CTLs, one ATL, and an exclusive right-turn lane

Exhibit 2-1
ATL Configuration Types



Each of the configurations shown in Exhibit 2-1 consists of a right-hand lane addition upstream of the intersection and a right-hand merge downstream of the intersection. Results from a web survey conducted as part of this research effort found that 85 percent of ATL applications had both a right-hand lane addition upstream and right-hand merge downstream. The remaining sites included right-turn drop lanes downstream that generally ended at a commercial driveway entrance or left-hand merges. The guidelines presented in this document do not address ATLs with right-turn drop lanes and left-hand merges given the relatively few known applications of that configuration.

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TRAFFIC OPERATIONS

The operational characteristics of an ATL are similar to that of a CTL, as described in the signalized intersection chapters of the HCM 2010 (*2*), with one critically important exception: *lane utilization*. The HCM 2010 does not currently account for the lane utilization impacts associated with limited-length lanes.

An adjustment to the HCM procedures is needed to more accurately reflect the amount of traffic that is anticipated to use the ATL. These guidelines present two approaches for estimating the amount of traffic that will use an ATL:

- **Statistical model.** Directly estimates the amount of through traffic that will use the ATL using a deterministic approach. This model is used in conjunction with the HCM 2010 signalized intersection procedure (Chapter 3).
- **Microsimulation.** Through the modification of lane choice parameters to more accurately reflect actual lane usage, microsimulation software can be applied to predict the performance of an ATL (Appendix A).

SAFETY

Adding an ATL *may* decrease an intersection's safety due to the potential for additional sideswipe crashes compared to an intersection without an ATL. However, because an ATL will reduce congestion it may result in fewer rear-end and other congestion-related crashes. It is not clear whether the trade-off between increases in some crash types and decreases in others will generally result in net positive or negative changes in crash frequency. It is clearer, though, that the types of crashes that may increase with an ATL would be less severe than typical crashes at major signalized intersections, on average. Overall, the expectation of a net positive safety impact from an ATL is not unreasonable. The analysis of crash data certainly did not highlight any unusual safety concerns at the ATL sites investigated.

GEOMETRIC AND TRAFFIC DESIGN

Many fundamental geometric and traffic design principles of CTLs apply to ATLs:

- The geometric design of the ATL should meet drivers' expectations;
- Signing and pavement markings should be applied to reinforce the messages conveyed by the geometric design of the ATL;
- Adequate sight distance should be provided to adequately accommodate advance decision making and emergency stops; and
- Driveways and other impedances should be located outside of the intersection influence area (which for ATLs includes the entire effective ATL length including upstream and downstream tapers).

The unique geometric and traffic design elements of ATLs relate to the determination of their length and the use of signs and pavement markings. The upstream ATL length should be sufficiently long to accommodate the maximum back of queue on the approach (could be in the CTL or ATL) to ensure that the ATL remains accessible throughout the cycle.

The downstream ATL length should enable vehicles from a stopped position to reach the desired prevailing speed before reaching the beginning of taper. It should also ensure that adequate gaps exist in the adjacent CTL, particularly at high speeds, to enable safe merge maneuvers before vehicles reach the beginning of taper.

Supplemental signs should be applied in advance of the intersection and on mast arms or span wires to indicate that the ATL is intended for use as a through lane and not inadvertently assumed to be a right-turn-only lane.

Pavement marking arrows should be considered for application in advance of the downstream merge to provide additional notification to the driver.

USER CONSIDERATIONS

This section presents considerations for the four primary modes (pedestrians, bicyclists, transit, and auto) and highlights their unique considerations related to the analysis and design of ATLs.

Pedestrians

Similar to when a CTL is added, when an ATL is added, the distance pedestrians must travel to cross one or more intersection legs is increased. This increased distance produces the following effects:

- **Increased pedestrian exposure to traffic.** By increasing crossing distance, ATLs may place pedestrians at higher risk. According to the AASHTO *Highway Safety Manual*, the greater number of lanes at a signalized intersection, the higher is the likelihood of a vehicle–pedestrian crash (*4*).
- **Reduced pedestrian level of service on side-street approaches.** ATLs increase the total crossing distance for pedestrians, resulting in reduced pedestrian comfort and a lower level of service (LOS) for crossing pedestrians, per the Signalized Intersections LOS methodology for pedestrians included in the HCM 2010 (*2*).
- **Increased minimum pedestrian crossing time.** Assuming a typical 12-foot lane and a walk time of 3.5 feet per second, the addition of an ATL will increase the minimum walk time by approximately 3.5 seconds. When pedestrian walk times govern the minimum time a green light is provided to a side-street approach, this effect will increase the proportion of green time provided to the side street approach and reduce the proportion of green time allocated to the main-street approach. To the extent that the increased minimum green contributes to overall pedestrian delay, this will negatively impact pedestrian LOS.

Bicyclists

Unless a bicycle lane is provided, cyclists should be assumed to use the ATL rather than other through lanes. Many bicyclists may feel uncomfortable in an ATL's merge section due to the "struggle" for available space. If a bicycle lane is available, its location relative to the general traffic lanes may create additional conflict points within a signalized intersection that contains ATLs.

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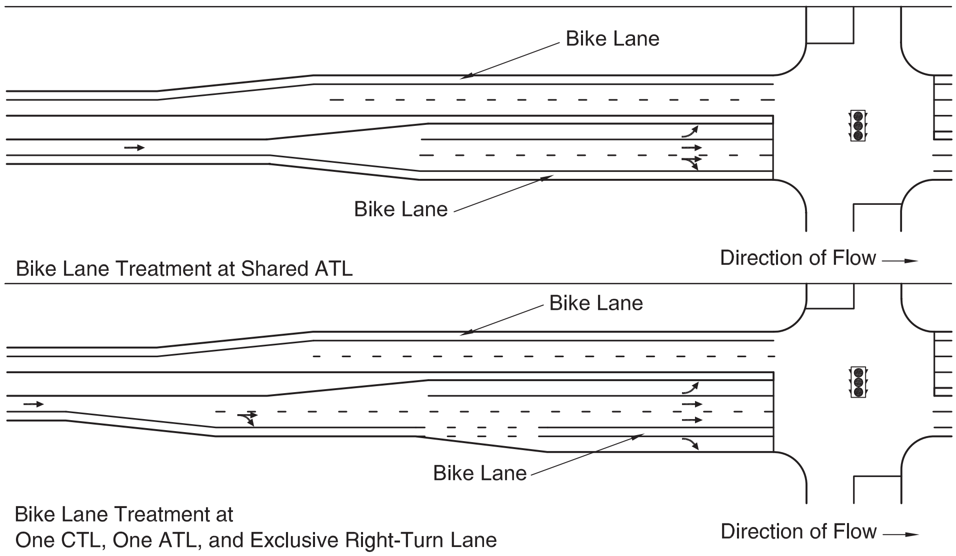
For bicyclists on side-street approaches, ATLs increase total crossing distance. This increase will negatively affect bicycle LOS for side-street approaches, according to the Signalized Intersection LOS methodology included in the HCM 2010 (2). Exhibit 2-2 shows potential bicycle treatments with and without exclusive right-turn lanes at signalized intersections.

Exhibit 2-2
Bicycle Treatment Examples



Transit

Bus stops could be located within an ATL on either the near side or the far side of the intersection, depending on transit agency policy, local land uses, and signal timing. Depending on the roadway classification and/or traffic volume, bus stops are sometimes also located within the near-side right-turn lane or in a bus pullout bay on the far side of the intersection. Exhibit 2-3 illustrates potential bus stop locations based on the final configuration of an intersection.

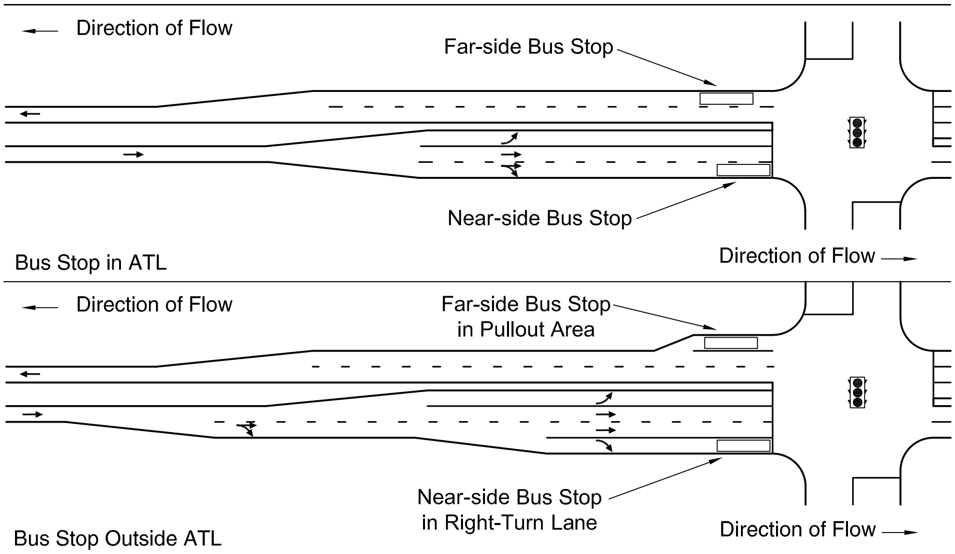


Exhibit 2-3
Potential Bus Stop Locations

Merging with general traffic can often be difficult for bus operators. In some jurisdictions, it is the law to yield to buses. The *Transit Capacity and Quality of Service Manual* (TCQSM) provides a method for estimating delay as a result of buses merging into traffic (*5*).

Depending on the guidelines and preferences of the transit agency, and the agency owning the roadway, a right-turn lane may be used as a bus pullout, or a bus pullout could be provided beyond the intersection.

Far-side stops often allow buses to take better advantage of the signal progression provided along the roadway, but other considerations such as facilitating transfers to bus routes on cross streets and proximity to transit passenger generators may dictate the use of a near-side stop. If no pullout area is provided, then buses would stop in the outside lane (e.g., the ATL). Motorists typically avoid the outside/auxiliary lane when buses are present, so a high frequency of buses along the street would tend to discourage ATL use.

Other observations from the research indicate:

- For relatively short cycle lengths, near-side bus stops had a limited impact on the intersection operations.
- Far-side stops within the downstream ATL caused motorist upstream to reposition themselves.
- Where buses stopped in right-turn lanes (upstream) or bus pullout areas (downstream), they were able to find acceptable gaps to merge back into the traffic stream.

Auto

Motorists typically seek to minimize delay while traveling through intersections, which means they are likely to consider using the ATL when there is risk of not clearing the intersection in the green phase from the CTL and/or when they can wait in a shorter queue.

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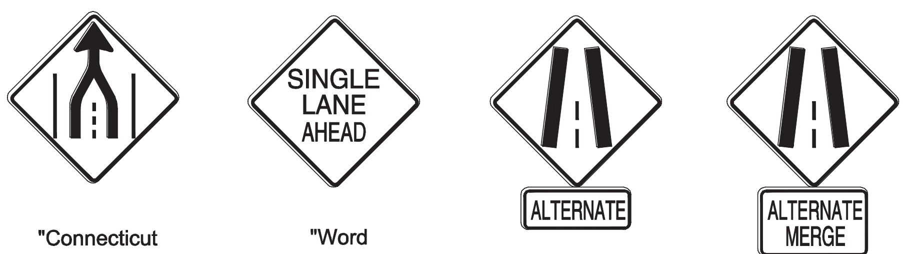
Certain messages need to be conveyed throughout the ATL to make motorists aware of the ATL and to encourage its use:

- Prior to the intersection, the driver needs to be made aware of the ATL lane being added.
- At the intersection, the driver needs to know that the ATL serves through traffic and not just turning movements.
- After departing the intersection, the driver needs to be made aware of the impending mandatory merge condition.

A noted concern from many motorists and highway agency staff members is the use, or misuse, of ATLs by aggressive drivers. Aggressive drivers may choose to use the less-utilized ATL to by-pass vehicles in the CTL. Certain agencies, such as the Maryland State Highway Administration and Connecticut Department of Transportation (*6*), have experimented with signs indicating an alternating merge area to both encourage use of the ATL by removing the priority of the CTL over the ATL and to encourage courteous behavior. Exhibit 2-4 illustrates some lane-merging signs.

Exhibit 2-4
Alternate Merge Sign Examples



"Connecticut Experimental" Warning Sign

"Word Message" Warning Sign

"Maryland Symbol & Rider" Warning Signs

3. OPERATIONAL ANALYSIS

This chapter presents the operational guidelines for evaluating ATLs at signalized intersections. It is founded on a method to predict the volume of traffic that will use an ATL. In addition to evaluating ATL and intersection performance, the results from the operational analysis are needed to determine the recommended minimum design lengths for the upstream and downstream ATL described in Chapter 5.

This method supplements the Highway Capacity Manual 2010 (2) procedures. The HCM 2010 does not directly account for the effects of short lane additions (including ATLs) in its lane utilization factor f_{LU}. Instead, it directs users to apply a simulation tool to predict the through-movement volume in the short lane. While some ATL characteristics can be modeled through micro-simulation, the models presented here are based primarily on empirical observations taken at a number of existing signalized ATL approaches across the United States. A detailed discussion of how microsimulation may be used to evaluate ATL performance is provided in Appendix A. Appendix B describes the computational engine that incorporates the ATL lane use prediction model presented in this chapter.

Given its unique operating characteristics and lower utilization, an ATL should always be treated as a separate lane group, regardless of whether the lane is shared with right turns or is exclusive. Thus, an approach that consists of a separate left-turn lane, one CTL, one ATL, and one exclusive right-turn lane would have four lane groups as shown in Exhibit 3-1.

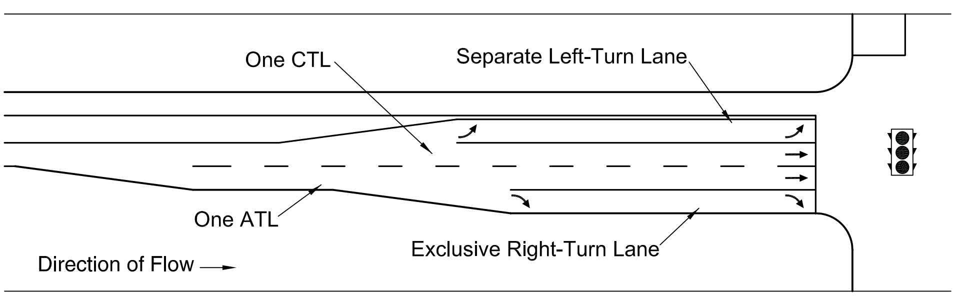


Exhibit 3-1
Exclusive ATL Lane Group Diagram

While the HCM 2010 treats a shared through-right lane as a separate lane group (which is different from how the HCM 2000 lane groups were designated), it still combines all exclusive through lanes into a single lane group. This process is not appropriate in the presence of an ATL because the lane utilization of the ATL is much lower than that of a traditional CTL.

This chapter presents the following information:

- Principles of ATL operations
- Data collection required for analysis
- Analysis techniques for ATL operations

Guidelines on the Use of Auxiliary Through Lanes at Signalized Intersections

OPERATIONAL PRINCIPLES

Results from extensive field observations and data analyses have demonstrated that ATL lane usage is governed by two primary factors: (1) the through movement's degree-of-saturation on the subject approach, and (2) the prevailing approach geometry.

The supporting data and evidence is presented in the following section.

Summary of Field Data

A total of 22 ATL approaches across the United States were selected for field investigation and data collection based on the results of a web-based survey of transportation practitioners. All study approaches add ATLs to the right of the CTL and have a right-hand merge downstream. The sites have limited obstructions to ATL use (e.g., driveways, transit stops, work zones, etc.) and represent a range of geographic locations, geometric conditions, and levels of congestion. Exhibit 3-2 displays a diagram of a typical ATL.

Exhibit 3-2
ATL Diagram

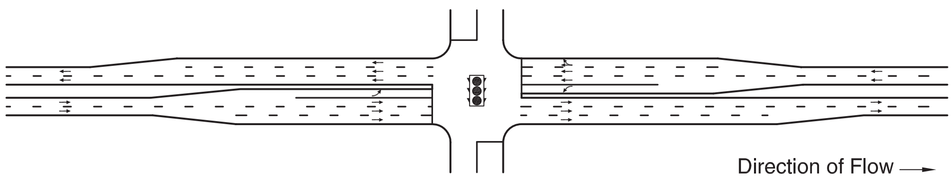


Exhibit 3-3 and Exhibit 3-4 list the 14 one-CTL and 8 two-CTL approaches observed in this study. The two exhibits display location information, ATL length components, whether the ATL is exclusive or shared, and the level of ATL utilization by through traffic. ATL utilization in this context is defined as the percentage of approach through traffic, calculated by dividing ATL through volume by the total through volume on the approach.

As shown in Exhibits 3-3 and 3-4, nearly all ATLs are underutilized compared to the lane utilization factors in the HCM 2010. According to the HCM 2010, the theoretical utilization should be 47.5 percent for an ATL with one CTL and 31.7 percent for an ATL with two CTLs (2). This information confirms the earlier statement regarding the need to consider the ATL as a separate lane group.

Exhibit 3-3
Summary of Study Approach Characteristics for 1-CTL Sites

Approach	Location	Type	Upstream ATL Length (feet)	Down stream-ATL Length (feet)	Min. ATL Utilization % Through	Average ATL Utilization % Through	Max. ATL Utilization % Through
EB Walker at Murray	Beaverton, OR	Shared	570	150	21	28	35
WB Walker at Murray	Beaverton, OR	Shared	220	350	23	29	32
EB NC 54 at Fayetteville	Durham, NC	Exclusive	1650	450	19	23	27
NB La Canada at Magee	Tucson, AZ	Shared	780	430	15	19	25
SB La Canada at Magee	Tucson, AZ	Shared	580	720	11	18	27
EB Magee at La Canada	Tucson, AZ	Shared	620	390	14	19	25
WB Magee at La Canada	Tucson, AZ	Shared	700	500	9	14	19
NB La Canada at Orange Grove	Tucson, AZ	Shared	640	590	11	19	25
SB La Canada at Orange Grove	Tucson, AZ	Shared	730	560	18	19	24
EB Walker at 185th	Beaverton, OR	Exclusive	410	220	34	40	44
WB Walker at 185th	Beaverton, OR	Shared	350	310	13	15	17
SB Sunset Lake at Holly Springs	Holly Springs, NC	Shared	420	950	3	9	13
NB Garrett at Old Chapel Hill	Durham, NC	Exclusive	320	300	13	19	24
SB Garrett at Old Chapel Hill	Durham, NC	Exclusive	330	380	15	23	27

EB = Eastbound, WB = Westbound, NB = Northbound, SB = Southbound

Exhibit 3-4
Summary of Study Approach Characteristics for 2-CTL Sites

Approach	Location	Right-Turn Type	Upstream ATL Length (feet)	Down-stream Length (feet)	Min. ATL Utilization % Through	Average ATL Utilization % Through	Max. ATL Utilization % Through
NB MD 2 at Arnold	Annapolis, MD	Exclusive	800	300	15	19	22
SB MD 2 at Arnold	Annapolis, MD	Exclusive	1670	1060	13	20	31
EB MD 214 at Kettering	Bowie, MD	Exclusive	830	510	2	5	8
NB IL 171 at IL 64	Melrose Park, IL	Shared	890	1000	13	18	24
SB IL 171 at IL 64	Melrose Park, IL	Shared	1150	830	14	18	23
NB IL 171 at Roosevelt	Melrose Park, IL	Shared	290	230	4	6	9
SB IL 171 at Roosevelt	Melrose Park, IL	Exclusive	450	360	21	26	30
SB US 1 at New Falls of Neuse	Wake Forest, NC	Exclusive	470	1040	11	13	15

EB = Eastbound, WB = Westbound, NB = Northbound, SB = Southbound

Effect of Traffic Congestion on ATL Utilization

The primary motivation for a driver to use an ATL is to save travel time by either avoiding long queues by moving around slower vehicles or avoiding waiting at the light for more than one signal cycle (cycle failure). Thus, the level of ATL use is controlled by operational elements of the intersection, including:

- **Approach through-movement flow**. Higher through flow rates on the approach encourage more vehicles to move to the ATL. This result has been confirmed in several general studies of short-lane use (*7*, *8*, and *9*).
- **Signal timing**. The lower the ratio of effective green for the approach to intersection cycle length, the lower is the capacity of the approach. Consequently, drivers are motivated to switch to the ATL to avoid a cycle

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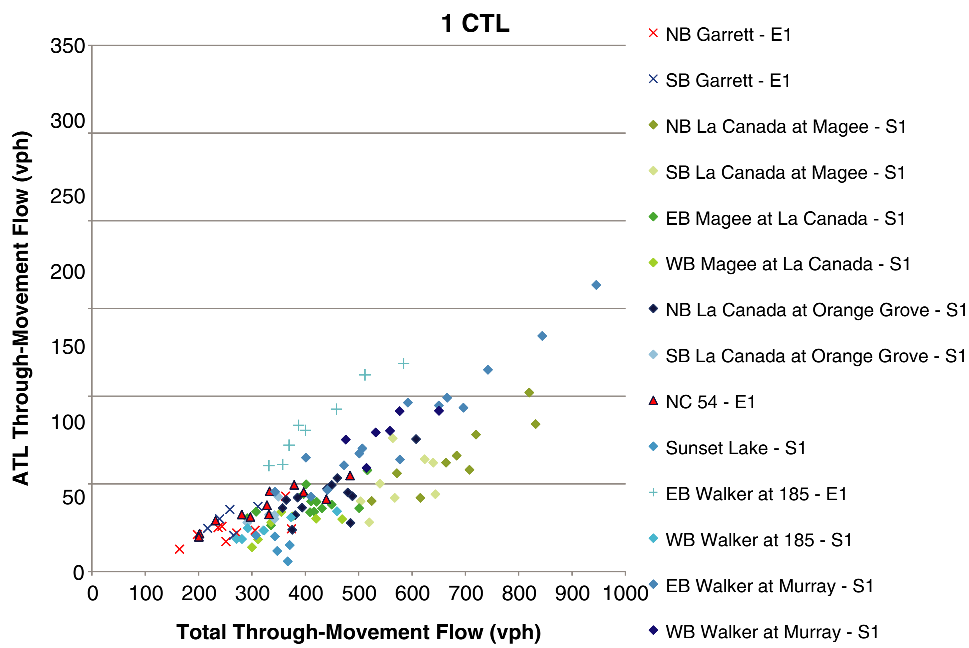
failure. Additionally, a longer cycle length creates longer queues in the CTL(s), which also encourages drivers to switch to the ATL.

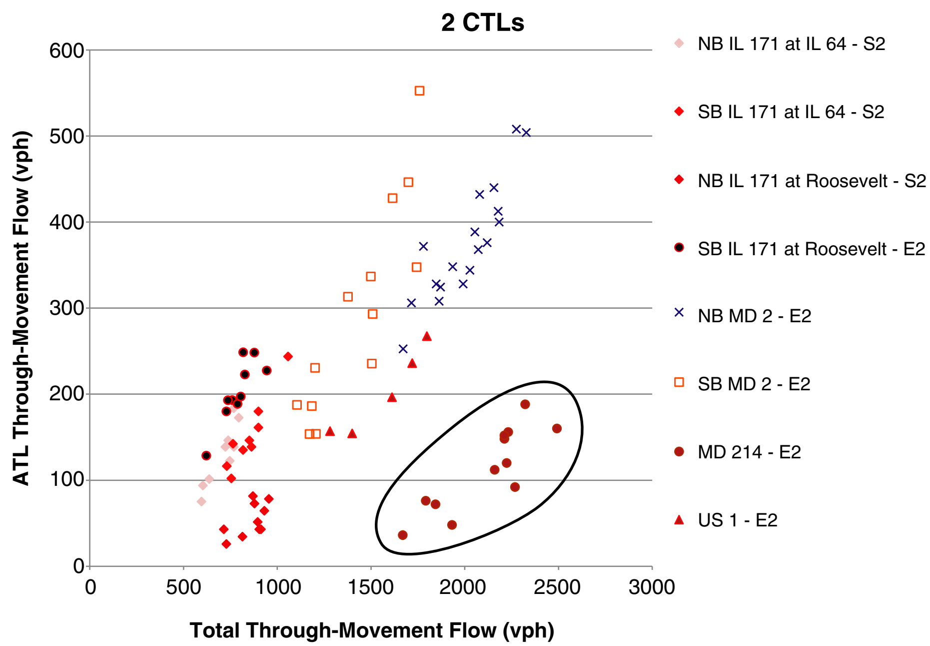
- **Arrival type**. Most drivers choose to use the ATL while traffic is still queued on the approach. Therefore, an ATL approach with a high number of arrivals on green—usually achieved by good signal progression—would experience lower ATL use than one with a random arrival pattern.
- **Right-turning vehicles and driveways**. Driveways along either the upstream or downstream length of the ATL create the potential for right-turning vehicles to block the passage of ATL drivers, which discourages ATL use. A heavy flow of right turns from a shared ATL has the same effect, as shown in previous research (*7*, *8*). Additional details on the effects of right turns are provided in the ATL volume-estimation section later in this chapter.

Exhibit 3-5 displays a plot of ATL through-movement flow rate against total approach through-movement flow rate for all sites (each with a different marker), broken down by the number of CTLs. All the indicated flow rates are based on 15-minute counts expanded to an hourly rate. In the event that only hourly volumes are available, they must first be divided by the peak-hour factor (PHF) to yield the corresponding 15-minute peak flow rate.

The relationship shown in the exhibit between congestion and ATL use is relatively strong, and more evident than a relationship between through traffic and the percentage of ATL utilization, expressed as a fraction of all through traffic. This latter relationship is weaker because ATL flow rate increases as the overall through flow rate increases, making the ratio of the two more or less a constant. For this reason, ATL flow in vehicles per hour (vph) was modeled directly rather than predicted from percentage of utilization.

Exhibit 3-5
ATL Through-Movement Flow vs. Total Through-Movement Flow





EB = Eastbound, WB = Westbound, NB = Northbound, SB = Southbound
E1 = Exclusive, one CTL; S1 = Shared, one CTL; E2 = Exclusive, two CTLs; S2 = Shared, two CTLs

Many of the figures and tables in this report have been converted from color to grayscale for printing. The electronic version of the report (posted on the web at www.trb.org) retains the color version.

Guidelines on the Use of Auxiliary Through Lanes at Signalized Intersections

Exhibit 3-6 displays a plot of ATL through-movement flow against X_T, the level of through-movement congestion, with X_T defined as the approach through volume-to-capacity (v/c) ratio:

Equation 3-1

$$X_T = \frac{V_T}{N \times S_T \times \frac{g}{C}}$$

where:

V_T = Through-movement demand flow rate on the ATL approach,

N = Number of CTLs on the approach,

S_T = Through-movement adjusted saturation flow rate per lane,

g = Effective green time for the approach through movement, and

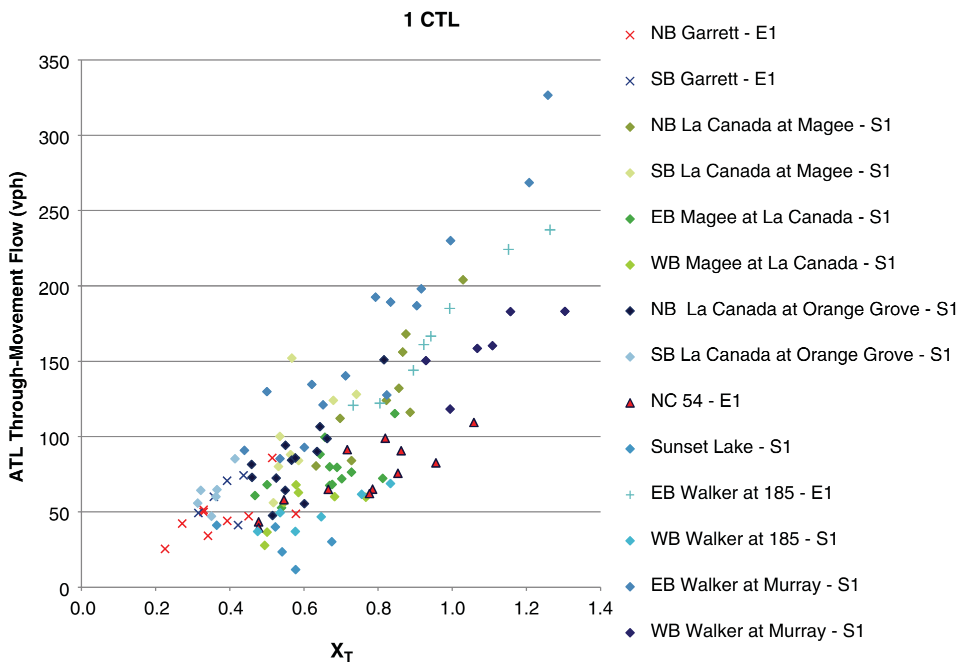
C = Intersection cycle length.

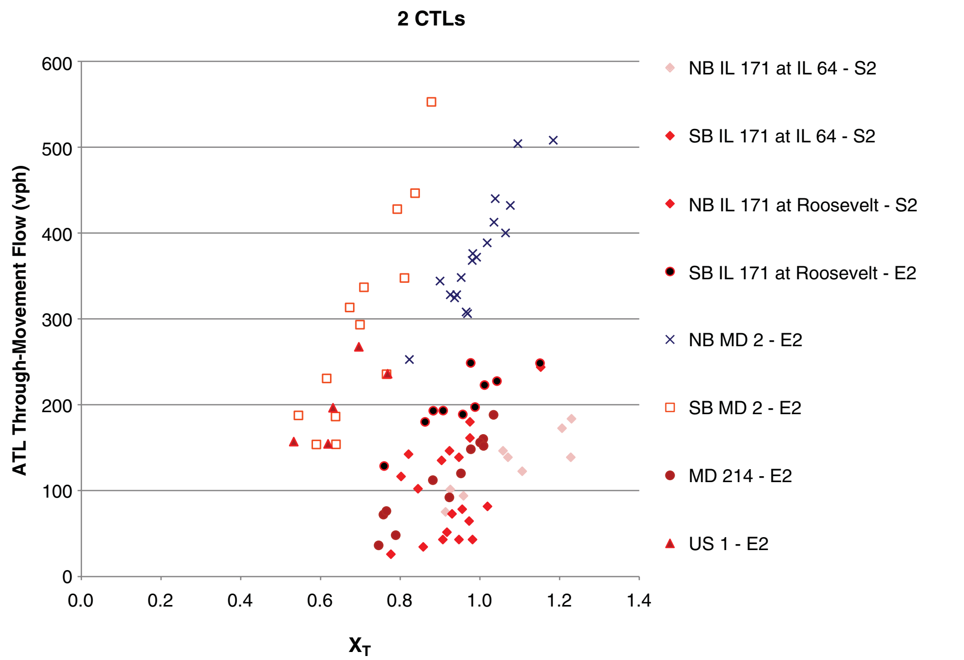
Equation 3-1 computes the v/c ratio for the CTIs only because that factor was found to be the primary motivator for using the ATL. Also, all calculations should be based on 15-minute flow rates, including the average green and cycle time, in the event that the traffic signal is actuated.

The relationships displayed in Exhibits 3-5 and 3-6 imply that separate models are necessary to predict the ATL flow for one-CTL and two-CTL approaches. A two-CTL site was omitted in the model development phase because it exhibited different characteristics than the other sites. That site, MD 214 (the data for which are circled at the bottom of Exhibit 3-5), had excellent signal progression, which inhibited the use of the ATL, even though through traffic flows were quite high. The remaining models should be considered valid primarily under random arrival conditions and should be used with caution under other circumstances.

In summary, ATLs are more likely to be used by drivers on intersection approaches that operate near their through-movement capacity without an ATL in place. Lane utilization is also affected by arrival type, with improved progression inhibiting the use of the ATL due to limited queuing and delay on the approach, and by the volume of right-turning movements at the intersection or adjacent driveways.

Exhibit 3-6
ATL Flow vs. Level of Through-Movement Congestion (X_T)





EB = Eastbound, WB = Westbound, NB = Northbound, SB = Southbound
E1 = Exclusive, one CTL; S1 = Shared, one CTL; E2 = Exclusive, two CTLs; S2 = Shared, two CTLs

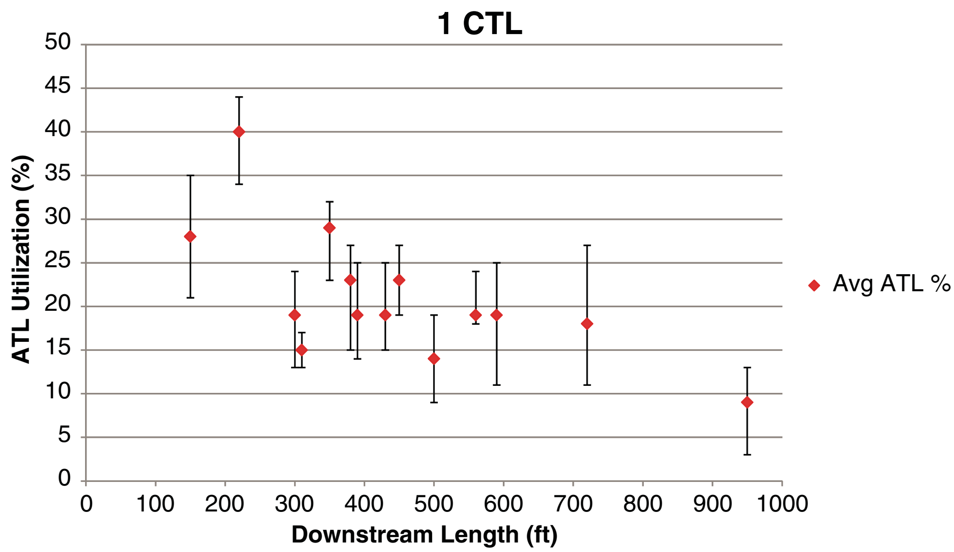
Guidelines on the Use of Auxiliary Through Lanes at Signalized Intersections

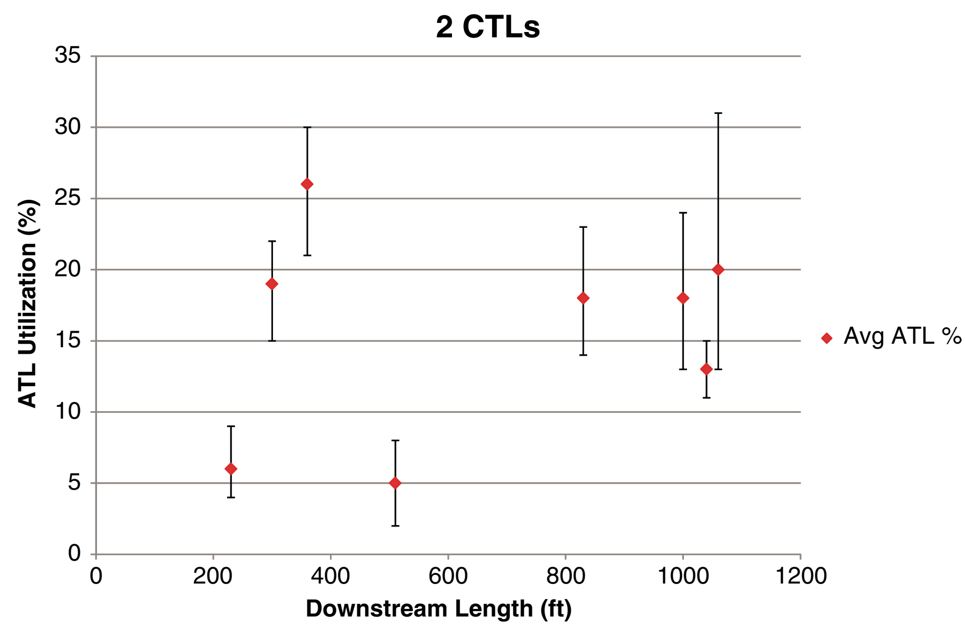
Effect of ATL Geometry

The upstream storage length of the ATL should be long enough to adequately contain the maximum expected (i.e., 95th percentile) queue in the ATL. Ideally, it should also be longer than the maximum expected queue in the adjacent CTL to ensure that drivers have access to the ATL.

The results of this research indicate that the downstream length of an ATL has virtually no impact on the level of ATL use, in spite of several earlier studies that hypothesized that a longer downstream length would encourage ATL use (*7*, *8*, *9*, *10*, *11*). Exhibit 3-7 displays a plot of the observed ATL utilization for each study approach against the corresponding downstream length.

Exhibit 3-7
Minimum, Average, and Maximum ATL Utilization vs. Downstream Length





The exhibit shows the minimum, average, and maximum ATL utilization per site, which are also distinguished by the number of CTLs. It is clear from the data that downstream length plays little, if any, role in enticing drivers to use the ATL.

From a design perspective, the downstream ATL length should be long enough to enable drivers starting from a stopped queue in the ATL to accelerate to a safe merging speed. It should also allow drivers traveling through the intersection during the green phase to find a suitable gap for merging into the adjacent CTL traffic stream. Still, as ATLs are inherently an interim capacity improvement at an intersection, the ultimate length may be limited based on available right-of-way, environmental constraints, and construction costs. ATL design elements are discussed further in Chapter 5.

Other Factors Affecting ATL Use

The following operational and design characteristics should also be considered during ATL design, although their effects were not fully quantified in the statistical lane-use models because of the limited number of observations:

- **Downstream congestion**. A bottleneck downstream of the ATL merge area due to the presence of a signalized intersection, a lane drop, or heavy driveway traffic onto the roadway may cause queued traffic to spill back onto the ATL and affect its operations.
- **Posted speed**. The higher the posted speed limit, the greater is the speed differential between queued vehicles in the CTL that begin to accelerate when the signal turns green and vehicles arriving on green that may pass more easily in the ATL. This situation may encourage greater ATL use, but likely requires a longer downstream length for safe merging.
- **Sight distance at the intersection approach**. Drivers feel more comfortable using an ATL when they can see there are no obstructions in the merge area.

DATA COLLECTION REQUIREMENTS

Conducting a traffic operations analysis for an ATL requires the same input data as needed for a signalized intersection analysis performed using the HCM 2010 method. These data include 15-minute peak-period flow rates and heavy vehicle percentages, geometric data, and signal timing data.

If driveways are present in the ATL, the driveway volume should be estimated and added to the right-turn movements at the intersection.

Left turns are assumed to operate from one or more exclusive turn lanes and to not influence the operation of the adjacent CTL or ATL. Such was the case at each site visited for this research.

The following bullet items summarize the data that must be measured in the field or estimated in order to predict the through-movement approach volume that will use the ATL:

- Through-movement demand flow rate on the approach, in vehicles per hour

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- Right-turn flow rate on the approach (only for proposed shared through/right ATLs), in vehicles per hour; also right-turn flow rates into downstream driveways if those are available and deemed to be significant
- Effective green time for the approach, in seconds during the peak 15-minute period
- Intersection cycle length, in seconds during the peak 15-minute period
- Adjusted saturation flow rate for through and right-turn movements on the approach (using HCM 2010 methods), in vehicles per hour.

ATL VOLUME ESTIMATION

This section describes a step-by-step analytical method to predict the through-movement volume that will use an ATL. The method is based principally on the demand-to-capacity relationship of an intersection approach without an ATL, and estimates the expected volume in the ATL based on various parameters. The base estimation method is founded on models built from field data collected on ATL use. Separate prediction models were developed for one-CTL and two-CTL approaches.

The field model estimates are constrained by upper bound estimates from the HCM 2010 model, which specify the maximum through volume to be expected in any exclusive or shared lane, where through traffic has a choice of lanes. The upper bound estimate also guarantees consideration of right-turn traffic effects, even for those cases where field observations did not show an impact due to low right-turning movements. While the method predicts ATL volume, the utilization percentage can be calculated from the results if desired.

Approaches with One CTL

A key parameter for the analysis of an ATL facility with one existing CTL is X_T, the ratio of through-movement demand to capacity, also listed earlier in Equation 3-1:

Equation 3-2

$$X_T = \frac{V_T}{S_T \times \frac{g}{C}}$$

where:

V_T = 15-minute through-movement demand flow rate on the approach, expressed in vehicles per hour;

S_T = Adjusted through saturation flow rate per lane on the approach, in vehicles per hour;

g = Effective green time for the approach, in seconds; and

C = Intersection cycle length, in seconds.

In Equation 3-2, V_T is the total through demand flow rate, whereas S_T is the per-lane saturation flow rate of the CTL. Once X_T is computed, the through-movement flow rate in the ATL can be predicted using Equation 3-3 ($R^2 = 0.781$):

Equation 3-3

$$V_{ATL} = 20.226 + 81.791 \times X_T^2 + 1.65 \times \frac{V_T^2}{10{,}000}$$

where:

V_{ATL} = The predicted through-movement flow rate in the ATL (in vehicles per hour), and all other variables are as previously defined.

The remaining flow rate in the continuous lane, V_{CTL}, is obtained by subtracting V_{ATL} from VT. This method can be used to estimate ATL use on approaches with one CTL in situations when the ATL will be an exclusive lane and when it will be a shared lane with right turns. Equation 3-3 does not contain a right-turn volume variable, because the measured right-turn volumes in the field were not high enough to impact the ATL through volume for observed shared ATL sites. This does not mean that right-turn effects will be ignored. In fact, those will be accounted for in the estimation of an upper-bound flow rate using HCM 2010 methods.

ATL Approaches with Two CTLs

For an approach with two CTLs and a proposed shared ATL, an additional parameter X_R (the right-turn volume-to-capacity ratio) must be estimated as given in Equation 3-4 ($R^2 = 0.768$):

Equation 3-4

$$X_R = \frac{V_R}{S_R \times \frac{g}{C}}$$

where:

V_R = Right-turn flow rate for the proposed shared ATL (this term could include right-turn traffic entering the downstream driveways if that flow rate is available and deemed to be significant); and

S_R = Adjusted right-turn saturation flow rate in the proposed shared ATL (usually defaults to 0.85 S_T).

In the case of an exclusive ATL, X_R is set to zero in Equation 3-5. The through-movement flow rate (in vehicles per hour) in the ATL can then be predicted using Equation 3-5:

Equation 3-5

$$V_{ATL} = 29.24 - 90.291 \times X_R + 17.3 \times \frac{V_T}{100}$$

Similar to the one-CTL case, V_T represents the total approach through volume. Upon computing V_{ATL}, the remaining volume in both continuous lanes (V_{CTL}) is again obtained by subtracting V_{ATL} from V_T. This research did not show

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evidence of uneven lane utilization across the two continuous lanes, and V_{CTL} is therefore assumed to be divided equally across the two CTLs.

Upper-Bound Values for ATL Use

Regardless of the predicted ATL flow rate derived from Equations 3-3 or 3-5, when given a choice, drivers will generally seek the lane that will minimize their own queue position service time. This upper bound on the typical through flow rate for an ATL is best represented by the equal v/s (volume-to-adjusted saturation flow rate) approach adopted in the HCM 2010 (*2*). It essentially states that through traffic on an approach will divide itself across several eligible lanes in a manner that equalizes all lane v/s ratios serving the through traffic.

Therefore, if an exclusive ATL is contemplated, the upper bound for the ATL through flow rate for the single CTL case can be estimated using Equation 3-6:

Equation 3-6

$$V_{ATL,MAX} = V_T\left(1 - \frac{0.50}{f_{LU}}\right)$$

In the case of two CTLs, the upper bound is computed using Equation 3-7:

Equation 3-7

$$V_{ATL,MAX} = V_T\left(1 - \frac{0.667}{f_{LU}}\right)$$

where:

$V_{ATL,MAX}$ = Upper bound for ATL through flow rate, in vehicles per hour; and

f_{LU} = HCM 2010 lane utilization factor (see HCM 2010; Exhibit 18-30 for default values).

In the case of a shared through-right ATL, the lane utilization factor is not applicable because lane choice is governed by the possible impedance caused by right turns in the shared lane. Instead, the upper bound for ATL flow rate is estimated on the basis of the equal v/s concept, using Equation 3-8:

Equation 3-8

$$V_{ATL,MAX} = Max\left\{0, \frac{V_T}{N} \times \left[1 - \frac{\frac{V_R}{S_R}}{\frac{V_T}{N-1\ S_T}}\right]\right\}$$

where:

N = Number of CTLs and shared ATLs on the proposed approach,

V_R = The right-turn flow rate from the shared ATL (in vehicles per hour including possibly right turns onto downstream driveways), and

S_R = The right-turn saturation flow rate in vehicles per hour.

NUMERICAL ILLUSTRATION OF ATL VOLUME PREDICTION

A two-CTL approach carries a through traffic flow rate of 1,000 vehicles per hour along with 191 right turns per hour in an exclusive right-turn pocket during the peak 15-minute period. The approach is signal controlled and receives an effective green time of 30 seconds in a 120-second cycle. The traffic engineer is contemplating converting the short right-turn pocket into a shared ATL. The engineer is also interested in testing the effect of adding an exclusive through ATL on the approach. The ATL use and feasibility will be estimated for both scenarios.

Shared ATL Scenario

Using Equation 3-4 and assuming that the adjusted

S_T = 1,800 vph per lane and

S_R = 1,800 x 0.85 = 1,530 vph per lane, then

$$X_R = \frac{191}{1{,}530 \times \frac{30}{120}} = 0.50$$

The predicted ATL through flow rate from Equation 3-5 is:

$$V_{ATL} = 29.24 - 90.291 \times 0.50 + 17.3 \times \frac{1{,}000}{100} = \ 157 \text{ vph}$$

The relevant upper-bound value for through traffic in the shared ATL is computed from Equation 3-8, with $N = 3$

$$V_{ATL,MAX} = Max\left\{0, \frac{1{,}000}{3} \times \left[1 - \frac{\frac{191}{1{,}530}}{\frac{1{,}000}{3{,}600}}\right]\right\} = \ 184 \text{ vph}$$

In this scenario, the volume prediction from Equation 3-5 is lower than the volume using the equal v/s criterion. The shared ATL is predicted to attract 157 existing through-movement vehicles per hour, or about 16 percent of the total through-movement flow. The lateral through-lane volume distribution will be 157 + 191 = 348 vph in the shared ATL, and (1,000 -157)/2 = 422 through vehicles per hour in each of the two exclusive CTLs.

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Exclusive ATL Scenario

In this case, Equation 3-4 is used with X_R set to 0, yielding V_{ATL} = 202 vph, which is higher than the shared lane case, as expected. The maximum value of through traffic that equalizes the queue service time is estimated from Equation 3-7 using a default HCM 2010 value of lane utilization f_{LU} = 0.908 (*2*, Exhibit 18-30). Substituting into Equation 3-7 gives $V_{ATL,\,MAX}$ = 265 vph. The estimated exclusive ATL flow rate is the lower of the two estimates at 202 vph, and the per-lane through flow rate in the CTLs is (1,000 – 202)/2= 399 vph.

It is clear from the analysis that either the shared or exclusive ATL scenario will relieve the approach congestion considerably. By comparing the before-and-after v/c ratios, one can see that while right turns may experience a higher v/c ratio and higher delays in the shared lane scenario, through traffic will benefit considerably from the ATL addition.

A summary of the computed v/c ratios in the three scenarios is depicted in Exhibit 3-8. Further estimates of delays, LOS, and queue lengths associated with ATL installations are provided with the computational engine described in Appendix B. A first-cut analysis of the example results would indicate that converting an exclusive right-turn pocket to a shared ATL appears to be a sufficient treatment in the short term, assuming current flows and signal plans do not change appreciably, and that the ATL's length is dimensioned properly.

Exhibit 3-8
Movement and Lane v/c Ratios Before and After ATL Conversion or Addition

Movement	Baseline v/c	v/c After Conversion to Shared ATL	v/c After Adding Exclusive ATL*
Through Traffic	1.167	0.984 (in CTL)	0.50 in ATL 0.93 in CTLs
Right-Turn Traffic	0.50	0.850 (traffic in shared ATL)	0.50

* Exclusive ATL scenario assumes maintaining the exclusive right turn lane

4. SAFETY

ATLs are primarily implemented as an operational treatment, but ATLs certainly have safety implications. ATLs may be expected to have a fewer number of some types of crashes when compared to a conventional intersection handling the same volume, because ATLs allow for smoother, less congested operations. On the other hand, ATLs may also cause an increase in other types of crashes due to the added merging area. This chapter explores these safety trade-offs based on empirical crash data and simulation-based safety models.

Various design elements were observed in an analysis of crash data from 16 sites across four U.S. states over a period of 9 years. These 16 sites were also included in the data used to develop the operational models in Chapter 3. Crash reports from within the ATL and its tapers were collected from the responsible agencies in each of the four states. Rear-end and sideswipe crashes were the crash types thought to be most closely related to ATL operation. Overall, the average reported frequency of rear-end and sideswipe crashes was 4.5 crashes per year per site. This is a relatively low frequency when compared to intersections generally identified as potentially hazardous in safety studies. This relatively low frequency indicates that these sites were probably not unsafe as designed.

This research also employed the FHWA Surrogate Safety Assessment Model (SSAM) (*12*), which can be used in conjunction with microsimulation programs like VISSIM (*13*) to record simulated traffic conflicts. SSAM has the potential to allow practitioners to quantitatively examine the safety consequences of an alternative like an ATL, even if no crash prediction model is available. Although the analysis objective of this research was to correlate SSAM conflicts with the crash data taken from the 16 study sites, the crash sample size was ultimately too low to draw any significant conclusions. However, the trends in the SSAM conflict output allowed the researchers to identify several design elements that may affect an ATL's safety. Appendix A contains guidance on how analysts could use SSAM to help examine the safety of an ATL in the future.

SAFETY PRINCIPLES

ATLs add lane-changing activity to the through-movement lanes at a signalized intersection. This activity may lead to an increase in sideswipe crashes, especially near the downstream merge. At the same time, an increased through-movement capacity may prevent some rear-end crashes on the approach by decreasing congestion. In particular, the following ATL elements are critical to its safe operation:

- **Downstream length**. A sufficient downstream ATL length and taper is needed to allow for safe merging operation into the adjacent CTL traffic stream by providing drivers with enough distance to accelerate and find acceptable gaps in the CTL traffic.
- **Access control**. Driveways along an ATL create potential hazards for drivers who are preoccupied with merging into the adjacent CTL traffic

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stream. During the data collection for this project, driveway-related conflicts were identified in the field. Right-turning vehicles from a shared ATL create a similar hazard.

- **Sight distance**. Sites with an adequate view of the downstream ATL from the stop bar experienced more ATL use, presumably because drivers feel more comfortable using an ATL when they can see the entire downstream merge area. In addition, with an adequate view of the end of the ATL, drivers in the ATL can plan for their merge back into the CTL more carefully.
- **Queuing downstream of the ATL merge**. Traffic spilling back into the ATL taper from a downstream bottleneck could create a safety issue. Analysts should pay particular attention to potential spillback into an upstream ATL that could occur from a downstream bottleneck.
- **Taper design**. The length and rate of the ATL taper should conform to AASHTO (*1*) and MUTCD policy (*3*).
- **Signing, marking, and lighting**. An ATL should be clearly signed as a through-movement lane so that drivers are not discouraged from using it. Lighting may also promote better nighttime operations.

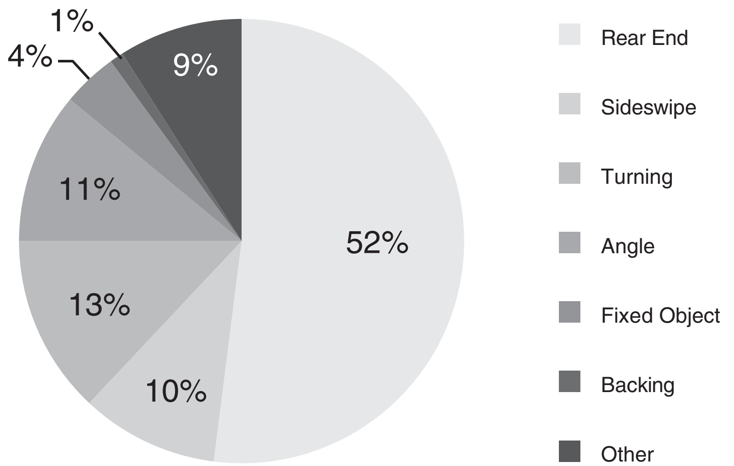
OBSERVED SAFETY PERFORMANCE

The 16 ATL study sites produced a combined average of 4.5 related (sideswipe plus rear-end) crashes per year on the ATL, indicating that these sites were likely not unsafe as designed. Although this research could not do so, it might be possible in the future to develop a crash modification factor (CMF) to convert a conventional intersection approach to one with an ATL. It might also be possible to use crash prediction models from the *Highway Safety Manual* (*4*), calibrated for a particular state, to estimate the number of crashes that would have occurred at a particular site if the ATL had not been installed. Until the data are available to estimate a CMF or calibrate a crash prediction model, the best interpretation of the available evidence is that ATLs at the studied sites did not seem to add many crashes.

Proportion of ATL Crashes

Although a crash reconstruction analysis was not within the scope of this research, it is generally true that the rear-end and sideswipe crashes that are the types most likely to be related to ATLs are not typically as severe as other crash types such as angle, head-on, and run-off-road crashes. Exhibit 4-1 displays a breakdown of the field crash data obtained for all 16 sites by crash type.

Exhibit 4-1
Breakdown of ATL Crash Types



The total number of crashes reported at all 16 sites was 1,050—this amounts to approximately eight crashes per site per year, including both related and non-related ATL crashes. Although the majority of crashes (52 percent) were rear-end crashes, only 10 percent were sideswipe crashes, which might be expected to be higher in ATLs. Exhibit 4-2 displays a summary of the crash data collected from each site.

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Exhibit 4-2
Summary of Crash Data

Approach	Number of Years Analyzed	Rear End Crashes	Sideswipe Crashes	Total Crashes
SB MD-2 at Arnold Rd *	9	57	13	112
NB MD-2 at Arnold Rd *	9	45	6	99
SB La Canada Dr at Magee Rd	9	42	5	54
EB NC-54 at Fayetteville Rd	6	41	12	207
WB Walker Rd at Murray Blvd	6	34	2	45
NB La Canada Dr at Orange Grove Rd	9	33	6	44
WB Magee Rd at La Canada Dr	9	29	5	48
EB Walker Rd at 185th St	9	28	1	63
WB Walker Rd at 185th St	9	27	2	58
EB Magee Rd at La Canada Dr	9	27	3	35
SB La Canada Dr at Orange Grove Rd	9	24	2	32
EB Walker Rd at Murray Blvd	6	23	4	34
NB Garrett Rd at Old Chapel Hill Rd	6	20	12	115
SB Sunset Lake Dr at Holly Springs Rd	6	17	12	33
NB La Canada Dr at Magee Rd	9	15	0	22
SB Garrett Rd at Old Chapel Hill Rd	6	12	4	49
Total	**126**	**474**	**89**	**1050**

* Denotes 2-CTL approach

Although, as noted previously, calibrated crash prediction models from the HSM were not available for the four states analyzed in this effort, the researchers employed uncalibrated models to make comparisons on the proportions of crash types observed. Exhibit 4-3 shows the proportion of sideswipe crashes among all related crashes (sideswipe plus rear-end) for uncalibrated HSM crash models and the 16 ATL sites based on a summary of crash records. The exhibit shows that the proportions generally matched well. Z-tests for proportions revealed that only the proportion from the North Carolina data had a significant difference from the HSM prediction at a 95 percent confidence level. For all other states, individually and combined, the difference between the HSM prediction and the project data was not statistically significant. Exhibit 4-3 lends support to the idea that the crash types experienced at the ATL sites studied were not much different from crash types experienced at comparable conventional intersections.

Exhibit 4-3
Comparison of Sideswipe Crash Data

State	Proportion of Sideswipe among All Related Crashes	
	HSM	ATL Data
Arizona	0.15	0.12
Maryland	0.11	0.16
North Carolina	0.14	0.28
Oregon	0.13	0.06
Combined	**0.13**	**0.15**

Distribution of Crashes Relative to Location in ATL

The rear-end and sideswipe crash data were aggregated by relative location within the ATL, as shown in Exhibit 4-4. The line for total crashes is simply the sum of rear-end and sideswipe crashes. Note that the distribution of sideswipe crashes is spread more evenly over the length of a typical ATL than the distribution of rear-end crashes. This suggests that, while rear-end crashes usually occur in the queuing areas near the intersection, sideswipe crashes are more likely to occur in other areas of the ATL. Also note that almost exactly half of these crashes were upstream of the intersection and half were downstream.

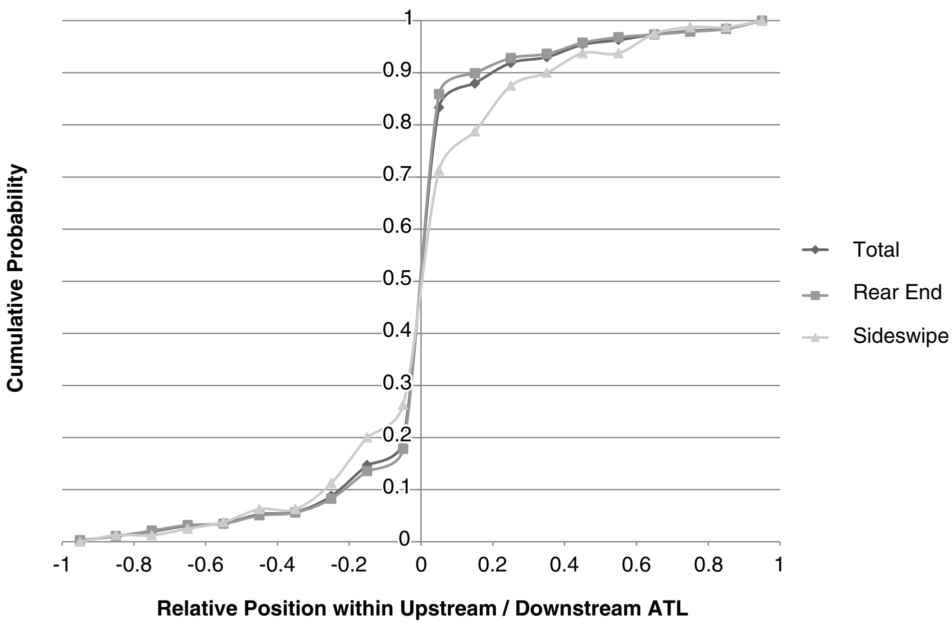


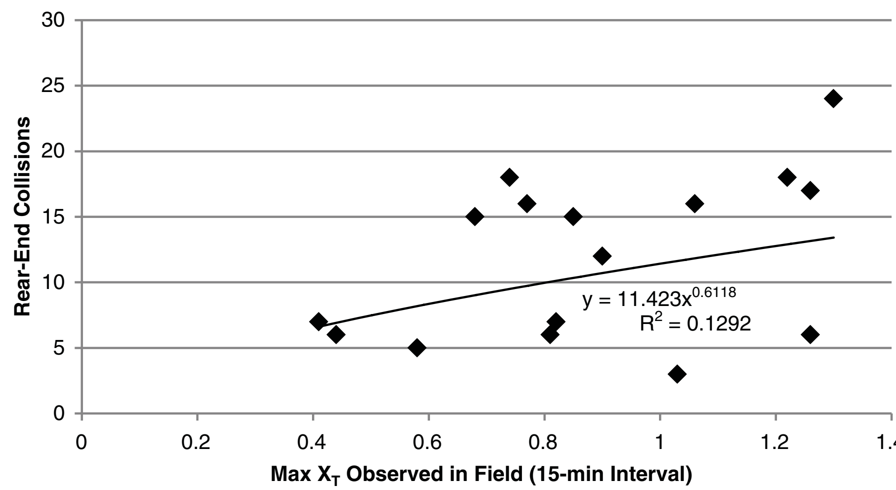
Exhibit 4-4
Field Crash Data Distribution versus Relative ATL Position

Relationship Between Crashes and Congestion

Exhibit 4-5 plots the number of rear-end crashes from 2006 to 2008 against the maximum X_T obtained from field data collected in 2009 and 2010. X_T indicates the level of congestion in the through-movement lanes assuming no ATL is present. The line in Exhibit 4-5 is the best-fit linear relationship between the maximum X_T observed and rear-end crash frequency for each of the 16 sites. Only the most recent 3 years of crash data were used in order to shorten the time period between safety and operational data collection, considering that all of the operational data were obtained in 2009 and 2010.

Guidelines on the Use of Auxiliary Through Lanes at Signalized Intersections

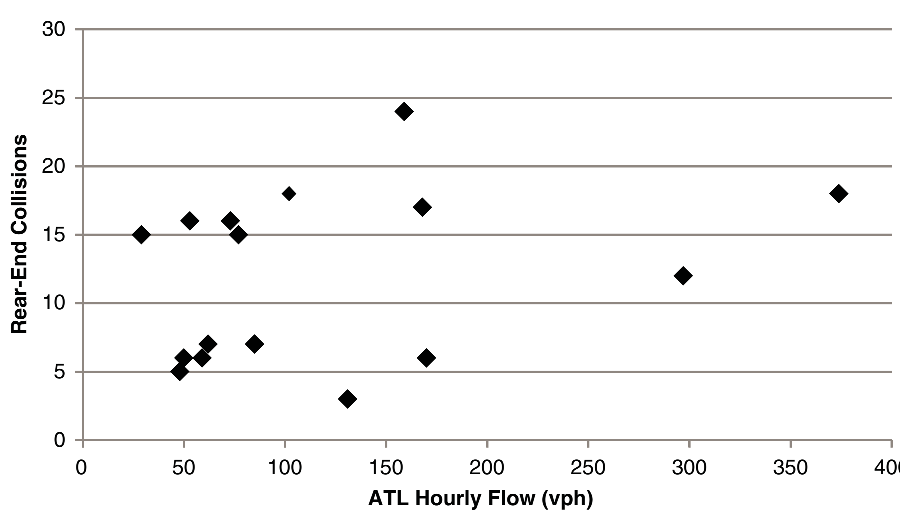
Exhibit 4-5
2006–2008 Crash Data Trends versus Maximum X_T Observed from Data



As shown in Exhibit 4-5, the relationship between rear-end crashes and congestion, as represented by X_T, is very weakly correlated, with little observable trend above $X_T = 0.8$. Not surprisingly, the number of rear-end crashes appears to be less frequent when congestion levels are very low compared to the remaining data set.

Exhibit 4-6 displays the trend between rear-end crashes and average ATL flow observed in the field for each of the 16 sites. This exhibit does not indicate that more crashes occur at ATLs with higher flow rates—consequently, it does not provide evidence that a well-utilized ATL is less safe than a poorly utilized ATL. The two influential points in the far right portion of the exhibit with very high ATL flow are the sites with two CTLs.

Exhibit 4-6
2006–2008 Rear-End Crashes versus Average ATL Hourly Flow Observed from Data



Relationship between ATL Crashes and Total ATL Length

Exhibit 4-7 compares sideswipe crashes (combined over all analysis years in the dataset, unlike the preceding exhibits) at each site to total ATL length (sum of upstream ATL length, intersection width, and downstream ATL length not including tapers). While it may be hypothesized that longer ATLs allow for safer merging, it is also possible that more exposure to merging areas would lead to more frequent sideswipe crashes. Based on the direction of the linear relationship shown in Exhibit 4-7 (again the best-fit line), it appears that the probability of sideswipe crashes increases as the length of the ATL increases.

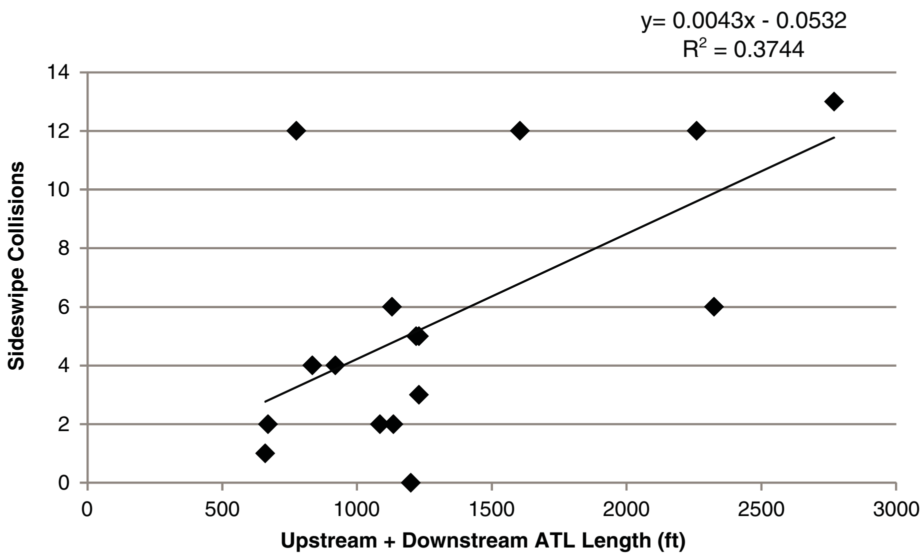


Exhibit 4-7
2006–2008 Rear-End Sideswipe Crashes/Year versus ATL Total Length

In summary, the analysis of the data from the 16 study sites showed some relationships between rear-end crashes and congestion, between rear-end crashes and flow rates in the ATLs, and between sideswipe crashes and ATL length. However, the relationships are weak and causation is unclear in all cases, so practitioners should not over-interpret the findings. In the future, perhaps calibrated crash prediction models for ATLs will be available to provide firmer guidance to practitioners considering ATLs.

SAFETY EVALUATION CONSIDERATIONS

The following guidance is recommended for conducting a safety evaluation of an existing ATL:

- Collect crash data for the ATL approach and remove non-ATL-related crashes.
- Closely examine rear-end and sideswipe crashes along the approach with the ATL, including the tapers.
- Collect crash data over as long a time as possible given that important safety-related conditions remained unchanged.

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- Exercise caution in observing when the ATL was constructed and not include data from prior to the ATL opening.
- Use a method similar to the safety analysis of conventional intersections as described in the HSM (*4*) to evaluate the crash data.
- Review the crash data from the 16 sites examined in this chapter to understand how typical ATLs perform.

Evaluating the safety implications of ATL proposals or designs is currently difficult given the lack of crash prediction models or CMFs. Until those tools are available, practitioners should be confident that, based on the data presented in this chapter, well-designed ATLs are not likely to cause safety problems. An SSAM analysis could also be used when a practitioner wishes to examine the potential safety effects of building an ATL or altering an ATL's design or operational elements. As Appendix A describes, an SSAM analysis requires a calibrated microsimulation model of the intersection that exhibits an appropriate estimate of the flow in the ATL. Ten or more simulation runs should be used to populate the sample size. During SSAM analysis of the trajectory files, only rear-end and lane-change conflicts should be examined, and a time-to-crash (TTC) threshold of 1.5 seconds is preferred to yield a larger sample size. The practitioner should then look for the relative change in conflict frequency when a design element (e.g., downstream length) or operational element (e.g., X_T) is altered to draw conclusions about the safety effects of the ATL design.

5. GEOMETRIC AND TRAFFIC DESIGN

This chapter describes the typical design approach for an ATL and provides guidance for determining the upstream and downstream ATL lengths, tapers, and layout for signs and pavement markings. It requires as input the results from a traffic operational analysis (Chapter 3) and safety assessment (Chapter 4).

The guidance in this chapter is intended to supplement the national resources on intersection design highlighted in Chapter 1, including the AASHTO Green Book (*1*) and MUTCD (*3*), as well as local agency design standards and policies.

DESIGN APPROACH

Prior to beginning a design for an ATL, it is important to recognize (a) the relationship and interaction among traffic operations, safety, and design of the ATL and (b) physical, environmental, or right-of-way constraints of the proposed ATL location that may preclude achievement of an ideal ATL design.

Understanding the Relationship among Operations, Safety, and Design

The relationships among the operations, safety, and design of an ATL are dynamic and may require an iterative approach in the design process. For example, providing advanced and overhead signs may attract more traffic to use the ATL, which in-turn would require longer ATL lengths both upstream and downstream of the intersection. The following list describes a few examples of how traffic design parameters influence operational and safety performance of ATLs:

- **Upstream ATL length.** If the upstream lane is too short and becomes blocked, through traffic is unable to access it. Longer upstream ATLs are more inviting and encourage through traffic to use the ATL.
- **Downstream ATL length.** Downstream lanes that are too short tend to discourage drivers who do not feel there is sufficient distance to comfortably merge into the CTL downstream. Short downstream lanes may also require drivers to merge while still accelerating, which could increase the chances of a crash. Downstream lanes that are too long increase the exposure area for conflicts and may result in unexpected merges far beyond the intersection.
- **Signing and pavement markings**. Signing and pavement markings that encourage use of the ATL as a through lane are likely to result in an increase in its use. Similarly, signing and pavement markings that provide clear guidance in advance of the downstream merge can encourage safe merging behavior. However, cluttered or confusing signing and pavement markings may negatively affect safety by causing drivers to “tune out” and ignore the messages.

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Understanding the Effects of Constraints

A constrained site is one where the length of the upstream or downstream ATL is limited by physical, environmental, cost, and/or right-of-way constraints.

Exhibit 5-1 illustrates a site where the upstream ATL length is unconstrained and Exhibit 5-2 shows a constrained site where the upstream ATL length is limited.

Exhibit 5-1
Unconstrained Site

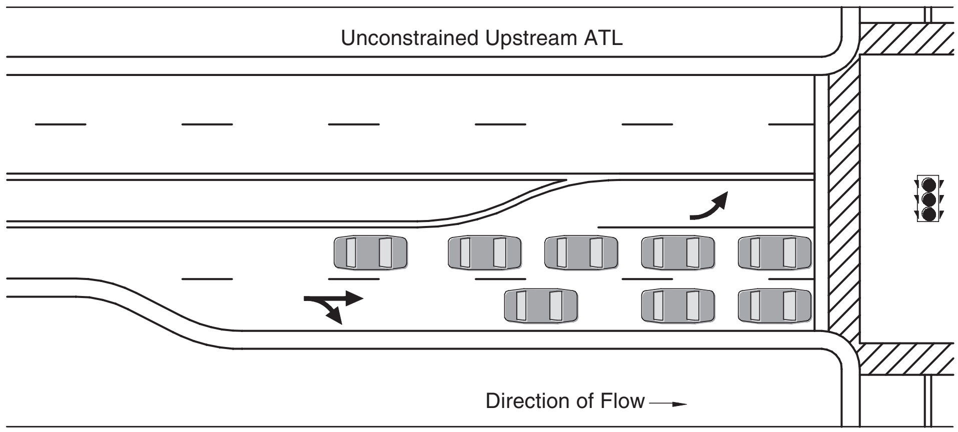
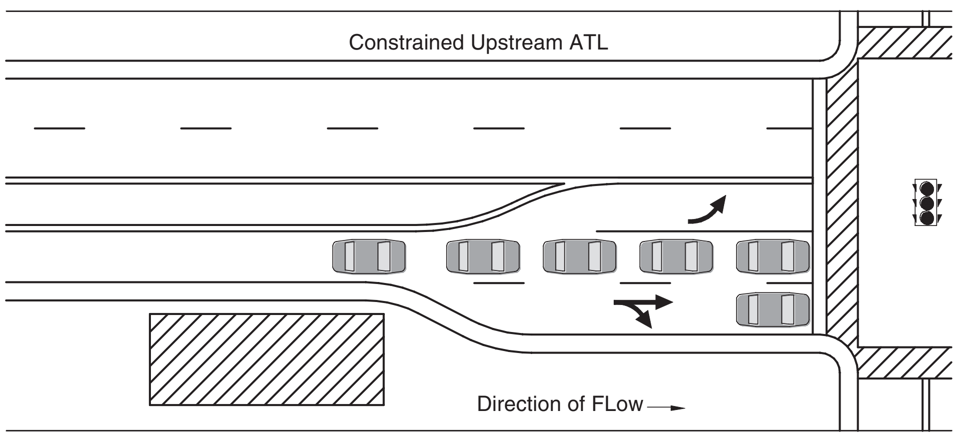


Exhibit 5-2
Constrained Site



As shown in Exhibit 5-2, access to the ATL is blocked in the constrained scenario, which increases the back-of-queue in the CTL.

ATL sites with constraints on the downstream end of the ATL could also experience similar effects. If a lane is perceived by drivers as being too short, many will avoid the ATL and continue to use the CTL.

For these reasons, it is likely an ATL that is constrained, either upstream or downstream, will experience less use than what is predicted in the operational method described in Chapter 3. In these situations, the practitioner must apply judgment in assessing the anticipated safety and operational effects of the constrained ATL in order to determine the net benefit gained by the ATL. In some cases, the practitioner may find that a constrained ATL does not provide sufficient distance downstream of the intersection to accommodate merge maneuvers given prevailing speeds on the approach and driver expectations. In other cases, the practitioner may find that while ATL use at a constrained site is less than desired, it is appropriate because it provides additional capacity benefit to address the congestion problem.

Preliminary Assessment

ATL design is influenced by many factors, including project type, area type, local agency operational and design policies, and facility characteristics. Regardless of the development stage of the project, the first step is to gather available evaluation data to initiate a preliminary assessment that will guide the alternatives development process.

A preliminary assessment begins with an understanding of the context of the corridor for the adjacent land uses and existing adjacent intersections for the typical users they serve. There are a variety of factors that influence intersection configurations, including the level of anticipated pedestrian and bicycle activities, as well as the presence of driveways and their spacing relative to the intersection. The ultimate objective is to understand how adding an ATL will compare to the base condition under current and forecast conditions.

Practitioners should understand the range of intersection applications for the variety of design environments. In most cases, the evaluation of an ATL will fall under one of three possible scenarios:

- **A new intersection on a new facility**. New road connections with new intersections are provided as part of a typical road network expansion. Traffic demand forecasts may indicate the need for additional through capacity at signalized intersections.
- **A new intersection on an existing facility**. Introducing a new intersection to serve either a new road connection or access to a new development may require an ATL at a proposed signal to meet operational requirements for the facility.
- **An existing intersection on an existing facility**. Traffic growth along a facility may trigger the need to add capacity at an existing intersection. Adding an ATL could provide operational relief for an intersection that is not meeting the desired operational performance.

These guidelines focus on an intersection configuration that includes an upstream lane add and a downstream right-hand merge as illustrated in Exhibit 5-3.

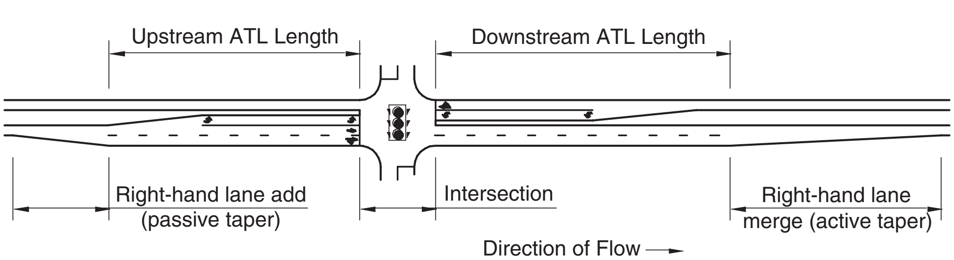


Exhibit 5-3
ATL Configuration

Guidelines on the Use of Auxiliary Through Lanes at Signalized Intersections

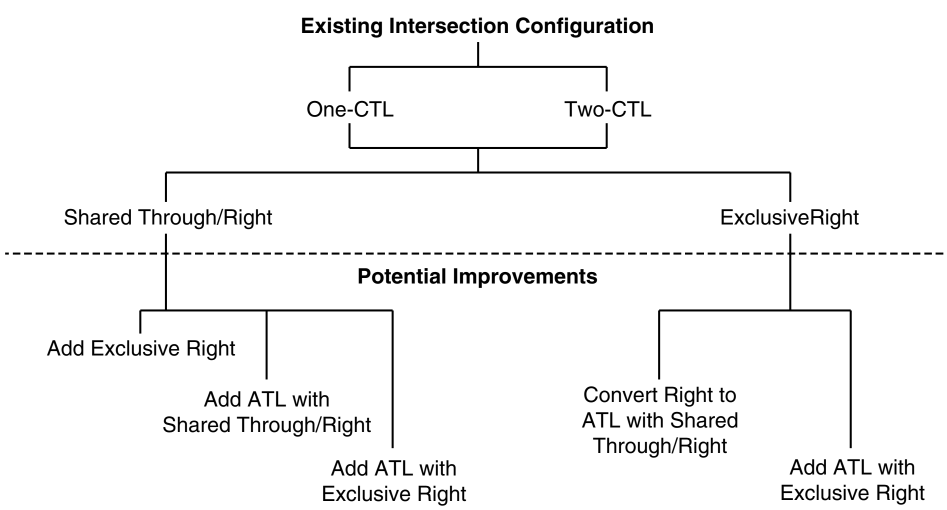
Assessing Need for an Exclusive Right-Turn Lane

As part of the ATL design process, the practitioner should evaluate the need for an exclusive right-turn lane. The decision on whether to construct a separate right-turn lane should follow local agency practice. It should consider the anticipated volume in the design year, safety effects, and the operational effect it may have on usage of the ATL.

Exhibit 5-4 contains a flowchart that illustrates the possible combinations of lane assignments for an ATL approach. These guidelines focus on one-CTL and two-CTL facilities with intersections that have either a shared through/right outside lane or an exclusive right-turn lane. Exhibit 5-5 shows the following range of options that can be considered for improving a one-CTL facility without an exclusive right-turn lane:

- Add a right-turn lane
- Add an ATL with a shared through/right lane
- Add an ATL with an exclusive right-turn lane

Exhibit 5-4
Design Approach Flowchart



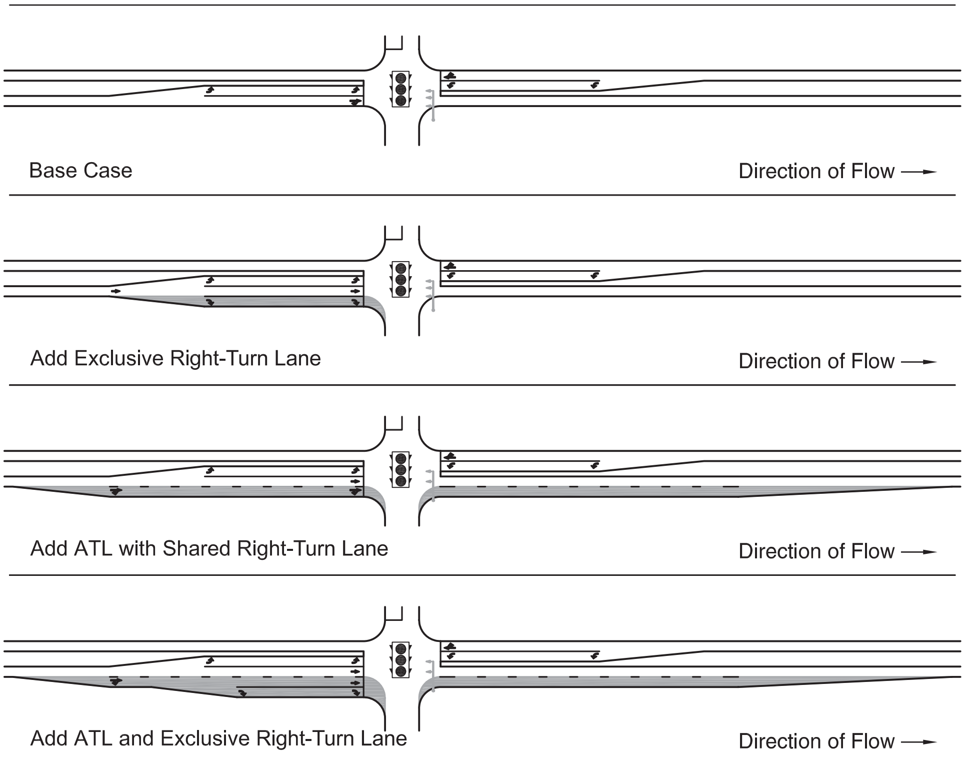


Exhibit 5-5
Potential Improvements for One-CTL Configuration

Considering the Effect of Driveways

Motorists entering and exiting driveways add friction to an outside lane on a multilane facility and discourage the use of the lane. The same is true when driveways are located within an ATL. A driveway in the upstream ATL portion may cause the ATL to operate as a typical right-turn lane, while a high-volume driveway immediate downstream of the intersection would discourage motorists from using the ATL through the intersection.

Where possible, driveways should be located outside of the ATL and its tapers. However, situations may arise where driveway access may be needed within the ATL. In this case, the practitioner must apply judgment to determine the anticipated safety and operational effects of the driveway on ATL performance. While the operational model described in Chapter 3 does not account for driveway effects, it is assumed that the presence of driveway activity will result in lower use of the ATL compared to a condition where no driveways are present. The presence of the driveway is also expected to increase the potential for rear-end and angle crashes.

Applying Existing Guidance

The AASHTO Green Book does not provide guidance for ATLs at signalized intersections but includes information about auxiliary lane applications. However, the auxiliary lane discussions within the Green Book refer to high-speed facilities and free-flow conditions.

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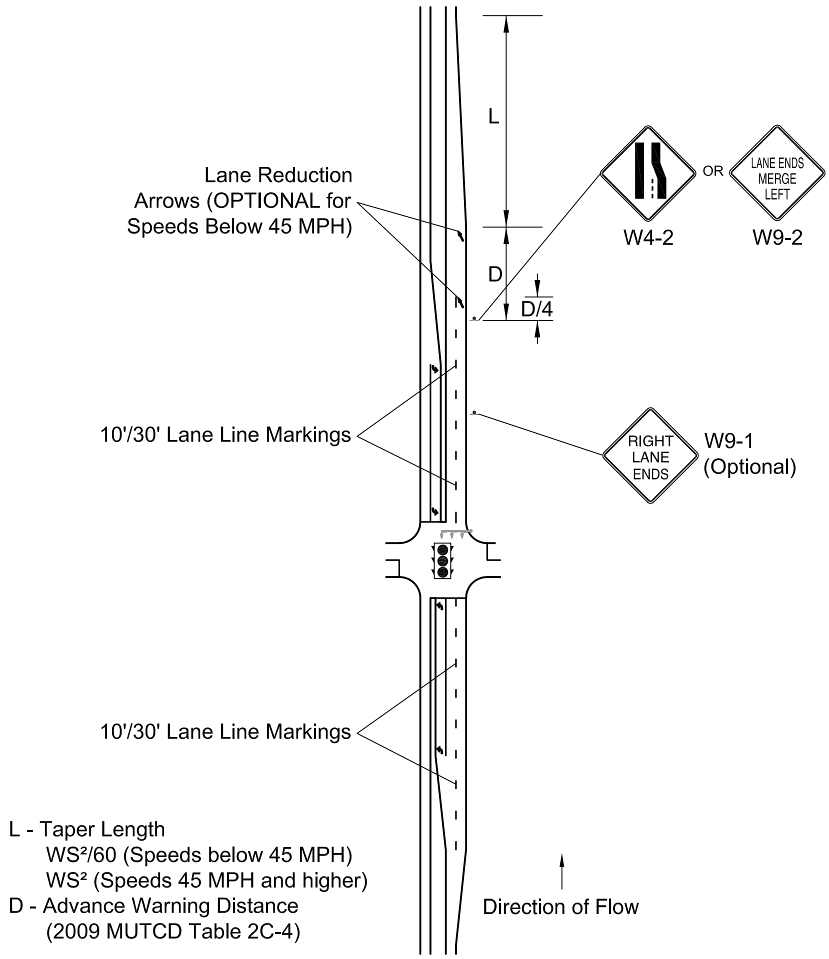
The MUTCD provides permanent signing and pavement markings guidance associated with an ATL design, especially the downstream portion of an ATL. Exhibit 5-6 shows the current MUTCD guidance for signing and striping.

Exhibit 5-6
Current MUTCD Signing and Striping Guidance



As illustrated in Exhibit 5-6, the MUTCD identifies one permanent sign located at the merge of the ATL and one optional sign to guide drivers leaving the intersection (MUTCD Figure 3B-14):

- At the merge of the ATL either the "Lane Ends" W4-2 sign or "Lane Ends Merge Left" W9-2 sign should be installed at the advance warning sign distance indicated in MUTCD Table 2C-4.
- Prior to the required signage, the "Right Lane Ends" W9-1 sign may be considered to emphasize that the travel lane is ending.

Exhibit 5-6 also illustrates the pavement markings (MUTCD Figure 3B-14) associated with an ATL:

- The "Lane Line" pavement marking stops three-quarters of the advance warning sign distance (MUTCD Table 2C-4) before the actual ATL end.
- Supplemental "Lane Reduction Arrows" to emphasize the ATL is ending and motorists should merge.

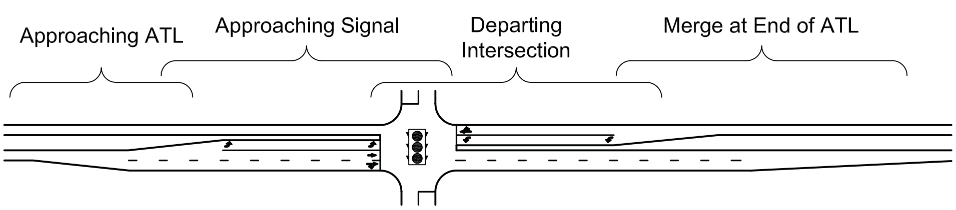
DESIGN ELEMENTS

This subsection addresses typical user questions and provides appropriate guidance from a design point of view. When considering an ATL design, typical questions include:

- What are the minimum and desired distances for the upstream ATL length and downstream ATL length?
- What signs and pavement markings should be applied for the ATL, and where should they be placed?
- What are the preferred taper rates for beginning (passive taper) and ending (active taper) the ATL?

Key design features should be communicated to drivers as they travel through an ATL at a signalized intersection. As illustrated in Exhibit 5-7, there are four unique segments of the ATL that require driver actions that differ from those required by the geometric ATL design sections. These driver interpretation segments consist of Approaching ATL, Approaching Signal, Departing Intersection, and Merge at End of ATL.

Exhibit 5-7
ATL Segments Requiring Unique Driver Action



These segments overlap, and each has a unique purpose; requires a specific set of driver actions; and provides segment-specific guidelines for geometric parameters, signing, and pavement markings.

Signing is an important element of ATL design. Signing needs are influenced by the characteristics of each individual ATL segment. In addition, sign type and placement influence the operations of the ATL. A review of local highway agency signing practice for ATLs found that most agencies call for sign spacing standards less than the spacing guidance identified in the MUTCD as depicted in Exhibit 5-6. Based on field observations, sites with sign spacing less than the guidance identified in the MUTCD did not appear to experience adverse safety or operational performance. In many cases the MUTCD sign spacing guidance could not be achieved at the study sites due to constraints. For these reasons, the signing guidelines presented in this chapter call for sign spacings less than MUTCD guidance where constraints are present.

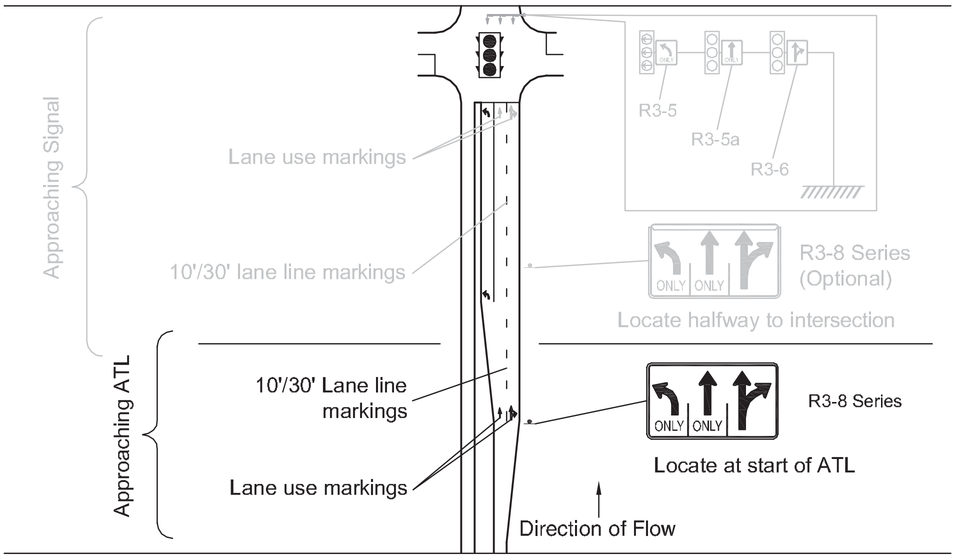
The visibility of pavement markings is typically influenced by weather conditions (especially during the presence of snow), and practitioners should not rely solely on striping guidance for channelization. Striping needs must be evaluated in conjunction with the conceptual geometric design.

Approaching ATL Segment

This segment informs the approaching driver of the start of an additional through lane at the next intersection. Supplemental signage and pavement markings should encourage drivers to use all intersection through lanes. Exhibit 5-8 illustrates the associated signing and pavement markings along this segment.

The following subsections provide guidance for determining the key design elements associated with the Approaching ATL segment.

Exhibit 5-8
Signing and Pavement Markings for Approaching ATL Segment



Upstream ATL Length

The upstream ATL length should be long enough to accommodate the design queue in the ATL and ensure that it is not blocked by the CTL during any point in the cycle. It should also accommodate deceleration from the approaching CTL to the back of the queue in the ATL. In addition, the start of the ATL should be visible early enough for approaching motorists to make informed decisions. The facility's approaching horizontal alignment, the presence of a vertical crest curve, or a horizontal-vertical alignment combination may require the ATL upstream portion to be lengthened to ensure the ATL introduction is visible.

Exhibit 5-9 provides a step-by-step approach for determining the minimum recommended upstream ATL length based on the anticipated back of queue in the CTL and ATL. The practitioner may determine that a longer upstream distance is needed based on prevailing traffic and geometric conditions. Note that the approach shown in Exhibit 5-9 requires application of the operational procedure described in Chapter 3. Appendix C contains a detailed description for calculating the minimum upstream and downstream ATL lengths.

Exhibit 5-9
Analysis Steps for Determining Upstream ATL Length

Step 1 Gather Input Data

- Total approach through and right-turn flow rates.
- Cycle length and effective green time for the subject approach.
- Saturation flow rate for both through and right-turn movements.

Step 2 Estimate ATL flow rate based on the one-CTL or two-CTL model in Chapter 3

Step 3 Calculate the ATL through flow rate using HCM 2010

- Assume equal lane volume-to-saturation flow rate (v/s) based on HCM 2010 shared or exclusive lane group volume distribution.

Step 4 Select the ATL volume as the lower ATL flow rate from steps 2 and 3

Step 5 Calculate performance measures for ATL and CTL

- Includes lane volumes, capacity, control delay, and back of queue using HCM 2010 signalized intersection procedures.
- For shared ATLs, include the right-turn flow rate in the lane flow computations.

Step 6 Estimate the 95th percentile queues

- Calculate for both ATL and CTL using HCM 2010 procedures.

Step 7 Determine minimum upstream ATL length

- Should provide both storage and unimpeded access to the ATL.
- Determine based on the maximum of the 95th percentile queues in the ATL and CTL, respectively.
- Calculate the queue storage distance based on an estimate of average vehicle spacing in a stopped queue for a given vehicle fleet mix (approximately 25 feet per vehicle).

Passive Taper

A passive taper rate of 10:1 or greater should be applied where the ATL is introduced. During slow-speed congested conditions, a 10:1 passive taper is adequate. A higher taper rate is appropriate for higher-speed locations. Local agencies typically have design guidelines for the introduction of an additional

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through lane and/or turn lane, which are either for a reverse curve along a specific length or a straight taper.

Signing

Side-mounted signing at the start of the ATL should be considered to effectively communicate to drivers that the ATL is intended to be used as a through lane. Field observations and data analysis appear to show higher ATL use at sites with advance lane-use signing. As described in Section 2B.22 of MUTCD, Advance Intersection Lane Control (R3-8 series) signs may be used to indicate the configuration of all lanes ahead.

Pavement Markings

Standard "Lane Line" pavement markings should be considered to clearly define the added through lane. In addition, a supplemental "Standard Through-Lane Arrow" should be considered at the start of the ATL to communicate the purpose of the added lane.

Approaching Signal Segment

When approaching the intersection, drivers should be reminded that the lane configuration on the approach to the intersection continues beyond the intersection. Without this reinforcement through drivers may be discouraged from using the ATL.

The design elements for this segment include the right-turn lane, curb radii, signing (overhead and side-mounted), and pavement markings. Exhibit 5-10 illustrates the recommended signing and pavement markings along this segment.

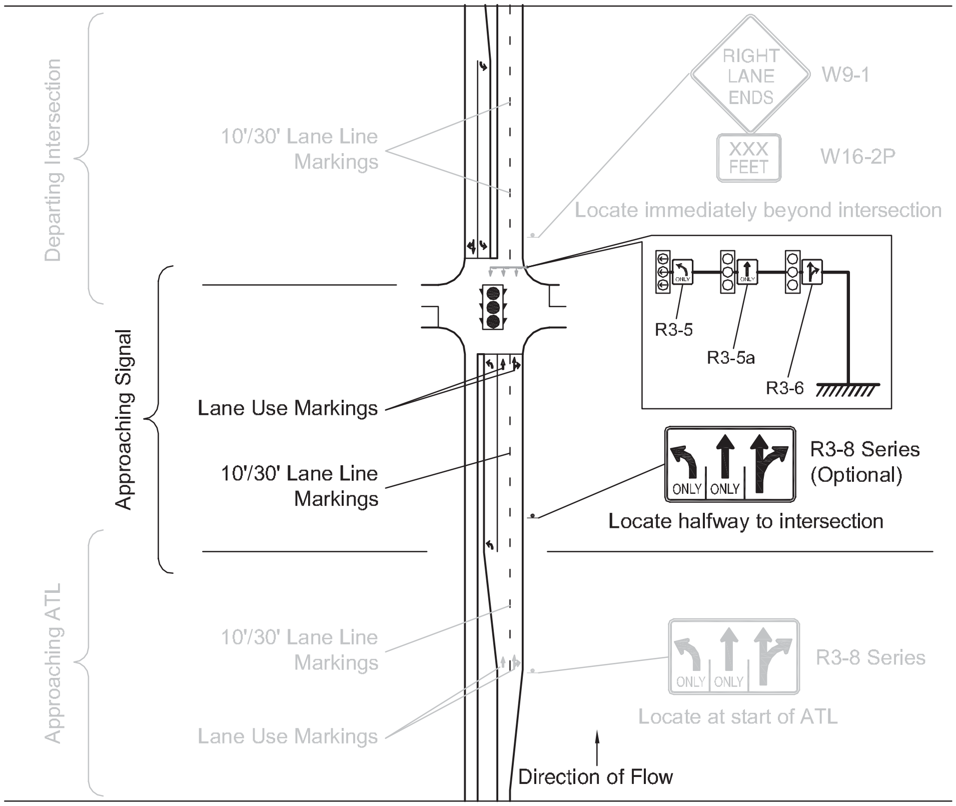

Exhibit 5-10
Signing and Pavement Markings for Approaching Signal Segment

Right-Turn Lane

As part of the ATL evaluation and design process, the practitioner should assess whether a separate right-turn lane is needed in addition to the ATL in accordance with local agency design practice. If a right-turn lane is provided, the start of the ATL should be located a sufficient distance from the start of the right-turn lane to separate decision points and minimize driver confusion, as illustrated in Exhibit 5-11.

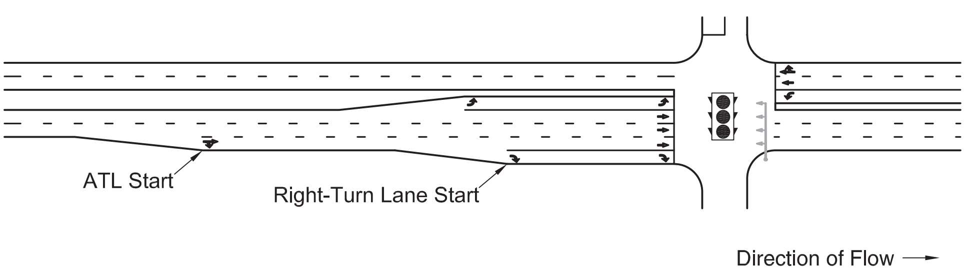

Exhibit 5-11
Appropriate Spacing between ATL Start and Right-Turn Lane

Curb Radii

Practitioners should consider the appropriate design vehicle and potential impact to other users when selecting a curb-return radius. Larger curb-return radii or three-centered curves for right-turns result in less deceleration in the

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ATL and higher ATL use. However, larger radii result in longer crossing distances for pedestrians and faster vehicular speeds at the crosswalk locations compared to smaller radii.

Overhead Signing

Similar to advance side-mounted signing at the start of the ATL, overhead signing for the mast arm or span wire should be considered to effectively communicate to drivers that the ATL is intended to be used as a through lane. Field observations and data analysis appear to show higher ATL use at sites with overhead lane-use signing. Either the Mandatory Movement Lane Control signs (R3-5 or R3-5a) or the Optional Movement Lane Control sign (R3-6) can be applied. Both are regulatory (black-on-white lettered) signs.

Side-Mounted Signing

Depending on the length of the ATL and distance to an upstream side-mounted lane configuration sign (if present), the sign should be located halfway between the beginning of the ATL and the stop bar. This sign is an MUTCD Advance Intersection Lane Control sign (R3-8 series).

Pavement Markings Guidelines

Standard “Lane Line” pavement markings should be considered to clearly define the added through lane. In addition, a supplemental “Standard Through-Lane Arrow” should be considered at the stop bar of the ATL to communicate the purpose of the added lane.

Departing Intersection Segment

In this segment, which begins immediately downstream of the intersection, drivers should be reassured that the through lanes are continuing for an appropriate distance beyond the intersection before drivers in the ATL begin to merge into the CTL. Exhibit 5-12 illustrates the associated signing and striping along this segment.

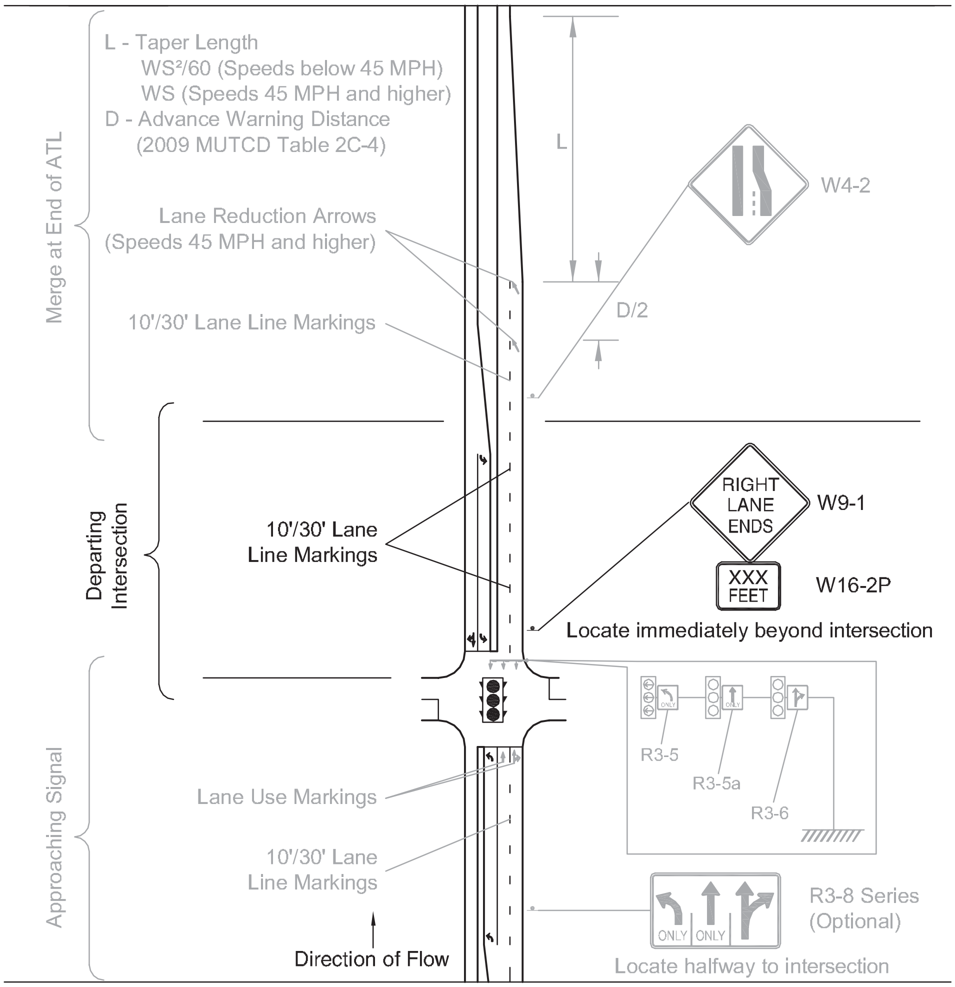

Exhibit 5-12
Signing and Pavement Markings for Departing Intersection Segment

Downstream ATL Length

Limited guidance is provided in national resource documents for determining the length of the downstream ATL. As part of this project, the research team developed a theoretical model to assist practitioners in determining this key design element. The method presented below is intended to be used as a guide for estimating the minimum appropriate downstream ATL length and not applied as a rigorous standard or requirement. It presents one option for estimating downstream ATL length. Individual agencies may have their own preferred method or guidelines.

Consideration should be given to the maximum downstream ATL length. ATLs with long downstream lengths may be perceived as a CTL and drivers may reach the end of the segment and realize unexpectedly that they are required to merge. From a review of the ATL study sites and other literature, it appears that a range of ¼ to ½ mile is an appropriate maximum value for downstream ATL length depending on prevailing speed, sight lines, and driveway/sidestreet activity.

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The method described in this subsection estimates the minimum downstream ATL length such that:

(a) Drivers in the ATL are able to reach the desired prevailing speed beginning from a stopped (queued) position and

(b) Adequate gaps are available in the CTL to enable a safe merge maneuver for vehicles that approach the traffic signal during the green phase when no queues are present.

In these guidelines, the distances described in (a) and (b) are referred to as DSL_1 and DSL_2, respectively. The greater of the two distances should be used to determine the minimum downstream ATL length. Additional distance may be appropriate based on the prevailing traffic and geometric conditions of the ATL approach. Appendix C provides a detailed description of the methodology used to determine DSL_1 and DSL_2.

The calculation for DSL_1, the minimum distance to accommodate acceleration from a stopped position, involves two steps:

1. Estimate the average uniform, random, and oversaturation back of queue (BOQ) for ATL and
2. Provide sufficient spacing between ATL vehicles at the prevailing roadway speed through the intersection after queues have cleared.

The equation for calculating DSL_1, measured from the far-side stop bar (in feet), is as follows:

Equation 5-1

$$DSL_1 = \frac{V^2}{2a} + (L + TV)(BOQ - 1) - INTW$$

where:

DSL_1 = Downstream length from far-side stop bar (in feet)

V = Prevailing roadway speed through the intersection after queues have cleared (in feet/second),

a = Acceleration rate from stop-line (in feet/second^2),

L = Spacing between vehicles at stop (in feet, typically 20–25 feet),

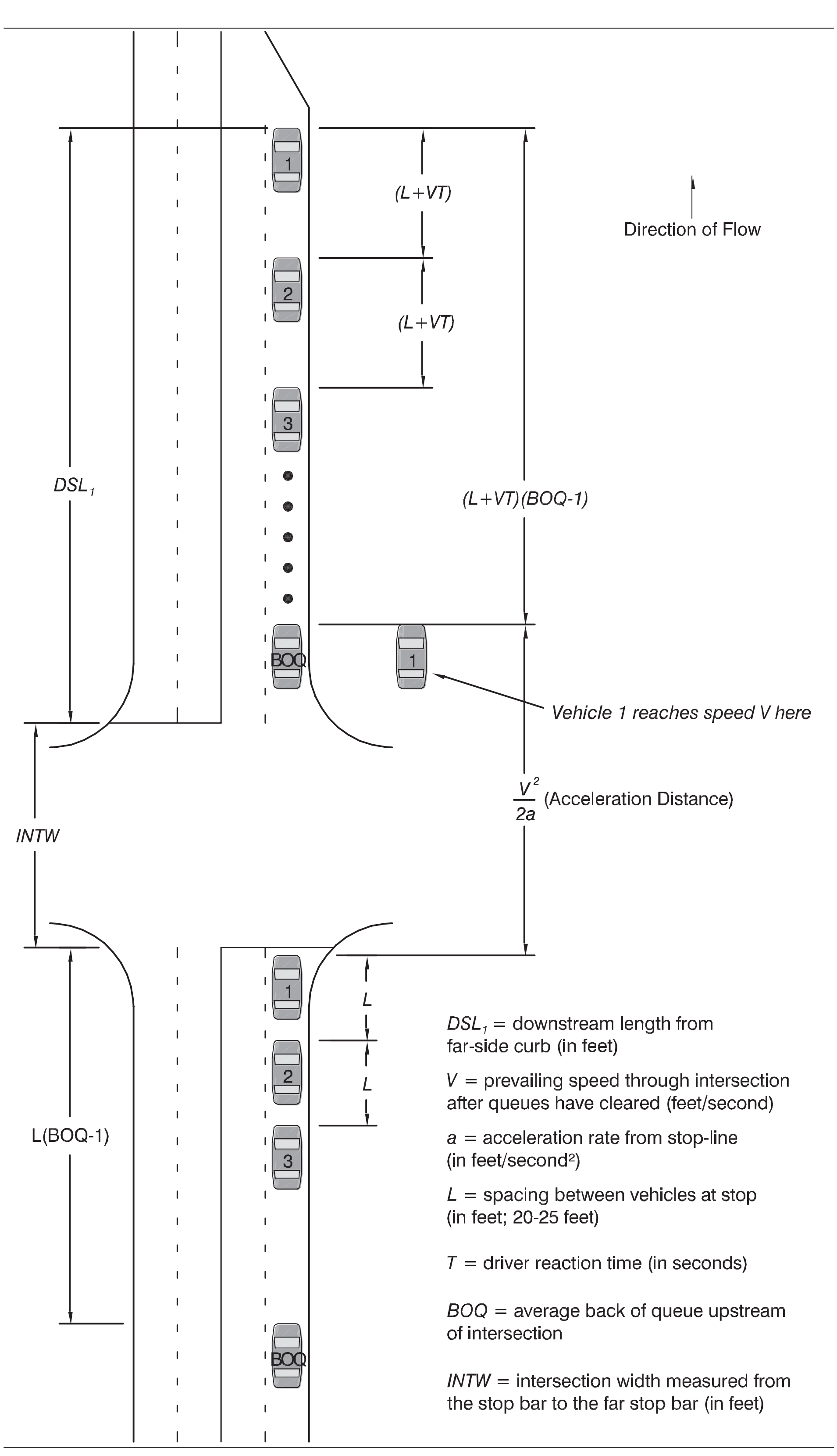
T = Driver reaction time (in seconds),

BOQ = Average back of queue upstream of intersection, and

$INTW$ = Intersection width measured from the stop bar to the far curb (in feet).

Exhibit 5-13 provides a graphical illustration of the method for calculating DSL_1.

Exhibit 5-13
Illustration of ATL Downstream Length (DSL_1) Calculation



Guidelines on the Use of Auxiliary Through Lanes at Signalized Intersections

The calculation of the minimum distance to provide adequate gaps for merging (DSL_2) is shown in the following equation (see Appendix C for more details):

Equation 5-2

$$DSL_2 = V(T + NUM \times G_r)$$

where:

NUM = The number of rejected gaps in the CTL. This could be either the mean value of rejected or a pre-specified percentile number of rejected gaps, as explained in Appendix C, and

G_r = Expected or average size of a rejected headway in the CTL (in seconds).

Based on initial testing and validation, the research team recommends applying DSL_2 assuming an 85^{th} percentile for rejected gaps, as opposed to the mean value. This is consistent with the use of the 85^{th} percentile in determining the design speed of a facility.

For one-CTL sites, DSL_2 will generally exceed DSL_1 for low-volume and low-speed approaches. For two-CTL sites, DSL_1 will most always govern the minimum downstream ATL length because of the higher volume of traffic and queue in the ATL.

Exhibit 5-14 shows potential ATL downstream lengths based on a set of operational parameters for an anticipated congested level at one-CTL facilities, while Exhibit 5-15 illustrates potential ATL downstream lengths at two-CTL facilities. These exhibits can be used for planning purposes to determine the minimum downstream ATL length for a given speed and congestion level as represented by X_T.

Exhibit 5-14
Planning Tool: ATL Downstream Guidance for One-CTL Approaches

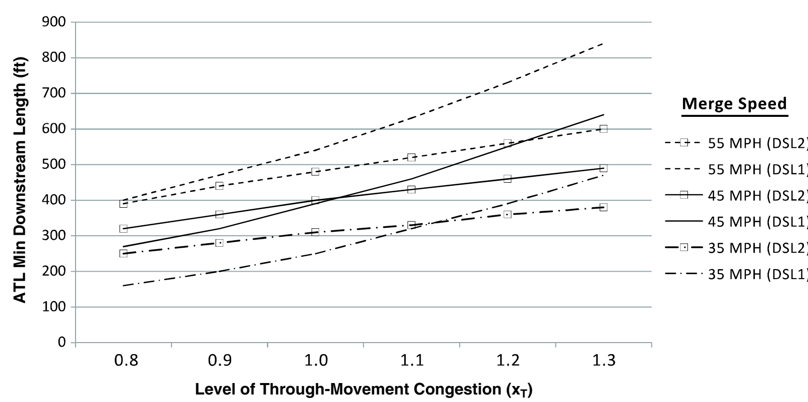
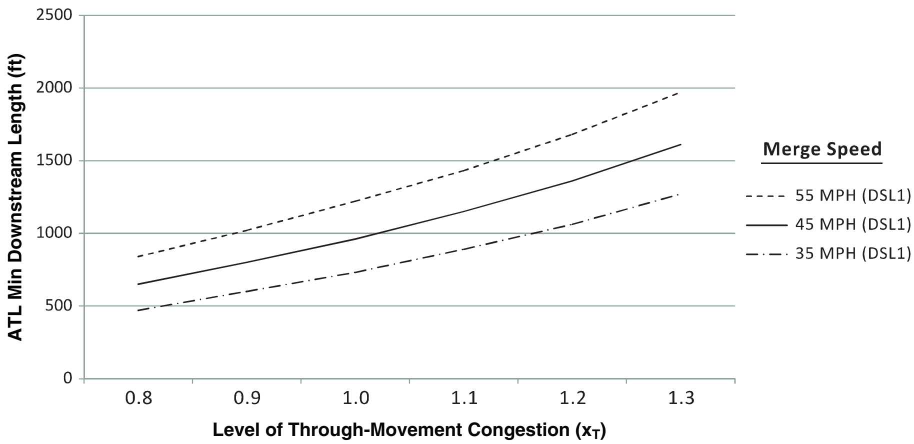


Exhibit 5-15
Planning Tool: ATL Downstream Guidance for Two-CTL Approaches



Practitioners should consider site-specific conditions when determining the appropriate downstream ATL length for their application. In addition, practitioners should consider the following for constrained conditions:

- The equations for DSL_1 assume that drivers in the ATL will accelerate to the prevailing roadway speed before attempting to merge; however, in many cases drivers will merge prior to reaching the prevailing speed. In addition, speeds are typically lower during the peak periods due to congestion along the corridor
- Observations indicate that drivers use a portion or all of the downstream taper for merging; thus, in some cases it may be appropriate for the practitioner to consider a portion of the taper as part of the downstream ATL length.

The practitioner must apply judgment in assessing the anticipated safety and operational effects of constrained conditions. In some cases, a constrained ATL site may not provide sufficient downstream ATL distance to accommodate merge maneuvers and driver expectations. In other cases, while ATL use at a constrained site is less than desired, it may provide the additional capacity needed to achieve a desired operating condition.

Signing

Signing in this segment is needed to effectively communicate to drivers that the ATL is ending a specific distance beyond the intersection. To accomplish this, consideration should be given to providing a side-mounted “Right Lane Ends” W9-1 sign approximately 50 to 100 feet minimum from the crosswalk (extension of opposite stop bar) along with a W16-2P or W16-2aP plaque that indicates the distance to the beginning of the taper.

Pavement Markings

Standard “Lane Line” pavement markings should be considered to clearly define the added through lane.

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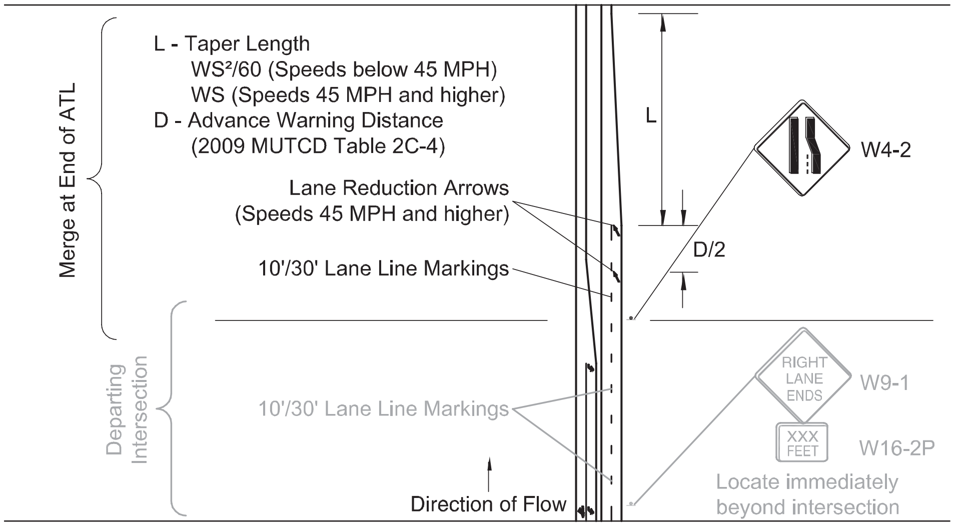
Merge at End of ATL Segment

Near the termination of the ATL and the taper segment, the driver needs to know that the extra lane is ending and that appropriate merge behavior is encouraged. Exhibit 5-16 illustrates the associated signing and striping for this segment.

Exhibit 5-16
Signing and Pavement Markings for Merge at End of ATL Segment



It should be noted that none of the observed study sites provided the advance placement of the warning signs as outlined in the 2009 MUTCD Table 2C-4. Some sites had the W4-2 signs located along the active taper.

Geometric Design Guidelines

The active taper should be consistent with MUTCD Figure 3B-14 based on the roadway speed.

Signing Guidelines

Consider providing the side-mounted W4-2 sign approximately halfway between the "Right Lane Ends" W9-1 sign located with the Departing Intersection segment and the end of the ATL. Ensure a minimum distance of 100 feet between W4-2 sign and the upstream "Right Lane Ends" W9-1 sign.

Pavement Markings Guidelines

Consider extending the standard "Lane Line" pavement markings to the end of the ATL to define the total length of the added through lane. In addition, supplemental "Lane Reduction Arrows" should be considered for speeds of 45 mph and higher.

6. SAMPLE APPLICATION

The purpose of this chapter is to demonstrate the application of the guidelines through a practical example. Several principles discussed previously in these guidelines are critical for the practitioner to consider throughout the ATL evaluation and design process:

- The ATL evaluation and design approach needs to account for the project's contextual environment as well as for applicable local, state, and federal policies, standards, and guidelines.
- An ATL has different operational characteristics from a CTL and should always be treated as a separate lane group, regardless of whether it is a shared lane or an exclusive lane.
- There is an iterative and dynamic relationship among geometric design choices, traffic operations performance, and the expected safety of an ATL.

This application example guides practitioners through the steps involved with conducting an operational evaluation of the addition of an ATL on a signalized intersection approach. Volume-to-capacity ratios, average delays, levels of service, and 95th percentile queue lengths under each alternative are computed on a lane-group basis according to standard *Highway Capacity Manual 2010* (*2*) procedures for a signalized approach. This sample application makes use of the computational engine that is described in Appendix B. Exhibit 6-1 illustrates the evaluation process.

Guidelines on the Use of Auxiliary Through Lanes at Signalized Intersections

Exhibit 6-1
Evaluation Process

Assess Multimodal Needs

- Identify facility needs for pedestrians, bicyclists, and transit riders

Evaluate Traffic Operations

- HCM analysis using statistical model to predict ATL
- Microsimulation

Assess Safety Effects

- Qualitative evaluation
- Conflict prediction

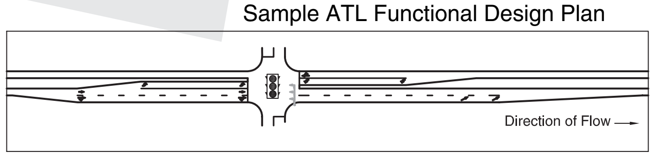
Calculate Design Elements

- Upstream Passive Taper
- Upstream ATL Length
- Downstream ATL Length
- Downstream Active Taper

Lay Out Individual Segments

- Approaching ATL
- Approaching Signal
- Departing Intersection
- Merge at End of ATL

Sample ATL Functional Design Plan



NOTES

- No additional data required beyond traditional intersection analysis
- Applicable to approaches with one or two continuous through lanes and an exclusive or shared right-turn lane

ATL APPLICATION EXAMPLE DESCRIPTION

The study intersection for this example is located at the crossroads of a principal arterial and a minor arterial in a suburban setting. Exhibit 6-2 identifies the key characteristics of the two roadways.

Exhibit 6-2
Sample Application Roadway Characteristics

Characteristics	Major-Street Roadway	Minor-Street Roadway
Classification	Principal Arterial	Minor Arterial
Avg. Annual Daily Traffic	25,000	15,000
Posted Speed	45 mph	35 mph
Lane Configuration	1 shared through/right lane 1 through-only lane 1 left-turn lane	1 shared through/right lane 1 left-turn lane

The local highway agency has received a significant number of complaints from citizens about back-ups on the eastbound approach at the intersection and future volume forecasts show additional traffic growth on the approach will only continue to degrade its operational performance. Options for adjusting the signal timing are very limited due to the high volume of traffic on the principal arterial and the intersection's location on a coordinated arterial.

The local highway agency is evaluating options for relieving the congestion on the eastbound approach. The minimum acceptable level of service for the design year is LOS E with a requirement that the volume-to-capacity ratio for all lane groups be less than 1.0 for the peak-hour period.

An arterial capacity analysis shows there is sufficient downstream capacity on the minor arterial to accommodate up to a 50 percent increase in through volume. However, because of right-of-way and funding constraints, the local highway agency has ruled out certain capacity-enhancing solutions such as adding a second CTL, converting to an alternative intersection configuration, or constructing dual left-turn lanes on the approach.

The volume-based data shown throughout this example represent the forecast demand on the eastbound approach, and not necessarily the volume measured through the intersection. This distinction is important as the final alternative selected should provide enough capacity to accommodate the full demand on the approach and not just the volume currently able to pass through the intersection. The term "volume-to-capacity ratio" will continue to be used, as it is the industry standard term for the performance measure of the volume or demand to the capacity of a movement, approach, or intersection.

The local highway agency is evaluating several improvement alternatives for the minor arterial eastbound approach:

- Alternative 0: Base case (do nothing)
- Alternative 1: Add an exclusive right-turn lane
- Alternative 2: Add a shared ATL
- Alternative 3: Add an ATL and an exclusive right-turn lane

The practitioner must be aware that these improvement alternatives are not the only alternatives that could be applied to address the congestion issue;

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however, for the purposes of this example, these are the agency's desired alternatives.

OPERATIONAL EVALUATION

Input Data

Exhibit 6-3 illustrates the design-year turning-movement volumes at the example intersection.

Exhibit 6-3
Turning-Movement Volumes

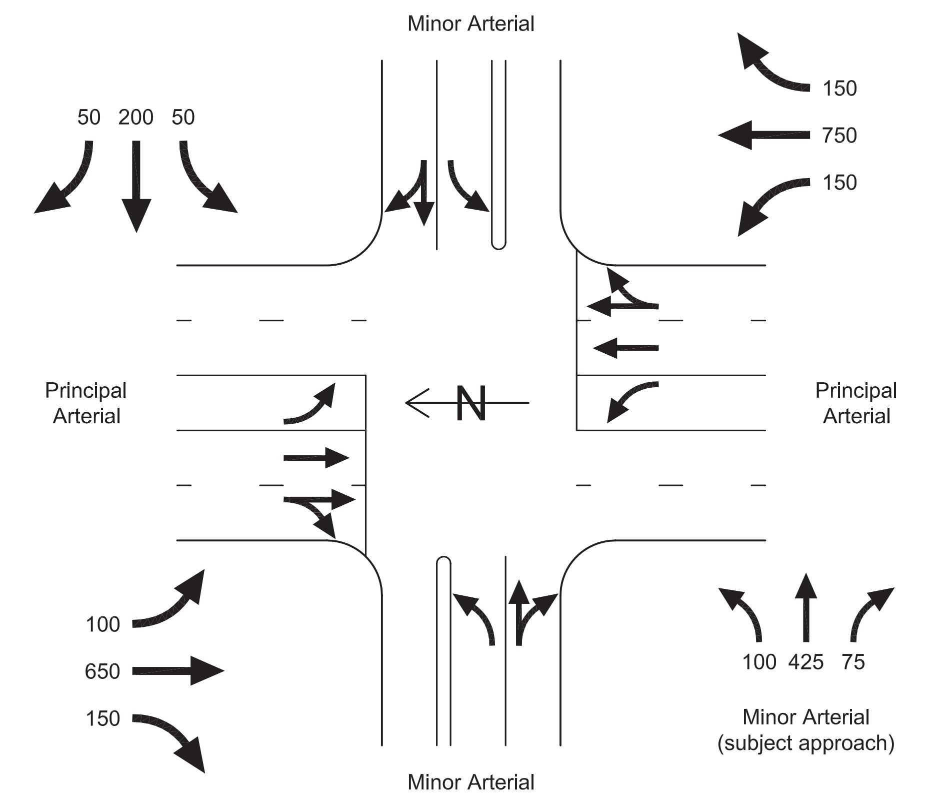

Exhibit 6-4 provides the specific input parameters to use in the operational evaluation of the approach alternatives.

Exhibit 6-4
Input Parameters

Input Parameter	Description
V_{TH} = 425 vph	Total approach through demand
S_{TH} = 1,800 vph	Through-movement saturation flow rate
V_{RT} = 75 vph	Total approach right-turn volume
S_{RT} = 1,550 vph	Right-turn movement saturation flow rate
V_A = 35 mph	Approach speed
IW = 110 ft	Intersection width, from stop bar to far curb
G_E = 25 sec	Approach effective green time
C = 110 sec	Intersection cycle length
L_{VEH} = 20 ft	Average length between vehicles under stop condition
A_{VEH} = 10 ft/sec^2	Average vehicle acceleration rate from stop condition
T_C = 6 sec	Critical gap in neighboring CTL traffic lane
R_T = 1 sec	Driver reaction time

The remaining sections describe the analysis and design steps for the sample application.

Insert Input Data into the Computational Engine

Exhibit 6-5 illustrates the input data for this example as entered in the one-CTL computational engine. It is important to understand when using the computational engine that input parameters should remain consistent through the evaluation of all alternatives unless site-specific data are collected to demonstrate otherwise. In this example, all of the input parameters remain consistent across all four treatment options.

Exhibit 6-5
Computational Engine Input Screen

1-CTL ONLY

COMPUTATIONS OF ATL LENGTHS (UPSTREAM AND DOWNSTREAM)-- FOR VARIOUS LANE CHOICES

	INPUT DATA HERE - CASE I IS THE BASELINE (SINGLE SHARED THRU+RIGHT LANE) ALL CELLS EXCEPT INPUT CELLS ARE PROTECTED			
1	ENTER THE CASE STUDY ID OR TITLE IN YELLOW BOX		HYPOTHETICAL CASE STUDY	
2	ENHANCEMENT: EXCLUSIVE RIGHT TURN LANE (Y/N)?	N	Please enter data in CAPS for first two entries	
3	ENHANCEMENT: ADDITIONAL EXCLUSIVE ATL (Y/N) ?	N	This entry cannot be "Y" if previous enry is "N"	
4	TOTAL APPROACH THROUGH VOLUME=	425	VPH	
5	RIGHT TURN VOLUME=	75	VPH	
6	APPROACH SPEED (MPH)=	35	MPH	
7	THRU SATFLOW PER LANE=	1800	VPH	
8	RIGHT SATFLOW PER LANE=	1550	VPH	
9	APPROACH EFFECTIVE GREEN=	25	SEC	
10	INTERSECTION CYCLE LENGTH=	110	SEC	
11	APPROACH EFFECTIVE GREEN WITH ATL / OTHER ADDS=	25	SEC	DEFAULT
12	AVERAGE VEHICLE SPACING AT STOP=	20	FT	20
13	AVERAGE ACCELERATION RATE FROM STOP =	10	FT/SEC/SEC	10
14	INTERSECTION WIDTH (STOPLINE TO FAR CURB)=	110	FT	40
15	CRITICAL GAP IN NEIGHBORING CTL TRAFFIC LANE=	6	SEC	6
16	DRIVER REACTION TIME=	1	SEC	1
	BASED ON THE INPUTS- THIS IS ANALYSIS CASE	III	1-CTL+SHARED ATL	

Evaluate Alternative ATL Configurations

This step involves toggling the input values in Line 2 and Line 3 to match the desired ATL configuration. To analyze an ATL with an exclusive right-turn lane, the input parameter in Line 2 is set to "Y", otherwise it is set to "N". If the ATL is exclusive and a right-turn lane is present, Line 3 is set to "Y", otherwise it is set to "N". The base case condition of a single CTL with shared right-turn movements is analyzed automatically.

Exhibit 6-6 displays the results from the evaluation of the four alternatives for the eastbound approach as reported from the computational engine.

Exhibit 6-6
Traffic Operations Analysis Results for the Eastbound Approach

Condition	Lane	V_{TH}	V_{RT}	V_{Tot}	v/c	Delay (sec)	LOS	95th% Queue (ft)
Base Case	CTL+RT	425	75	500	1.25	174	F	800
Add Right-Turn (RT) Lane	RT	0	75	75	0.21	36	D	100
	CTL	425	0	425	1.04	97	F	500
Add Shared ATL	ATL	138	75	213	0.55	43	D	200
	CTL	287	0	287	0.70	49	D	300
Add ATL & RT Lane	RT	0	75	75	0.21	36	D	100
	ATL	138	0	138	0.34	38	D	100
	CTL	287	0	287	0.70	49	D	300

Results from the analysis indicate the following:

- Under the base-case alternative, the eastbound approach has a volume-to-capacity ratio of 1.25 and operates at LOS F. These indicators show that the approach has more demand than the existing lane configuration and signal timing scheme can discharge through the intersection under forecast traffic conditions and that vehicles will experience high delays. This finding reinforces the need for a capacity improvement.
- With the addition of an exclusive right-turn lane, the CTL continues to operate at LOS F and slightly above capacity at a volume-to-capacity ratio of 1.04. Removing the right-turn demand from the CTL is not a sufficient improvement for this approach as the through demand is too high to be served by a single CTL.
- With the addition of the shared ATL, 138 out of 425 through vehicles (32 percent) are forecast to use the ATL. The result is that both the ATL and CTL operate below capacity and at LOS D. The 95th percentile back of queue is estimated to be 300 feet for the CTL.
- With the addition of an exclusive right-turn lane and an ATL, all of the right-turn volume shifts to the exclusive right-turn lane resulting in further improved operation of the ATL over the previous alternative. Given that the total through traffic in the CTL remains the same the performance of the CTL is identical to the shared ATL alternative.

Evaluate Anticipated Safety Effects

In addition to evaluating intersection operations, the potential safety impacts of installing an ATL will be investigated. As stated in Chapter 4, ATLs add lane-changing activity and this may lead to an increase of sideswipe crashes, especially in the downstream merge area. On the other hand, the forecast increase in through-movement capacity demonstrated in the above operational analysis may help prevent some rear-end and other congestion-related crashes on the ATL approach, especially since the approach is forecast to operate in a congested condition without the ATL.

The following list presents an assessment of safety considerations:

- **Access control.** There are no driveways in this example.

- **Sight lines.** The subject approach has adequate sight lines in this example. There are no visual obstructions within the sight lines.
- **Queuing downstream of the ATL merge.** There are no downstream bottlenecks causing queue spillback to the ATL.

Evaluate Multimodal Effects

This step evaluates effects on non-auto users to identify additional design needs for the ATL:

- **Pedestrians.** Pedestrian volumes in this example are low and the additional crossing time required to accommodate the ATL can be accommodated within existing signal timing.
- **Bicyclists.** Bicycle lanes are not being accommodated in this example.
- **Transit Vehicles.** No bus stops are included in the ATL in this example.

Select a Preferred Alternative

The selection of the alternative should consider multiple factors, including user considerations, operational performance, safety performance, cost, environmental impacts, time to implement, and public perception.

There are multiple ways to evaluate alternatives including but not limited to criterion rating, benefit-cost analyses, and best-value that meets the desired operational standard. For the purposes of this example application, the best-value alternative will be implemented, meaning the alternative with the least negative impact that satisfies operational performance standards will be selected as the preferred alternative, provided that it does not significantly compromise safety or other modes of travel. In this example, it is assumed that all of the alternatives are deemed feasible from user consideration, safety, and cost perspectives, and that the local highway agency is therefore focused on identifying the alternative with the lowest negative impact that meets its operational standard. The consideration of alternatives was conducted as follows:

- **Alternative 0.** Does not meet the local highway agency operational standard; therefore, this alternative is eliminated from further consideration.
- **Alternative 1**. Improves the operational performance of the eastbound approach, but still falls short of meeting the local highway agency operational performance standard; therefore, this alternative is also eliminated from further consideration.
- **Alternative 2**. Improves the operational performance of the eastbound approach to a satisfactory condition.
- **Alternative 3**. Improves the operational performance of the eastbound approach to a satisfactory condition, but requires additional lane widening to accommodate an exclusive right-turn lane in comparison to Alternative 2.

Based on this evaluation, and the earlier statement that each alternative is adequate from the user needs, safety, and cost perspective, Alternative 2

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provides the best value as it requires the least amount of widening, while still meeting the local highway agency's operational standards. Alternative 2, the addition of a shared through plus right-turn ATL, will be carried forward into the preliminary horizontal geometric design process.

PRELIMINARY HORIZONTAL GEOMETRIC DESIGN

The following section describes a step-by-step process to develop a preliminary horizontal design for the preferred alternative, the addition of a shared ATL. Refer to the exhibit at the end of this chapter for a detailed illustration of the preliminary horizontal design of the shared ATL in comparison to the existing eastbound approach configuration. The theory behind the design process is described in detail in Chapter 5.

Design Input Data

- Lane width: W = 11 feet;
- Approach design speed: S = 35 mph;
- Intersection width: I_W = 110 feet.

Step 1: Calculate the Length of the Design Elements

To gain an idea of the overall picture of the design needs for the eastbound approach and potential property, slope, drainage, and infrastructure impacts, the first step is to calculate the length of each of the four sections of the ATL. Steps 1a-1d identify the procedures for calculating the length of each of the ATL design elements:

- Passive taper
- Upstream ATL length
- Downstream ATL length
- Active taper

Step 1a: Determine the Length of the Passive Taper

Chapter 5 indicates that the minimum passive taper rate should be 10:1. Using an 11-foot lane width and applying the passive taper rate of 10:1, the minimum length for the passive taper is 11x10 = 110 feet.

Step 1b: Determine the Upstream ATL Length

The upstream ATL length should be sufficient to accommodate the maximum 95th percentile maximum vehicle queue on the approach along with any additional distance that is desired for deceleration. As shown in Exhibit 6-6, the maximum 95th percentile back of queue is 300 feet in the CTL. Given the 95th percentile back of queue in the ATL is expected to be 200 feet and prevailing speeds on the approach, a distance of 300 feet is deemed sufficient to accommodate safe deceleration (which is assumed to begin in the taper) for a vehicle that departs the CTL and reaches the back of queue in the ATL.

Step 1c: Determine the Downstream ATL Length

The minimum length for the section departing the intersection is computed using the computational engine and following the procedure described in Chapter 5. Exhibit 6-7 summarizes the geometric parameters for this design. The downstream ATL length calculations based on the two methodologies show the following results:

DSL_1 = 220 feet

DSL_2 = 250 feet

The greater of the two distances should be used to determine the minimum downstream ATL length, which for this example is 250 feet. Given the posted speed (35 mph), lack of driveways, clear sight lines, and available right-of-way, the downstream ATL length of 275 feet is selected for this design.

Exhibit 6-7
Summary of Geometric Parameters

Condition	Upstream ATL Length Based on Storage Q-Length (ft)	Downstream ATL Length (ft)	Downstream ATL Length Based on CTL-Gap Acceptance Distance (ft)
Add Shared ATL	300	220	250

Step 1d: Determine the Length of the Active Taper

The minimum length for the active taper is calculated in a manner consistent with MUTCD (3) recommendations. In this example the width of the ATL is 11 feet and the speed of the minor arterial is 35 mph. The downstream merge section length is calculated as:

$$\text{Active Taper} = \frac{11 \times 35^2}{60} = 225 \text{ feet}$$

Step 2: Assess the Viability of Installing the ATL

Once the design elements are defined, existing slopes, drainage areas, rights-of-way, utilities, and other infrastructure should be evaluated out to a width of approximately 15 to 25 feet from the existing curb or edge of pavement line to gain an idea of the effects that will occur due to the addition of the ATL. In this example, the cross section assumed for the ATL addition is an 11-foot wide ATL, with a 6-inch vertical curb, a 6-foot attached sidewalk, and a 4:1 cut/fill slope to tie into existing ground. In this example, there are no major conflicts within the cross-sectional area.

Step 3: Design the Upstream Full-Width Lane Segment of the ATL

This step involves identifying the signing and pavement markings for the upstream segment given the length of the passive taper and upstream ATL length described in Step 1. The following treatments are recommended:

- Place a 10-foot skip stripe with 30-foot breaks along the entire length of the upstream full-width lane.

- At the upstream start of the full lane width of the ATL, place a lane configuration sign (side-mounted MUTCD R3-8 series sign) and add lane-use pavement markings to both the ATL and CTL lanes at this same point to provide lane-use confirmation for drivers.
- Place overhead lane configuration signs for both the ATL and CTL on the signal mast arm for the approach to provide additional confirmation of lane use for drivers.

Step 4: Design the Downstream Full-Width Lane Segment of the ATL

Similar to Step 3, this step identifies the signing and pavement markings for the downstream ATL segment:

- Place a 10-foot skip stripe with 30-foot breaks along the entire length of the downstream full-width lane.
- Provide a side-mounted "Right Lane Ends" W9-1 sign approximately 50 feet minimum from the crosswalk (extension of opposite stop bar).
- Place the "Lane Ends" W4-2 sign at a point halfway between the extension of the opposite stop bar and the end of the full-width lane segment, approximately 150 feet from the extension of the opposite stop bar. Note: Ensure a minimum distance of 100 feet between the W4-2 sign and the upstream "Right Lane Ends" W9-1 sign.

Step 5: Design the Tie-ins at the Intersection

Design the curb tie-ins on both the upstream and downstream sides of the intersection to connect the ATL to the principal arterial cross street, as described in the following bullets:

- Determine the appropriate design vehicle for the intersection based on local standards. In this example, the design vehicle is a WB-50.
- Place an appropriate radius for the curb return to connect the ATL to the cross street exit leg based on the WB-50 envelope. In this example, a 50-foot curb return radius is used.
- Place an appropriate radius for the curb return to connect the principal arterial approach to the ATL based on the WB-50 envelope. In this example, a 50-foot curb return radius is used.

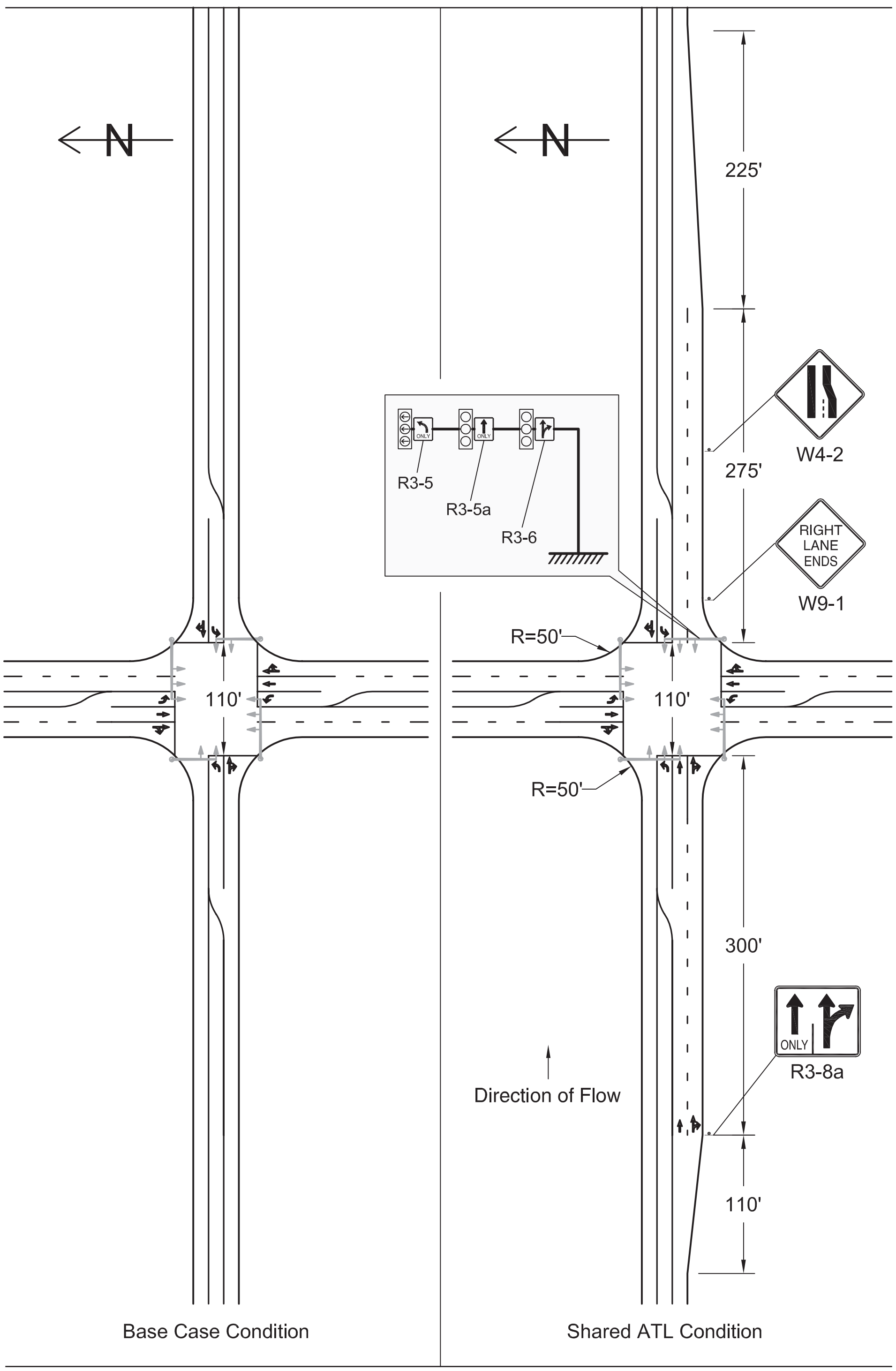
SUMMARY

Exhibit 6-8 illustrates the result of the design process for the sample application of the one-CTL approach with a shared ATL.

Remaining design steps for an ATL are similar to that of any full (continuous)-lane widening design process. They include developing plans for the vertical profile, drainage, and utility relocations (where necessary) and preparing final design plans, specifications, and a cost estimate for the ATL improvement.

Sample Application

Exhibit 6-8
Comparison of the Base Case to the Preferred Alternative Design



7. REFERENCES

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APPENDIX A

A SIMULATION-BASED APPROACH TO ATL EVALUATION

These guidelines are primarily focused on deterministic approaches for predicting operations of an auxiliary through lane (ATL) adjacent to one or two continuous through lanes (CTL). The ATL volume prediction models described in Chapter 3 are based on a deterministic analysis framework and are directly compatible with the *Highway Capacity Manual* (HCM) procedures.

The HCM recognizes that the use of alternative analysis tools, and specifically microsimulation approaches, has merit in a number of applications. In an effort to study the utility of microsimulation tools for ATL applications, this appendix describes guiding principles and considerations for applying simulation to ATL evaluation. The discussion covers both the operational evaluation of ATLs (delays, queue lengths, etc.), as well as approaches for estimating safety performance measures (conflicts) from simulation using the SSAM post-processing tool developed by FHWA (*1*).

The lessons learned described in this appendix are closely related to the experience of the research team for NCHRP Project 3-98, which involved a significant microsimulation modeling and calibration effort. The project used the VISSIM simulation package (*2*), but this appendix describes the analysis principles in generic terms to the extent possible.

Principles of Lane Change Algorithms

Microsimulation tools explicitly model the movement of individual vehicles using a series of behavioral rules known as algorithms. Among these, lane changing algorithms are most critical for accurately describing ATL behavior. Most simulation models distinguish between "voluntary" and "mandatory" lane changes. *Voluntary lane changes* apply when a driver has multiple lanes available on the desired route, and switches lanes to—for example—pass a slower vehicle. The key point here is that the subject vehicle would have arrived at its desired destination regardless of whether it changed lanes. *Mandatory lane changes* on the other hand, are those that are necessary for performing a turning maneuver or for prepositioning in anticipation of a downstream lane drop. In other words, a mandatory lane change has to take place if a vehicle is to continue on its desired path. In the application to ATLs, the driver's decision to enter the ATL is generally a consequence of a voluntary lane change (e.g., to pass a queue of vehicles in the CTL). To be precise, the desire for a voluntary lane change is initially triggered by the car-following algorithm if the target vehicle's desired speed exceeds that of a vehicle ahead of it in the same lane. The voluntary lane change then describes the process of searching for suitable gaps in the adjacent lane (in this case, the ATL), and then ultimately switching lanes. On the other hand returning from the ATL to the CTL represents a mandatory lane change. Most simulation tools have different parameter sets in their voluntary and mandatory lane change algorithms and the analyst needs to understand the associated settings to accurately model the lane-changing behavior.

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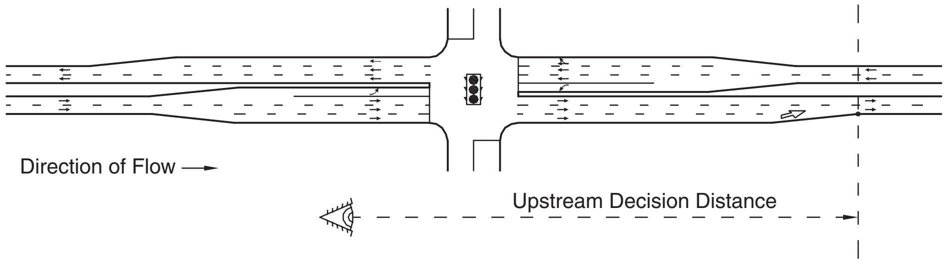
In the case of mandatory lane changes, a common parameter used in the algorithm is the upstream decision distance. This distance is typically measured relative to the ATL lane drop and refers to the point at which drivers begin to be concerned with the lane drop. Exhibit A-1 illustrates this concept.

Exhibit A-1
Illustration of Upstream Decision Distance in Simulation



The upstream decision distance describes the point at which the mandatory lane change algorithm becomes active. In most simulation tools, drivers will begin trying to merge at this decision point if gaps are available and will become increasingly aggressive about their lane-changing behavior as the distance to the downstream drop decreases. Further, in most cases, the mandatory lane change algorithm will override any voluntary lane changes. As a result, no voluntary lane changes will take place past the upstream ATL decision point, and consequently no CTL-to-ATL maneuvers will take place past that point. In this context, it is important to emphasize that a coded upstream decision distance that is greater than the total ATL length *will prevent any voluntary lane changes into the ATL and will therefore result in zero through flow on the ATL.*

In NCHRP Project 3-98, this upstream decision distance (described in VISSIM as the lane change distance, LCD), proved to be the single best predictor of ATL lane utilization and a critical calibration factor to replicate field-observed ATL utilization in VISSIM.

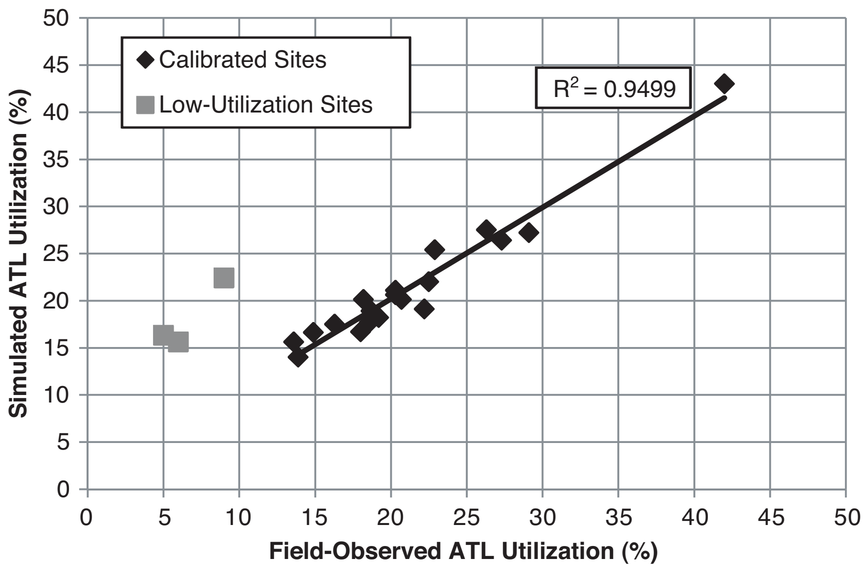
Calibration of Simulation Models

Consistent with any simulation analysis, the parameter set used in the simulation model needs to be calibrated to match field conditions or known relationships in traffic flow theory. Calibration can include various changes to built-in simulation algorithms, including speed distributions, car-following logic, or lane-changing parameters. Significant research is available on the topic of simulation calibration, including material compiled by FHWA in the Traffic Analysis Toolbox. For this discussion, the topic of calibration is condensed to the specific application to ATLs.

The foremost goal in the calibration of a simulated CTL-ATL system is to match the field-observed ATL utilization or, in the absence of field data, the ATL volume predicted from the models presented in these guidelines. By varying the LCD parameter in VISSIM, the research team was able to successfully calibrate 19 of the 22 studied ATL approaches. The remaining three approaches exhibited very low utilization (less than 10 percent). These low-utilization percentages could not be replicated without also making significant adjustments to the car-following logic, which in turn resulted in more simulated “crashes.”

Exhibit A-2 shows the resulting relationship between field-observed and simulated ATL percentages for the 19 approaches (black) and a best-fit line. The three low-utilization approaches (gray) are treated as outliers.

Exhibit A-2
Calibration Result Showing Field-Observed vs. Simulated ATL Utilization



The simulated ATL utilization percentages shown in Exhibit A-2 were the result of free lane selection by drivers on the intersection approach, subject to the algorithms of car-following, lane changing, etc. The ATL utilizations were not "forced" in the sense that a fixed percentage of through traffic was routed through the ATL. In this sense, the resulting R^2 of 0.95 shows a high rate of success in calibrating ATL utilization through the LCD parameter in VISSIM.

Other calibration efforts may include accurate coding of turning-movement flows, speed distributions, signal-timing parameters, etc. The analyst should further validate some of the outputs from the simulation model to field data if available. These outputs may include approach delays, total through travel time, or vehicle queues.

ATL Utilization Prediction Model

Given the sensitivity of the LCD parameter on ATL utilization, an effort was made to predict the correct LCD setting for (future) ATL sites, where the true utilization is unknown. The dependent variable LCD was expressed in the following way:

LCD % Total: the LCD expressed as a percentage of the total ATL length, computed as

$$LCD\%TOTAL = \frac{LCD}{Total\ ATL\ Length} \times 100\%$$

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Other forms of the dependent variable were explored, but the one quoted above emerged as the preferred definition. Several explanatory variables were hypothesized to affect the LCD used to calibrate VISSIM, including traffic volumes, approach speeds, upstream and downstream length, and a distinction between single and dual CTLs. Ultimately, the following two explanatory variables were used in the LCD prediction model:

Volume: through traffic flow rate expressed in vehicles per hour (vph)

Upstream: the length of the ATL segment upstream of the stop bar, in feet

The resulting model predicting LCD%TOTAL as a function of these two variables is given below:

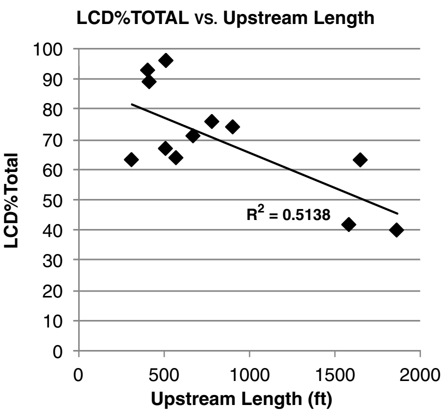
$$LCD\%Total = 89.696 - .01125\ Upstream\ - .0172\ Volume$$

$$R^2 = 0.622$$

The R^2 value suggests that 62.2 percent of the variability in the LCD variable that provided the best match to the field data is explained by the variables in the model for the regression data set. This suggests that the model can be used to arrive at a reasonable initial estimate for the LCD parameter if VISSIM is used to model the ATL. For other simulation tools, this model may similarly guide an initial parameter estimate, but the model has not been calibrated for such applications.

The model suggests that the LCD begins at 89.696 percent of the total ATL length, which coincides approximately with the highest LCD value observed in previous VISSIM calibration. That term is then discounted with increasing upstream length and through volume. This implies that ATL utilization *increases* with increasing upstream length and through volume. This relationship is consistent with field observation. A closer exploration of the two explanatory variables also suggests a good model fit as shown in Exhibit A-3.

The exhibit shows that LCD%Total is approximately linear with respect to the upstream length of the ATL and the combined through volume.



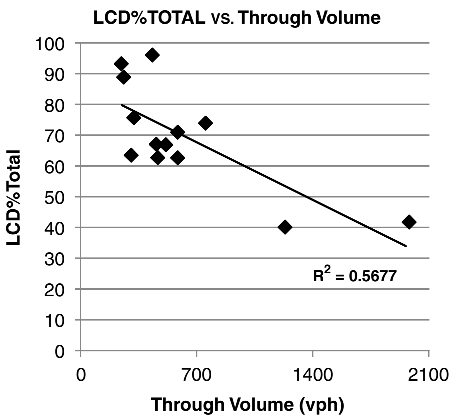


Exhibit A-3
Sensitivity of LCD%TOTAL vs. Upstream Length and Through Volume

Surrogate Safety Assessment

As part of the safety analysis, the researchers investigated a technique to use the Surrogate Safety Assessment Methodology (SSAM) in conjunction with a calibrated VISSIM model in order to predict safety conflicts at ATL approaches. SSAM was developed by FHWA as a post-processing tool to estimate vehicular conflicts from simulation trajectory files. These raw simulation output files store the speed, position, and acceleration of every simulated vehicle during each simulation time step among other data. From the trajectory files, SSAM defines a conflict, for example, if two vehicles occupied the same space within a user-defined time-to-crash (TTC) threshold. Full details on the SSAM tool and definitions of terms can be found in the documentation for SSAM (*1*).

In this research, the SSAM tool was applied to all 16 of the ATL approaches that were part of the safety evaluation in Chapter 4. This evaluation was performed after the ATL utilization was calibrated to empirical observations. The results of this investigative conflict study were not fully validated by the crash data presented in Chapter 4, mostly due to the low crash sample sizes, flaws in crash reporting, and other errors. Nonetheless, the SSAM output can still be used to examine relationships between conflict frequency and key ATL design elements such as downstream length.

From the calibrated simulation models, SSAM uses the trajectory (*.trj) files generated by the simulation and can apply various filters during analysis to define a conflict:

Conflict type. SSAM distinguishes between *angle*, *lane change*, and *rear-end* conflicts by the angle at which the conflict occurs. Only lane change and rear-end conflicts were targeted in this analysis.

Time to crash (TTC). The threshold for what defines a "conflict" is the TTC, which can be adjusted to 0.5, 1.0, or 1.5 seconds. This analysis used a TTC equal to 1.5 seconds to get a conservative estimate of the number of conflicts to compare with crash data.

Link. The analyst can filter conflicts by the link ID number used in the simulation tool. This allows the analyst to filter conflicts by the upstream or downstream portion of the ATL (or by multiple ATL approaches within one

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simulated intersection) as long as they are numbered as separate links in the simulation network.

Trajectory file. If multiple runs are simulated, the analyst can obtain the conflict frequency for each trajectory file within the multi-run simulation.

Using these methods, the analyst can compare design alternatives such as downstream length, speed, congestion, and the presence or absence of an ATL. Exhibits A-4 and A-5 show how the number of SSAM rear-end and sideswipe conflicts, respectively, changed for an exclusive lane with respect to downstream ATL length and X_T. Rear-end conflicts remained relatively consistent as downstream length increased, but the number of sideswipe conflicts spiked at a downstream length of 800 feet. This may be due to some quirk in the simulation or SSAM logic and the low sample size of sideswipe conflicts. Conflicts tended to increase fairly steadily with increasing X_T, as might be expected.

Exhibit A-4
SSAM Rear-End Conflict Comparison (No Right Turns)

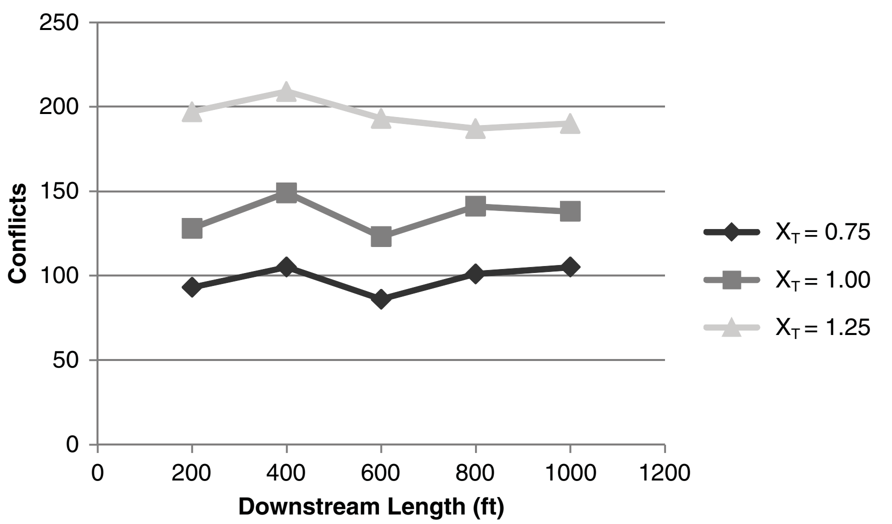
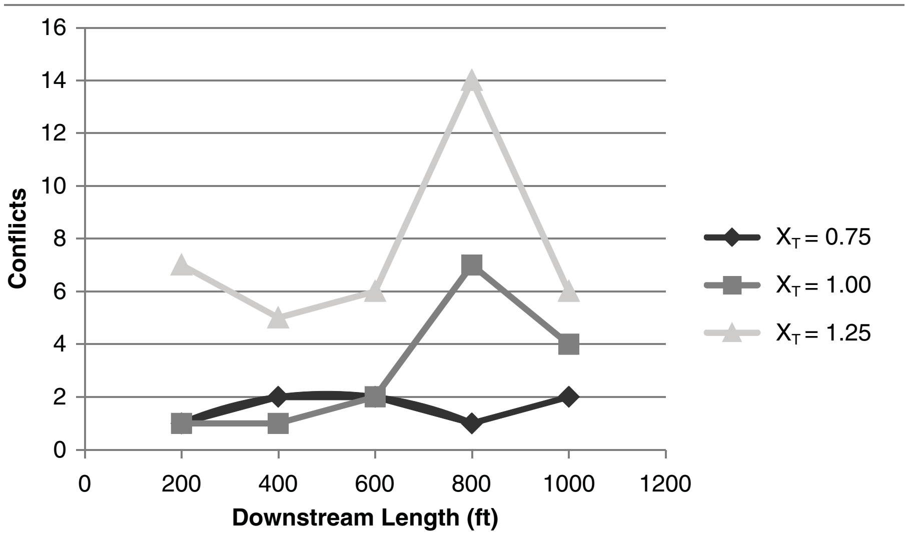


Exhibit A-5
SSAM Sideswipe Conflict Comparison (No Right Turns)



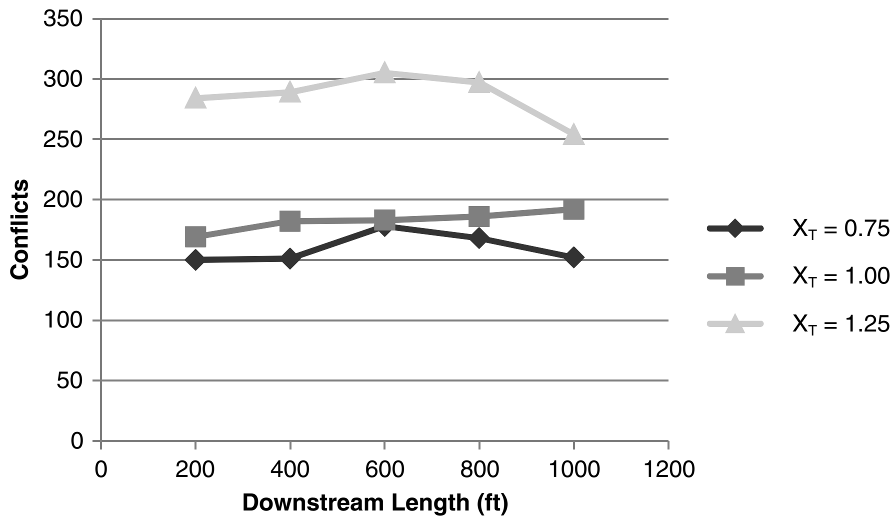


Exhibit A-6
SSAM Rear End Conflict Comparison (200 Right-Turning Vehicles per Hour)

Exhibits A-6 and A-7 show the same types of comparisons for a shared ATL with 200 right turns per hour. The exhibits indicate that low-to-moderately congested approaches had low levels of conflicts when compared to those simulated at X_T = 1.25. While rear-end conflicts remained relatively unaffected by changes in downstream length, the number of sideswipe conflicts tended to increase as downstream length increased. This could be explained by the exposure, as a greater downstream length tended to generate more conflicts in SSAM simply because the conflict area was lengthened. Note that if the number of conflicts was normalized by downstream length, a decreasing trend would emerge. Also note that there were many more conflicts generated by the shared lane than by the exclusive ATL scenario.

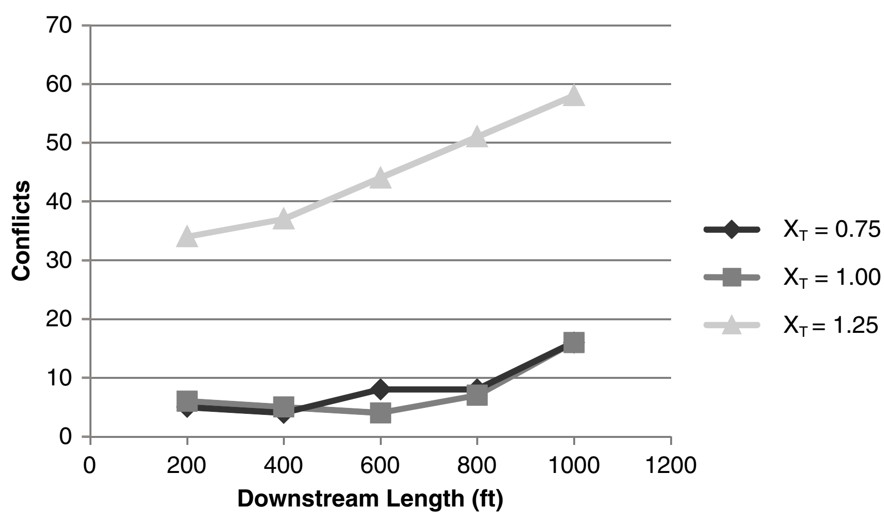


Exhibit A-7
SSAM Sideswipe Conflict Comparison (200 Right-Turning Vehicles per Hour)

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The analysis of variance for the rear-end conflict data across all levels tested indicated that there were statistically significant interactions between the right-turn volume and X_T and between the right-turn volume and the downstream length. The former interaction is intuitive, as the effect of right-turning vehicles as a detriment to safety magnifies when there is more through traffic in the shared ATL. In terms of the sideswipe conflicts, multiple significant interactions existed—some of these were unexpected and may be due to the low sample size for sideswipe conflicts.

In general, it appears that the SSAM logic confirms intuition. First, it appears that changes in downstream length are not associated with changes in the observed number of conflicts in the ATL. Second, shared ATLs (at least those with 200 or more right-turning vehicles per hour) tend to have more conflicts than exclusive ATLs. Finally, the crash increase with the increase in X_T discussed in Chapter 4 was supported by the increase in conflicts with X_T shown in Exhibits A-4 through A-7, particularly as X_T increased beyond 1.0.

Proposed Work Flow of ATL Simulation Study

If an analyst is studying the feasibility of an ATL intersection improvement, the following list of steps represent a proposed analysis work flow. Please note that additional steps may be necessary, depending on the specific location, and the practitioner should exercise sound judgment in any simulation analysis.

Step 1: Gather input data, including existing and proposed intersection geometry, traffic turning movements (current and forecast), approach speed limits, and signal timing data.

Step 2: Model baseline, representing the existing intersection without ATL approaches.

Step 3: Calibrate baseline, by comparing the modeled operations to field data or other analysis approaches. Make any necessary adjustment to traffic volumes, speed inputs, signal timing, or other simulation algorithms.

Step 4a: Estimate initial LCD parameter, using the predictive model in this appendix as a function of the total (future) through traffic flow and proposed total ATL length. An initial estimate of the ATL upstream and downstream lengths is therefore needed for this analysis.

Step 4b: Estimate ATL predicted volume, using the models described in Chapter 3 of these guidelines. These estimates will be used to validate that the ATL utilization is modeled correctly.

Step 5: Model ATL geometry, using proposed geometry, signal timing, and volumes (step 1), and the initial LCD parameter from Step 4a.

Step 6: Calibrate ATL operations, by modifying the LCD until the simulated ATL volume matches (approximately) the predicted volume from Step 4b. As a general guidance, a longer LCD will result in lower utilization of the ATL.

Step 7: Evaluate ATL performance, by running repeated iterations of the baseline and ATL scenarios and comparing the average performance. A suggested performance measure is the total through travel time, which is readily compared to field data. Additionally, approach delay and queue lengths are important performance measures that are also predicted in the deterministic HCM analysis approach.

Step 8: Evaluate safety performance, by extracting trajectory files from simulation and analyzing for conflicts in the SSAM post-processing tool. To estimate ATL safety performance, the SSAM evaluation should be limited to the specific ATL link in question and should distinguish between rear-end and lane-changing conflicts, as well as conflicts in the upstream and downstream portions of the ATL.

Depending on the objective of the analysis, it may be useful to obtain performance measures on a per-lane basis, to be able to isolate the performance of the ATL. As general guidance, it is important to use the same definitions of performance measures for baseline and any ATL scenarios to assure an even comparison. For example, any travel time segments should be defined for a distance long enough to contain the longest queue length in the baseline scenario and should not be changed when moving to the ATL scenario.

References

1. Surrogate Safety Assessment Model (SSAM). Version 2.0. Federal Highway Administration. Siemens ITS: 2004.
2. VISSIM. Version 5.30-02. PTV America: Portland, Oregon, 2010.

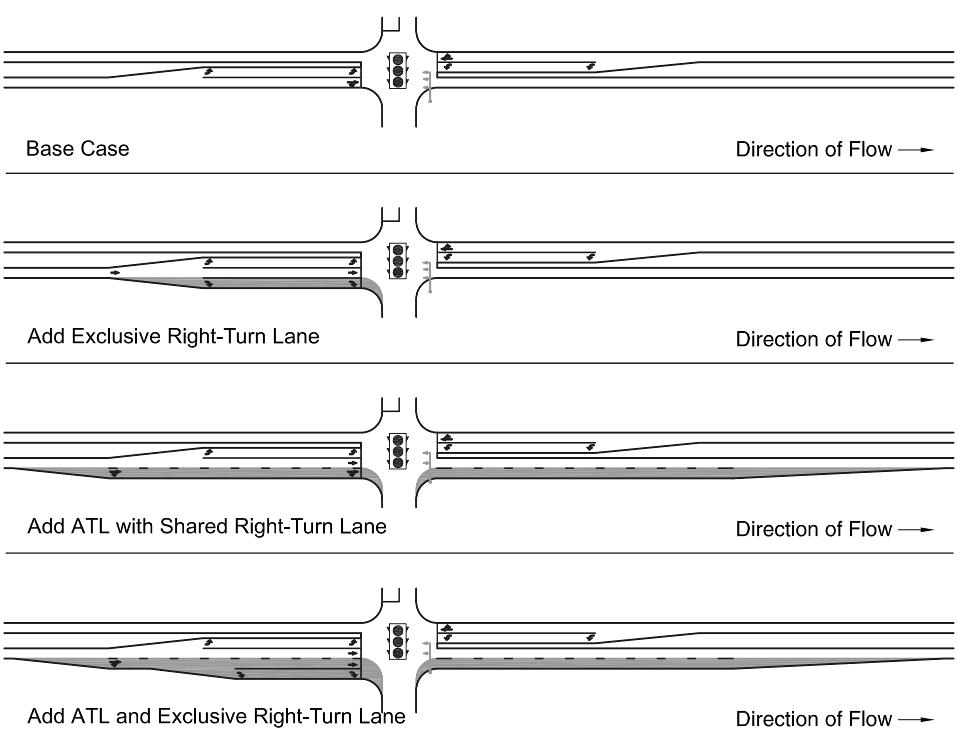
APPENDIX B

COMPUTATIONAL ENGINE

The computational engine described in this appendix implements the procedures described in Chapter 3 in a Microsoft® Excel spreadsheet environment for both one-CTL and two-CTL approaches. The base geometric configuration for one-CTL approaches is a shared CTL and an exclusive left-turn lane, as illustrated in the top portion of Exhibit B-1. Three possible design scenarios can be evaluated in the computational engine as indicated in the exhibit:

- Add an exclusive right-turn pocket (no ATL),
- Add an ATL with shared right turns, or
- Add an exclusive ATL and an exclusive right-turn pocket.

Exhibit B-1
Design Options for One-CTL Case



A similar set of design options is provided in the same spreadsheet for a two-CTL configuration.

The Input Dialog Box

The input dialog box for a one-CTL case is depicted in Exhibit B-2. Users enter information for the geometric configuration and signal timing in Lines 1–5 consisting of the number of CTLs (1 or 2), whether an ATL is present (Yes or No), if an exclusive right-turn lane is present (Yes or No), the effective green time for

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the through movement, and the cycle length for the intersection. Users can input information for up to two scenarios to perform a comparative analysis.

Exhibit B-2
Input Dialog Box

I. GEOMETRIC CONFIGURATION AND SIGNAL TIMING

		Scenario 1	Scenario 2
1	Number of CTLs (1 OR 2)	1	1
2	ATL (Y/N)?	N	Y
3	Exclusive right-turn lane (Y/N)?	N	N
4	Effective green time for through movement(s) (sec) =	25	25
5	Cycle length (sec) =	110	110

II. APPROACH CHARACTERISTICS

		User Input (Applies to Both Scenarios)	Comment
6	Total approach through volume (vph) =	425	
7	Total saturation flow rate for CTL(s) (vph) =	1800	Add sat flow across both lanes for 2 CTL approaches
8	Right-turn volume (vph) =	75	
9	Right-turn lane saturation flow rate (vph) =	1550	
10	Prevailing approach speed (mph) =	35	Speed at which vehicles approach intersection during green phase
11	Average vehicle spacing at stop bar (ft) =	25	Default value = 25 ft
12	Average acceleration rate from stop bar (ft/sec/sec) =	10	Default value = 10.0 ft/sec/sec
13	Intersection width measured from stop bar to far curb (ft) =	110	
14	Critical gap in adjacent CTL (sec) =	6	Default value = 6.0 seconds
15	Driver reaction time (sec) =	1	Default value = 1.0 seconds
16	Confidence level for calculation of downstream length =	0.85	Express as decimal between .85 and .95

Approach characteristics are entered in Lines 6–16. These values apply to both scenarios 1 and 2. The input requirements include volumes and adjusted saturation flow rates for the through and right-turn movements (note that all procedures assume that through movements are free of any impedance caused by left-turn movements if left-turn movements are present). Additional input information consists of prevailing approach speed, average vehicle spacing at stop bar, acceleration rate from stop bar, intersection width, critical gap for merging from ATL into CTL, driver reaction time, and a confidence level for calculating the downstream ATL length.

Note that items 12–16 are primarily related to determining the downstream ATL length and can be defaulted to the values shown on the right-hand column.

Summary Results Tabulation

Results from the computational engine are summarized at the lane-by-lane and approach levels, as shown in Exhibit B-3.

Exhibit B-3
Summary of Results Layout

III. LANE-BY-LANE RESULTS

Lane	Configuration	TH Vol (vph)	RT Vol (vph)	TH + RT Vol (vph)	XALL	Avg. Delay (sec/veh)	LOS	95th % Queue (ft)
Scenario 1								
1	SHARED CTL	425	75	500	1.25	**174.2**	**F**	1000
2								
3								
4								
TOTAL		425	75	500				
Scenario 2								
1	CTL	287	0	287	0.70	**48.7**	**D**	400
2	SHARED ATL	138	75	213	0.55	**43.1**	**D**	300
3								
4								
TOTAL		425	75	500				

IV. APPROACH RESULTS

	Avg. Delay (sec/veh)	LOS	ATL Utilization (ATL TH/Total TH)	Estimated Min. ATL Length: Upstream ATL (ft)	Estimated Min. ATL Length: Downstream ATL (ft)
Scenario 1	**174.22**	**F**	N/A	**NA**	**NA**
Scenario 2	**46.33**	**D**	32%	**400**	**230**

The computational engine provides lane-by-lane analysis for two user-defined geometric scenarios. Measures include the lane volume allocation, the degree of saturation (X_{ALL}), average control delay, LOS, and 95th percentile queue by lane (except for the two exclusive CTLs, which are treated as a single lane group as per the HCM 2010).

The computational engine also summarizes average control delay, LOS, ATL utilization, and the estimated minimum length for the upstream and downstream ATL at the approach level based on the procedures described in the guidelines.

In the case shown in Exhibit B-3, a one-CTL approach was analyzed without an ATL (Scenario 1) and with an ATL (Scenario 2). In this example, a total of 138 vehicles per hour out of 425 vehicles per hour for the through movement are expected to use the ATL, which results in an ATL utilization of 32 percent. This reduces the approach control delay for the through and right-turning movements from 174 seconds per vehicle (LOS F) to 46 seconds per vehicle (LOS D).

The right-hand side of the approach results table shows the estimated design length for the upstream and downstream ATL using the procedures described in Chapter 5. The upstream length needed to provide queue storage for unimpeded access to the ATL is estimated at 400 feet, based on the ATL 95th percentile queue. The minimum downstream length for this example is estimated to be 230 feet. These values do not include taper lengths.

APPENDIX C

ESTIMATION OF DESIGN LENGTHS OF ATL COMPONENTS

Introduction

A key design element of ATLs is the appropriate length of the ATL's upstream and downstream components. Although it may be hypothesized that a longer ATL promotes higher ATL use, extensive field observations of ATLs tend to contradict this theory. In fact, some of the ATL sites used to develop the operational models in the "ATL Volume Estimation" section in Chapter 3 had high ATL utilization and short downstream lengths. Instead, the primary motivator for using the ATL appears to be a defensive one: avoiding a cycle failure when traffic in the adjoining CTL is moderately to highly congested.

Based on the above premise, the required ATL upstream length is predicated on the provision of adequate storage for and access to the ATL from the neighboring CTL. The downstream length, on the other hand, is predicated on servicing the queued vehicles in the ATL so that they can accelerate to the approach free flow speed and smoothly merge before reaching the end of the downstream taper. Gap availability and acceptance in the CTL for ATL vehicles operating under relatively high-speed, uninterrupted conditions must also be considered. Therefore, the recommended minimum downstream length is the greater of the lengths determined from these two operating conditions.

Note that the lengths determined from this method represent minimum design requirements for ATLs. Poor downstream sight distance, lack of proper signage (or existence of overhead lane signs), presence of downstream driveways, and significant right-turn-on-red (RTOR) flow from cross-street traffic may all necessitate adjustments to the minimum length to accommodate those effects. Finally, the minimum ATL lengths developed in this section are predicated on the assumption that an ATL will in fact be built. This is a strong assumption, but it is one that relies on the engineer's judgment on the practical need for such a lane. Because one of the major outputs of these guidelines is the predicted ATL through flow rate under various conditions, it is incumbent on the practitioner to decide whether the estimated ATL volume indeed warrants the additional lane, especially if the anticipated flow is only one to three vehicles per cycle on average. However, if the decision is to proceed with an ATL installation, then the procedure described in the next section can be followed.

ATL Length Estimation Procedure

This procedure is built around the ATL flow rate estimation models described in the "ATL Volume Estimation" section in Chapter 3. Since there are separate models for one-CTL and 2-CTL cases, the same reasoning applies to the ATL length estimation process. The procedure is implemented in two Microsoft Excel spreadsheets that estimate minimum ATL length and provide other important performance measures as outputs. The starting point of the analysis has no ATL presence. For the one-CTL case, the procedure considers an approach with a single shared through-right continuous lane, while the 2-CTL case assumes an exclusive through-movement lane and a shared through-right continuous lane. In all cases, left turns are assumed to operate from an exclusive lane or pocket and therefore are not part of the analysis.

An outline of the procedure as it relates to the ATL upstream length determination is explained in the following steps:

1. Identify whether the one-CTL or 2-CTL case applies.
2. Supply the data required for ATL flow rate estimation including:
    a. Total approach through and right-turn flow rates,
    b. Cycle length and effective green time for the subject approach, and
    c. Saturation flow rate for both through and right-turn movements.
3. Estimate the ATL flow rate based on the one-CTL or 2-CTL model in the "ATL Volume Estimation" section in Chapter 3.
4. Calculate the ATL through flow rate assuming equal lane volume-to-adjusted saturation flow rate (v/s) based on the HCM 2010 shared or exclusive lane-group volume distribution.
5. Take the predicted ATL flow rate as the lower estimate from steps 3 and 4.
6. Calculate the ATL and CTL volumes, capacity, control delay, and back of queue using the HCM 2010 signalized intersection procedures. For shared ATLs, include the right-turn flow rate in the lane flow computations.
7. Estimate the 95th percentile queues in both the ATL and CTL (for one CTL lane in the case of two CTLs) using HCM procedures.
8. Select a storage length based on the greater of the 95th percentile queues in the ATL and CTL. Queue storage or access distance is calculated based on an estimate of average vehicle spacing in a stopped queue.

The determination of the requisite downstream length requires a further set of input parameters, some of which may be defaulted as shown in parentheses, namely:

- Approach free flow speed or speed limit,
- Average acceleration rate from a stop on the ATL (10 feet/second^2),
- Intersection width measured from the stop line to the far curb (40 feet),
- Minimum acceptable headway in CTL traffic stream (6 seconds), and
- Driver reaction time (1 second).

The downstream length estimation based on storage of vehicles at the desired spacing in the downstream length (DSL_1) proceeds as follows.

Estimate the average uniform, random, and oversaturation back of queue (BOQ) for ATL through traffic only (Q1 + Q2 in HCM terminology). This approach incorporates two opposing and simplifying assumptions. The first is that the required length will be based on the average BOQ as opposed to the 95th percentile value as was done in the upstream case. This is offset by another assumption where all through-movement vehicles in the ATL are assumed to be contiguous in the queue and not separated intermittently by right-turning vehicles in a shared lane, which would result in a larger separation between through-movement vehicles. This procedure assumes that the effects of the two assumptions will balance.

The downstream storage criterion is based on providing sufficient spacing between ATL vehicles at the free flow speed or speed limit. Since vehicles accelerate from the stop line position, the downstream distance measured from the far curb can be shown to be:

$$DSL_1 = \frac{V^2}{2a} + (L + TV)(BOQ - 1) - INTW$$

Where:

V = free flow speed or speed limit (in feet/second),

A = acceleration rate from stop line (in feet/second^2),

L = spacing between vehicles at stop (in feet),

T = driver reaction time (in seconds), and

INTW = intersection width measured from the stop bar to the far curb (in feet).

The second criterion for estimating required downstream length is based on gap availability and acceptance under uninterrupted flow conditions, especially on high-speed approaches. The concept is that, after traveling a reaction distance past the intersection, an ATL driver must find an acceptable merge gap in the neighboring CTL within the confines of the downstream ATL length. Using assumptions on the headway distribution in the CTL and a minimum acceptable merge headway value, the distance measured from the far curb can be shown to be:

$$DSL_2 = V(T + NUM \times G_r)$$

Where:

NUM = the number of rejected gaps in the CTL. This could be either the mean value of rejected gaps or a pre-specified percentile number of rejected gaps, as explained below.

G_r = expected or average size of a rejected headway in the CTL (in seconds).

Guidelines on the Use of Auxiliary Through Lanes at Signalized Intersections

This model used to calculate DSL_2 is based upon a gap acceptance procedure with the following assumptions:

- Drivers begin searching for gaps as soon as they pass the stop bar,
- Drivers have reached the operating speed of the arterial,
- Drivers are homogeneous with regard to a critical headway or gap (t_c), and
- Traffic in the adjacent CTL follows an exponential headway distribution.

The following steps describe the model development:

Step 1. Determine the number of rejected gaps encountered until an acceptable gap is found. Let p be the probability of rejecting a gap in the CTL, t_c be the size of the critical headway, and h be the time headway between vehicles in the CTL. Then

$$p = P(h \le t_c) = 1 - e^{-\lambda t_c}$$

where λ is the flow rate in the CTL (in vehicles per hour).

Then the probability of rejecting exactly i gaps is $p^i (1 - p)$ and the expected number of rejected gaps is:

$$N_r = \sum_{i=0}^{\infty} ip^i (1-p) = p(1-p)\sum_{i=0}^{\infty} \frac{d}{dp} p^i = p(1-p)\frac{d}{dp}\left(\frac{1}{1-p}\right)$$
$$= \frac{p(1-p)}{(1-p)^2} = \frac{p}{1-p}$$

An alternative approach to using N_r is to design the downstream length to accommodate the 95th number of rejected gaps, as opposed to the mean value. In this case, we would like to determine the number of rejected gaps that would only be exceeded at most (1 – α) percent of the time. In other words, find I such that the number of rejected gaps X is such that

$$P(X > I) < 1 - \alpha$$

or conversely
$$P(X \le I) \ge \alpha$$

which can be then expressed as

$$\sum_{i=0}^{I} p^i (1-p) \ge \alpha$$

Solving for I gives the condition for the percentile rejected gap:

$$I(\alpha,p) \geq \frac{\ln(1-\alpha)}{\ln(p)} - 1$$

For example, if the probability of a rejected gap p = 0.50 and a 95th percentile confidence level on the number of rejected gaps is desired, then

$$I\,(0.95{,}0.50) \geq \frac{\ln 0.05}{\ln 0.50} - 1 = 3.32$$

This compares with a mean number of rejected gaps of

$$N_r = 0.50\ /\ (1 - 0.50) = 1.0$$

In the remaining steps, the user may choose to apply either the percentile or mean value of rejected gaps.

Step 2. Determine the expected size of a rejected gap, $E(t \mid t < t_c)$:

$$G_r = \frac{E(t)}{P(t < t_c)}$$

where

$$E(t) = \int_0^{t_c} t \times f(t)dt = \int_0^{t_c} \lambda t\, e^{\lambda t} dt = \left[-te^{-\lambda t}\right]_0^{t_c} - \int_0^{t_c} e^{-\lambda t} dt$$

using integration by parts, and after simplifying gives:

$$E(t) = \frac{1}{\lambda}\left(1 - e^{-\lambda t_c}\right) - t_c e^{-\lambda t_c}$$

Since $P(t < t_c) = 1 - e^{-\lambda t_c}$

$$E(t|t < t_c) = \frac{1}{\lambda} - \frac{t_c e^{-\lambda t_c}}{1 - e^{-\lambda t_c}}$$

Step 3. Calculate the expected waiting time for an acceptable gap, which is equal to the product of the number of rejected gaps and the expected size of a rejected gap:

$$\frac{p}{1-p} \times E(t|t < t_c) = \frac{1 - e^{-\lambda t_c}}{e^{-\lambda t_c}} \times \left(\frac{1}{\lambda} - \frac{t_c e^{-\lambda t_c}}{1 - e^{-\lambda t_c}}\right) = \frac{1 - e^{-\lambda t_c}}{\lambda e^{-\lambda t_c}} - t_c$$

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Optionally, if one selected the percentile gap approach, then the waiting time for the (alpha) percentile rejected gap would be

$$I\,(\alpha, p)\{\frac{1}{\lambda} - \frac{t_c e^{-\lambda t_c}}{1 - e^{-\lambda t_c}}\}$$

Step 4. Calculate the distance traveled before an acceptable gap is found:

$$D = V\left(\frac{1 - e^{-\lambda t_c}}{\lambda e^{-\lambda t_c}} - t_c\right)$$

or in the case of the percentile gap:

$$D = V\ I\,(\alpha, p)\{\frac{1}{\lambda} - \frac{t_c e^{-\lambda t_c}}{1 - e^{-\lambda t_c}}\}$$

where V is the operating speed in feet per second.

Incorporating the reaction time T, the total distance traveled (in feet) is given by

$$DSL_2 = V\left(T + \frac{1 - e^{-\lambda t_c}}{\lambda e^{-\lambda t_c}} - t_c\right) = V(T + N_r G_r)$$

or in the case of the percentile gap,

$$DSL_2 = V\,[T + I\,(\alpha, p)\ G_r]$$

The computational engine described in Appendix B provides both a mean and percentile option for computing the design value of DSL_2.

Abbreviations and acronyms used without definitions in TRB publications:

AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI–NA	Airports Council International–North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	Air Transport Association
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
HMCRP	Hazardous Materials Cooperative Research Program
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
PHMSA	Pipeline and Hazardous Materials Safety Administration
RITA	Research and Innovative Technology Administration
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S.DOT	United States Department of Transportation