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## **STATE HIGHWAY ADMINISTRATION**

### **RESEARCH REPORT**

# ***AN INTEGRATED WORK-ZONE COMPUTER SYSTEM FOR CAPACITY ESTIMATION, COST/BENEFIT ANALYSIS, AND DESIGN OF CONTROL***

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16. Abstract <p>This project produced an integrated computer system that enables engineers at the Maryland State Highway Administration to analyze the impact of a work-zone operational plan and to estimate the resulting cost/benefit. The proposed system consists of an intelligent user-interface, an analytical computing module, a microscopic simulation model, and an output analysis module. Depending on the nature of a proposed work-zone plan, one can either perform the preliminary estimate with the embedded analytical module or conduct an in-depth cost-benefit analysis with its simulation model. To capture the unique behavioral patterns of local drivers in response to perceived work-zone operations, this study conducted a series of field observations on car-following, lane-changing, and headway distributions among vehicles approaching lane-closure locations, and applied all field-observed information in calibrating key model parameters. This is to ensure that all analysis results produced from the proposed work-zone analysis program accurately reflect the actual benefits, costs, and resulting traffic impacts on Maryland's highway.</p>			
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# Table of Contents

Table of Contents .....	1
List of Figures .....	2
List of Tables .....	3
1. Introduction .....	1
2. Literature Review .....	2
2.1. Definition of work-zone capacity .....	2
2.2. Work-zone capacity models .....	3
2.3. Critical factors associated with work-zone capacity .....	3
3. Field Surveys .....	4
3.1. Geometry features .....	4
3.2. Work-zone schedules .....	6
3.3. Survey plan .....	6
3.4. Data collected .....	12
4. Work-Zone Capacity Model .....	15
4.1. Analysis of survey data .....	15
4.2. Simulation calibration .....	19
4.3. Model development .....	23
5. A Lane Closure Analysis Program (LCAP) .....	24
5.1. Introduction .....	24
5.2. Previous research findings .....	24
5.3. System framework .....	25
5.4. Primary system features .....	27
6. Conclusion .....	35
References .....	36

# List of Figures

Figure 1. Overall Map of I-95 Northbound between MD216 and MD100 .....	5
Figure 2. Key Areas of a Work Zone and Its Impact Area.....	7
Figure 3. Example Survey Report for September 6, 2007 (a) Page 1; (b) Page 2 .....	12
Figure 4. Work-Zone Configuration and Camcorder Locations on September 5, 2007 .....	13
Figure 5. Snapshot of the Traffic-Counting Software.....	14
Figure 6. Snapshot of the Video-Based Behavior Analysis Software.....	14
Figure 7. One-minute Traffic Counts for Each Lane at Loc. 3 on September 5, 2007 .....	16
Figure 8. One-minute Traffic Counts for Each Lane at Loc. 4 on September 5, 2007 .....	16
Figure 9. One-Minute Traffic Count for All Lanes at Location 4 on September 5, 2007.....	17
Figure 10. One-Minute Traffic Count for All Lanes at Location 2 on September 5, 2007....	17
Figure 11. Histogram of Headway Distribution in Lane 2 at Location 1 on September 6, 2007.....	18
Figure 12. Histogram of Headway Distribution in Lane 1 at Location 1 .....	18
Figure 13. Geometry of the Simulation Network for September 6, 2007 (unit: feet).....	20
Figure 14. Distribution of Available Capacity with Various Incoming Flow and Six Example Truck Percentage Levels.....	23
Figure 15. Input Interface of MD-QuickZone .....	25
Figure 16. Interfaces of LCAP System: (a) LCAP Basic, (b) LCAP Pro .....	26
Figure 17. System Frameworks of LCAP Basic and Pro Versions.....	27
Figure 18. Input Interface for Traffic Demands and Truck Percentage Distribution.....	28
Figure 19. Estimation Module of LCAP Basic .....	29
Figure 20. Interface of the Estimation Module in LCAP Pro .....	30
Figure 21. Automated Simulation Execution in LCAP .....	31
Figure 22. Knowledge-Based Module Showing Description of One Model in the Literature.....	32
Figure 23. Output Module Showing Summarized Results in a Colored Table.....	33
Figure 24. LCAP Web Site.....	34

# List of Tables

Table 1. List of Ramps on I-95 Northbound between MD216 and MD100 .....	5
Table 2. Work-Zone Schedules on Surveyed Workdays .....	6
Table 3. Statistical Comparison of Headways during Work-Zone Period in Lanes 1 and 2 at Location 1 on September 6, 2007 .....	19
Table 4. Statistical Comparison of Headways of Passenger Cars Following Trucks during Work-Zone Period in Lanes 1 and 2 at Location 1 on September 6, 2007.....	19
Table 5. Detailed Geometric Features of the CORSIM Network for September 6, 2009 .....	20
Table 6. Free Flow Scenario in the Base Case.....	20
Table 7. Comparison of Flow Counts at Location 1 for the Case of September 6, 2007 .....	21
Table 8. Comparison of Flow Counts at Location 3 for the Case of September 6, 2007 .....	21
Table 9. Comparison of Queue Length at Location 3 for the Case of September 6, 2007 .....	21
Table 10. Impact of Rubbernecking Factor at Location 3 on September 6, 2007 .....	22
Table 11. Model Validation with Car-Following Factors at Location 3 on September 6, 2007 ...	22
Table 12. Calibrated Simulation Parameters for Four-to-Two Work Zones in Maryland.....	23

# 1. Introduction

Highway work zones have been widely recognized as one main type of contributors to increased delays and deteriorating traffic safety on highway networks. To contend with the safety- and delay-related issues caused by work-zone activities, most highway agencies over the past decade have devoted tremendous resources to the optimal design of work-zone operations and to the implementation of various control strategies. The effectiveness of those operational or control strategies, however, is conditioned on an accurate estimate of the available work-zone capacity and the resulting traffic impacts. This critical issue of reliably estimating the available roadway capacity under various work-zone conditions, unfortunately, has not been adequately addressed either in the literature or in practice.

This study, proposed in response to the need for a reliable tool for operational analysis of work zones in Maryland, has the primary objective of developing a computer system for guiding potential users, including Maryland State Highway Administration (SHA) engineers, staff, and consultants, in analyzing available roadway capacity for a variety of work zones in Maryland. The proposed system will have the following functions:

- Estimating the available capacity for various types of work zones under different traffic conditions, based on work-zone data from field observations in Maryland and calibrated simulation models; and
- Embedding the calibrated simulation model with a user-friendly interface to assist advanced users in analyzing more complex scenarios, such as work zones near a ramp that may incur spillback to the lead arterial.

All models and programs developed in this study are based on both field data collected from Maryland work zones and simulated data from models that have been calibrated with field observations. The calibrated simulation models can accurately reflect the behavior of local driving populations. This ensures that SHA engineers, when performing the alternative analyses for work-zone operations, can reliably estimate the costs and benefits and design the best operational plan.

This report will first review earlier studies on work-zone capacity estimation and then describe the work-zone traffic surveys conducted for this study. After analyzing the collected field data on work zones and discussing model development methodology, this report will present the computer program developed as part of this project, along with recommendations for future improvements.

## 2. Literature Review

### 2.1. Definition of work-zone capacity

The main purpose of a “work-zone capacity” study is to discover the maximum feasible throughput that can be achieved under different traffic conditions. The potential maximum throughput depends on the type of work-zone operations to be implemented.

As more studies on advanced work-zone control strategies emerge in the literature and in practice (3), the upper limit of so-called “work-zone capacity” has been raised almost every year. The research presented here focuses on providing a reliable estimate of available capacity for traditional work-zone operations in Maryland, which follow the Manual on Uniform Traffic Control Devices (MUTCD) guidelines and Maryland’s current work-zone regulations.

Some existing definitions of the available capacity of a work zone include:

- The Texas Transportation Institute (TTI) defined capacity as the hourly traffic volume under congested traffic conditions and work-zone capacity as a full hour of volume counted at the site of lane closures when traffic is queued upstream of the site (1).
- A Pennsylvania study used the hourly traffic volume converted from the recorded maximum five-minute flow rate at the site as the work-zone capacity (2).
- In a California study, the authors first measured volumes for each three-minute interval during congested conditions (2). Then, all sample three-minute intervals were averaged and multiplied by 20 to determine the one-hour capacity. They also offered a definition of capacity as the flow rate passing through a segment with lane closures under congested conditions (2).
- Dixon and Hummer (North Carolina) defined capacity as the flow rate at which traffic behaviors quickly change from uncongested to queued conditions (4). Under this definition, the traffic volume observed immediately before queue formation is the work-zone capacity.
- Jiang (5) proposed another definition of work-zone capacity: the flow rate just before a sharp speed drop followed by a sustained period of low speeds and fluctuating traffic flow.

Most studies in the literature define work-zone capacity as the observable maximum throughput upstream of the work zone. This maximum throughput usually occurs right before the formation of a traffic queue due to work-zone operations. While the current research uses this definition, it also focuses on the maximum throughput that can be sustained over a period of time when a traffic queue is about to form or has formed due to work-zone activities. The reason is that this model is designed to help the SHA evaluate the resulting traffic queue over a period of work-zone operations rather than to find a maximum throughput value that may last only a very short period of time.



## 2.2. Work-zone capacity models

Over the past several decades, researchers have devoted much effort to formulating a model that can reliably estimate work-zone capacity. Several new models have been reported in the literature in the past five years.

In South Carolina, Sarasua et al. (6) developed two models for two-to-one, three-to-one, and three-to-two work-zone scenarios, based on two phases of field observations at 35 sites. The initial capacity model used Greenshield's model, and the alternative method took the 85<sup>th</sup> percentile value from a cumulative density graph as an estimate of the work-zone capacity.

Benekohal et al. (7) collected data from three short-term and eight long-term two-to-one work zones in Illinois and identified a 15-minute time period, either before a rapid speed drop or after a substantial speed increase, which sustained the highest flow rate with no flow fluctuation. Their study used the flow rate over such a time period to represent the ideal capacity of the site.

Ping and Zhu (8) and the Florida Department of Transportation (DOT) (9) used CORSIM models to generate work-zone data for two-to-one, three-to-one, and three-to-two work-zone scenarios. Both studies applied regression methods to develop the capacity models based on the simulation results. The Florida DOT study constructed two models, one for planning use and the other for operational purposes.

## 2.3. Critical factors associated with work-zone capacity

In developing the work-zone capacity model, researchers have explored a variety of factors that may affect the maximum flow rate over the work zone. Some of the factors are listed below:

- Percentages of trucks
- Pavement grade
- Number of lanes
- Number of lane closures
- Lane width
- Work-zone layout (lane merging, lane shifting, and crossover)
- Work intensity (work-zone type)
- Length of closure
- Work-zone speed
- Interchange effects, proximity of ramps, and presence of ramps along the work zone
- Work-zone location (urban or rural)
- Work-zone duration (long term or short term)
- Work time (daytime or night)
- Work day (weekday or weekend)
- Weather conditions (sunny, rainy, or snowy)

- Pavement conditions (dry, wet, or icy)
- Driver composition (commuters or noncommuters, such as tourists)
- Lateral clearance
- Type of control devices and their placement

This research aimed to develop a model that could represent local driving behaviors in Maryland; and field data is essential to establishing such a model. As it is unrealistic to capture all potential traffic scenarios in field surveys, this research calibrated microscopic simulation models based on comprehensive surveys at a number of sites during the research period. The calibrated simulation model was then used to generate data for more scenarios. Previous research (3) has shown that this simulation-based method, if calibrated properly with local field data, is sufficient for capturing local driving characteristics and generating realistic scenarios.

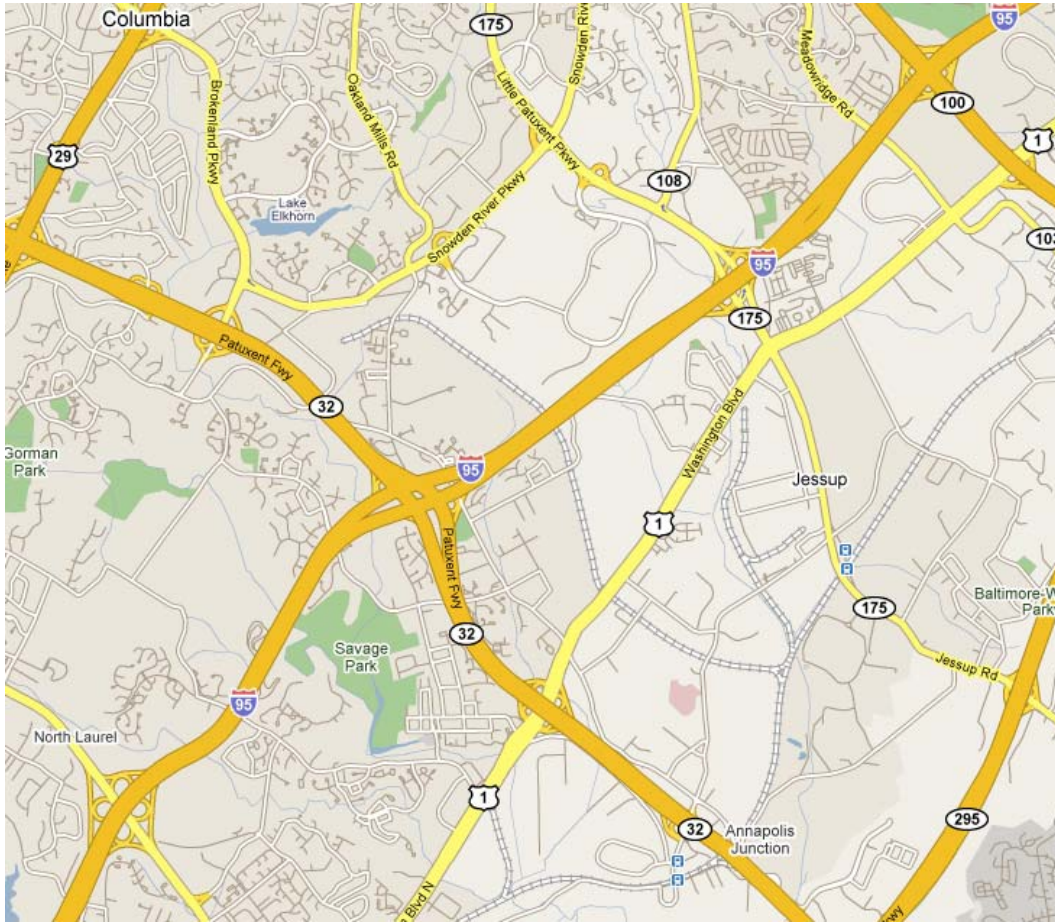
### **3. Field Surveys**

Field surveys are crucial for capturing the behavior patterns of Maryland drivers in this research. Sufficient field data ensures that the calibrated microscopic simulation model can represent the actual responses of local driving populations to different types of work-zone operations in Maryland. The research team can then rely on the model to generate data for additional work-zone scenarios under various traffic conditions that are not available for survey in the research period. When more field data are available for use, one can follow the model development procedure introduced in the next section to improve the overall model reliability.

The field surveys in this research focused on four-to-two work-zone scenarios, where two lanes are closed on a four-lane travel way. In order to identify the complex interactions of factors that affect the available work-zone capacity and to reliably calibrate the models, this research developed a comprehensive survey plan to capture important traffic characteristics and phenomena along a work zone and its upstream segment.

#### **3.1. Geometry features**

The field surveys took place on I-95 northbound between MD216 and MD100 (see Figure 1) over eight workdays. This freeway segment has four through lanes, two of which were closed at some sections for resurfacing during the survey period. The segment also has nine ramps, as listed in Table 1.



\*Source: <http://maps.google.com>

**Figure 1. Overall Map of I-95 Northbound between MD216 and MD100**

**Table 1. List of Ramps on I-95 Northbound between MD216 and MD100**

ID	Crossing Road	Type of Ramp
1	Rest area	Off-ramp
2	Rest area	On-ramp
3	MD32 EB	Off-ramp
4	MD32 WB	Off-ramp
5	MD32 WB	On-ramp
6	MD32 EB	On-ramp
7	MD175 WB/EB	Off-ramp
8	MD175 EB	On-ramp
9	MD175 WB	On-ramp

### 3.2. Work-zone schedules

The work-zone activities reported in our field surveys on I-95 northbound were all scheduled in the evening. The research team conducted surveys on seven workdays between September 4 and 17, 2007. The work-zone setup started around 8 PM on all but one day (September 4, 2007 had a starting time at 9 PM). The work-zone setup typically took about 15 minutes. Table 2 summarizes the work-zone starting time on each survey day.

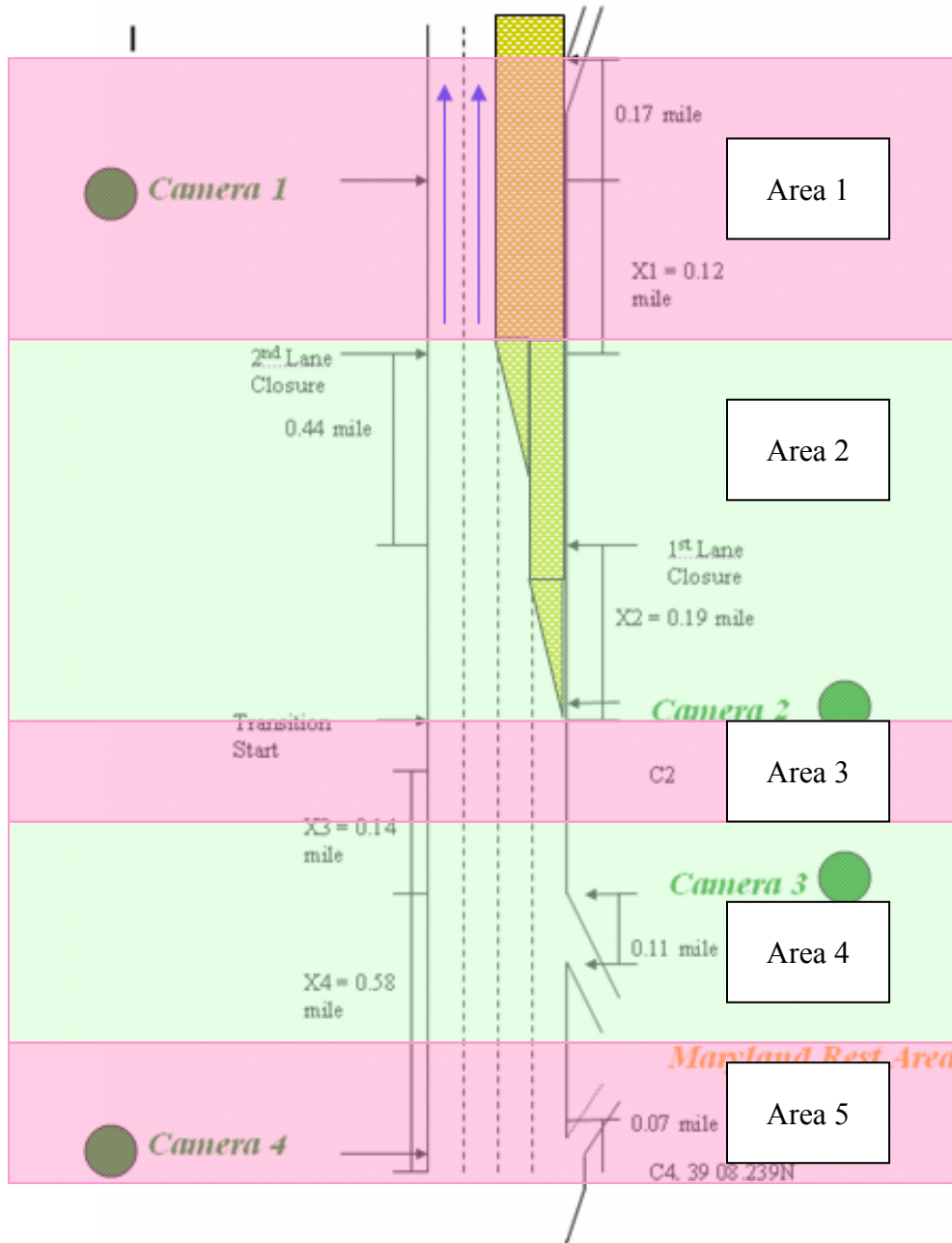
**Table 2. Work-Zone Schedules on Surveyed Workdays**

Date	Work-zone start time	Survey start time
9/4/07	9 PM	8:50 PM
9/5/07	8 PM	7:45 PM
9/6/07	8 PM	7:45 PM
9/10/07	8 PM	7:45 PM
9/12/07	8 PM	7:45 PM
9/17/07	8 PM	7:45 PM

### 3.3. Survey plan

In order to reliably capture the behavior of Maryland drivers under work-zone impacts, this research developed a comprehensive survey plan for collecting detailed information at the microscopic level. Our pilot surveys showed that an on-site counting device could efficiently collect traffic flow information for any customized time intervals. But such a counting process cannot reliably collect information of microscopic behavioral patterns, such as car following and merging. Hence, the research team designed an integrated survey method that consists of on-site video data recording at fixed locations, on-site floating vehicle survey, and in-house video processing with computer programs specifically developed by the Traffic Safety and Operations Laboratory at the University of Maryland (UMD) for driving behavior analysis.

The research team used three to five video camcorders at key locations to capture the traffic patterns under work-zone impacts. Figure 2 illustrates a typical four-to-two work zone with the two right lanes closed. The highlighted key areas are reported below:



**Figure 2. Key Areas of a Work Zone and Its Impact Area**

*Area 1: After the start of 2-lane closure*

Vehicles travel through Area 1 at relatively stable speeds, determined by the interactions between drivers and the work activities, and between each individual driver and surrounding traffic conditions. Note that the traffic conditions in Area 1 may be impacted by a bottleneck downstream of the work zone, e.g., queue spillback from a congested ramp. Such complex traffic conditions were not included in the surveys, but could be analyzed later with the calibrated simulation models

*Area 2: Merging area between the first cone and the start of 2-lane closure*

In this area, traffic merges from the closed lanes to the open lanes. The lane reduction causes dramatic speed drop when the flow rate is high. Note that the 2-lane closure generally involves two separate lane-reduction tapers, the upstream one for four-lane to three-lane transition and the downstream one for three-lane to two-lane transition.

*Area 3: Before the first cone*

In this area, drivers may voluntarily change from the lanes to be closed in advance to their physical closure. The percentage of drivers who prefer to merge early varies among local driving populations. This is one of the key areas where some advanced work-zone control strategies can be implemented to smooth the merging traffic flows and to improve the overall work-zone throughput.

*Area 4: Queuing area upstream of the work zone*

The presence of a queue in the segment upstream of the work zone may affect drivers' decisions on selecting travel lanes. Some drivers prefer to merge early to avoid the difficulty in changing lanes at low travel speeds, while other drivers like to fully utilize all lanes up to the actual lane closure point. The queue length varies with the traffic demand and the available work-zone capacity, and the end of the queue changes dynamically. It is difficult to observe the queue evolution at a fixed location even with reliable queue length estimation.

*Area 5: Area further upstream with no queue*

In this area, traffic flow rate does not reach the roadway capacity and drivers experience very limited work-zone impacts. They may have already seen the work zone warning signs deployed according to the MUTCD (10), but only a few drivers have changed lanes in response. Traffic flow information in this area can serve as the base for determining the actual traffic demand to go through the work zone. As the traffic flows from the ramps between Area 5 and Area 3 were very light in each survey, the impact of ramp traffic was ignored in analyzing the survey data.

Because road resurfacing work may be carried out at inconsecutive sections and the work plan has to change accordingly at the very last moment, it is essential that survey planners consider all real-world constraints when designing the survey plans. This research carefully designed all surveys to account for the following uncertainties:

- Starting time of work-zone setup

Although the work-zone operation was planned to start at a certain time each day, the actual starting time could differ from the scheduled time, depending on the construction team's preparation and management. It is crucial to survey traffic conditions before the start of

work-zone setup, which is usually marked by the placing of cones for the first taper. All surveyors were notified that the starting time of the survey depends on the actual start time of the work. If the traffic is light and no queue is observed due to a late start, the survey team should push back the starting time, as the observable traffic throughput may be much less than the available work-zone capacity.

- Starting location of work zone

The starting location of a four-to-two work zone is the upstream end of Area 2 in Figure 2. MUTCD (10) requires that the lane-reduction taper and buffer be located between this location and the actual work area and both have a length no less than a minimal value. In practice, these lengths are determined by the contractor who deploys the work-zone equipment. This makes it unrealistic to predict the starting location of a work zone before workers place the first cone, although the actual work area—in this case, the segment to be resurfaced—can be obtained from the construction team prior to the survey. If one camcorder is to be placed at this location in the video-based survey, one surveyor will need to monitor workers' activities and place the video camcorder once the location has been confirmed.

- Taper and buffer areas

For scenarios with multiple lanes being closed, SHA typically requires multiple transition tapers. A two-lane closure generally involves two separate lane-reduction tapers, the upstream one for four-lane to three-lane transition and the downstream one for three-lane to two-lane transition (Figure 2).

The buffer area is defined as the area with a full lane-closure but before the actual work area. The actual length of this area is determined by the contractor who set up the work zone. It affects the exact starting point of the two-lane closure and is hard to determine at the planning stage.

Based on an analysis of the information to collect, the work-zone activities, and other real-world constraints, the research team finalized the survey plan for the two-lane road resurfacing project on I-95 northbound between MD216 and MD100, as following:

#### Types of survey work

The survey team was divided into two groups: stationary surveyors with video camcorders and floating surveyors to observe the traffic evolution. The stationary surveyors were responsible for placing the camcorders to cover the required areas. If surveyors could not locate the target areas for recording before the actual work started, they would wait at the locations estimated by the survey planner. The floating surveyors worked in pairs: one driver to drive through all 5 work-zone areas and all camera locations, and one data collector, to record the timestamp and the geographic coordinates from a GPS unit when passing critical locations (i.e., geometry change points due to work-zone setup, the end of a queue, and the locations of any other unexpected events).

### Survey procedures

At the planning stage, the survey planner coordinated with the construction team to obtain the starting time and location of the work area. The planner then estimated the taper and buffer lengths based on prior surveys and/or information from contractors. The planner also estimated the locations of the two ends of Area 5 for given work areas.

The survey required a minimum of three video camcorders to cover the upstream section of Area 1, the inside of Area 2, and the downstream end of Area 5. This report labels these three locations as C1, C2, and C4, respectively. Additional manpower, when available, was assigned to one or two more locations in Area 4 to record the queue evolution. The additional camcorder locations are labeled as C3a and C3b from downstream (or C3 if there was only one additional video location).

Each video surveyor was required to start video recording at least 15 minutes prior to the scheduled work-zone operations and continue until at least 45 minutes after the work zone was fully implemented. This ensured that the data analysis could fully capture traffic trends before and after work-zone operations, as well as during the period when traffic flows reached a relatively stable state.

### Report and summary

The survey planner prepared a form for each surveyor to fill in basic information such as geographical coordinates of the video camcorder locations, the duration of the video-recording, and any unexpected traffic events (such as incidents). After the survey, a summary was generated for the overall work-zone setup and survey locations. An example survey report is shown in Figure 3.



## Daily Work-Zone Survey Report

Item	Content					
General	Date	9/8/2007		Location	I-95 NB near exit 32	
	Time	7-9:15 pm		Weather	nice and calm	
	Traffic	free flowing traffic before the construction starts				
	Personale	Nan Zou; Catherine Zeng; Woon Kim; Yue Liu; Zichuan Li; Xiaodong Zhang				
Geometry			Latitude	Longitude		
	Transition area	Transition Start	N39.08.788		W076.50.559	
		1st Lane Closure	N39.08.914		W076.50.470	
		2nd Lane Closure	N39.09.238		W076.50.197	
		more Lane Closure	none		none	
Grade						
Shoulder width						
Work zone activity	Lateral dims			# of Equipment		
	WZ schedule			# of Workers		
	S or L term			Type of WZ		
Camcorders	C1	Location:	Latitude	39.09.298	Longitude	76.50.091
		Surveyor	Xiaodong Zhang			
		Start-time	8:10 PM			
		End-time	check			
		Tape or DVD	Tape			
		No.				
	C2	Location:	Latitude	39.08.778	Longitude	76.50.586
		Surveyor	Yue Liu			
		Start-time	7:45 PM			
		End-time	check			
		Tape or DVD	DVD			
		No.				

1 of Page 2

(a)

Cont'd

Camcorders	C3	Location:	Latitude	39.08.678	Longitude	76.50.630		
		Surveyor	Zichuan Li					
		Start-time	7:39 PM					
		End-time	9:17 PM					
		Tape or DVD	DVD					
	No.							
	C4	Location:	Latitude	39.08.239	Longitude	76.50.950		
		Surveyor	Woon Kim					
		Start-time	19:41:50					
		End-time	9:15 PM					
Tape or DVD		Tape						
No.								
Moving vehicle	Real-time Queue	Surveyor 1	Nan Zou	Location of End of Queue				
		Surveyor 2	Catherine Zneg	Longitude	Latitude			
		Time 1:	20:17:08	39.08.150	76.51.069	End of Queue/1&2 lan		
		Time 2:	20:18:33	39.08.231	76.50.963	End of Queue 3rd lane		
		Time 3:	20:37:22	39.07.988	76.51.410	End of Queue/1&2 lan		
		Time 4:	20:37:48	39.08.057	76.51.250	End of Queue 3rd lane		
		Time 5:	20:55:37	39.08.006	76.51.310	End of Queue, 1/2/3 la		
		Time 6:	20:55:51	39.08.039	76.51.310	End of Queue, 4th lan		

Note:

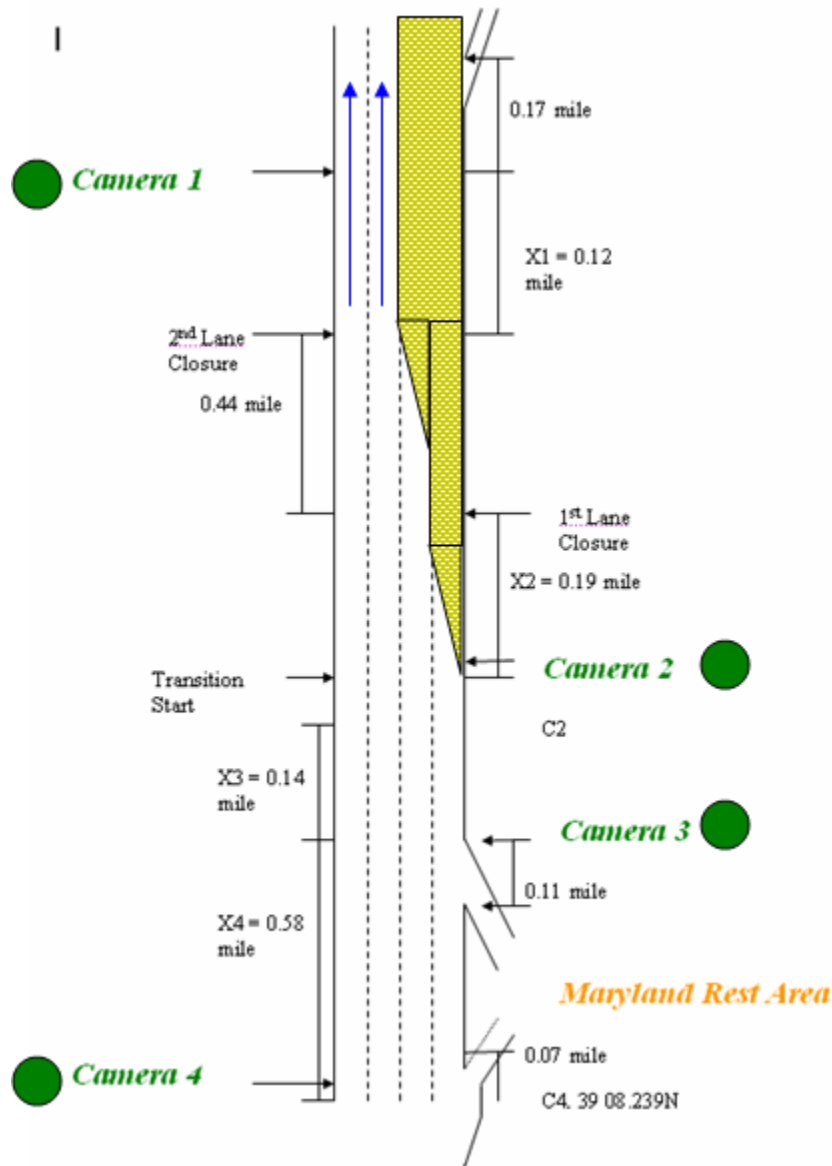
- \* major backup once the enter the workzone;
- \* no police present
- \* Liu's GPS is 1hr slow
- \* end of queue: first "almost" stop
- \* more Queue:
- > Time: 21:08:04 39.10.032/76.48.542 (end of workzone; after last cone)

(b)

Figure 3. Example Survey Report for September 6, 2007 (a) Page 1; (b) Page 2

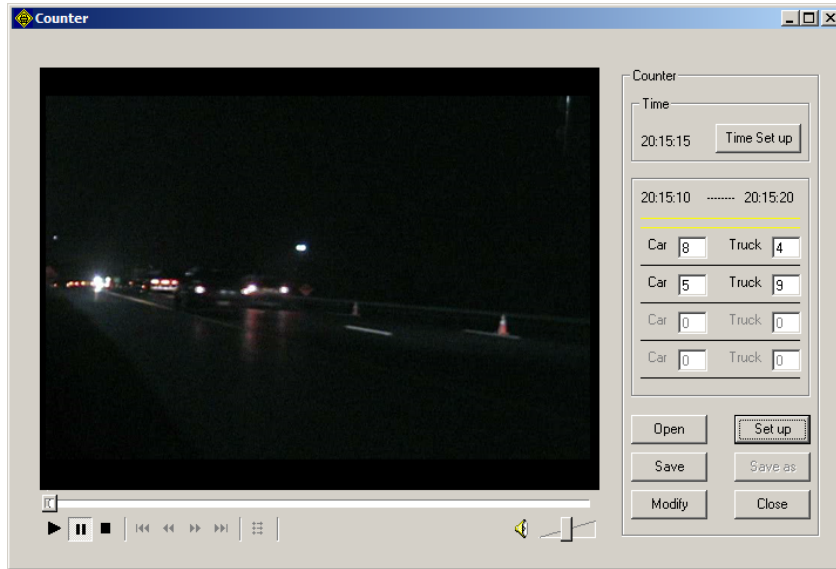
### 3.4. Data collected

This study conducted seven comprehensive surveys for I-95 northbound between MD216 and MD100. The data analysis started by plotting the recorded geographical coordination points and work-zone configurations on the basic geometric drawings of the segment. Figure 4 illustrates the work-zone configuration and video locations for the survey conducted on September 5, 2007. The four green dots represent the camera locations C1 to C4 on that day. There are two ramps between C3 and C4 for traffic from/to the Maryland rest area. Because traffic on these ramps is very light in the evening, this study ignored their impacts.



**Figure 4. Work-Zone Configuration and Camcorder Locations on September 5, 2007**

The research team then processed all videos and extracted the following fundamental information for each individual vehicle in the videos: the time when the vehicle passed the scene, the vehicle's travel lane, and the vehicle type (passenger car or truck). The collected information was then aggregated into intervals of predefined duration, using the software that was designed to facilitate the video-based vehicle counting process (see Figure 5).



**Figure 5. Snapshot of the Traffic-Counting Software**

The research team used another program (see Figure 6) to further analyze videos for locations C1 and C2 to obtain driving behavior information at the microscopic level, including the headway distribution and lane-changing behaviors in the merging area.



**Figure 6. Snapshot of the Video-Based Behavior Analysis Software**

## 4. Work-Zone Capacity Model

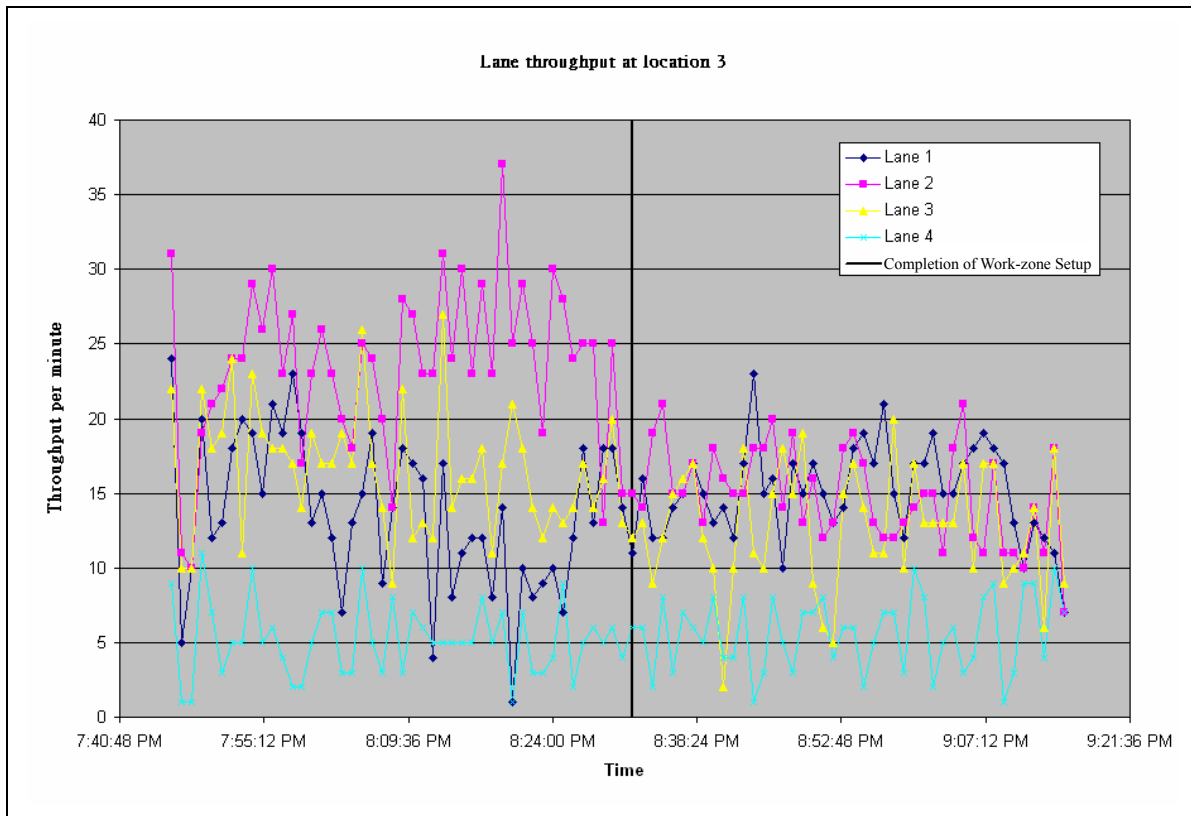
### 4.1. Analysis of survey data

This research analyzed the collected traffic information on different lanes and over different time periods (i.e., before work-zone setup, during the setup, and during 2-lane closure). The analysis covered three aspects, i.e., traffic demand, available work-zone capacity, and driving behavior.

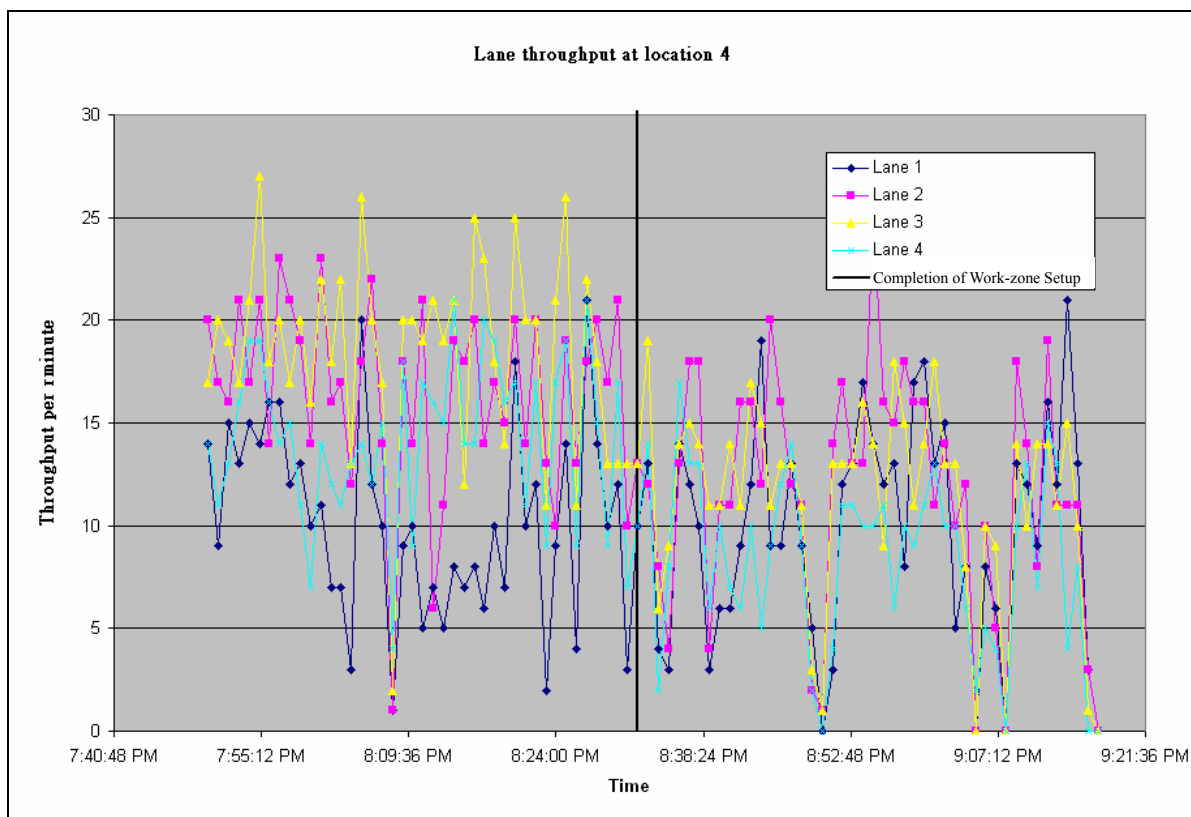
#### Traffic demand

As described in the previous chapter, Camera C4 was located for capturing the incoming traffic patterns upstream of the work zone. Camera C3 was also upstream of the work zone, but it sometimes presented queues caused by work-zone activities.

Figure 7 and Figure 8 illustrate one-minute traffic counts for each lane on September 5, 2007. Travel lanes are labeled from 1 to 4 starting at the left lane. The survey started around 8:32 PM, approximately 40 minutes before contractors finished setting up the four-to-two work zone (indicated by the solid black vertical line in the figures). The graphical results show that the work zone had significant impacts on the traffic volume at location 3. Lanes 2 and 3 had significantly different volumes during the 20-minute period before the completion of the work-zone setup (i.e., when cones were all in place), compared to the period after the start of 2-lane closure. This difference was not observed at location 4. Note that the distribution of traffic over lanes exhibited the same changes at location 4, as shown in Figure 8. It is also noted that the number of vehicles staying in lanes 3 and 4 at location 4 reduced significantly after the work-zone was setup.



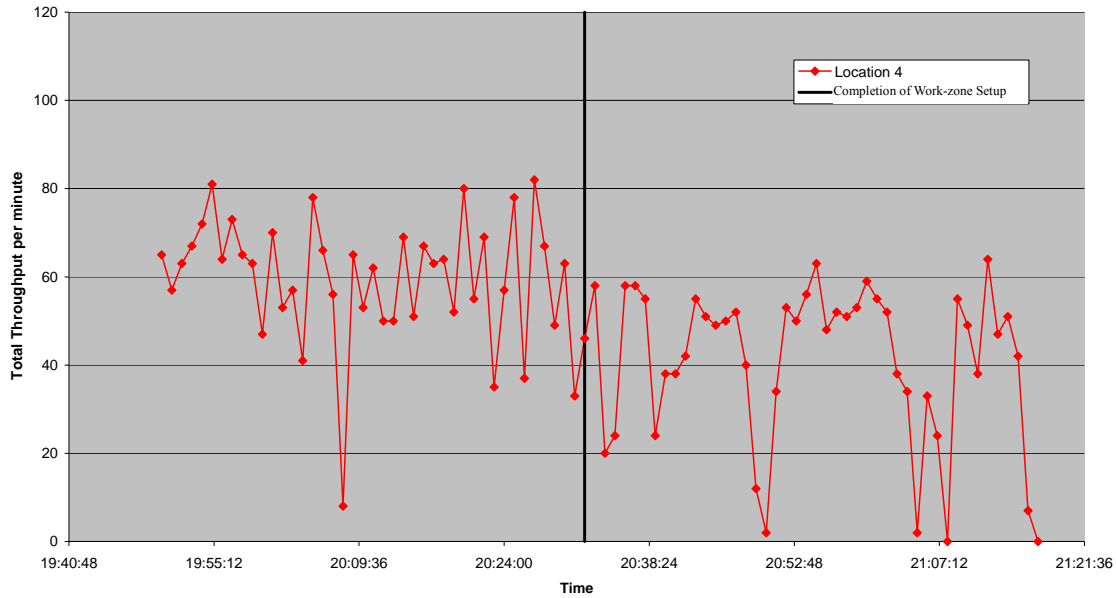
**Figure 7. One-minute Traffic Counts for Each Lane at Loc. 3 on September 5, 2007**



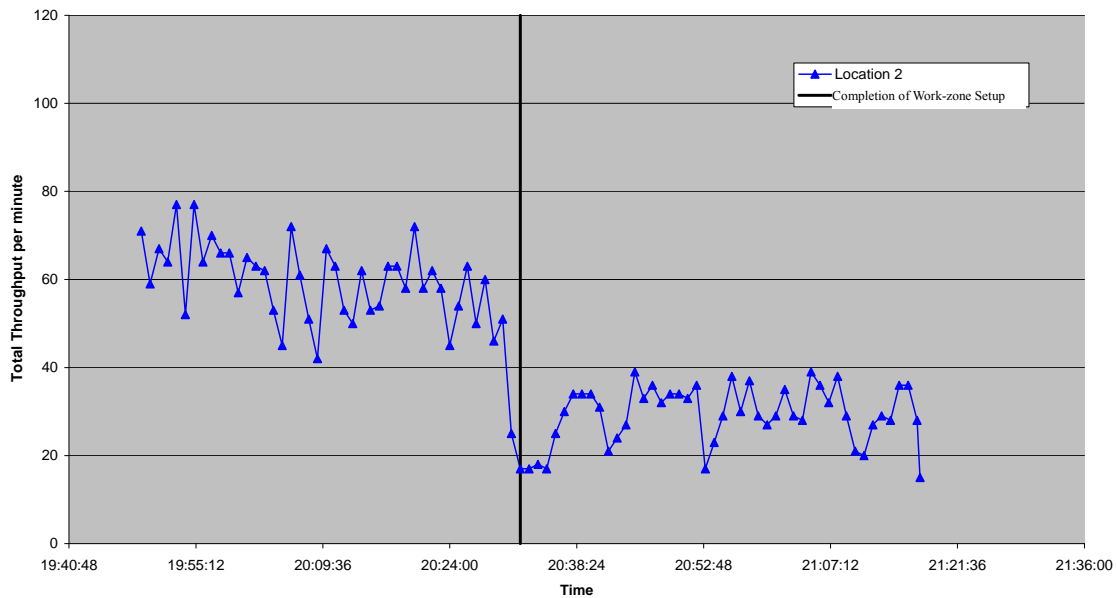
**Figure 8. One-minute Traffic Counts for Each Lane at Loc. 4 on September 5, 2007**

Available work-zone capacity

The available work-zone capacity can be defined as the observed maximum throughput under a traditional work-zone management strategy. As shown in Figure 9 and Figure 10, the upstream traffic volume observed at location 4 started to decrease slightly around the time the work-zone setup was completed, when the throughput at location 2 (the merging area) shows a significant drop. This mainly occurred due to the merging activities at location 2, which caused significant speed reduction.



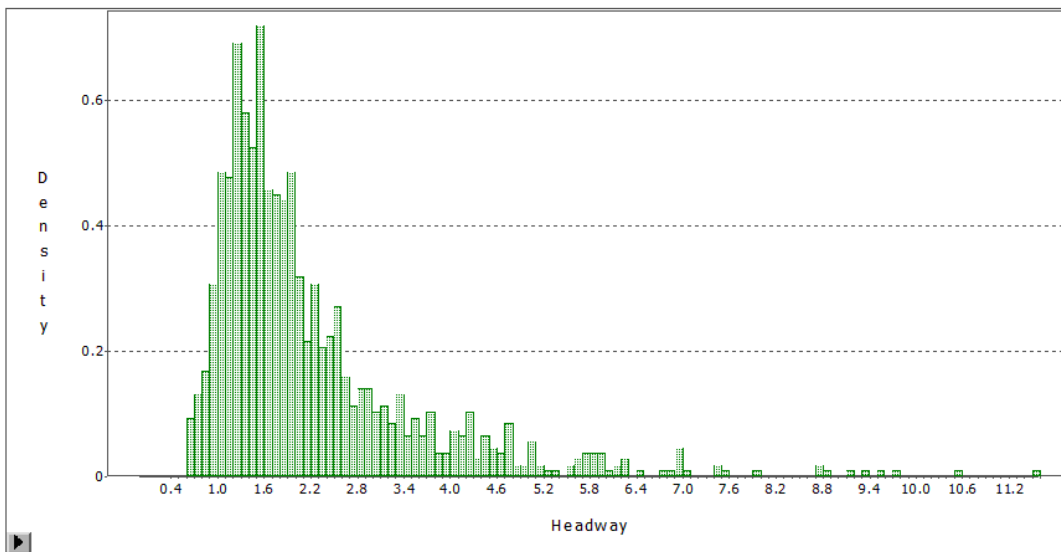
**Figure 9. One-Minute Traffic Count for All Lanes at Location 4 on September 5, 2007**



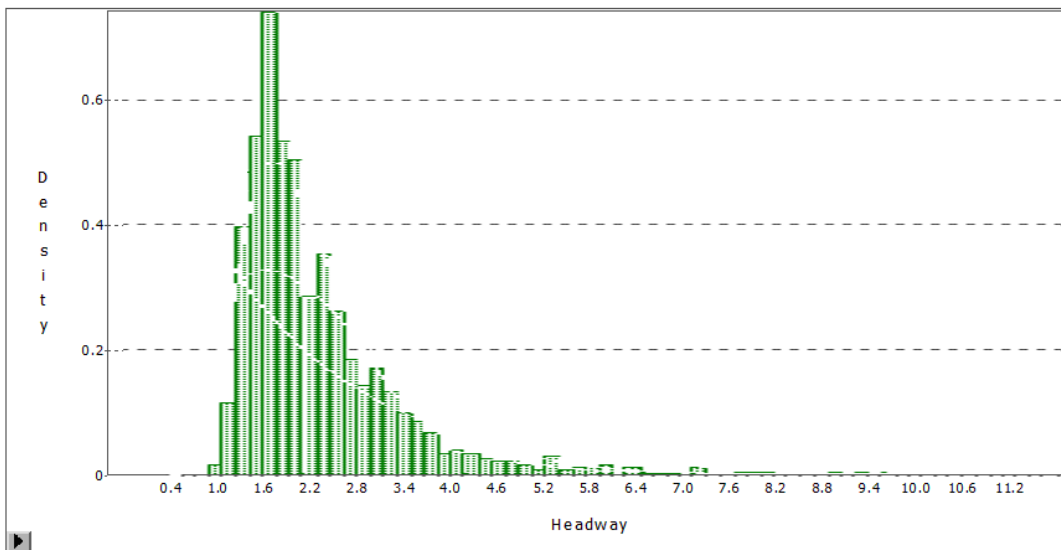
**Figure 10. One-Minute Traffic Count for All Lanes at Location 2 on September 5, 2007**

### Driving behaviors

By using the video processing software to capture the movement of vehicles at intervals of 1/25 seconds, the research team was able to analyze driving behaviors at a microscopic level. Figure 11 shows the histogram of headway distribution in the work-zone period in lane 2 at location 1 on September 6, 2007. The distribution follows a log-normal curve with the mean around 1.8 seconds. The vehicle headway distribution in lane 1 at the same location (see Figure 12) has a similar shape, but the statistical results indicate that the behaviors varied between the two lanes.



**Figure 11. Histogram of Headway Distribution in Lane 2 at Location 1 on September 6, 2007**



**Figure 12. Histogram of Headway Distribution in Lane 1 at Location 1 on September 6, 2007**



**Table 3. Statistical Comparison of Headways during Work-Zone Period in Lanes 1 and 2 at Location 1 on September 6, 2007**

	Lane 1	Lane 2
Mean of Headway (sec)	1.311	1.859
Sample size	620	790
Std deviation (vplph)	1.327	1.147
Maximum value (sec)	8.86	6.539
Minimum value (sec)	0.712	0.619

Table 3 shows that the average headway in lane 1 was 0.5 seconds smaller than in lane 2. This may be partly due to the higher average travel speed in lane 1, which is the far left lane. Note that the headway distribution is affected by the truck percentage. Data shown in Table 4 are consistent with the common observation that drivers tend to have larger headways when following trucks. The average headway of passenger cars following trucks is three times longer than when following cars in lane 1. Therefore, truck percentage is a very important factor to account for in the model for estimating the available work-zone capacity. Note that sample size shown in Table 4 is less than the total number of trucks in the traffic during the same time interval.

**Table 4. Statistical Comparison of Headways of Passenger Cars Following Trucks during Work-Zone Period in Lanes 1 and 2 at Location 1 on September 6, 2007**

	Lane 1	Lane 2
Mean of Headway (sec)	4.311	3.104
Sample size	32	124
Std deviation (vplph)	3.835	1.937
Maximum value (sec)	21.9	11.6
Minimum value (sec)	0.798	0.941

## 4.2. Simulation calibration

As described in previous sections, the research team developed a simulation-based modeling approach to estimate available work-zone capacity for various scenarios. Field data was used to calibrate key microscopic simulation parameters so as to ensure the simulation model can represent the local driving populations. The calibrated simulation model was then used to generate more scenarios that are not covered by the field surveys.

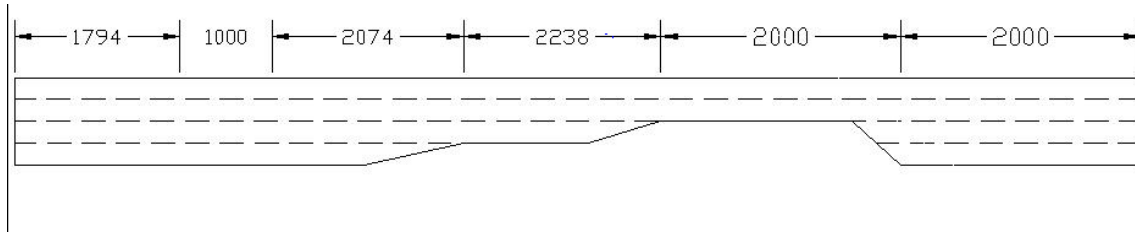
Three microscopic simulation parameters are well recognized for affecting driving behaviors in work zones, including 1) free-flow speed, 2) rubbernecking factor, and 3) car-following sensitivity (3). This research uses CORSIM, the microscopic traffic simulation model developed and supported by the Federal Highway Administration.

Vehicle entry headway

This research evaluated three methods for generating the incoming traffic: normal distribution, uniform distribution, and Erlang distribution with  $\lambda=1$ . The results showed that an Erlang distribution with  $\lambda=1$  generated traffic flows that were most similar to those observed at location C4 on different days. Therefore, all simulation models tested and developed in this research employed an Erlang distribution with  $\lambda=1$  for generating incoming traffic to the work zone.

Simulation networks

Different simulation networks were constructed for each survey day to represent the different work zones. The microscopic simulation models developed in this study can fully represent the actual geometric features of each work zone. Figure 13 and Table 5 provide detailed information for the work zone surveyed on September 6, 2007.



**Figure 13. Geometry of the Simulation Network for September 6, 2007 (unit: feet)**

**Table 5. Detailed Geometric Features of the CORSIM Network for September 6, 2009**

Link#	1	2	3	4	5	6
Length (ft)	1794	1000	2074	2238	2000	2000
Number of Lanes	4	4	4	3	2	4
Number of Dropped Lanes	0	0	1	1	0	0
Number of Added Lanes	0	0	0	0	2	0
Distance for Added or Dropped Lanes from Upstream Node	-	-	1874	2138	1980	-

Free-flow speed

Kang et al. (11) have demonstrated how free-flow speed distribution is crucial for developing a microscopic simulation model to support advanced work-zone control strategies. This study started with a base case of free-flow scenario, as shown in Table 6. Rubbernecking factor and car-following sensitivity were assumed to have default value of 0% and 100%.

**Table 6. Free Flow Scenario in the Base Case**

Link #	1	2	3	4	5	6
Free-Flow Speed (mph)	65	60	55	55	55	65
Rubbernecking Factor (%)	0	0	0	0	0	0
Car-Following Sensitivity (%)	100	100	100	100	100	100

The base case generated acceptable results at location 1 (Table 7) in terms of vehicle counts, but the generated results had large errors at location 3 in both vehicle counts and queue lengths (Table 8 and Table 9). Comparison of speed is not included in the analysis due to the lack of measurement of actual speed. Further investigations showed that a free-flow speed of 55 mph in the simulation for Link 2, where camera 3 was located, could generate acceptable vehicle counts at location 3 within an acceptable error range.

**Table 7. Comparison of Flow Counts at Location 1 for the Case of September 6, 2007**

Location 1			
Time	Flow Counts		Error (%)
	CORSIM Simulation	Survey Data	
20:12-20:27	917	864	6.1
20:27-20:42	889	842	5.6
20:42-20:57	881	838	5.1

**Table 8. Comparison of Flow Counts at Location 3 for the Case of September 6, 2007**

Location 3			
Time	Flow Counts		Error (%)
	CORSIM Simulation	Survey Data	
19:42-19:57	1154	1171	-1.5
19:57-20:12	832	938	-11.3
20:12-20:27	742	741	0.1
20:27-20:42	735	746	-1.5

**Table 9. Comparison of Queue Length at Location 3 for the Case of September 6, 2007**

Queue Length from the Transition Starting Point (Location 3)			
Time	CORSIM Simulation (feet)	Survey Data (feet)	Error (%)
20:17	2490	7006	-64.5

Rubbernecking factor

The study continued to calibrate the rubbernecking factor in each link. Taking location 3 as an example, Table 10 shows that using a rubbernecking factor of 10 percent could generate vehicle counts that best replicate the survey results for location 3.

**Table 10. Impact of Rubbernecking Factor at Location 3 on September 6, 2007**

Location Camcorder3									
Time	Number of Vehicles (free-flow speed: 55 mph)								
	Survey Data	r.n. =0	r.n. =10	r.n. =20	r.n. =30	r.n. =40	r.n. =50	r.n. =60	r.n. =70
19:42-19:57	1171	1154	1171	1073	1011	875	821	-	-
19:57-20:12	938	832	850	853	896	849	778		
20:12-20:27	741	742	778	811	861	851	777		
20:27-20:42	746	735	698	711	716	788	760		
Error Percentage (%)									
19:42-19:57	-	-1.5	0.0	-8.4	-13.7	-25.3	-29.9	-	-
19:57-20:12		-11.3	-9.4	-9.1	-4.5	-9.5	-17.1		
20:12-20:27		0.1	5.0	9.4	16.2	14.8	4.9		
20:27-20:42		-1.5	-6.4	-4.7	-4.0	5.6	1.9		

r.n. = rubbernecking factor (%)

Car-following sensitivity

The car-following sensitivity will affect headway distribution in the traffic simulation model. Table 11 shows the error rates with different car-following sensitivity values at location 3 on September 6, 2007, with a free-flow speed of 55 mph and a rubbernecking factor of 10 percent.

**Table 11. Model Validation with Car-Following Factors at Location 3 on September 6, 2007**

Location 3									
Time	Traffic Counts (Free-Flow Speed=55 mph and, in Link 3, Rubbernecking=10%)								
	Survey Data	C.F.S. =120	Error (%)	C.F.S. =140	Error (%)	C.F.S. =150	Error (%)	C.F.S. =160	Error (%)
19:42-19:57	1171	1051	-10.2	1005	-14.2	1047	-10.6	968	-17.3
19:57-20:12	938	834	-11.1	927	-1.2	931	-0.7	922	-1.7
20:12-20:27	741	835	12.7	937	26.5	927	25.1	892	20.4
20:27-20:42	746	768	2.9	747	0.1	753	0.9	839	12.5
Queue(feet)	7006	5706	-18.6	5806	-17.1	5756	-17.8	6279	-10.4

C.F.S. = Car-Following Sensitivity (%)

Combination impacts

To account for the complex interactions of the three simulation parameters, the research team devoted special efforts to identify their best combination for each link at different time periods (i.e., before work-zone setup, during the setup, and during the lane-closure).

The final sets of calibrated parameters are shown in Table 12. Note that this combination set was derived from real-world data collected from four-to-two work zones in Maryland. One can

use these parameters to generate more cases for four-to-two work zones with different traffic conditions and other complex factors, such as ramp impacts. One may also use this data set for other types of work zone if no field data are available.

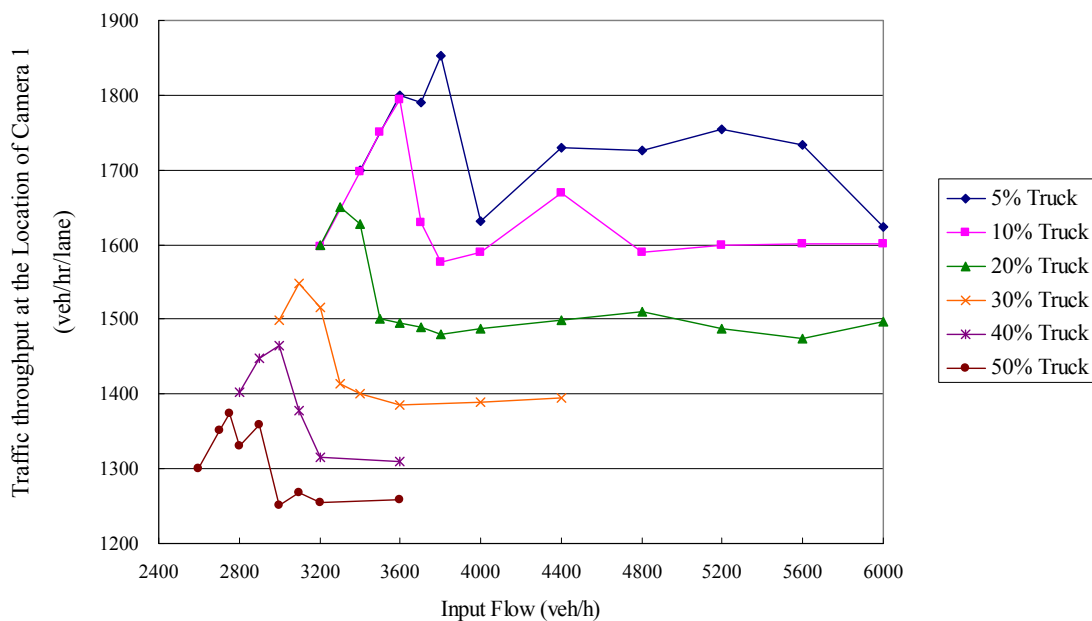
**Table 12. Calibrated Simulation Parameters for Four-to-Two Work Zones in Maryland**

Link #	1	2	3			4		5	6
Free-Flow Speed (mph)	65	60	55			55		55	65
Rubberneck Factor(%)	0	0	0	10	50	0	2	0	0
Time period	all	all	1	2	3	1, 2	3	all	all
Car-Following Factor(%)	100	100	160			100		100	100

### 4.3. Model development

In order to assess the impacts of incoming traffic flow and truck percentage on the available work-zone capacity, this research generated a large number of scenarios with the well-calibrated simulation program. Note that this study used the default algorithms and parameters in CORSIM to simulate the impact of lateral distance, a factor considered in several existing capacity models (2), due to the lack of data.

Using the sampling procedure from our previous studies, the research team generated a sample set of four-to-two work zones with different truck percentages and traffic volumes (2400 to 6000 vph). Figure 14 plots the distribution of available work-zone capacity with different incoming traffic flows and six truck percentages ranging from 5 to 50 percent.



**Figure 14. Distribution of Available Capacity with Various Incoming Flow and Six Example Truck Percentage Levels**

All the available data on work-zone capacity generated were organized and incorporated into an automated computer program that can assist SHA engineers/staff and consultants in estimating the available work-zone capacity on the Maryland highway network. This computer program will be presented in the next chapter. It is noted that the simulation parameters calibrated from the four-to-two work zone have also been used to generate scenarios for other types of work zones work-zone due to the lack of field data.

## **5. A Lane Closure Analysis Program (LCAP)**

### **5.1. Introduction**

Estimating the available capacity of a work zone may require a large amount of data, including hourly demand with time-varying truck percentages and potential lane closure plans. In response to SHA's need to automate the entire process, this research integrated the developed capacity model into a computer program that can help SHA engineers/staff and consultants to efficiently determine the available traffic capacity under given work-zone operations and traffic conditions, and to estimate the resulting queues from candidate work-zone schedules. This computer tool is named the Lane Closure Analysis Program (LCAP).

### **5.2. Previous research findings**

Prior to the development of LCAP, SHA engineers used MD-QuickZone (12) for work zone analysis, which runs on top of the Excel interface. The following limitations have prevented MD-QuickZone from being widely used to estimate work-zone delays in Maryland.

- Lack of an intuitive user interface

Users often get confused about the input interface as the input fields are simply spreadsheet cells without intuitive instructions. There is neither effective error-preventing mechanism. Users may easily input data into the wrong cells (see Figure 15).

- Lack of ability to model many real-world geometric features of work zones

MD-QuickZone can only model a work zone with no ramp impacts, whereas work zones in Maryland often involve ramps because of the short spacings between most neighboring interchanges (i.e., one to two miles). Without properly modeling the ramp impacts upstream or downstream of a work zone, traffic engineers cannot reliably estimate delays.

- Lacks of calibration to reflect Maryland driving behaviors

The work-zone capacity model used in MD-QuickZone, which estimates the maximum throughputs of work zones under traditional work-zone controls, is the general model suggested in Highway Capacity Manual (HCM) published in 1999; this model cannot account for local

driving behaviors in Maryland, such as car-following sensitivities and rubbernecking factors.

- Lack of ability to compare multiple work-zone models

MD-QuickZone can only handle one hard-coded model. This inability to use more than one work-zone capacity model has made MD-QuickZone incapable of taking advantage of different models for varying conditions. It also prevents the use of additional models in the future to improve MD-QuickZone’s reliability.

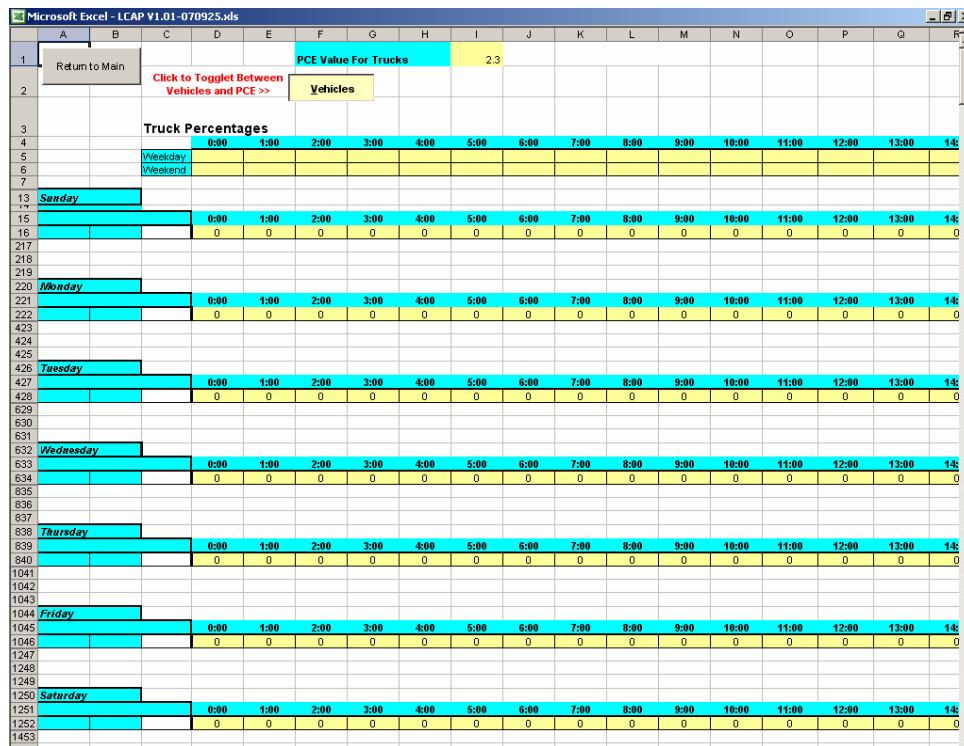


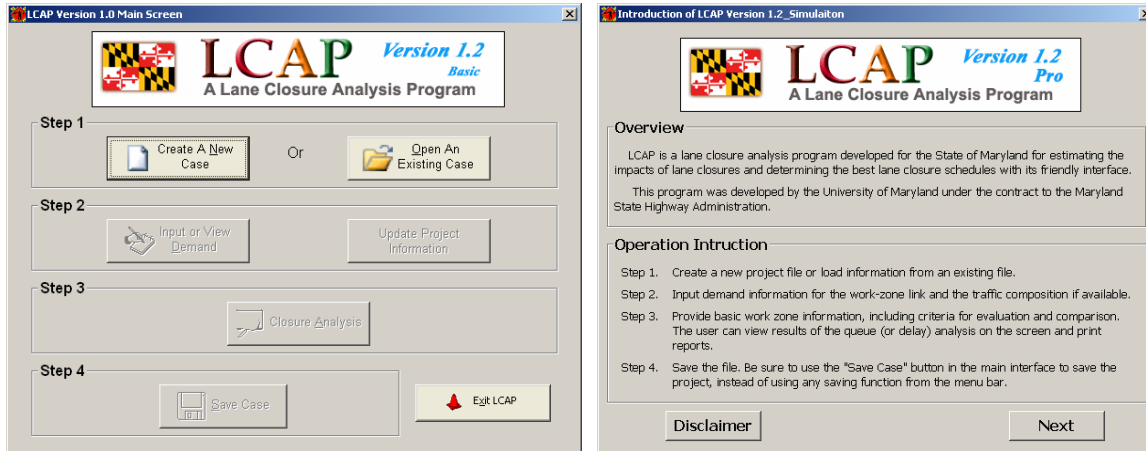
Figure 15. Input Interface of MD-QuickZone

In response to the limitations of MD-QuickZone, the UMD research team undertook the project of creating an improved work-zone estimation program for Maryland. The LCAP system is designed to meet the SHA’s needs and has a customized interface. LCAP was developed as a Microsoft Windows program, which provides much more flexibility than the Excel environment. Windows programs can better support the required user-friendly interface, which helps improve users’ work efficiency and prevent operating errors. The new system framework also provides users the potential flexibility of using different work-zone models and allows the integration of advanced traffic tools, such as microscopic simulation.

### 5.3. System framework

The general framework of LCAP consists of the following key modules: 1) an input module, 2) an estimation module, 3) a knowledge-based module, 4) an output and comparison module,

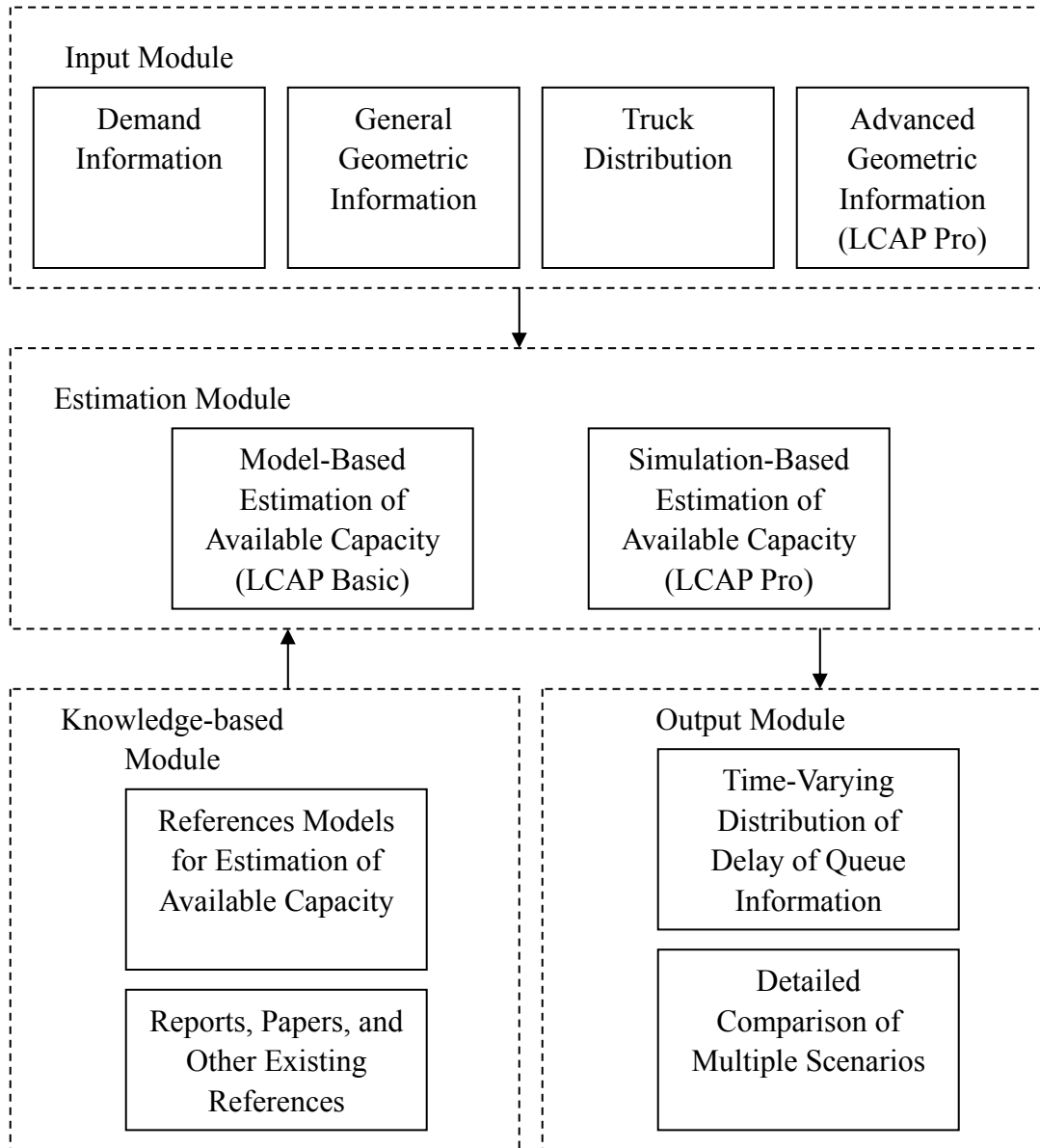
and 5) the LCAP web site. In order to meet the needs of different users, LCAP was developed to have a Basic version and a Pro version (Figure 16).



(a) (b)  
**Figure 16. Interfaces of LCAP System: (a) LCAP Basic, (b) LCAP Pro**

The difference between the two versions of LCAP is the estimation module. The Basic version of LCAP uses only the model developed in the previous chapters of this report's to estimate the available capacity of work zones for general scenarios. It does not take into account the effects of various complex factors, such as ramp volumes. Users can quickly obtain an estimate for a typical work-zone configuration and evaluate the resulting traffic queues. LCAP Pro was designed for engineers and consultants who need to precisely estimate the available capacity of work-zone operations on a complex roadway segment with ramp impacts. Hence, the Pro version has the embedded ability to execute CORSIM and can perform detailed simulations of work-zone traffic conditions and compute the resulting modes at a microscopic level, as illustrated in Figure 17.





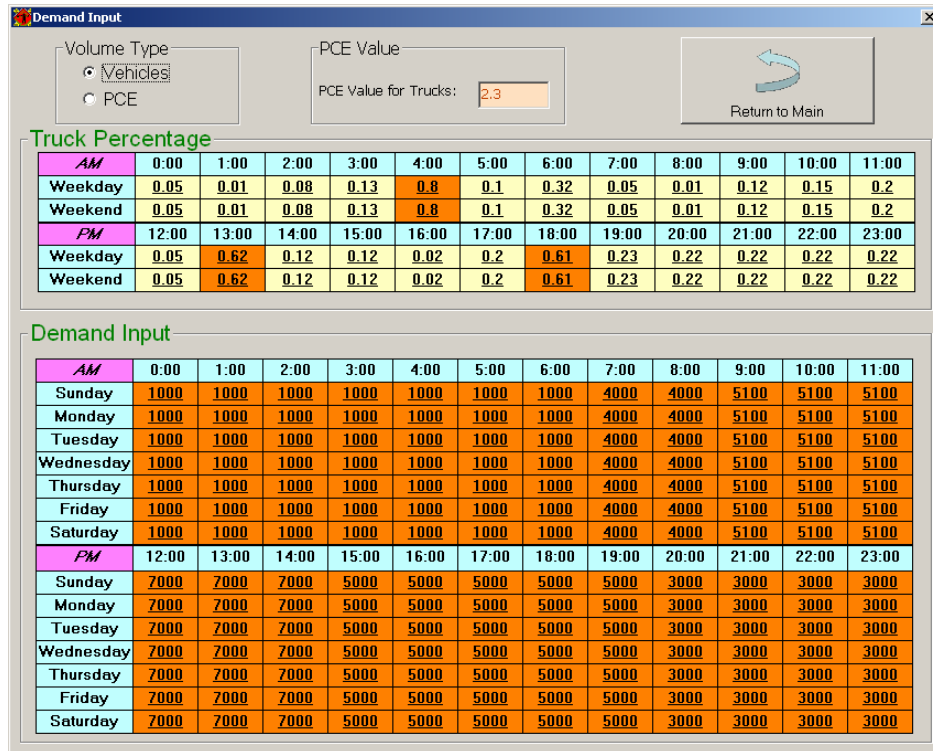
**Figure 17. System Frameworks of LCAP Basic and Pro Versions**

## 5.4. Primary system features

### Input module

Inputting hourly volume distributions and hourly truck percentages is usually the most time-consuming task when estimating the available capacity for work zones. The LCAP input module helps users to efficiently input such data during each hour on different weekdays. To prevent input errors, LCAP provides users with a well-organized interface along with an easy-to-understand mechanism for tracing all of the changes in the current working session. The

research team conducted usability tests of different designs for the input interface, with different color themes. Figure 18 shows the final design of the volume/truck-percentage input interface. Users can easily input demands and truck distributions into designated fields. The updated cells in the current session will be highlighted in orange, while unchanged cells have a light yellow background color. Users can then easily review the changes they have made.



**Figure 18. Input Interface for Traffic Demands and Truck Percentage Distribution**

The usability test comparing LCAP and MD-QuickZone clearly showed that first-time users needed much shorter learning times when using the LCAP interface. LCAP’s self-explanatory input interface let first-time users easily find the right places to input demands and truck percentages, and error rates dropped significantly for moderately experienced users of the LCAP interface.

Estimation module

The main objective of the estimation module is to estimate the available work-zone capacity based on the traffic scenario and work zone configuration input by users.

LCAP integrates the model developed in this study (see previous chapters) for estimating the available capacity of Maryland work zones (see Figure 19). In order to best utilize previous research software created by the SHA and other highway agencies, LCAP Basic also integrates three existing models for capacity estimation, including 1) the Maryland work-zone capacity guidelines (13), 2) the capacity model developed by the SHA and the UMD in 2001 (14), and 3)

the model from the Highway Capacity Manual 2000 (HCM2000) for short-term work zones (15). For users wanting to explore the details of embedded estimation models, LCAP provides the knowledge-based module, with references and an introduction to each model's structure and key parameters.

**Figure 19. Estimation Module of LCAP Basic**

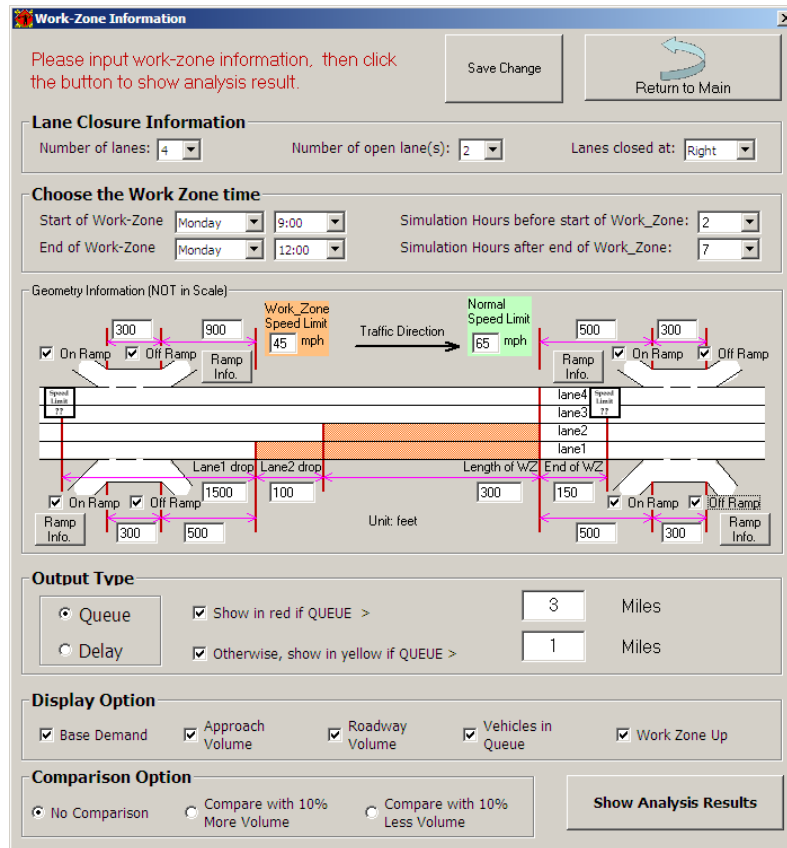
LCAP allows users to select different estimation models to comparing and analyzing work-zone control strategies. Users also have the option to override the estimation model's output for special operation scenarios. This flexibility is crucial to the potential application of LCAP, as SHA traffic engineers often need to fine-tune the results automatically generated by the program to account for special constraints.

In addition to incorporating previous work-zone research products in developing LCAP, this research also considered the fact that the SHA and other highway agencies and research institutions will continue to the work-zone research in the future. Therefore, the research team designed the estimation module with an open architecture, allowing future developers or users to conveniently remove or replace any model in LCAP with minimal programming effort. With this open model structure, LCAP can incorporate any estimation model for advanced work-zone control strategies, such as dynamic late-merge controls (3).

Using the interface of the estimation module, users can also specify the starting and ending dates and times-of-day for the work zone to be analyzed, as well as the preferred format for

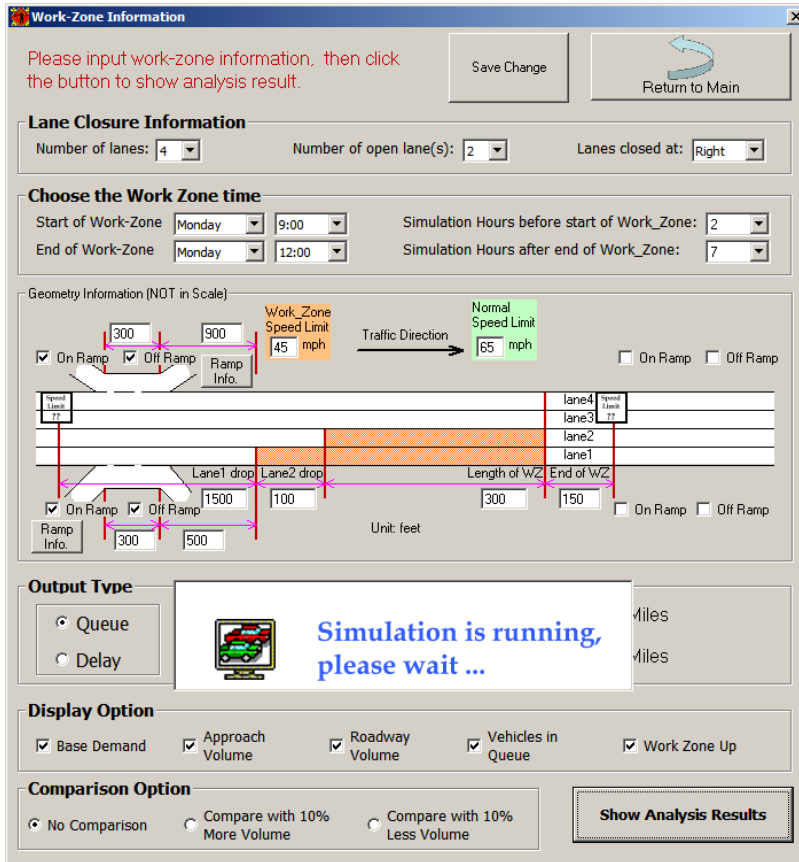
model output (Figure 19).

Sharing the same input and output modules with the Basic version, the LCAP Pro version provides a more advanced interface, allowing users to specify complex geometric features along the work-zone segment. For example, Figure 20 shows a four-to-two work zone with both on-ramps and off-ramps before and after the work zones. Users can customize such input information as speed limits and ramp lengths, as well as ramp volumes.



**Figure 20. Interface of the Estimation Module in LCAP Pro**

The LCAP Pro version is capable of automatically executing a microscopic simulation model, CORSIM, to estimate the available work-zone capacity and the resulting queue length. Once users have input volume, truck percentages, work-zone geometry, and work-zone control parameters, LCAP Pro will automatically build the simulation network for CORSIM and then execute the simulation software. Once the simulation execution is completed (usually within 15 seconds for a typical work zone), LCAP Pro will retrieve the simulation outputs, which include the estimated available work-zone capacity and the resulting queue distribution (see Figure 21). With this automated simulation execution and data retrieving technique, LCAP Pro allows users to take advantage of existing microscopic traffic simulation programs without having any prior knowledge. Note that both previous research (16) and the usability tests have demonstrated that LCAP Pro significantly reduced user anxiety, especially for those having never used any traffic simulation software.

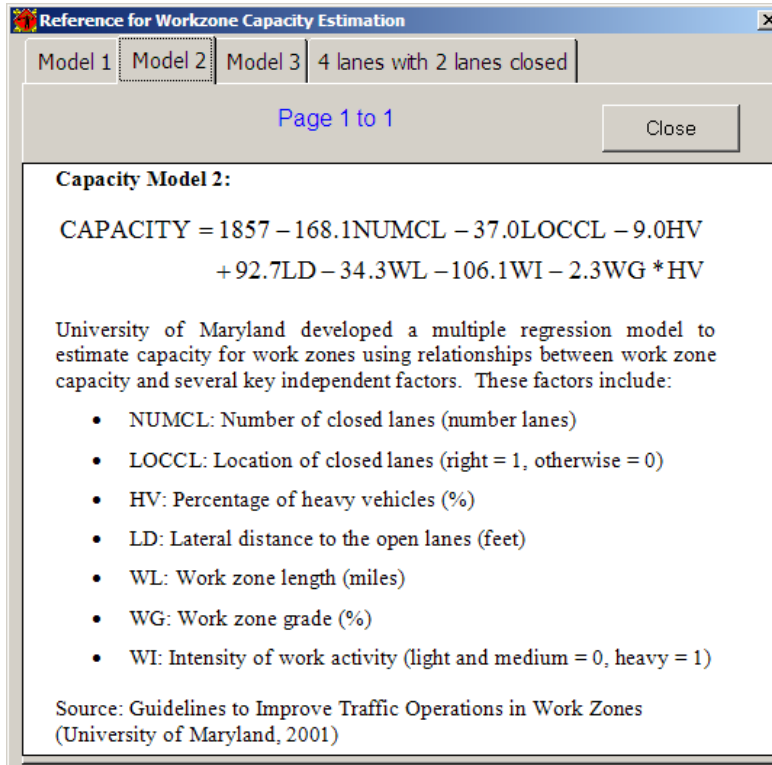


**Figure 21. Automated Simulation Execution in LCAP**

Knowledge-based module

The knowledge-based module is designed to help users better understand the embedded estimation models. This module provides references, model formulations, and guidelines (see Figure 22). Such information is mainly for advanced users who may want to explore more about the options.

As mentioned in previous sections, this knowledge-based module can be easily updated by adding/ removing models.



**Figure 22. Knowledge-Based Module Showing Description of One Model in the Literature**

Output and comparison module

To help traffic engineers compare the impacts of various work-zone control strategies, the output module functions to organize the outputs from the estimation module and present critical information with a friendly interface. Based on the customized queue definition, the output module creates a table and uses different cell background color to illustrate the hourly queuing information or vehicle delays due to the work-zone activities (see Figure 23). Some output items are described below:

- Starting and ending times: the starting and ending times of each time interval to be studied. In LCAP, the interval is set to be one hour.
- Base Demand: the demand user put in using the input module. Users can easily check if the demand displayed is correct.
- Vehicles in Queue: the total number of vehicles that encountered traffic queues during each time period. Its value is directly affected by the available work-zone capacity and the traffic demand distribution.
- Queue Length: the length (in miles) of the traffic queue caused by the work zone. Note that a queue will be highlighted only when meeting the queue criteria input by the user.

- Work zone (WZ) up: An “X” mark in this field means that the work zone is set up and in operation during this time interval. Users can use this information to determine whether the traffic queue is caused by recurrent congestions or by work-zone operations.

	Start Time	End Time	Base Demand	Approach Volume	Roadway Volume	Vehicle in Queue	Queue Length (Miles)	WZ Up
1	Mon-7:00	Mon-8:00	4000	3999	4000	1	0	
2	Mon-8:00	Mon-9:00	4000	4001	4001	0	0	
3	Mon-9:00	Mon-10:00	5100	3528	5100	1572	2.06	X
4	Mon-10:00	Mon-11:00	5100	3490	6672	3192	4.19	X
5	Mon-11:00	Mon-12:00	5100	3246	8292	5046	6.63	X
6	Mon-12:00	Mon-13:00	7000	7297	12046	4749	6.24	
7	Mon-13:00	Mon-14:00	7000	5674	11749	6075	7.99	
8	Mon-14:00	Mon-15:00	7000	5554	13075	7521	9.89	
9	Mon-15:00	Mon-16:00	5000	7515	12521	5006	6.58	
10	Mon-16:00	Mon-17:00	5000	7742	10006	2264	2.97	
11	Mon-17:00	Mon-18:00	5000	7246	7264	18	0.02	
12	Mon-18:00	Mon-19:00	5000	5006	5018	12	0.01	
13	Mon-19:00	Mon-20:00	5000	5003	5012	9	0.01	
14	Mon-20:00	Mon-21:00	3000	3018	3009	0	0	

**Figure 23. Output Module Showing Summarized Results in a Colored Table**

In the output module, users can compare results from two scenarios with different work schedules to find a plan with the least traffic impact. Advanced users can also explore the results from different work-zone capacity estimation models and investigate the difference in the estimated queue distribution.

LCAP web site

This research provides a portal web site (<http://attap.umd.edu/lcap>) for LCAP users to obtain information, to download the most recent versions of LCAP Basic and Pro, and to find links to other work-zone-related research jointly conducted by the SHA and the UMD. The research team maintains the web site (see Figure 24) and will continue updating the LCAP program. This web site helps the SHA to provide continually improved LCAP programs and also allows the UMD to interact with LCAP end users for troubleshooting, bug fixes, and future improvements.

An Applied Technology and Traffic Analysis Program

Office of Traffic & Safety  
State Highway Administration

SHA

Traffic Safety & Operations Laboratory

UNIVERSITY OF MARYLAND  
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Highlights Projects Publications Tools Resources

## Lane Closure Analysis Program (LCAP)

**Introduction**

The Lane Closure Analysis Program (referred to as LCAP) is developed for the Maryland State Highway Administration by the University of Maryland. This study intends to develop an advanced model for estimating work-zone capacities and produce an integrated and user-friendly computer program for SHA engineers staff to analyze a variety of work-zone associated issues, including guidelines for work zone design, and methodologies for capacity estimation, traffic impact analysis, cost/benefit evaluation, lane-closure penalty assessment, as well as incentive/disincentive estimates for various implementation plans.

**Versions**

LCAP v1.2 now has two versions, Basic and Pro versions. The Basic version provides users tools for quick estimation of the delay caused by work-zones with its integrated capacity model, which is developed and calibrated with Maryland's driving behaviors. The Pro version integrates a microscopic simulation module, which can estimate the impact of the work-zone with consideration of more factors, including complex geometry features and drivers interaction to work-zone warning signs and traffic conditions.

**Downloads**

[LCAP v1.2 Basic \(Executable Only\)](#) (last update: 7/28/2008)

[LCAP v1.2 Basic Setup Package](#) (last update: 7/28/2008)

[LCAP v1.2 Pro \(Executable Only\)](#) (last update: 3/3/2009)

[LCAP v1.2 Pro Setup Package](#) (last update: 3/3/2009)

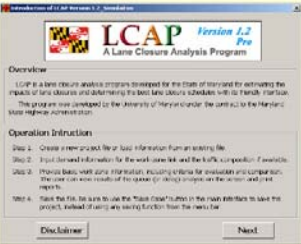




Figure 24. LCAP Web Site



## 6. Conclusion

This report presented a complete set of procedures for constructing an analytical model for work-zone capacity estimation, which consist of field surveys, data analysis, and model development. Based on the field observations of traffic characteristics and empirical rules for differentiating the work zone and its impact segment, this research has developed a comprehensive survey methodology that involves multiple video camcorders and floating surveyors. The proposed procedure also includes an approach that can use the field survey results to calibrate a microscopic simulation so as to capture local driving behaviors. This report presented a case study based on field data collected over seven days on the segment of I-95 between MD216 and MD175.

The research team integrated the research findings into a computer program, called LCAP. The program was created to help engineers and consultants in Maryland quickly estimate the potential impacts of different types of work zone under various operational schedules. LCAP has a Basic version that integrates the estimation model developed in this research and some previous studies, and a Pro version that takes advantage of an advanced microscopic simulation model for analyzing more complex geometric features, such as ramps in work-zone areas.

The products developed in this research can serve as effective tools for SHA engineers to conveniently take best advantage of the joint efforts by SHA/UMD researchers over the past several years and to convert all valuable research results to improved work productivity. With these decision/information tools, SHA will be able to further improve its work-zone design efficiency and gain significant tangible benefits, such as reducing design costs, simplifying the analysis procedure, and reducing traffic delays, accidents, fuel consumption, and emissions.

Future studies along the same line are to help SHA engineers develop user-friendly tools for conducting work-zone analysis. Such tools shall provide the following vital functions to SHA users: (1) efficient modeling of the target work-zone area, even with complex geometric features and recurrent/nonrecurrent demand distributions; (2) effective assessment of the costs and benefits for various candidate implementation strategies; and (3) reliable recommendations for traffic control strategies under time-varying traffic conditions to minimize both delay and accidents.

The recommended work scope for further studies includes:

- Develop an advanced framework for integrating and best utilizing all of SHA's existing work-zone modules, including LCAP, MDZone and MD-QuickZone;
- Modify or redesign existing modules to make them suitable for direct integration into the framework;
- Improve all system modules with capabilities to model complex geometric features and traffic demand distributions;
- Investigate the necessity and feasibility of including methodologies and approaches developed by other states;
- Build a web-based and knowledge-based module for storing and sharing work-zone-related research findings.

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