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16. Abstract
The principal goal of this project was to evaluate the operational effectiveness of the CLAS system as a space management tool to optimize daily operations in a primary corridor. This project focused on the operational evaluation of CLAS under recurrent conditions, both *before* and *after* CLAS was used to change lane assignments on a pre-timed basis. An analysis of baseline data (turning movement counts) was made to determine candidate sites where daily changes were appropriate. Once candidates for lane assignment changes were determined, traffic operations data necessary for calculating intersection performance measures were collected with permitted double-turn (*before*) and shared-turn (*after*) CLAS time-of-day changes, and statistical analysis techniques used to compare *before* and *after* traffic operations.

The CLAS concept was installed along the westbound frontage road of US 290 with the anticipation of being used for both incident management and time-of-day operations. The benefits of using CLAS for recurring demand management (at the three interchanges) identified as the most likely candidates for recurring operations were mixed. Improvements in lane balance in some cases were often tempered by increased lane delays, especially at right-turn CLAS applications. Although some reductions in delay and queuing were found, statistically significant reductions in approach delay and queuing were not indicated for the three studied locations. However, this result is considered a function of location and operational characteristics of the intersections studied and not necessarily the effectiveness of the CLAS concept in other locations. Further study is recommended to establish the range of characteristics where time-of-day operations can be most effective. The study of the CLAS concept for incident management will be conducted in FY 1999.

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EVALUATION OF CHANGEABLE LANE ASSIGNMENT SYSTEM FOR DAILY OPERATIONS

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Report 2910-1
Project Number 7-2910
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Sponsored by the
Texas Department of Transportation

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DISCLAIMER

The contents of this report reflect the views of the authors, who are responsible for the opinions, findings, and conclusions presented herein. The contents do not necessarily reflect the views or policies of the Texas Department of Transportation (TxDOT). This report does not constitute a standard, specification, or regulation. This report is not intended for construction, bidding, or permit purposes. The engineer in charge of this project was Merrell E. Goolsby, P.E. #29551.

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1.0 INTRODUCTION

The frontage road system is an essential element of design and operation of urban freeways in Texas. Freeways in the Houston area have typically been designed and built with continuous frontage roads over their entire length. These frontage roads are usually two or three lanes wide and signalized at interchanging cross streets. Maintaining acceptable operations at frontage road intersections that experience varying turning movement volumes can be a significant challenge to transportation agencies in the Houston area and across Texas.

When these interchanges experience high turning movement demands, permitted double turns may maximize traffic throughput. However, traffic demands can have entirely different characteristics between AM, Mid-Day, and PM peak operations, leading to the need for different lane use controls on a time-of-day (TOD) basis. In addition to the recurring daily traffic patterns that may require differing lane use control, freeway incidents often impact frontage roads by creating high frontage road traffic demands as diversion from freeway mainlanes occurs. While lane use information at intersections is typically communicated via pavement markings and static signing, static traffic control devices cannot accommodate situations where turning movement demands vary significantly over short periods of time (e.g., cyclical variations or during incidents). This shortcoming of static traffic control can significantly impact the efficiency of traffic operations when permitted lane use does not adequately match traffic demands.

The Changeable Lane Assignment System (CLAS) on frontage roads addresses the lane imbalances seen on both a TOD basis and when freeway incidents change typical frontage road traffic demands. As traffic signals have long been used as a "time management" technique for optimizing traffic operations, CLAS is used as a "space management" technique to add an additional dimension to optimizing traffic operations.

OVERVIEW AND BACKGROUND INFORMATION

The CLAS concept has evolved over several years and is built on the experience of several prototype installations in Houston and Dallas. The Texas Transportation Institute (TTI) developed and tested the fiber-optic signing used in the CLAS system as a part of Highway Planning and

Research (HPR) Project 1232—Task 5.1, Dynamic Lane Assignment Systems, sponsored by the Texas Department of Transportation (TxDOT). TTI Research Report 1232-18 entitled "Space Management: An Application of Dynamic Lane Assignment" (1) documents the results of this research. The early research was divided into three phases: 1) testing fiber-optic sign design features (legibility, target value, etc.); 2) developing second generation signing and testing operations of the signing systems (transition operations, driver understanding, and comprehension of the signing) (2); and 3) field evaluation (a static "flip-type" sign at the North Central Expressway at Mockingbird Lane diamond interchange in Dallas and a fiber-optic installation at the IH-10 and Bingle/Voss diamond interchange in Houston).

Results of the early research indicated that changeable lane assignment systems have the potential to reduce delays and queue lengths during changing traffic volume and turning movement conditions. As a result, the Houston Intelligent Transportation System (ITS) Priority Corridor program implemented the CLAS concept at interchanges along the westbound frontage road of US 290 in northwest Houston and Harris County, shown in Figure 1. CLAS signing systems were located along the westbound frontage road where full-time permitted double-turn operation existed, which used static signing and pavement markings. It was envisioned that the CLAS system could serve two purposes: 1) increase frontage road operation during freeway incidents; and 2) implement TOD operations for those locations with variable turning demands.

Development of the CLAS project by TxDOT included the design, installation, and evaluation of 10 changeable lane assignment control systems that have the capability to alter permissive double turns at frontage road interchanges based on traffic demands, either on a TOD basis or during freeway incident conditions. Each of the installations consists of two overhead lane control signs located approximately 61 m (200 ft) upstream of the stopline and an at-intersection sign across the intersection. Figure 2 shows the typical layout of overhead and at-intersection CLAS sign installations. The CLAS system has three basic displays: a double-turn display, a shared-turn display, and a transition display. Figure 3 shows the three displays generated by the fiber-optic CLAS signs.

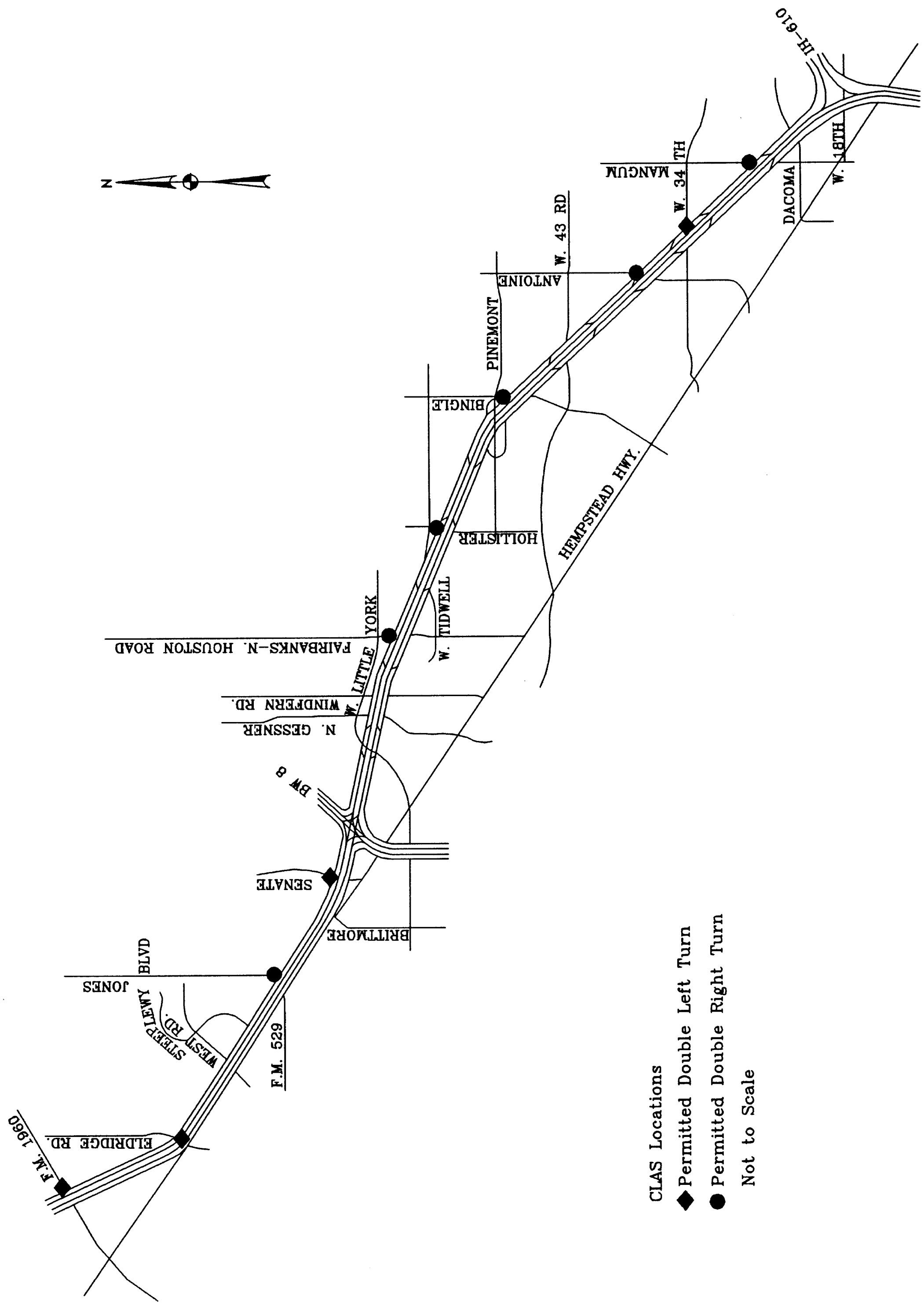


Figure 1. Limits of the US 290 Northwest Freeway Study Corridor

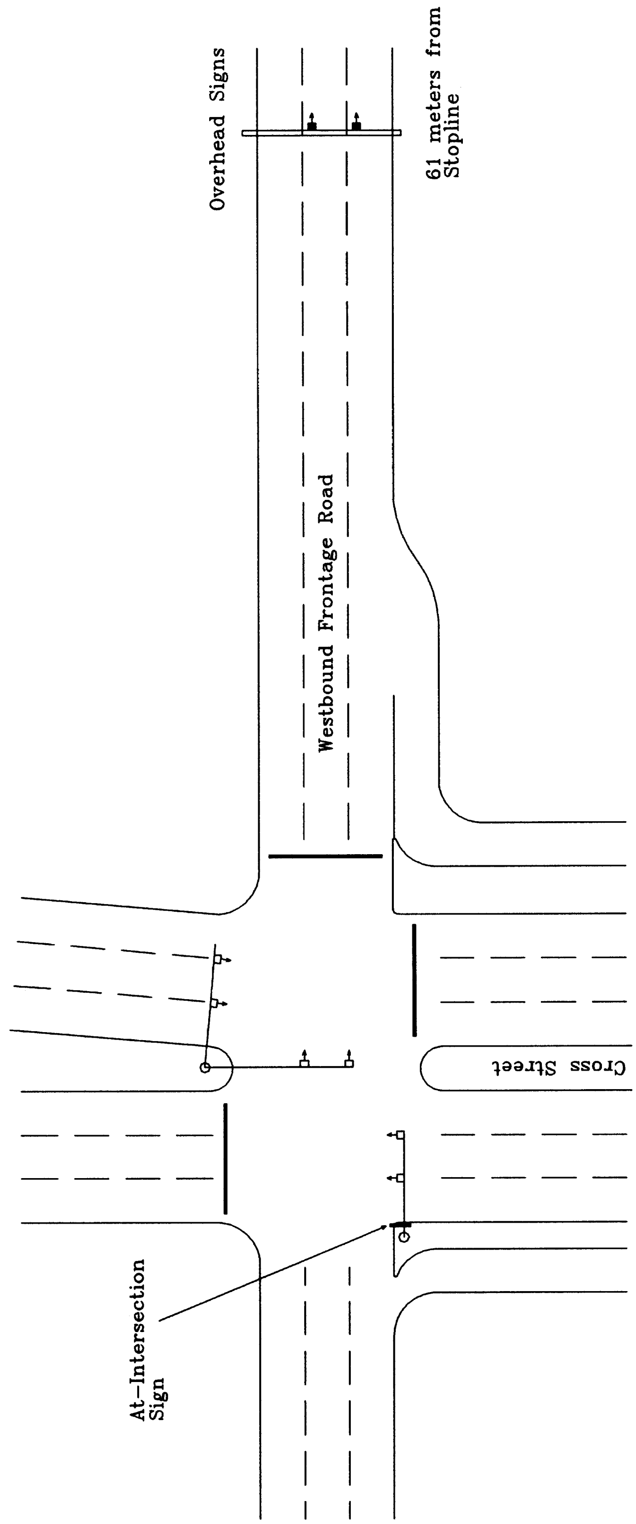


Figure 2. Typical CLAS Installation

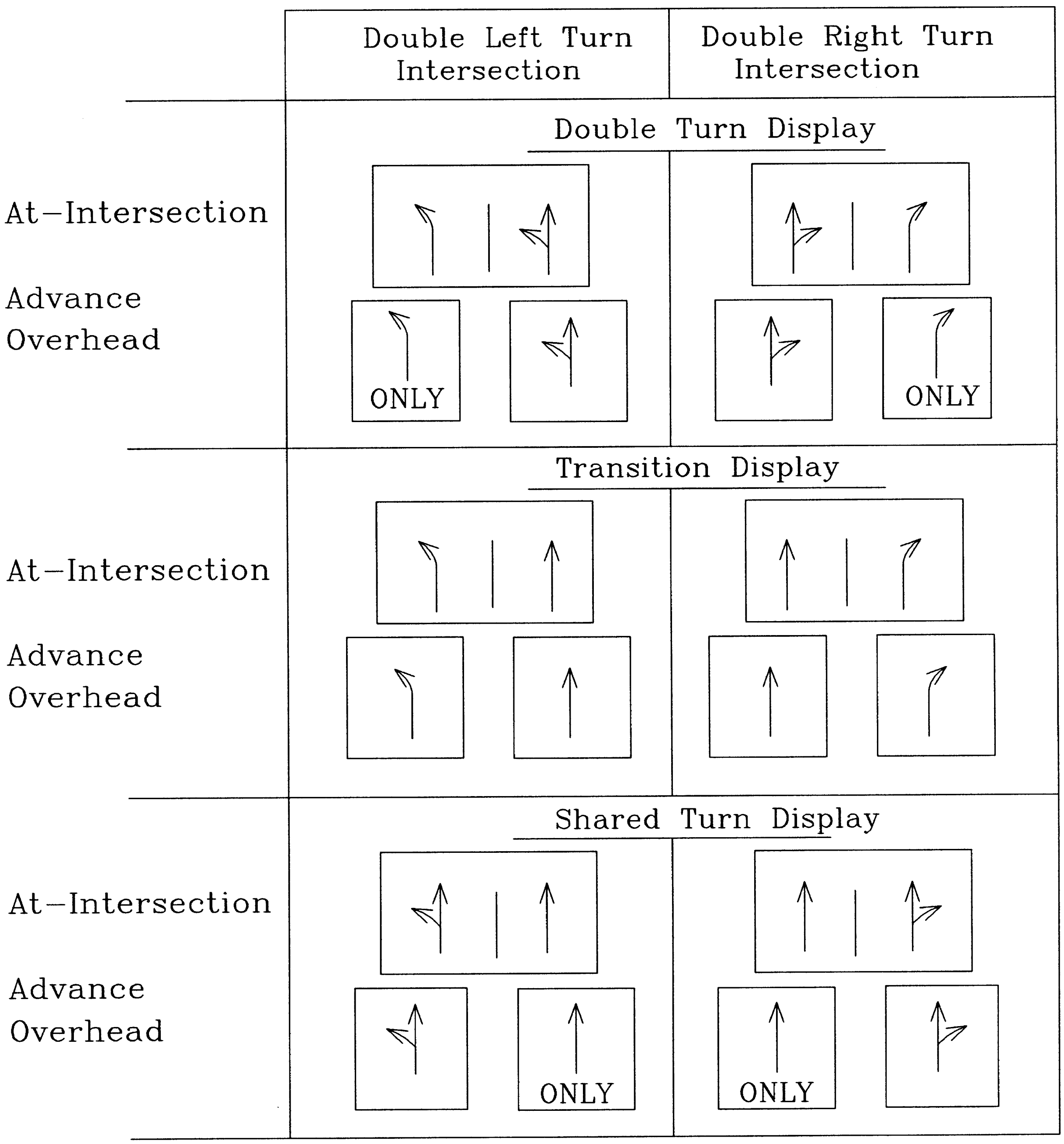


Figure 3. Displays Generated by CLAS Signing (double right turn intersection)

Prior to the deployment of CLAS, the 10 locations utilized standard static permissive double-turn signing—four with double left turns and six with double right turns. Thus, when CLAS signing was installed, the normal display was permissive double turns—the long-standing operation to which motorists were accustomed. When TOD or incident conditions warranted, the CLAS signs were to be changed to shared lane usage. Therefore, in the *before* and *after* studies, the *before* condition refers to double-turn operation and the *after* condition to shared-turn operation.

STUDY OBJECTIVES

The principal goal of this study was to evaluate the operational effectiveness of the CLAS system as a space management tool to optimize TOD operations in the Priority Corridor. This goal was achieved through (and the study methodology based on) the following four objectives:

1. Evaluate which diamond interchanges along the US 290 corridor are candidates for this evaluation of the use of CLAS to change lane assignments on a TOD basis.
2. Identify the measures of effectiveness by which to evaluate traffic operations *before* and *after* the use of CLAS for TOD operations.
3. Evaluate the traffic conditions *before* and *after* the use of CLAS for TOD operations based on specified measures of effectiveness.
4. Compare traffic operations *before* and *after* CLAS is used for TOD operations and evaluate the effectiveness of CLAS during TOD operations at the study interchanges.

2.0 STUDY METHODOLOGY

This study focused on the operational evaluation of CLAS under typical conditions, both *before* and *after* CLAS was used to change lane assignments on a pre-timed basis. An analysis of baseline data (turning movement counts) was made to identify candidate sites where TOD changes were appropriate. All CLAS approaches operated as either left or right permitted double-turn approaches. Appendix A summarizes the procedures used to identify the four time periods (at three different interchanges) where lane assignments would be changed from permissive double turn to a shared-turn configuration on a predetermined TOD schedule. The analysis recommended the following lane assignments at each CLAS approach:

- Mangum would operate in basic shared-turn configuration between 11:00 a.m. and 2:00 p.m. on weekdays. Permitted double right turn operation would be in effect at all other times.
- West 34th would operate in basic shared-turn configuration between 2:00 p.m. and 8:00 p.m. on weekdays. Permitted double left turn operation would be in effect at all other times.
- Hollister would operate in permitted double right turns from 2:00 p.m. to 6:00 a.m. on weekdays and operate in the basic shared-turn configuration from 6:00 a.m. to 2:00 p.m. Hollister would operate in double right turn configuration 24 hours on Saturday and Sunday. Following completion of the study and analyses, it was found that the Hollister AM peak period results were unuseable, as the city of Houston made significant changes to signal timing between the *before* and *after* study periods, in order to correct operational problems (unrelated to CLAS) at the interchange.
- Antoine, Bingle, Fairbanks/North Houston, Beltway 8/Senate, Jones, Eldridge, and FM 1960 would continue to operate in permitted double-turn configuration 24 hours a day, seven days per week.

Once candidates for lane assignment changes were determined, traffic operations data necessary for calculating intersection performance measures were collected *before* and *after* CLAS TOD changes and statistical analysis techniques used to compare *before* and *after* traffic operations.

MEASURES OF EFFECTIVENESS

The primary goal in using CLAS for daily recurring operations is to accommodate traffic demands (especially turning traffic) that vary during the day. Space management techniques would be expected to minimize lane distribution imbalances across all lanes of the approach, resulting in shorter queues and less total approach delay. Queue length at onset of green (measured by the number of vehicles in the queue) and average vehicle delay were identified as the primary measures of effectiveness (MOEs) for making comparisons of the *before* (with permissive double turns) and *after* (with shared-turn operations) TOD implementation of CLAS. A secondary measure of effectiveness identified was lane use violations.

DATA COLLECTION

Once candidate interchanges for TOD operations were identified, additional data were collected to quantify traffic conditions at the three interchanges (Mangum, West 34th, and Hollister) *before* TOD operations began. The data collection plan included a combination of manual queue counting and video recording of traffic demand.

Figure 4 shows the data collection setup. A camera was used to record traffic movements at the stop line. Since long queues could not be adequately estimated from the video tapes, study personnel stationed at the rear area of expected queuing recorded traffic demands (with respect to the red and green intervals of signal operations) and the queues at the onset of effective green. They collected manual queue counts for one to two hours during the peak periods identified in the 24-hour tube counts and manual turning movement counts.

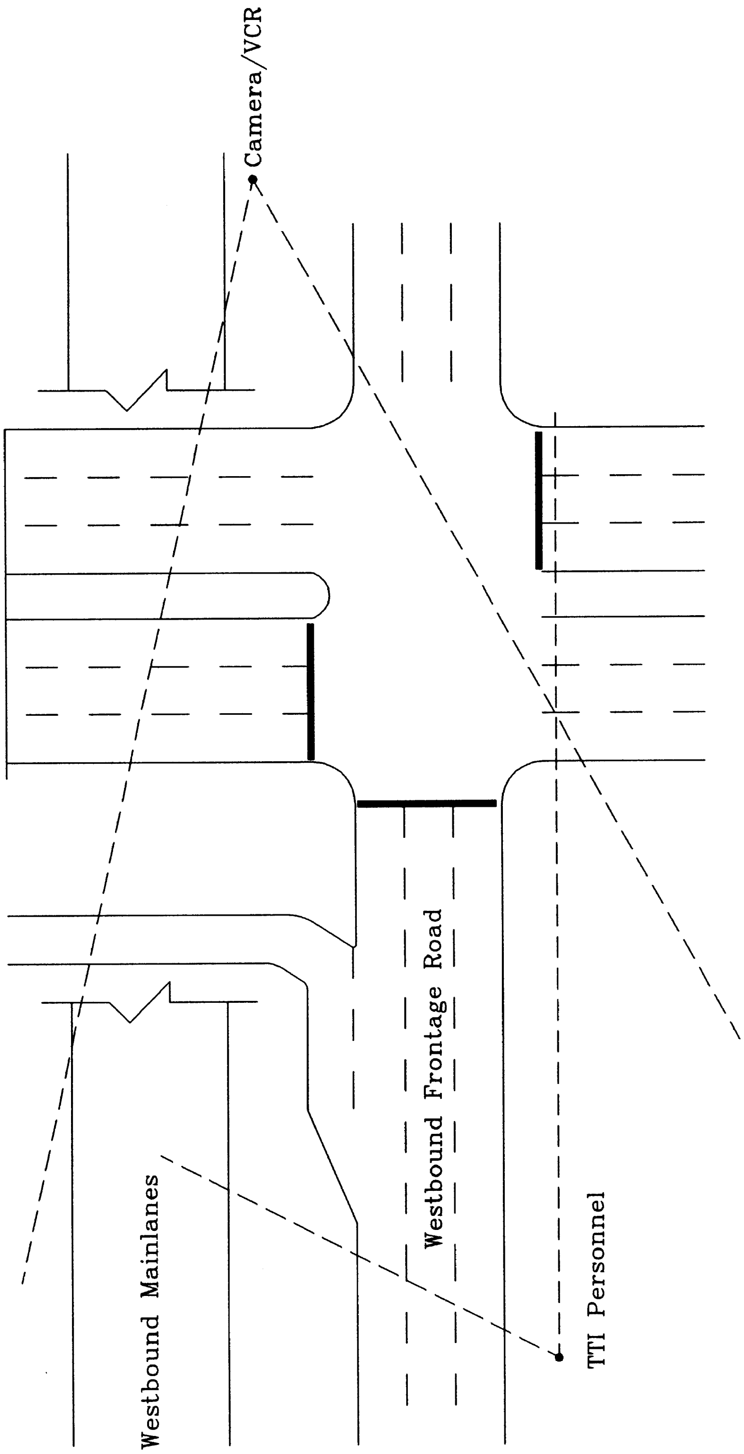


Figure 4. Typical Data Collection Setup

To ensure that data was collected during atypical traffic conditions, reducing the chances of estimating MOEs from data influenced by outside events (incidents, weather conditions, etc.), queue study turning movement counts were compared to the automatic tube count data and previous manual turning movement counts. During data collection, TTI personnel halted collection if any unusual events occurred. *Before* data was collected on one day for all cycles during one peak period at each interchange. *After* data was collected for all cycles during the peak period for three separate days (one day during the first two weeks of TOD operation, one day during the ninth week of TOD operation, and one day during the 17th week of TOD operation).

Data Reduction

Use of CLAS for TOD recurring operation is intended to reduce delay and queues by more uniformly distributing vehicles across all travel lanes. Therefore, MOEs were found for each individual lane. The analysis period used for this study was the peak 60 minute period during each peak period. Queue lengths at onset of effective green were found for each lane. During data collection, personnel noted several signal timing parameters in the field. Cycle length, green time, vehicle arrivals during the green and red intervals, and departures served during the green and red intervals were each noted for individual lanes. For this analysis, the cycle was assumed to begin at the onset of the red interval and end at the onset of the red interval for the next phase of the frontage road approach.

Data collected in the field consisted of the time of onset of red, time of onset of green, queue length at onset of red, and vehicles arriving during the red interval. Data collection of vehicles serviced during the green interval and those vehicles departing during the red interval (right-turns-on-red) were taken from video recordings. Other arrival and queue information was derived from mathematical equations. Figure 5 gives a graphical representation of the calculations to derive the queue length at onset of green and arrival rate during green. At the onset of red, there are Q_{Rn} number of vehicles in queue at the beginning of the n^{th} cycle. Vehicles arrive on the red interval until at the onset of green Q_{Gn} vehicles are in queue. When the signal indication changes to green, the vehicles move through the approach, and the queue begins to dissipate. At the onset of red of the next $(n+1)^{th}$ cycle, there are Q_{Rnn+1} vehicles in queue. The vehicles in queue at the onset of green (Q_{Gn}) result from the addition of the vehicles in queue at the onset of red (Q_{Rn}) and those vehicles arriving during the red interval (A_{rn}) minus any vehicles departing during the red interval (D_{Rn}), or

$$Q_{Gn} = Q_{Rn} + A_{Rn} - D_{Rn} \quad \text{(equation 1).}$$

Because Figure 5 is a simplified representation of queuing at signalized intersections, it does not show the vehicles departing during the red interval. At the study intersections, this situation is found where vehicles are allowed the opportunity for right-turn-on-red or (at 34th) to U-turn.

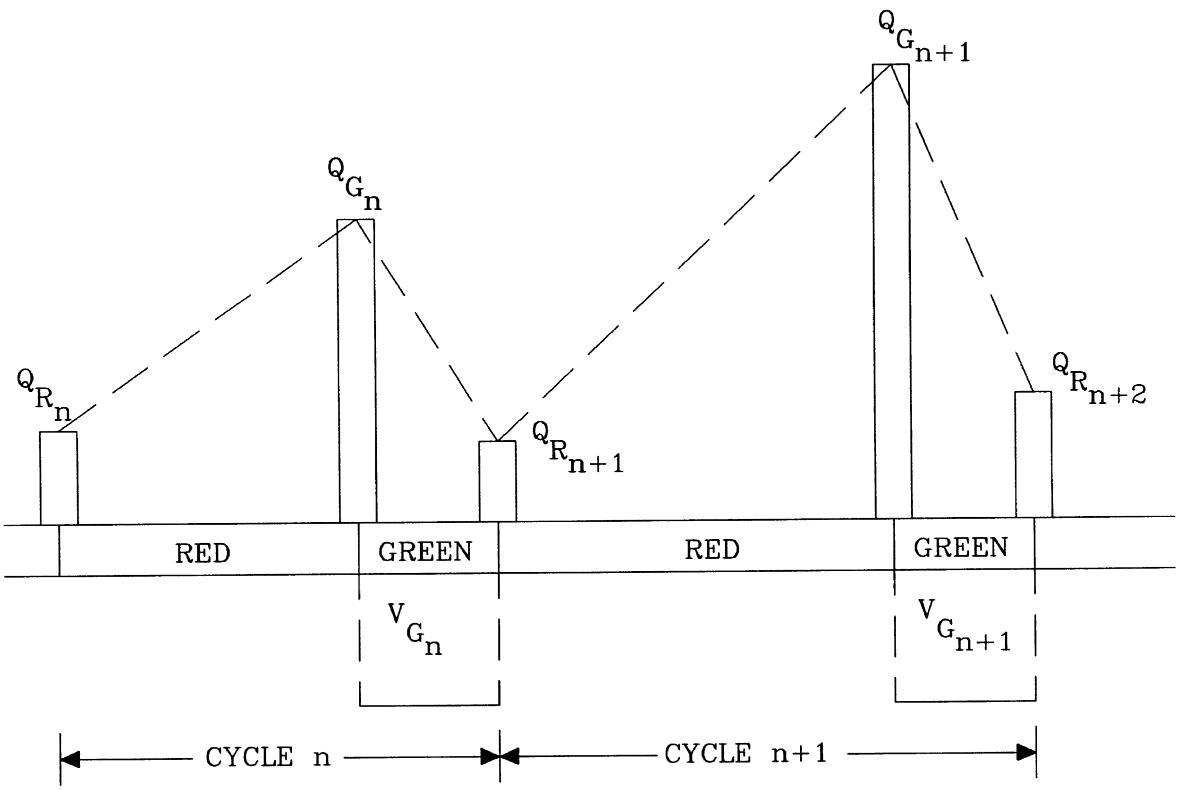
Vehicles arriving on green can be found mathematically by subtracting the difference between queues at the onset of red (Q_{Rn}) and onset of green (Q_{Gn}) from the number of vehicles served during the green interval (V_{Gn}), or

$$A_{Gn} = V_{Gn} - (Q_{Gn} - Q_{Rn+1}) \quad \text{(equation 2).}$$

As previously mentioned, the queue length at onset of red, arrival rate during the red interval, and vehicles served during the green interval (and in the case of right-turn-on-red, vehicles served during the red interval) were noted from videotape and in-field data collection. Table 1 shows an example of the reduced data collected at West 34th on February 10, 1998.

Delay Calculation Procedure

Figure 6 presents the basic queuing model showing the cumulative arrival pattern with respect to time, A(t), and the cumulative departure or service pattern, D(t). The effect of the signal is seen in the departure pattern D(t) where, since there are no vehicles serviced during the red interval, the pattern is horizontal. The area between curves A(t) and D(t) indicates that vehicles are waiting in queue. The y-axis gives the length of the queue, in number of vehicles, at any time. The vehicles arriving in the queue leave the queue at the time shown by the horizontal projection of the difference between the curves. In essence, the area between the curves represents the total vehicle seconds lost to waiting in the queue, in other words the total approach delay.



LEGEND

Q_{G_n} = Queue at the onset of green in the n^{th} cycle

Q_{R_n} = Queue at the onset of red in the n^{th} cycle

V_{G_n} = Volume served in the green for approach

A_{G_n} = Arrivals on the approach in green in n^{th} cycle

A_{R_n} = Arrivals on the approach in red in n^{th} cycle

Figure 5. Queue Diagram for Calculation of Arrival Rates

Table 1. Example of Reduced Data for Queue and Arrival Rates

Tr	Qr			Tg	Red	Qg			Ar			Vg			Green	Ag		
	L	M	R		Interval	L	M	R	L	M	R	L	M	R	Interval	L	M	R
16:30:10	0	0	0	16:31:13	0:01:03	12	12	10	12	12	10	18	18	20	0:00:40	7	6	11
16:31:53	1	0	1	16:32:50	0:00:57	8	9	8	7	9	7	9	11	10	0:00:40	2	2	2
16:33:30	1	0	0	16:34:30	0:01:00	6	11	13	5	11	13	15	19	18	0:00:40	10	8	5
16:35:10	1	0	0	16:36:10	0:01:00	5	10	9	4	10	11	9	18	21	0:00:33	5	8	10
16:36:43	1	0	0	16:37:33	0:00:50	5	10	10	4	10	11	11	17	17	0:00:42	6	7	6
16:38:15	0	0	0	16:39:13	0:00:58	10	8	7	10	8	9	13	20	13	0:00:42	4	13	5
16:39:55	1	1	1	16:40:52	0:00:57	7	10	17	6	9	17	12	19	21	0:00:38	5	9	3
16:41:30	0	0	0	16:42:30	0:01:00	11	12	8	11	12	9	14	20	14	0:00:39	4	8	5
16:43:09	1	0	0	16:44:10	0:01:01	7	12	11	6	12	11	10	15	15	0:00:38	4	5	6
16:44:48	1	2	2	16:45:30	0:00:42	7	6	10	6	4	8	13	8	10	0:00:36	8	3	0
16:46:06	2	1	0	16:46:48	0:00:42	5	6	4	3	5	4	10	12	11	0:00:37	6	8	7
16:47:25	1	2	0	16:48:09	0:00:44	3	11	9	2	9	11	7	16	17	0:00:38	4	5	6
16:48:47	0	0	0	16:49:30	0:00:43	5	7	8	5	7	9	8	14	11	0:00:30	5	10	3
16:50:00	2	3	1	16:50:50	0:00:50	6	11	8	4	8	8	12	17	17	0:00:36	6	9	9
16:51:26	0	3	1	16:52:13	0:00:47	6	11	8	6	8	8	13	18	15	0:00:35	8	10	7
16:52:48	1	3	1	16:53:30	0:00:42	4	9	8	3	6	7	10	21	12	0:00:38	6	16	6
16:54:08	0	4	2	16:54:51	0:00:43	6	10	9	6	6	7	11	17	18	0:00:37	8	10	11
16:55:28	3	3	2	16:56:13	0:00:45	9	10	9	6	7	7	18	18	16	0:00:35	12	11	9
16:56:48	3	3	2	16:57:31	0:00:43	11	15	8	8	12	7	13	21	18	0:00:42	4	8	11
16:58:13	2	2	2	16:59:13	0:01:00	13	17	17	11	15	16	16	16	25	0:00:42	8	5	9
16:59:55	5	6	2	17:00:51	0:00:56	15	19	15	10	13	13	22	22	22	0:00:45	9	9	11

West 34th PM, February 10, 1998.

Note:

Tr = Time at onset of red interval
Qr = Queue at onset of red interval
Tg = Time at onset of green interval
Qg = Queue at onset of green interval

Ar = Vehicle arrivals during red interval
Vg = Vehicles served during green interval
Ag = Vehicle arrivals during green interval

L = Left (inside) lane
M = Middle lane
R = Right (outside) lane

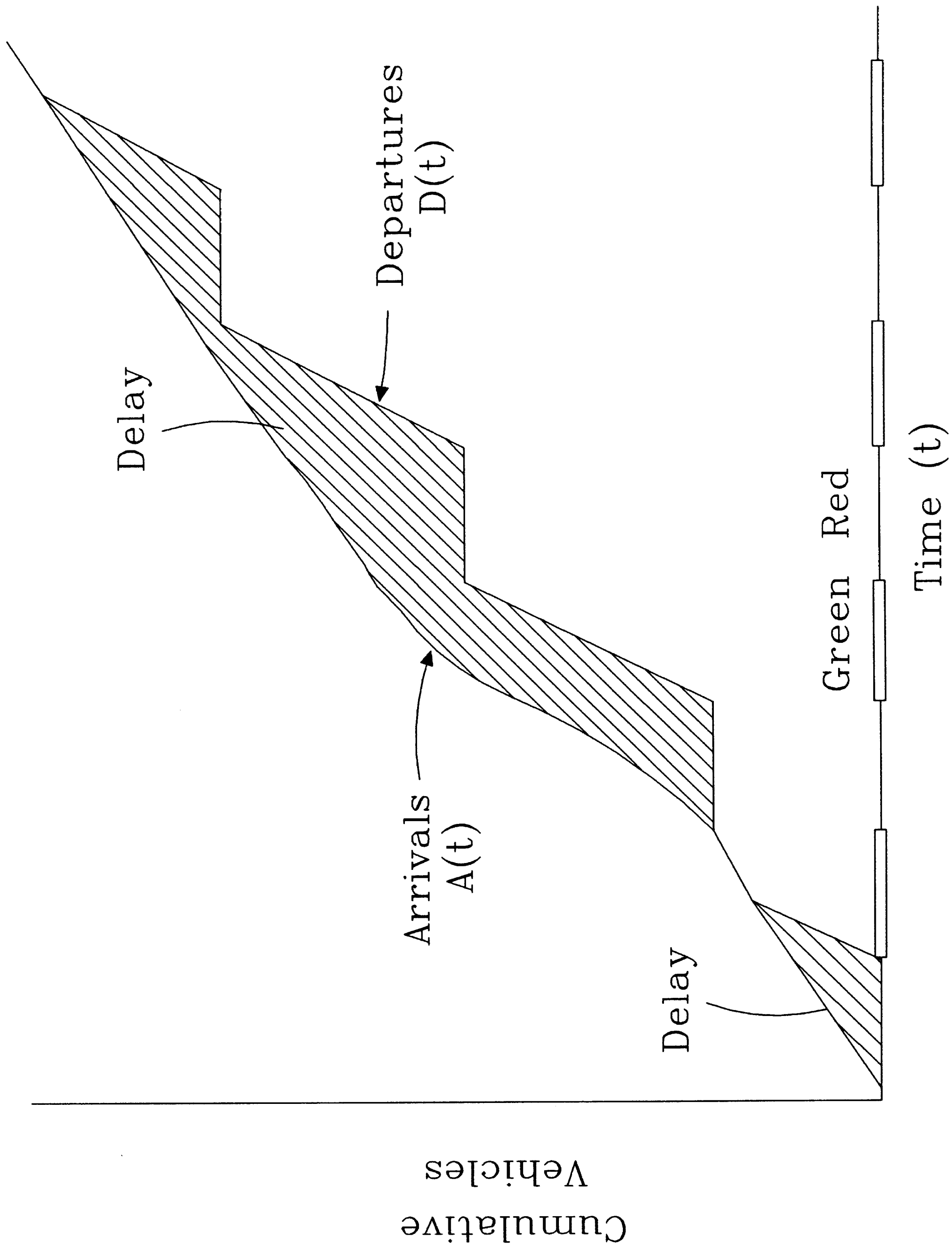


Figure 6. Queuing Diagram for Signalized Intersections

The relationships of Figure 6 are applied as in Figure 5 in order to simplify data collection and delay calculations. The difference between the cumulative number of vehicles served and arriving is the net number of vehicles in queue at the intersection at any time. This method of delay calculation assumes uniform distribution of the arrivals over the red and green intervals.

The data collected and reduced were used to develop the pattern of queue buildup since the slope is equal to the arrival rate during the red interval. The queue dissipation pattern cannot be determined simply from taking the slope of the line from queue at onset of green to queue at onset of red of the next cycle because vehicles will depart at a saturation flow rate, not at a rate to equally distribute themselves over the entire green interval. Therefore, the next step in the analysis was to determine the service rate or saturation flow rate on each subject approach.

The saturation flow rate is defined as "the equivalent hourly rate at which vehicles can traverse an intersection approach under prevailing conditions, assuming that a green signal is available at all times and no lost times are experienced, in vehicles per hour green or vehicles per hour green per lane" (3). The saturation flow rate is the inverse of the time (in seconds) that it takes to service each vehicle. The Highway Capacity Manual procedure for the calculation of saturation flow rate was followed for the estimation of saturation flow rates during each study period. For each lane, vehicle headways were measured for each vehicle in the queue at the onset of green. The average headway of the fourth vehicle to the last vehicle in queue was calculated, and the inverse of this value was calculated as the saturation flow rate. An example of this calculation is shown in Table 2. This table summarizes the data collected for the middle lane of West 34th on February 10, 1998, for 15 cycles during the PM peak period. The saturation flow rate was calculated for each lane at each approach for each study period. Video recordings were used to determine when each vehicle crossed the stopline at the approach, and a headway calculation program was used to determine each individual headway. The average saturation flow rates for each approach (by lane) are summarized in Table 3.

Table 2. Calculation of Saturation Flow Rates

Vehicle	Headway (seconds)														
	Cycle 1	Cycle 2	Cycle 3	Cycle 4	Cycle 5	Cycle 6	Cycle 7	Cycle 8	Cycle 9	Cycle 10	Cycle 11	Cycle 12	Cycle 13	Cycle 14	Cycle 15
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	1.98	1.65	2.20	2.69	2.41	1.87	2.69	2.36	2.31	2.03	2.36	2.04	2.03	1.48	2.14
3	1.70	1.48	1.81	2.08	2.04	1.38	2.14	1.81	1.76	2.42	1.76	1.70	1.54	1.65	1.82
4	2.31	1.81	2.31	2.15	1.75	1.53	2.25	1.76	2.47	1.92	1.86	1.59	2.03	2.03	2.14
5	2.36	1.81	2.09	2.25	1.65	1.38	1.21	1.81	1.92	2.20	1.98	1.65	2.96	1.87	1.92
6	2.20	1.76	1.53	4.17	1.38	1.86	1.32	2.03	2.14	1.98	1.65	1.37	1.60	1.75	1.92
7	2.03	1.65	1.65	1.93	1.04	1.87	1.59	1.76	2.25	1.59	1.76	1.54	1.59	1.65	1.70
8	1.16	1.81	2.03	2.25	1.21	1.76	2.14	3.24	3.96	1.32	2.47	1.37	1.65	2.97	1.76
9	1.53	1.59	1.71	1.54	1.21	2.42	1.49	1.92	1.76	1.53	1.70	1.65	1.59	2.58	1.21
10	1.32	1.54	1.53	1.31	1.31	1.64	1.48	1.38	1.97	1.54	1.43	2.36	2.42	2.75	1.92
11	1.21	2.75	1.43	1.82	1.65	2.31	1.65	1.48	1.54	1.32	1.48	1.49	3.35	1.59	1.65
12	1.43	2.42	1.43	1.42	1.27	2.09			1.27	1.76	1.60	1.20	1.04	1.65	1.32
13	2.08		1.87	2.15	1.92	2.25				1.92	1.37	1.54	1.32	1.31	1.32
14	1.32		1.81	1.26	1.43	1.04				1.54	1.54	1.71	2.25	2.81	3.18
15	1.87			1.26	1.37	1.27					1.42	1.42		1.75	2.86
16	1.70			0.94							1.43			1.98	1.37
17	1.38			1.26							1.54				1.43
18	2.03			1.81											1.87
19				1.38											
20															

Middle Lane, US 290 WB Frontage Road at West 34^{th}, PM Peak Period, 2/11/98.

Total Headway = 284.65 seconds
Total Average Headway = 1.77 seconds
Total Vehicles = 161 vehicles
Lane Saturation Flow = 2036 vphgpl

Table 3. Summary of Saturation Flow Study Results							
	Headway (seconds)			Saturation Flow Rate (vphgpl)			
	Left	Middle	Right	Left	Middle	Right	Approach
MANGUM MID-DAY PEAK HOUR — right turn CLAS							
Before	2.05	1.77	2.25	1,757	2,039	1,598	5,394
After	2.08	1.90	2.12	1,739	1,890	1,700	5,330
HOLLISTER AM PEAK HOUR — right turn CLAS							
Before	1.94	1.94	n/a	1,852	1,860	*	n/a
After	1.70	1.75	1.99	2,129	2,062	1,815	6,006
HOLLISTER MID-DAY PEAK HOUR — right turn CLAS							
Before	1.92	1.86	2.14	1,880	1,933	1,684	5,497
After	1.93	1.87	2.14	1,863	1,929	1,687	5,480
WEST 34TH PM PEAK HOUR — left turn CLAS							
Before	2.01	1.84	1.81	1,793	2,028	1,846	5,668
After	1.92	1.75	2.02	1,879	2,052	1,789	5,720

*No queuing was observed in the right lane during the study period so that saturation flow rates could be calculated. Right turning vehicles had 100% right turn on red opportunity, so that no queuing was observed in the rightmost lane during this study period.

The queue dissipation rate can be determined from the difference of the service rate and arrival rate during the green interval. The green interval portion of the departure pattern was drawn with the appropriate slope, and the resulting areas were measured using a trigonometric solution. Note the slope of the arrival rate curve A(t) would be steeper during peak periods and flatter during lower demand periods. An example of the delays calculated for each lane is shown in Table 4. Table 4 summarizes the expected delay for a portion of the PM peak period on the US 290 frontage road approach to West 34th on February 11, 1998. Data collected in other peak periods and at other frontage road approaches were reduced in similar calculations.

Table 4. Example of Delay Calculations

			Left Lane			Middle Lane			Right Lane		
Vehicles in Queue at Onset of Green	Total Approach Delay (veh*sec)	Average Approach Delay (sec/veh)	Tq (sec)	Total Delay (veh*sec)	Average Delay (sec/veh)	Tq (sec)	Total Delay (veh*sec)	Average Delay (sec/veh)	Tq (sec)	Total Delay (veh*sec)	Average Delay (sec/veh)
34	1681.3	30.02	34.81	586.9	32.60	28.88	551.3	30.63	DNC	543.2	27.16
25	989.0	32.97	17.03	324.6	36.07	17.46	335.1	30.46	18.19	329.3	32.93
30	1393.9	26.81	22.25	276.7	18.45	30.09	495.5	26.08	35.64	621.7	34.54
24	1134.0	23.63	13.58	213.9	23.77	30.95	454.7	25.26	DNC	465.3	22.16
25	952.7	21.17	13.27	183.2	16.65	25.07	375.3	22.08	28.83	394.1	23.19
25	1033.9	22.48	23.56	407.8	31.37	31.25	357.0	17.85	18.88	269.1	20.70
34	1619.1	31.14	18.03	291.1	24.26	30.42	465.6	24.51	DNC	862.4	41.07
31	1363.3	28.40	26.37	475.0	33.93	33.29	559.8	27.99	22.13	328.5	23.47
30	1352.8	33.82	16.89	303.1	30.31	27.65	531.9	35.46	33.15	517.8	34.52
23	809.8	26.12	23.53	250.4	19.26	12.44	205.3	25.67	20.42	354.1	35.41
15	491.1	14.88	13.98	182.0	18.20	17.18	198.5	16.54	13.31	110.6	10.06
23	844.3	21.11	7.24	98.9	14.12	25.35	425.4	26.59	27.12	320.1	18.83
20	653.0	19.79	14.16	142.9	17.86	DNC	256.0	18.29	20.53	254.1	23.10
25	1151.2	25.03	16.99	251.0	20.92	34.86	541.7	31.87	33.37	358.5	21.09
25	1067.4	23.20	20.61	202.8	15.60	DNC	542.6	30.14	27.61	322.0	21.46
21	902.2	20.98	11.05	127.1	12.71	DNC	489.7	23.32	24.11	285.4	23.79
25	1096.4	23.84	19.77	188.3	17.12	33.87	470.3	27.67	DNC	437.8	24.32
28	1385.3	26.64	DNC	476.7	26.48	DNC	488.6	27.14	DNC	420.0	26.25
34	1485.9	28.58	25.91	443.5	34.12	39.99	686.9	32.71	35.12	355.5	19.75
47	2641.3	46.34	39.48	706.6	44.17	38.07	893.6	55.85	DNC	1041.1	41.64
49	2998.8	45.44	DNC	911.3	41.42	DNC	1184.9	53.86	DNC	902.7	41.03

February 11, 1998 at US 290 FR @ West 34th, PM peak period by lane.

Note: Tq = Time for vehicles to clear the queue (seconds)
DNC = Queue did not clear

3.0 ANALYSIS AND RESULTS

As outlined in the study methodology, data were collected and summarized for the *before* (permitted double turns) and *after* (shared-turns) TOD lane assignment changes. This chapter of the report focuses on analyzing the data collected and reporting results. Unless otherwise noted, the term *delay* means average vehicle delay, *queue* represents the number of vehicles in queue at onset of green, *before* is the period of time before the recommended TOD changes took effect (February 3, 1998), and *after* represents the period after TOD changes occurred.

METHODOLOGY OF STATISTICAL ANALYSIS

The following sections explain the statistical analyses used to draw conclusions about the differences or uniformity in the traffic data. While some of these sections focus on the preliminary data analysis, the bulk concentrates on the statistical comparison of queue length and delays for the *before* and *after* data collection periods.

Normalizing the Data

Since several days of *after* data were collected, it was necessary to ensure that the different data sets exhibited similar characteristics before combining for statistical comparisons. If characteristics found among data collected on different days were not similar, the data would need to be normalized or set with respect to common background variables which most affect delay and queue lengths.

Perhaps the two greatest influences on delays and queues (given similar traffic demands) are length of cycle and duration of red interval. If these two parameters vary day to day (or even cycle by cycle), this would not allow for a direct, unbiased comparison of delays and queues for two or more different days (or cycles). It is recognized that given a longer cycle length and red interval, longer queues and increased delay would occur. However, an increase in cycle length alone may not contribute to a significant increase in delay on an approach if an adequate increase in green time accompanies the increased cycle length. It is therefore necessary to normalize the MOEs (queues and delays) with respect to cycle length. At each of the study locations, signal timings are on a time-of-day pretimed operation. However, field observations did find that cycle lengths and red intervals could vary somewhat.

Another traffic performance measure that has impact on delay and queuing is traffic demand. When vehicles arrive at a signal on the red interval, they are delayed by the red indication and the resulting queue present when they arrive. Therefore, it is necessary to also normalize the data with respect to traffic demand volumes in order to account for the additional delays and length of queue that varies with the commonly random nature of arrivals at an intersection.

The analysis of delays and queues is done on a cycle by cycle method. This methodology results in a need to normalize the delays and queues by dividing each of these parameters by the per cycle demand, essentially reducing the assumed impact of cycle-by-cycle variance in cycle lengths, red intervals, and green intervals on traffic demand. An example of a set of normalized data is shown in Table 5. The queue is normalized by dividing the number of vehicles in queue at onset of green in cycle *n* by the total vehicle demand during the same cycle. The units of the normalized queue are vehicles/vehicles of demand volume (per cycle). Delays are normalized in the same manner, by dividing the average vehicle delay by the per cycle demand volume. The units of the normalized delay are seconds/vehicle/vehicle of demand volume (per cycle).

Table 5. Example of Normalized Data

Total Demand per Cycle (vehicles)	Queue at Onset of Green (vehicles)	Average Approach Delay (sec/veh)	Normalized Queue (veh/veh)	Normalized Delay (sec/veh/veh)
58	34	30.02	0.5862	0.5177
29	25	32.97	0.8621	1.1367
52	30	26.81	0.5769	0.5155
48	24	23.63	0.5000	0.4922
44	25	21.17	0.5682	0.4811
49	25	22.48	0.5102	0.4587
49	34	31.14	0.6939	0.6355
49	31	28.40	0.6327	0.5796
44	30	33.82	0.6818	0.7687
29	23	26.12	0.7931	0.9008
33	15	14.88	0.4545	0.4510
37	23	21.11	0.6216	0.5705
39	20	19.79	0.5128	0.5074
44	25	25.03	0.5682	0.5688
47	25	23.20	0.5319	0.4937

Testing for Uniformity and Normality of Data

After TOD lane assignment changes were made, study personnel collected data during the first, ninth, and 17th weeks of operation. They anticipated that violations would increase when CLAS TOD operations began, but decrease with time as drivers became accustomed to the lane assignment changes. Even though this *after* data was collected on three different days for the violation portion of the study, it was necessary to group the three days of data to complete the majority of the analysis (testing for changes in delays and queues).

Each data set used should represent typical traffic operations, not those influenced by external influences (freeway incidents, etc.). Any data sets found to possibly be affected by external influences should not be grouped with data found to be typical. If found to be atypical, data sets would not be grouped with data found typical for a given study approach. Including such data might skew results, leading to false conclusions about the changes in traffic operations from *before* to *after* lane assignment changes were made.

The reduced data (similar to data shown in Table 1) for queues and delays were normalized for each data set. The analysis of variance (ANOVA) test was undertaken on the grouped set of *after* data for each study approach. However, *before* the ANOVA test was performed, the data were checked to ensure they satisfied the basic assumption of an ANOVA test, which is that the data must fit a normal distribution (4).

For each data set the mean and standard deviation was calculated and used to develop an expected distribution. The observed frequency was then checked for goodness-of-fit to the normal distribution using the chi-square test. Chi-square tests compare how well a set of data match a given distribution. The hypothesis for the chi-square test was that the observed data set fit the normal distribution with the level of significance for the test equal to 0.05. The null hypothesis was accepted if the observed chi-square value was less than the critical chi-square value. If the null hypothesis was accepted (or could not be rejected), then there was insufficient statistical evidence that the data did not fit the normal distribution. The full results of each chi-square test are shown in Appendix B, each table summarizing statistical analysis for each of the study approaches.

Testing for Differences Between Approach Lanes

Use of CLAS on a TOD basis is meant to reduce lane imbalances, leading to reduced queues and delays. In order to assess the effect of the use of CLAS as a space management tool, statistical analysis was undertaken to examine the differences in delays and queues across different lanes on each study approach. These tests were done on the *before* and *after* conditions separately to determine not if the queues changed *before* to *after*, but if lane balance existed *before* and *after* across an approach.

The procedure used to compare average queue lengths and average vehicle delay was similar to the analysis used to compare the uniformity of data collected on different days. The ANOVA test was used to test if the mean values of delays and queues were equal for each lane. The null hypothesis for this ANOVA test was "the mean values for delay (or queues) are equal across all lanes on the approach." The null hypothesis was rejected if the observed F-value was greater than critical F-value. These tests were performed at a level of significance of 0.05. If the null hypothesis was rejected (the delays or queue lengths for at least one lane was significantly different than others on the approach), Fisher's Least Significant Difference test of multiple comparison was used to determine which lane was significantly different.

Testing for Differences Between *Before* and *After* Lane Assignment Changes

The most important analysis of changing lane assignment on a TOD basis was how delays and queues changed from *before* to *after* TOD changes took effect. These differences were analyzed using the standard t-test to compare average normalized values of delay and queues *before* and *after* TOD changes. The null hypothesis for this test is "there is no difference in the value of mean normalized delay (or normalized queue length) for traffic conditions *before* or *after* lane assignment changes." These tests were performed at a level of significance of 0.05.

ANALYSIS RESULTS BY STUDY SITE

Each analysis of the effects of the changes made in lane assignment based on the TOD change recommendations is summarized in the following sections. Please refer to the previous section on statistical analysis for discussion on rationale for each statistical test. Complete results for each test may be found in Appendix B.

Analysis of CLAS TOD Operations—Mangum Mid-Day

A brief summary of the results at Mangum during the Mid-Day peak hour is as follows:

- All three days of *after* data were combined into one data set for comparison to the *before* data.
- Delay decreased (however, not at a 95 percent statistically significant level) on the approach after the CLAS lane use changes took effect.
- Queues increased significantly in the rightmost lane after the CLAS lane use changes took effect, but reductions in queue lengths in the left and middle lanes (as traffic shifted to a lane balance) resulted in no significant change in the average queue length on the approach. This effect was expected due to the removal of a 100 percent right-turn-on-red opportunity in the right lane. Delays decreased on the overall approach, but not to a statistically significant level.

The frontage road approach has three lanes, with CLAS controlling right turn movement. Typical hourly turning movement traffic volumes for the *before* and *after* period are:

Movement	Before	After
Left Turn	397 (27%)	395 (27%)
Straight	662 (45%)	665 (46%)
Right Turn	414 (28%)	382 (27%)
TOTAL	1473 (100%)	1442 (100%)

The first step in the statistical analysis of *before* and *after* conditions at Mangum during the Mid-Day peak hour was to normalize the queue and delay data (for each cycle). All groups of normalized data exhibited qualities of the normal distribution. The *after* set of data was then checked for uniformity using the ANOVA procedure. The average delays and queues for all three *after* data sets were found to be statistically the same; therefore, all three days were grouped to represent *after* conditions for the remaining analyses. Table 6 summarizes the statistical analysis of the normalized mean comparison of the three *after* data collection periods.

Table 6. ANOVA Test for Equal Mean Queue and Delay *After* Data: Mangum Mid-Day Peak Hour									
(F-test for differences between days of data collection Ho: means are equal)									
Normalized Delays on Approach					*Normalized Queues on Approach*				
Date	Mean	F	F_{crit}	Test Conclusion	Date	Mean	F	F_{crit}	Test Conclusion
2/98	1.1719	0.6813	3.0470	Do not reject Ho	2/98	0.7619	0.5582	3.0470	Do not reject Ho
4/98	1.2265	*Conclude all three days of after data collection have statistically same average vehicle delay. Can group all 3 days together for after data.*			4/98	0.7838	*Conclude all three days of after data collection have statistically same average approach queue length. Can group 3 days for after data.*		
6/98	1.2726				6/98	0.8111			

Queues and Delays Across Lanes

The main objective of using CLAS to optimize lane assignment on a TOD basis is to alleviate lane imbalances on the frontage road approach. The statistical results for Mangum Mid-Day are summarized in Table 7. The statistical analysis showed no significant difference in delay among lanes (*before* or *after* TOD lane assignment changes). The average queue length in the right lane was significantly lower than the left or middle lane queues during *before* traffic conditions. However, no significant difference was found in average queue length *after* TOD lane assignment changes took effect, hence a lane balance existed. This lane balance was caused by the occasional block of right-turn-on-red opportunity by a through vehicle. While no significant differences in delay are evident for the *after* condition, the change in lane assignment to shared-turns caused a queue balance to occur.

Table 7. ANOVA Test for Equal Mean Queue and Delay: Mangum Mid-Day Peak Hour									
(F-test for differences between queues and delays by lane and approach; Ho: means are equal)									
Lane	Mean	F	F_{crit}	Test Conclusion	Lane	Mean	F	F_{crit}	Test Conclusion
Normalized Delays Before					*Normalized Queues Before*				
Left	4.9875	1.4085	3.0473	Do not reject Ho	Left	0.9622	9.3553	3.0473	Reject Ho
Middle	4.5656	*Conclude all three lanes experience statistically the same average vehicle delay.*			Middle	0.9607	*Conclude at least one of the lanes is different. Fisher's LSD indicated the right lane has significantly lower queues than left or middle.*		
Right	3.7931				Right	0.5954			
Normalized Delays After					*Normalized Queues After*				
Left	4.2413	0.1619	3.0125	Do not reject Ho	Left	0.8588	1.2319	3.0125	Do not reject Ho
Middle	4.2800	*Conclude all three lanes experience statistically the same average vehicle delay.*			Middle	0.8977	*Conclude all three lanes experience statistically the same average queue length (lane balance exists).*		
Right	4.5607				Right	0.8060			

Queues and Delays Before and After CLAS TOD Changes

The most important comparison of this research was to determine if the TOD lane assignment change significantly improved operations at each study approach. The results of the analysis are presented in Table 8. The analysis revealed that average delays decreased for the entire approach, left lane, and middle lane, and increased for the right lane. However, these decreases and increases were *not statistically significant differences* in delay between *before* to *after* lane assignments. Queue lengths in the right lane were found to have significantly increased from *before* to *after* the change to the shared-turn lane assignment.

It is interesting to note that while queue length increased in the right lane from *before* to *after*, no statistically significant increase in delay was observed. This may be explained by the observation that as drivers approach the intersection during the beginning of the red interval, they tend to choose the left and middle lanes so they may not interfere with right turning traffic. However, as queues build in the left and middle lanes, drivers approaching the back of the queue realize the right lane is available for the through movement and begin to use the right lane to queue for the through movement near the middle or end of the red interval. While the opportunity for right-turn-on-red is lost, it may typically not be lost until near the end of the red interval, leaving the average delay about the same, but significantly increasing the average queue length in the right lane at the onset of the green interval.

Table 8. Direct Comparison of *Before* and *After* Queues and Delays: Mangum Mid-Day Peak Hour

t-Test for differences between delays and queues pre/post TOD implementation (Ho: means *before* and *after* are same)

Lane	Mean *Before*	Mean *After*	t	t_{crit}	Test Conclusion	Comments
			Normalized Delay			
Left	4.9875	4.2413	1.2571	1.9700	Do not reject Ho	*Conclude no significant change in delay in left lane before to after.*
Middle	4.5656	4.2800	0.5477	1.9700	Do not reject Ho	*Conclude no significant change in delay in middle lane before to after.*
Right	3.7931	4.5607	-0.6241	1.9700	Do not reject Ho	*Conclude no significant change in delay in right lane before to after.*
Approach	1.3203	1.2237	1.3506	1.9949	Do not reject Ho	*Conclude no significant change in delay on approach before to after.*
			Normalized Queue			
Left	0.9622	0.8588	1.1397	1.9944	Do not reject Ho	*Conclude no significant change in queue in left lane before to after.*
Middle	0.9607	0.8977	0.7484	1.9700	Do not reject Ho	*Conclude no significant change in queue in middle lane before to after.*
Right	0.5954	0.8060	-2.2524	1.9700	Reject Ho	*Conclude that the right lane experienced a significant increase in queue length after lane assignments changed to shared turns.*
Approach	0.8011	0.7856	0.4083	1.9700	Do not reject Ho	*Conclude no significant change in overall approach queue length before to after.*

Analysis of CLAS TOD Operations: Hollister Mid-Day

A brief summary of the results at Hollister during the Mid-Day peak hour is as follows:

- All three days of *after* data were combined into one data set for comparison to the *before* data.
- No lane balance existed before CLAS changed indications from double-right to shared-right. The opportunity for right-turn-on-red *before* lane use created significantly lower queues and delays in the right lane. The change to shared operations did not alleviate this lane imbalance.
- Delays and queues significantly increased *after* the change to shared-right turn operations, both in the rightmost lane, and for the overall approach.

The frontage road approach has three lanes, with CLAS controlling right turn movement. Typical hourly turning movement traffic volumes for the *before* and *after* period are:

Movement	Before	After
Left Turn	236 (16%)	248 (18%)
Straight	787 (53%)	790 (56%)
Right Turn	466 (31%)	372 (26%)
TOTAL	1489 (100%)	1410 (100%)

Once the queue and delay information was normalized, each set of *before* and *after* queue and delay data was tested for fit to a normal distribution using the chi-square test. All groups of normalized data exhibited qualities of the normal distribution. The *after* set of data was then checked for uniformity among the different days of data collection. The statistical results are presented in Table 9. The average delays and queues for all three *after* TOD change data sets were found to be statistically the same; therefore, all three days were grouped to represent *after* conditions for the remaining analyses.

Table 9. ANOVA Test for Equal Mean Queue and Delay *After* Data: Hollister Mid-Day Peak Hour									
(F-test for differences between days of data collection Ho: means are equal)									
Normalized Delays on Approach					*Normalized Queues on Approach*				
Date	Mean	F	F_{crit}	Test Conclusion	Date	Mean	F	F_{crit}	Test Conclusion
2/98	1.5639	0.5646	3.0603	Do not reject Ho	2/98	0.8881	0.3292	3.0603	Do not reject Ho
4/98	1.4937	*Conclude all three days of after data collection have statistically same average vehicle delay. Can group all 3 days together for after data.*			4/98	0.9073	*Conclude all three days of after data collection have statistically same average approach queue length. Can group all 3 days for after data.*		
6/98	1.4536				6/98	0.8658			

Queues and Delays Across Lanes

The next step in the analysis was to test for the differences in delays and queue lengths across lanes to determine if lane imbalances existed either *before* or *after* changes in lane assignment. Statistical results are summarized in Table 10 (detailed statistical output is shown in Appendix B). The statistical analysis revealed that *before* delays were significantly lower in the right lane than either the left or middle lanes. *After* the lane assignments were changed, the delays experienced in the right lane increased to the level where they were not statistically different than those in the left and middle lanes. However, the left lane experienced significantly lower delays than the middle lane.

Table 10. ANOVA Test for Equal Mean Queue and Delay: Hollister Mid-Day Peak Hour									
(F-test for differences between queues and delays by lane and approach; Ho: means are equal)									
Lane	Mean	F	F_{crit}	Test Conclusion	Lane	Mean	F	F_{crit}	Test Conclusion
Normalized Delays Before					*Normalized Queues Before*				
Left	4.2293	12.4320	3.0564	Reject Ho	Left	0.9193	36.9789	3.0564	Reject Ho
Middle	5.0735	*Conclude at least one of the lanes is different. Fisher's LSD indicated the right lane has significantly lower delay than left or middle.*			Middle	1.0952	*Conclude at least one of the lanes is different. Fisher's LSD indicated the right lane has significantly lower queues than left or middle.*		
Right	2.5642				Right	0.4862			
Normalized Delays After					*Normalized Queues After*				
Left	4.7634	3.7724	3.0168	Reject Ho	Left	0.8865	11.5984	3.0168	Reject Ho
Middle	5.9010	*Conclude at least one of the lanes is different. Fisher's LSD indicated the middle lane has significantly higher delay than the left lane.*			Middle	1.1156	*Conclude at least one of the lanes is different. Fisher's LSD indicated the middle lane has significantly higher queues than left or right.*		
Right	5.0419				Right	0.9142			

The queues *before* were significantly lower in the right lane, and after the lane assignment was changed, queues in the right lane balanced with those in the left lane, with significantly longer queues in the middle lane. Lane balance did not occur *before* or *after* the change from double to shared turns.

Queues and Delays Before and After CLAS TOD

The most important comparison of the analysis was to determine if the TOD lane assignment change significantly improved operations at each study approach. The results of the analysis are presented in Table 11. The statistical analysis revealed that while the average delays increased for the entire approach from *before* to *after,* the left lane and middle lane did not experience a significant increase in delay. Delays did significantly increase in the right lane from *before* to *after* when lane assignments were changed. The analysis also revealed similar results for average queue lengths, whereby the average queue lengths increased on the combined approach and on the right lane, but no significant queue length increase was experienced on the left and middle lanes. Queue lengths and delays increased on the overall approach and the right lane because of the additional vehicles in queue in the right lane. The full-time opportunity for right-turn-on-red was taken away by the shared-turn configuration, and additional delay was experienced by vehicles waiting in queue in the right lane—enough, in fact, to significantly increase the average delay on the entire approach.

Table 11. Direct Comparison of *Before* and *After* Queues and Delays: Hollister Mid-Day Peak Hour

t-Test for differences between delays and queues pre/post TOD implementation (Ho: means *before* and *after* are same)

Lane	Mean *Before*	Mean *After*	t	t_{crit}	Test Conclusion	Comments
Normalized Delay						
Left	4.2293	4.7634	-1.5463	1.9723	Do not reject Ho	*Conclude no significant change in delay in left lane before to after.*
Middle	5.0735	5.9010	-1.6618	1.9723	Do not reject Ho	*Conclude no significant change in delay in middle lane before to after.*
Right	2.5642	5.0419	-3.3022	1.9723	Reject Ho	*Delay significantly increased from before to after in right lane.*
Approach	1.2505	1.6003	-3.7177	1.9723	Reject Ho	*Delay significantly increased from before to after on approach.*
Normalized Queue						
Left	0.9193	0.8865	0.6860	1.9723	Do not reject Ho	*Conclude no significant change in queue in left lane before to after.*
Middle	1.0952	1.1156	-0.2603	1.9723	Do not reject Ho	*Conclude no significant change in queue in middle lane before to after.*
Right	0.4862	0.9142	-5.5934	1.9723	Reject Ho	*Queue significantly increased from before to after in right lane.*
Approach	0.8114	0.9304	-3.0253	1.9723	Reject Ho	*Queue significantly increased from before to after on approach.*

Analysis of CLAS TOD Operations: West 34th PM Peak Hour

A brief summary of the results at West 34th during the PM peak hour is as follows:

- All three days of *after* data were combined into one data set for comparison to the *before* data.
- A lane balance was not indicated *before* or *after* CLAS lane use indication was changed from double-left to shared-left turns. The left lane experienced less delay and shorter queues than middle and right lanes in both instances.
- Queues decreased significantly on the entire approach when lane use was changed to shared-turn indications. Delays decreased for the left lane and for the total approach. However, the associated reduction in delay was not statistically significant.

The frontage road approach has three lanes, with CLAS controlling right turn movement. Typical hourly turning movement traffic volumes for the *before* and *after* period are:

Movement	Before	After
Left Turn	565 (28%)	474 (21%)
Straight	1326 (66%)	1663 (75%)
Right Turn	121 (06%)	88 (04%)
TOTAL	2012 (100%)	2225 (100%)

Once the queue and delay information was normalized, each set of *before* and *after* queue and delay data was grouped and tested for fit to a normal distribution using a chi-square test. All groups of normalized data exhibited qualities of the normal distribution. The *after* set of data was then checked for uniformity using the ANOVA procedure. Statistical results are presented in Table 12. When all data sets of normalized data were grouped, the entire distribution did not exhibit the qualities of the normal distribution. Fisher's test of least significant difference was used to determine which of the *after* data collection days were statistically different. The data collected during June 1998 was found to be significantly different than data for February and April 1998. As a result of these findings, data from the June 1998 data collection period were excluded from the *after* data set used in subsequent analyses.

Table 12. ANOVA Test for Equal Mean Queue and Delay *After* Data: West 34th PM Peak Hour									
(F-test for differences between days of data collection Ho: means are equal)									
Normalized Delays on Approach					*Normalized Queues on Approach*				
Date	Mean	F	F_{crit}	Test Conclusion	Date	Mean	F	F_{crit}	Test Conclusion
2/98	0.8575	6.5997	3.0681	Reject Ho	2/98	0.8450	9.1482	3.0681	Reject Ho
4/98	0.8441	*Conclude all three days of after data collection do not have statistically same average vehicle delay. Fisher's LSD test indicates June '98 data significantly different. Do not use June '98 data in after analysis.*			4/98	0.7831	*Conclude all three days of after data collection do not have statistically same average queues. Fisher's LSD test indicates June '98 data significantly different. Do not use June '98 data in after analysis.*		
6/98	0.6829				6/98	0.6547			

Queues and Delays Across Lanes

The next step in the analysis was to test for the differences in delays and queue lengths across lanes to determine if lane imbalances exist. The statistical results are summarized in Table 13. The statistical analysis revealed that there was no significant difference in delay among lanes *before* or *after* TOD lane assignment changes. However, the left lane during *before* conditions experienced significantly lower queue lengths than the middle and right lanes, indicating that motorists were not fully utilizing the left lane.

Table 13. ANOVA Test for Equal Mean Queue and Delay: West 34th PM Peak Hour									
(F-test for differences between queues and delays by lane and approach; Ho: means are equal)									
Lane	Mean	F	F_{crit}	Test Conclusion	Lane	Mean	F	F_{crit}	Test Conclusion
Normalized Delays Before					*Normalized Queues Before*				
Left	3.1409	1.1833	3.0664	Do not reject Ho	Left	0.8228	8.5184	3.0664	Reject Ho
Middle	2.3882	*Conclude all three lanes experience statistically the same average vehicle delay.*			Middle	1.0214	*Conclude at least one of the lanes is different. Fisher's LSD indicated the left lane has significantly lower queues than middle or right.*		
Right	2.7325				Right	1.0624			
Normalized Delays After					*Normalized Queues After*				
Left	2.6469	1.6191	3.0316	Do not reject Ho	Left	0.7721	3.8923	3.0316	Reject Ho
Middle	2.5072	*Conclude all three lanes experience statistically the same average vehicle delay.*			Middle	0.8425	*Conclude at least one of the lanes is different. Fisher's LSD indicated the left lane has significantly lower queues than middle or right.*		
Right	2.8175				Right	0.8983			

After lane assignments were changed, the left lane experienced significantly shorter queue length than the right lane, but no significant difference was shown between the left and middle lanes. The analysis also showed that no significant difference in queue lengths existed between the middle and right lanes. A lane balance was not achieved for *after* conditions because the average queue length in the middle and right lanes were significantly higher than those in the left lane.

While no significant differences in delay were evident *before* or *after* the lane assignments changed, the average queue lengths did exhibit a lane imbalance *before* lane assignments were changed. After lane assignments changed to a shared-turn configuration, a queue shift seemed to occur since it was found that the left lane had no significant difference in average queue length than the middle lane.

Queues and Delays Before and After CLAS TOD Changes

The most important comparison of this research was to determine if the TOD lane assignment change significantly improved operations at each study approach. The results of the analysis are presented in Table 14.

Table 14. Direct Comparison of *Before* and *After* Queues and Delays: West 34th PM Peak Hour

t-Test for differences between delays and queues pre/post TOD implementation (Ho: means *before* and *after* are same)

Lane	Mean *Before*	Mean *After*	t	t_{crit}	Test Conclusion	Comments
Normalized Delay						
Left	3.1409	2.6469	0.8225	2.0117	Do not reject Ho	*Conclude no significant change in delay in left lane before to after.*
Middle	2.3882	2.5072	-0.7698	1.9788	Do not reject Ho	*Conclude no significant change in delay in middle lane before to after.*
Right	2.7325	2.8175	-0.4258	1.9788	Do not reject Ho	*Conclude no significant change in delay in right lane before to after.*
Approach	0.8730	0.8608	0.2608	1.9788	Do not reject Ho	*Conclude no significant change in delay on approach before to after.*
Normalized Queue						
Left	0.8228	0.7721	0.7879	1.9788	Do not reject Ho	*Conclude no significant change in queue length in left lane before to after.*
Middle	1.0266	0.8425	4.0363	1.9790	Reject Ho	*Queue significantly decreased from before to after in middle lane.*
Right	1.0624	0.8983	3.1245	1.9788	Reject Ho	*Queue significantly decreased from before to after in right lane.*
Approach	0.9711	0.8236	3.7850	1.9788	Reject Ho	*Queue significantly decreased from before to after on approach.*

The analysis indicated a reduction in delay for the left lane and total approach, although not statistically significant. However, queue lengths did significantly decrease on the approach and in the middle and right lanes. Even though queues did decrease, no significant change in average queue length was observed for the left lane *after* the lane assignment change.

LANE USE VIOLATIONS

Direct comparison of safety at each frontage road approach studied was not viable given the time lag associated with accident information (one year or more). However, some insight could be gained from an examination of lane use violations *before* and *after* the lane assignments were changed, as these represent traffic conflicts. It is assumed that if lane assignments are not suitable for a given set of traffic conditions, there would be a tendency for some motorists to violate those lane assignments to shorten their individual time in queue. On the contrary, if lane assignments are appropriate, motorists will not tend to violate the lane assignment to gain advantage in the queue since a relative balance will occur. Table 15 summarizes peak hour violations for each day of data collection.

Table 15. Lane Use Violations: *Before* and *After* CLAS TOD Implementation

	Before	2/98	4/98	6/98		*Before*	2/98	4/98	6/98
Mangum Mid-Day Peak Hour					Hollister AM Peak Hour				
Cycles/Hour	44	42	43	42	Cycles/Hour	51	40	40	41
Vehicles	2,137	2,225	2,256	2,182	Vehicles	1,210	1,115	1,135	1,116
Violations	46	7	14	12	Violations	10	0	0	0
Violation/Cycles	1.045	0.167	0.326	0.286	Violation/Cycles	0.196	0.000	0.000	0.000
Violation/Vehicles	0.021	0.003	0.006	0.006	Violation/Vehicles	0.008	0.000	0.000	0.000
Hollister Mid-Day Peak Hour					West 34th PM Peak Hour				
Cycles/Hour	60	60	60	60	Cycles/Hour	51	52	51	40
Vehicles	1,473	1,442	1,462	1,606	Vehicles	1,505	1,410	1,400	1,416
Violations	48	5	1	3	Violations	26	2	0	7
Violation/Cycles	0.800	0.083	0.017	0.050	Violation/Cycles	0.510	0.038	0.000	0.175
Violation/Vehicles	0.033	0.003	0.001	0.002	Violation/Vehicles	0.017	0.001	0.000	0.005

Note: Violations/Vehicles represents the ratio of total violations per peak hour demand.

At each study frontage road approach, violations decreased after the lane assignments were changed. *Before* the lane assignment change, during double-turn operations, the violation was a through movement in "must turn" lane. The violation *after* the lane assignment change was a right or left turn from the middle lane. It was expected that violations would decrease with these changes. Violations did decrease significantly at each study approach, indicating fewer vehicle conflicts and a safer operation. This may imply that even though statistical reductions in delays and queues may not be seen for each approach *before* and *after* the lane assignment changed, driver expectations were not violated by using the shared-turn configurations at these approaches.

4.0 FINDINGS AND CONCLUSIONS

The goal of this study was to assess the effectiveness of using the CLAS signs installed on the westbound frontage road of US 290 to optimize lane use on a TOD basis. Data collection for *before* and *after* conditions was undertaken during several periods from October 1995 to June 1998. The data collected included automatic vehicle counts, manual turning movement counts, and manual and video recorded demand studies, saturation flow studies, and queue studies. An analysis of candidate intersections for TOD based changes was undertaken, and it was recommended that the lane use assignments for the Mangum (Mid-Day peak period), Hollister (AM and Mid-Day peak periods), and West 34th (PM peak periods) be changed from double-turn to shared-turn lane assignments. These changes were implemented February 3, 1998. Queue, saturation flow, and traffic demand data collection were completed during the first, ninth, and 17th weeks *after* the change. Following completion of the study and analyses, it was found that the Hollister AM peak period queue and delay data were unusable and were deleted from this report.

SUMMARY OF FINDINGS

Data collected in the field were then reduced, and delays and queues were calculated on a per cycle basis. Statistical comparisons revealed the following:

- Mangum Mid-Day. Delays decreased in the left and middle lane, as well as for the overall approach, although these changes were not statistically significant. During permitted double right turn operation (*before*), a lane imbalance existed (left lane and middle lane queues were significantly higher than queues in right lane). *After* the lane assignment was changed to the shared-turn configuration, a lane balance occurred. The increase in average queue length in the right lane *after* may be attributed to eliminating the full-time opportunity for right-turn-on-red and the additional queue due to an occasional vehicle blocking the right lane right-turn-on-red movement.
- Hollister Mid-Day. Both queue lengths and delays increased on the overall approach (and the right lane) because of the additional vehicles in queue in the right lane. The full-time opportunity for right-turn-on-red was removed by the shared-turn configuration, and additional delay was experienced by vehicles waiting in queue in

the right lane—enough, in fact, to contribute to a significant increase in the average delay on the entire approach.

Statistical analysis revealed that during operations as a double right turn approach (*before*), delays were significantly lower in the right lane than either the left or middle lanes. *After* the lane assignments were changed, delays in the right lane increased to the level where they were not statistically different than those in the left and middle lanes. However, the left lane experienced significantly lower delays than the middle lane.

Queues *before* were significantly lower in the right lane, and *after* the lane assignment was changed, queues in the right lane balanced with those seen in the left lane, with significantly longer queues in the middle lane. A lane balance did not occur *before* or *after* the change from double to shared-turns.

- West 34th PM. The statistical analysis revealed no significant change in delays occurred on the approach (or on any one lane) *before* or *after* the change from double left turn to shared left turn operation. However, queue lengths did significantly decrease on the approach (as well as the middle and right lanes). The average queue lengths did exhibit a lane imbalance *before* lane assignments were changed; however, *after* lane assignments changed to a shared-turn configuration, a queue shift seemed to occur. The left lane had no significant difference in average queue length than the middle lane.
- All Locations. CLAS violations (prohibited movement) decreased significantly from *before* to *after* the lane use changes were implemented.

CONCLUSIONS

Conclusions made from the findings of this study are as follows:

1. The CLAS concept was installed along the westbound frontage road with the anticipation of being used for both incident management and time-of-day operation. Benefits of using CLAS for recurring (TOD) demand management for the three intersections studied were mixed. While showing reduced delays and queuing in some locations and improved lane balance in some cases, the improved lane balance was sometimes countered by increased delays, especially at right turn CLAS

applications. The anticipated, statistically significant reductions in total approach delay were not observed at the three locations studied.

2. Operational characteristics and impacts of CLAS operation differ for double left turn and double right turn applications (i.e., permitting through vehicles in a right lane has a differing impact than through vehicles in a left lane) because of the relationship to the ability to turn right on red. This would imply use of a lower threshold (e.g., right turning percent of approach traffic) for eliminating permitted double right turn operations than would be used for eliminating double left turns.
3. Where a clear operational benefit (either a reduction of delay or queuing) is not indicated for the use of CLAS in permitted double-turn operation, shared operation should be considered since it results in a lower number of violations.
4. Conclusions can only be drawn from the analysis of the three CLAS locations studied and the range of operational characteristics these intersections represent. The primary anticipated benefits of CLAS—reduced approach delay and reduced queuing—were generally not found to be statistically significant at the three locations. However, the application of CLAS for TOD operation should not be discounted for locations with differing demand and vehicle turning characteristics. The study of the prototype (left turn) CLAS installation (5) found significant operational improvements from use in TOD operation at IH-10/Voss in Houston. Additional study is needed to assess those demand characteristics and the threshold conditions for implementation of CLAS TOD operations.

RECOMMENDATIONS

1. Additional evaluation of TOD operation on frontage roads at other locations is needed to assess demand characteristics and threshold conditions for implementation of CLAS TOD operations.
2. A unique network technology (Echelon LonWorks), which transmitted sign control data over the signs' power lines was incorporated in the design of CLAS. Use of the power lines for data transmission created deployment and maintenance problems. Both TxDOT and its contractor recommend that this technology not be designed into future CLAS projects and that conventional data communications methods be used instead.

5.0 REFERENCES

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APPENDIX A. ANALYSIS OF DAILY TRAFFIC OPERATIONS AND RECOMMENDATIONS FOR TOD LANE ASSIGNMENT CHANGES

SELECTION OF LOCATIONS FOR DAILY TRAFFIC OPERATIONS

One advantage of the CLAS system is that it can be used to manage space (or the allowable turning movements) during different time periods which have different turning movement demands. This analysis used turning movement counts, lane distribution counts, and queue studies to develop a schedule for pre-timed operation of the US 290 CLAS system. These data also provided the description of *before* conditions for the evaluation of CLAS operations.

Turning movement counts for each of the CLAS intersections were used to examine the possible lane distribution patterns for each time period (AM, Mid-Day, and PM peaks). Table A-1 summarizes this analysis. The average number of vehicles expected per cycle was computed for each movement. To account for the reduced capacity caused by turning vehicles, the left-turning vehicles were weighted by 1.05 (Highway Capacity Manual reduces capacity of left turns by a factor of 0.95—the weighting increases the space [or time] allotment for left-turning vehicles) and right turns were weighted by 1.18 (1/0.85 or the relative time a right turning vehicle occupies).

For instance for Mangum AM, a cycle length of 80 seconds results in 45 cycles per hour. If there are 202 left-turning vehicles, you could expect an average of 4.48 left-turning vehicles per cycle. Since it is known that turning vehicles take additional time to turn as compared to through vehicles, the 4.48 vehicles per cycle is multiplied by the factor of 1.05. This gives about 4.7 equivalent vehicles per cycle that turn left, with 4.4 vehicles through, and 6.8 equivalent turning vehicles turning right (262 total right turns/45 cycles/0.85). This technique is used to provide a relative measure of how much more time a turning vehicle requires compared to a through vehicle.

An example of how the lane configurations were determined for this study follows. For example, for the Mangum AM (possible double right), there are (on average) 4.7 vehicles turning left, 4.4 through vehicles, and 6.8 vehicles turning right. Since the left turns must share a lane with through moving vehicles, it is assumed that, on average, a lane balance would occur. The average vehicles in the left two lanes (4.6 vehicles) are compared to the average right turn arrivals per cycle (6.8). If the average right turns were greater than the average left and through shared volumes, a double right turn configuration was recommended. This configuration also insures the right lane would be available at all times for right-turn-on-red. At double left turn intersections, if the average right and through movement arrivals exceeded the right turn arrivals, a through configuration was recommended. Under this procedure, only Mangum Off-Peak, Hollister AM and Off-Peak, and West 34th PM would use the three through lane configuration.

Table A1. Lane Distribution Analysis

INTERSECTIONS WITH DOUBLE RIGHT CONFIGURATIONS

		Movement Volume					Vehicle/Cycle (LT+RT Adjusted)				
Mangum	C	L	T	RG	RR	RTotal	L	T	R	L+T Avg.	Config.
AM	80	202	200			262	4.7	4.4	6.8	4.6	DBL
OP	60	387	555			332	6.8	9.3	6.5	8.0	THRU
PM	80	250	871	174	437	611	5.8	19.4	16.0	12.6	DBL
Antoine	C	L	T	RG	RR	RTotal	L	T	R	L+T Avg.	Config.
AM	80	79	286			271	1.8	6.4	7.1	4.1	DBL
OP	60	63	606			533	1.1	10.1	10.5	5.6	DBL
PM	80	65	992	733	75	808	1.5	22.0	21.1	11.8	DBL
Bingle	C	L	T	RG	RR	RTotal	L	T	R	L+T Avg.	Config.
AM	80	26	438			293	0.6	9.7	7.7	5.2	DBL
OP	60	44	511			513	0.8	8.5	10.1	4.6	DBL
PM	80	28	1074	556	296	852	0.7	23.9	22.3	12.3	DBL
Hollister	C	L	T	RG	RR	RTotal	L	T	R	L+T Avg.	Config.
AM	80	279	414			221	6.5	9.2	5.8	7.9	THRU
OP	70	204	527			277	4.2	10.2	6.3	7.2	THRU
PM	80	67	832	226	252	478	1.6	18.5	12.5	10.0	DBL
FBNH	C	L	T	RG	RR	RTotal	L	T	R	L+T Avg.	Config.
AM	90	281	52			202	7.4	1.3	5.9	4.3	DBL
OP	70	292	71			419	6.0	1.4	9.6	3.7	DBL
PM	90	133	875	347	245	592	3.5	21.9	17.4	12.7	DBL
Jones	C	L	T	RG	RR	RTotal	L	T	R	L+T Avg.	Config.
AM	80	0	94			448	0.0	2.1	11.7	1.0	DBL
OP	60	0	236			801	0.0	3.9	15.7	2.0	DBL
PM	80	2	396	1271	537	1808	0.0	8.8	47.3	4.4	DBL

INTERSECTIONS WITH DOUBLE LEFT CONFIGURATIONS

		Movement Volume					Vehicle/Cycle (LT+RT Adjusted)				
W34th	C	L	T	RG	RR	RTotal	L	T	R	R+T Avg.	Config.
AM	80	579	411			52	13.5	9.1	1.4	5.2	DBL
OP	60	554	687			270	9.7	11.5	5.3	8.4	DBL
PM	80	559	1387	462	223	685	13.1	30.8	17.9	24.4	THRU
Eldridge	C	L	T	RG	RR	RTotal	L	T	R	R+T Avg.	Config.
AM	80	334	168			12	7.8	3.7	0.3	2.0	DBL
OP	60	462	221			25	8.1	3.7	0.5	2.1	DBL
PM	80	886	876	117	7	124	20.7	19.5	3.2	11.4	DBL
Senate	C	L	T	RG	RR	RTotal	L	T	R	R+T Avg.	Config.
AM	80	727	576			56	17.0	12.8	1.5	7.1	DBL
OP	60	399	585			86	7.0	9.8	1.7	5.7	DBL
PM	80	639	723	160	32	192	14.9	16.1	5.0	10.5	DBL
FM 1960	C	L	T	RG	RR	RTotal	L	T	R	R+T Avg.	Config.
AM	80	321	34			182	7.5	0.8	4.8	2.8	DBL
OP	60	341	35			275	6.0	0.6	5.4	3.0	DBL
PM	80	1095	107	538	474	1012	25.6	2.4	26.5	14.4	DBL

NOTE: C = cycle length; L = left turn; T = through; RG = right-turn-on-green; RR = right-turn-on-red; Config. = turn configuration; THRU = shared-turns; DBL = double turns; R = right turn

The recommended TOD operation for use in this study is summarized as follows:

> Antoine, Bingle, Fairbanks/North Houston, Beltway 8/Senate, Jones, Eldridge, and FM 1960 would continue to operate in permitted double-turn configuration 24 hours a day, seven days per week.
>
> Mangum would operate in permitted double right turn configuration from 6:00 a.m. to 11:00 a.m. and 2:00 p.m. to 6:00 a.m. on weekdays and operate in the basic shared-turn configuration from 11:00 a.m. to 2:00 p.m. Mangum would operate in double right turn configuration 24 hours on Saturday and Sunday.
>
> West 34th would operate in permitted double left turn configuration from 6:00 a.m. to 2:00 p.m. on weekdays and operate in the basic shared-turn configuration from 2:00 p.m. to 8:00 p.m. West 34th would operate in double left turn configuration from 8:00 p.m. to 6:00 a.m. on weekdays and 24 hours on Saturday and Sunday.
>
> Hollister would operate in permitted double right turns from 2:00 p.m. to 6:00 a.m. on weekdays and operate in the basic shared-turn configuration from 6:00 a.m. to 2:00 p.m. Hollister would operate in double right turn configuration 24 hours on Saturday and Sunday.

APPENDIX B. RESULTS OF STATISTICAL ANALYSES

TESTS FOR NORMALITY AND UNIFORMITY

Because *after* data was collected on three different days for the violation portion of the study, it was necessary to group these three days of data to complete the majority of the analysis (testing for changes in delays and queues).

Test for Normality

For each data set, the mean and standard deviation were calculated and used to develop an expected distribution. The observed frequency was then checked for goodness-of-fit to the normal distribution using the chi-square (X^2) test. Chi-square tests compare how well a set of data matches a distribution. The null hypothesis for the chi-square test was:

Ho: the observed data set fits the normal distribution
H1: the observed data set does not fit the normal distribution

Level of significance = 0.05.
Reject null hypothesis if $X^2_{observed} > X^2_{critical}$

Test for Uniformity

Each data set used should represent typical traffic operations, not those influenced by external influences (freeway incidents, etc.). Any data sets found to be possibly affected by external influences should not be grouped with data found to be typical. If found to be atypical, data sets would not be grouped with data found to be typical for a given study approach.

The analysis of variance (ANOVA) test was performed on the grouped set of *after* data for each study approach. The null hypothesis for this test was:

Ho: the normalized means for queues (or delays) observed on different days are equal
H1: the normalized means for queues (or delays) observed on different days are not equal

Level of significance = 0.05.
Reject null hypothesis if $F_{observed} > F_{critical}$

The F test identified only if one of the data collection dates was significantly different. If Ho could be rejected, Fisher's Least Significant Difference test was used to find which data were significantly different.

Table B1. Chi-square test for delay normality: Mangum Mid-day Before

Range	Prob.	Grouped Expected Frequency	Observed Frequency	Grouped Category Obs Freq.	Chi Square
0.2	0.0130		0		
0.4	0.0336		0		
0.6	0.0760		1		
0.8	0.1504	9.026	7	8	0.117
1.0	0.2621	6.700	8	8	0.252
1.2	0.4055	8.602	10	10	0.227
1.4	0.5629	9.449	9	9	0.021
1.6	0.7109	8.879	14	14	2.953
1.8	0.8299		2		
2.0	0.9117		4		
2.2	0.9599		3		
2.4	0.9841		0		
2.6	0.9945		1		
2.8	0.9984		0		
3.0	0.9996		0		
3.2	0.9999	17.338	0	10	3.106
3.4	1.0000				
3.6	1.0000				

Degrees of Freedom = 4 Observed Chi Square = 6.676

Number of Observations = 60 Table Value Chi Square = 9.488

Test Conclusion= **Do not reject Ho**

Table B2. Chi-square test for delay normality: Mangum Mid-day After

Range	Prob.	Grouped Expected Frequency	Observed Frequency	Grouped Category Obs Freq.	Chi Square
0.2	0.0151		0		
0.4	0.0405		0		
0.6	0.0933	16.789	12	12	1.366
0.8	0.1848	16.472	21	21	1.245
1.0	0.3179	23.953	36	36	6.059
1.2	0.4800	29.188	25	25	0.601
1.4	0.6456	29.805	31	31	0.048
1.6	0.7873	25.504	17	17	2.836
1.8	0.8889	18.288	15	15	0.591
2.0	0.9499	10.989	10	10	0.089
2.2	0.9807	5.533	8	8	1.100
2.4	0.9936		2		
2.6	0.9982		1		
2.8	0.9996		1		
3.0	0.9999		1		
3.2	1.0000		0		
3.4	1.0000		0		
3.6	1.0000	3.480	0	5	0.664

Degrees of Freedom = 8 Observed Chi Square = 14.599

Number of Observations = 180 Table Value Chi Square = 15.507

Test Conclusion= **Do not reject Ho**

Table B3. Chi-square test for queue normality: Mangum Mid-day Before

Range	Prob.	Grouped Expected Frequency	Observed Frequency	Grouped Category Obs Freq.	Chi Square
0.2	0.0093		0		
0.4	0.0583		1		
0.6	0.2157	12.942	11	12	0.069
0.8	0.4982	16.951	22	22	1.504
1.0	0.7817	17.008	16	16	0.060
1.2	0.9406		7		
1.4	0.9904		2		
1.6	0.9991		0		
1.8	1.0000		0		
2.0	1.0000		1		
2.2	1.0000		0		
2.4	1.0000		0		
2.6	1.0000		0		
2.8	1.0000		0		
3.0	1.0000		0		
3.2	1.0000		0		
3.4	1.0000		0		
3.6	1.0000	13.099	0	10	0.733

Degrees of Freedom = 2 Observed Chi Square = 2.365
Number of Observations = 60 Table Value Chi Square = 5.991
Test Conclusion= **Do not reject Ho**

Table B4. Chi-square test for queue normality: Mangum Mid-day After

Range	Prob.	Grouped Expected Frequency	Observed Frequency	Grouped Category Obs Freq.	Chi Square
0.2	0.0109		0		
0.4	0.0655	11.792	8	8	1.220
0.6	0.2337	30.268	37	37	1.497
0.8	0.5225	51.989	59	59	0.945
1.0	0.7995	49.852	45	45	0.472
1.2	0.9477	26.684	21	21	1.211
1.4	0.9919		7		
1.6	0.9993		1		
1.8	1.0000		2		
2.0	1.0000		0		
2.2	1.0000		0		
2.4	1.0000		0		
2.6	1.0000		0		
2.8	1.0000		0		
3.0	1.0000		0		
3.2	1.0000		0		
3.4	1.0000		0		
3.6	1.0000	9.415	0	10	0.036

Degrees of Freedom = 4 Observed Chi Square = 5.382
Number of Observations = 180 Table Value Chi Square = 9.488
Test Conclusion= **Do not reject Ho**

Table B5. Chi-square test for delay normality: Hollister AM Before

Range	Prob.	Grouped Expected Frequency	Observed Frequency	Grouped Category Obs Freq.	Chi Square
0.2	0.0062		0		
0.4	0.0359		0		
0.6	0.1358		3		
0.8	0.3455	17.622	19	22	1.088
1.0	0.6196	13.977	11	11	0.634
1.2	0.8428	11.386	11	11	0.013
1.4	0.9562		3		
1.6	0.9920		3		
1.8	0.9991		0		
2.0	0.9999		1		
2.2	1.0000		0		
2.4	1.0000		0		
2.6	1.0000		0		
2.8	1.0000		0		
3.0	1.0000		0		
3.2	1.0000	8.015	0	7	0.129
3.4	1.0000				
3.6	1.0000				

Degrees of Freedom = 2 Observed Chi Square = 1.863
Number of Observations = 51 Table Value Chi Square = 5.991
Test Conclusion= **Do not reject Ho**

Table B6. Chi-square test for delay normality: Hollister AM After

Range	Prob.	Grouped Expected Frequency	Observed Frequency	Grouped Category Obs Freq.	Chi Square
0.2	0.0029		0		
0.4	0.0060		0		
0.6	0.0118		0		
0.8	0.0218		0		
1.0	0.0384		0		
1.2	0.0641		3		
1.4	0.1015	12.181	9	12	0.003
1.6	0.1527		3		
1.8	0.2186	14.049	12	15	0.064
2.0	0.2984	9.579	13	13	1.222
2.2	0.3894	10.914	12	12	0.108
2.4	0.4868	11.698	14	14	0.453
2.6	0.5851	11.794	13	13	0.123
2.8	0.6783	11.184	10	10	0.125
3.0	0.7615	9.977	8	8	0.392
3.2	0.8312		3		
3.4	0.8863	14.979	3	6	5.382
3.6	0.9272	4.906	6	6	0.244
3.8	0.9557		2		
4.0	0.9745		2		
4.2	0.9861		2		
4.4	0.9928		3		
4.6	0.9965	8.317	1	10	0.340

Degrees of Freedom = 7 Observed Chi Square = 8.117
Number of Observations = 120 Table Value Chi Square = 14.067
Test Conclusion= **Do not reject Ho**

Table B7. Chi-square test for queue normality: Hollister AM Before

Range	Prob.	Grouped Expected Frequency	Observed Frequency	Grouped Category Obs Freq.	Chi Square
0.2	0.0044		0		
0.4	0.0812		1		
0.6	0.4300	21.930	25	26	0.755
0.8	0.8518	21.511	20	20	0.106
1.0	0.9882		3		
1.2	0.9998		2		
1.4	1.0000		0		
1.6	1.0000		0		
1.8	1.0000		0		
2.0	1.0000		0		
2.2	1.0000		0		
2.4	1.0000		0		
2.6	1.0000		0		
2.8	1.0000		0		
3.0	1.0000		0		
3.2	1.0000		0		
3.4	1.0000		0		
3.6	1.0000	7.559	0	5	0.866

Degrees of Freedom = 1 Observed Chi Square = 1.728
Number of Observations = 51 Table Value Chi Square = 3.841
Test Conclusion= **Do not reject Ho**

Table B8. Chi-square test for queue normality: Hollister AM After

Range	Prob.	Grouped Expected Frequency	Observed Frequency	Grouped Category Obs Freq.	Chi Square
0.2	0.0036		0		
0.4	0.0201		0		
0.6	0.0780	9.364	7	7	0.597
0.8	0.2163	16.589	17	17	0.010
1.0	0.4399	26.835	38	38	4.646
1.2	0.6852	29.440	31	31	0.083
1.4	0.8678	21.906	13	13	3.621
1.6	0.9599		4		
1.8	0.9914		6		
2.0	0.9987		2		
2.2	0.9999		2		
2.4	1.0000		0		
2.6	1.0000		0		
2.8	1.0000		0		
3.0	1.0000		0		
3.2	1.0000		0		
3.4	1.0000		0		
3.6	1.0000	15.866	0	14	0.219

Degrees of Freedom = 4 Observed Chi Square = 9.175
Number of Observations = 120 Table Value Chi Square = 9.488
Test Conclusion= **Do not reject Ho**

Table B9. Chi-square test for delay normality: Hollister Mid-day Before

Range	Prob.	Grouped Expected Frequency	Observed Frequency	Grouped Category Obs Freq.	Chi Square
0.2	0.0081		0		
0.4	0.0257		0		
0.6	0.0681		1		
0.8	0.1511	7.704	4	5	0.949
1.0	0.2831	6.732	11	11	2.707
1.2	0.4539	8.715	11	11	0.599
1.4	0.6340	9.181	7	7	0.518
1.6	0.7883	7.870	7	7	0.096
1.8	0.8959		5		
2.0	0.9570		1		
2.2	0.9852		2		
2.4	0.9958		0		
2.6	0.9990		2		
2.8	0.9998		0		
3.0	1.0000		0		
3.2	1.0000	10.797	0	10	0.059
3.4	1.0000				
3.6	1.0000				

Degrees of Freedom = 4 Observed Chi Square = 4.928
Number of Observations = 51 Table Value Chi Square = 9.488
Test Conclusion= **Do not reject Ho**

Table B10. Chi-square test for delay normality: Hollister Mid-day After

Range	Prob.	Grouped Expected Frequency	Observed Frequency	Grouped Category Obs Freq.	Chi Square
0.2	0.0018		0		
0.4	0.0067		0		
0.6	0.0206		0		
0.8	0.0541	7.787	5	5	0.998
1.0	0.1205	9.570	7	7	0.690
1.2	0.2302	15.795	24	24	4.262
1.4	0.3806	21.654	25	25	0.517
1.6	0.5518	24.658	25	25	0.005
1.8	0.7138	23.322	18	18	1.215
2.0	0.8410	18.322	15	15	0.602
2.2	0.9241	11.956	10	10	0.320
2.4	0.9691	6.480	6	6	0.036
2.6	0.9893		2		
2.8	0.9969	4.007	3	5	0.246
3.0	0.9992		0		
3.2	0.9998		1		
3.4	1.0000		0		
3.6	1.0000		0		
3.8	1.0000		0		
4.0	1.0000		0		
4.2	1.0000		0		
4.4	1.0000		0		
4.6	1.0000		0		
4.8	1.0000		0		
5.0	1.0000		0		
5.2	1.0000	0.448	0	1	0.678

Degrees of Freedom = 9 Observed Chi Square = 8.890
Number of Observations = 144 Table Value Chi Square = 16.919
Test Conclusion= **Do not reject Ho**

Table B11. Chi-square test for queue normality: Hollister Mid-day Before

Range	Prob.	Grouped Expected Frequency	Observed Frequency	Grouped Category Obs Freq.	Chi Square
0.2	0.0006		0		
0.4	0.0144		0		
0.6	0.1308	6.670	6	6	0.067
0.8	0.4759	17.602	23	23	1.656
1.0	0.8418	18.660	15	15	0.718
1.2	0.9805		4		
1.4	0.9991		3		
1.6	1.0000		0		
1.8	1.0000		0		
2.0	1.0000		0		
2.2	1.0000		0		
2.4	1.0000		0		
2.6	1.0000		0		
2.8	1.0000		0		
3.0	1.0000		0		
3.2	1.0000		0		
3.4	1.0000		0		
3.6	1.0000	8.068	0	7	0.141

Degrees of Freedom = 2 Observed Chi Square = 2.582
Number of Observations = 51 Table Value Chi Square = 5.991
Test Conclusion= **Do not reject Ho**

Table B12. Chi-square test for queue normality: Hollister Mid-day After

Range	Prob.	Grouped Expected Frequency	Observed Frequency	Grouped Category Obs Freq.	Chi Square
0.2	0.0003		0		
0.4	0.0070		0		
0.6	0.0680	9.795	8	8	0.329
0.8	0.3008	33.525	35	35	0.065
1.0	0.6725	53.513	54	54	0.004
1.2	0.9215	35.866	32	32	0.417
1.4	0.9914		9		
1.6	0.9996		3		
1.8	1.0000		0		
2.0	1.0000		0		
2.2	1.0000		0		
2.4	1.0000		0		
2.6	1.0000		0		
2.8	1.0000		0		
3.0	1.0000		0		
3.2	1.0000		0		
3.4	1.0000		0		
3.6	1.0000	11.301	0	12	0.043

Degrees of Freedom = 3 Observed Chi Square = 0.858
Number of Observations = 144 Table Value Chi Square = 7.815
Test Conclusion= **Do not reject Ho**

Table B13. Chi-square test for delay normality: West 34th PM Before

Range	Prob.	Grouped Expected Frequency	Observed Frequency	Grouped Category Obs Freq.	Chi Square
0.2	0.0006		0		
0.4	0.0117		0		
0.6	0.0952		2		
0.8	0.3631	15.977	11	13	0.555
1.0	0.7287	16.088	19	19	0.527
1.2	0.9416		10		
1.4	0.9943		1		
1.6	0.9998		1		
1.8	1.0000		0		
2.0	1.0000		0		
2.2	1.0000		0		
2.4	1.0000		0		
2.6	1.0000		0		
2.8	1.0000		0		
3.0	1.0000		0		
3.2	1.0000	11.936	0	12	0.000
3.4	1.0000				
3.6	1.0000				

Degrees of Freedom = 1 Observed Chi Square = 1.082
Number of Observations = 44 Table Value Chi Square = 3.841
Test Conclusion= **Do not reject Ho**

Table B14. Chi-square test for delay normality: West 34th PM After

Range	Prob.	Grouped Expected Frequency	Observed Frequency	Grouped Category Obs Freq.	Chi Square
0.2	0.0081		0		
0.4	0.0542		0		
0.6	0.2105	26.941	31	31	0.611
0.8	0.4983	36.845	41	41	0.469
1.0	0.7871	36.962	35	35	0.104
1.2	0.9449	20.194	15	15	1.336
1.4	0.9917		3		
1.6	0.9993		2		
1.8	1.0000		0		
2.0	1.0000		1		
2.2	1.0000		0		
2.4	1.0000		0		
2.6	1.0000		0		
2.8	1.0000		0		
3.0	1.0000		0		
3.2	1.0000		0		
3.4	1.0000		0		
3.6	1.0000	7.057	0	6.000	0.158

Degrees of Freedom = 3 Observed Chi Square = 2.678
Number of Observations = 128 Table Value Chi Square = 7.815
Test Conclusion= **Do not reject Ho**

Table B15. Chi-square test for queue normality: West 34th PM Before

Range	Prob.	Grouped Expected Frequency	Observed Frequency	Grouped Category Obs Freq.	Chi Square
0.2	0.0000		0		
0.4	0.0002		0		
0.6	0.0118		1		
0.8	0.1485		3		
1.0	0.5700	25.081	24	28	0.340
1.2	0.9186	15.339	11	11	1.227
1.4	0.9955		5		
1.6	0.9999		0		
1.8	1.0000		0		
2.0	1.0000		0		
2.2	1.0000		0		
2.4	1.0000		0		
2.6	1.0000		0		
2.8	1.0000		0		
3.0	1.0000		0		
3.2	1.0000		0		
3.4	1.0000		0		
3.6	1.0000	3.580	0	5	0.563

Degrees of Freedom = 1 Observed Chi Square = 2.130
Number of Observations = 44 Table Value Chi Square = 3.841
Test Conclusion= **Do not reject Ho**

Table B16. Chi-square test for queue normality: West 34th PM After

Range	Prob.	Grouped Expected Frequency	Observed Frequency	Grouped Category Obs Freq.	Chi Square
0.2	0.0040		0		
0.4	0.0431		1		
0.6	0.2176	27.858	29	29	0.047
0.8	0.5616	44.021	53	53	1.831
1.0	0.8621	38.475	28	28	2.852
1.2	0.9786	14.902	12	12	0.565
1.4	0.9985		4		
1.6	1.0000		0		
1.8	1.0000		1		
2.0	1.0000		0		
2.2	1.0000		0		
2.4	1.0000		0		
2.6	1.0000		0		
2.8	1.0000		0		
3.0	1.0000		0		
3.2	1.0000		0		
3.4	1.0000		0		
3.6	1.0000	2.743	0	5	1.858

Degrees of Freedom = 3 Observed Chi Square = 7.153
Number of Observations = 128 Table Value Chi Square = 7.815
Test Conclusion= **Do not reject Ho**

Table B17. ANOVA test for queue: Mangum Mid-day After

SUMMARY

Groups	Count	Sum	Average	Variance
Feb-98	60	45.7114	0.7619	0.0707
Apr-98	60	47.0273	0.7838	0.0536
Jun-98	60	48.6683	0.8111	0.0723

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	0.0732	2	0.0366	0.5582	0.5732	3.0470
Within Groups	11.5982	177	0.0655			
Total	11.6713	179				
Test Conclusion:	Do not reject Ho, conclude means are same					

Table B18. ANOVA test for delay: Mangum Mid-day After

SUMMARY

Groups	Count	Sum	Average	Variance
Feb-98	60	70.3159	1.1719	0.2431
Apr-98	60	73.5874	1.2265	0.1938
Jun-98	60	76.3575	1.2726	0.2343

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	0.3049	2	0.1524	0.6813	0.5073	3.0470
Within Groups	39.6021	177	0.2237			
Total	39.9070	179				
Test Conclusion:	Do not reject Ho, conclude means are same					

Table B19. ANOVA test for queue: Hollister AM After

SUMMARY

Groups	Count	Sum	Average	Variance
Feb-98	40	39.7874	0.9947	0.0586
Apr-98	40	44.4828	1.1121	0.1176
Jun-98	40	41.4578	1.0364	0.1205

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	0.2832	2	0.1416	1.4316	0.2431	3.0738
Within Groups	11.5736	117	0.0989			
Total	11.8568	119				
Test Conclusion:	Do not reject Ho, conclude means are same					

Table B20. ANOVA test for delay: Hollister AM After

SUMMARY

Groups	Count	Sum	Average	Variance
Feb-98	40	93.2038	2.3301	0.4865
Apr-98	40	100.6974	2.5174	0.6831
Jun-98	40	97.2914	2.4323	0.7967

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	0.7039	2	0.3519	0.5369	0.5860	3.0738
Within Groups	76.6877	117	0.6555			
Total	77.3915	119				
Test Conclusion:	Do not reject Ho, conclude means are same					

Table B21. ANOVA test for queue: Hollister Mid-day After

SUMMARY

Groups	Count	Sum	Average	Variance
Feb-98	52	46.1815	0.8881	0.0985
Apr-98	52	47.1814	0.9073	0.0415
Jun-98	40	34.6333	0.8658	0.0311

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	0.0390	2	0.0195	0.3292	0.7201	3.0603
Within Groups	8.3494	141	0.0592			
Total	8.3884	143				

Test Conclusion: Do not reject Ho, conclude means are same

Table B22. ANOVA test for delay: Hollister Mid-day After

SUMMARY

Groups	Count	Sum	Average	Variance
Feb-98	52	81.3214	1.5639	0.4251
Apr-98	52	77.6716	1.4937	0.1917
Jun-98	40	58.1444	1.4536	0.1262

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	0.2913	2	0.1457	0.5646	0.5699	3.0603
Within Groups	36.3778	141	0.2580			
Total	36.6692	143				

Test Conclusion: Do not reject Ho, conclude means are same

Table B23. ANOVA test for queue: West 34th After

SUMMARY

Groups	Count	Sum	Average	Variance	Fisher's LSD: Diff. from 2/98	0.103 Diff. from 4/98
Feb-98	43	36.3361	0.8450	0.0913		0.0620
Apr-98	43	33.6715	0.7831	0.0282	0.0620	
Jun-98	43	28.1510	0.6547	0.0134	0.1904	0.1284
					Jun-98 significantly different	

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	0.8106	2	0.4053	9.1482	0.0002	3.0681
Within Groups	5.5825	126	0.0443			
Total	6.3932	128				

Test Conclusion: Reject Ho, conclude at least one of the means are different

Table B24. ANOVA test for delay: West 34th After

SUMMARY

Groups	Count	Sum	Average	Variance	Fisher's LSD: Diff. from 2/98	0.121 Diff. from 4/98
Feb-98	43	36.8734	0.8575	0.1119		0.0134
Apr-98	43	36.2954	0.8441	0.0530	0.0134	
Jun-98	43	29.3650	0.6829	0.0196	0.1746	0.1612
					Jun-98 significantly different	

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	0.8120	2	0.4060	6.5997	0.0019	3.0681
Within Groups	7.7508	126	0.0615			
Total	8.5628	128				

Test Conclusion: Reject Ho, conclude at least one of the means are different

TEST FOR DIFFERENCES IN QUEUES AND DELAYS ACROSS LANES: *BEFORE* AND *AFTER* CONDITIONS INDEPENDENTLY

For each data set, the mean and standard deviation were calculated and used to test whether the mean values for queue length and average delay were equal across all lanes on an approach, in other words, to answer the question: "Does a queue imbalance exist?" An ANOVA procedure was used to test this question. The null hypothesis for the ANOVA test was:

Ho: the mean values of normalized average delay (or normalized average queue length) for all lanes on the approach are equal
H1: the mean values of normalized average delay (or normalized average queue length) for all lanes on the approach are not equal

Level of significance = 0.05
Reject null hypothesis if $F_{observed} > F_{critical}$

The F test identified only if one of the data collection dates was significantly different. If Ho could be rejected, Fisher's Least Significant Difference test was used to find which lane(s) was significantly different.

Table B25. ANOVA test for delay: Mangum Mid-day Before

SUMMARY

Groups	Count	Sum	Average	Variance
normdL	60	299.2508	4.9875	19.5103
normdM	60	273.9372	4.5656	6.6669
normdR	59	223.7941	3.7931	20.3330

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	43.5943	2	21.7971	1.4085	0.2473	3.0473
Within Groups	2723.7693	176	15.4760			
Total	2767.3636	178				

Test Conclusion: Do not reject Ho, conclude means are same

Table B26. ANOVA test for queue: Mangum Mid-day Before

SUMMARY

Groups	Count	Sum	Average	Variance	Diff. from L	Diff. from M
					Fisher's LSD:	0.222
normqL	60	57.7334	0.9622	0.4540		
normqM	60	57.6409	0.9607	0.1899	0.0015	
normqR	59	35.1261	0.5954	0.2047	0.3669	0.3653

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	5.3012	2	2.6506	9.3553	0.0001	3.0473
Within Groups	49.8652	176	0.2833			
Total	55.1663	178				

Test Conclusion: Reject Ho, conclude at least one of the means are different

Fishers LSD conclusion: Right Lane queue significantly lower than queue in middle and left lanes.

note:
normdL=normalized delay left lane
normdM=normalized delay middle lane
normdR=normalized delay right lane
normqL=normalized queue left lane
normqM=normalized queue left lane
normqR=normalized delay right lane

Table B27. ANOVA test for delay: Mangum Mid-day After

SUMMARY

Groups	Count	Sum	Average	Variance
normdL	180	763.4354	4.2413	4.8915
normdM	180	770.3971	4.2800	14.0774
normdR	180	820.9334	4.5607	82.4038

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	10.9415	2	5.4707	0.1619	0.8506	3.0125
Within Groups	18145.7137	537	33.7909			
Total	18156.6552	539				

Test Conclusion: Do not reject Ho, conclude means are same

Table B28. ANOVA test for queue: Mangum Mid-day After

SUMMARY

Groups	Count	Sum	Average	Variance
normqL	180	154.5815	0.8588	0.1207
normqM	180	161.5911	0.8977	0.3608
normqR	180	145.0756	0.8060	0.4481

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	0.7634	2	0.3817	1.2319	0.2926	3.0125
Within Groups	166.3936	537	0.3099			
Total	167.1570	539				

Test Conclusion: Do not reject Ho, conclude means are same

note:
normdL=normalized delay left lane
normdM=normalized delay middle lane
normdR=normalized delay right lane
normqL=normalized queue left lane
normqM=normalized queue left lane
normqR=normalized delay right lane

Table B29. ANOVA test for delay: Hollister AM Before

SUMMARY

Groups	Count	Sum	Average	Variance
normdL	51	162.0029	3.1765	1.8252
normdM	51	182.5790	3.5800	3.9207
normdR	51	120.8827	2.3702	29.9167

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	38.6972	2	19.3486	1.6276	0.1998	3.0564
Within Groups	1783.1316	150	11.8875			
Total	1821.8288	152				
Test Conclusion:	Do not reject Ho, conclude means are same					

Table B30. ANOVA test for queue: Hollister AM Before

SUMMARY

					Fisher's LSD:	0.128
Groups	Count	Sum	Average	Variance	Diff. from L	Diff. from M
normqL	51	41.4220	0.8122	0.0573		
normqM	51	38.6656	0.7581	0.0577	0.0540	
normqR	51	15.8341	0.3105	0.1304	0.5017	0.4477

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	7.7360	2	3.8680	47.2849	0.0000	3.0564
Within Groups	12.2704	150	0.0818			
Total	20.0064	152				

Test Conclusion: Reject Ho, conclude at least one of the means are different

Fishers LSD conclusion: Right Lane queue significantly lower than queue in middle and left lanes.

note:
normdL=normalized delay left lane
normdM=normalized delay middle lane
normdR=normalized delay right lane
normqL=normalized queue left lane
normqM=normalized queue left lane
normqR=normalized delay right lane

Table B31. ANOVA test for delay: Hollister AM After

SUMMARY

Groups	Count	Sum	Average	Variance	Diff. from L	Diff. from M
					Fisher's LSD:	1.614
normdL	120	1283.8607	10.6988	43.6886		
normdM	120	1247.5024	10.3959	39.1938	0.3030	
normdR	120	514.8781	4.2907	9.6422	6.4082	6.1052

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	3137.2070	2	1568.6035	50.8601	0.0000	3.0210
Within Groups	11010.4227	357	30.8415			
Total	14147.6296	359				

Test Conclusion: Reject Ho, conclude at least one of the means are different

Fishers LSD conclusion: Right Lane delay significantly lower than delay in middle and left lanes.

Table B32. ANOVA test for queue: Hollister AM After

SUMMARY

Groups	Count	Sum	Average	Variance	Diff. from L	Diff. from M
					Fisher's LSD:	0.186
normqL	120	169.5319	1.4128	0.4822		
normqM	120	157.7781	1.3148	0.5075	0.0979	
normqR	120	85.7812	0.7148	0.2460	0.6979	0.6000

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	34.2664	2	17.1332	41.5962	0.0000	3.0210
Within Groups	147.0459	357	0.4119			
Total	181.3123	359				

Test Conclusion: Reject Ho, conclude at least one of the means are different

Fishers LSD conclusion: Right Lane queue significantly lower than queue in middle and left lanes.

note:
normdL=normalized delay left lane
normdM=normalized delay middle lane
normdR=normalized delay right lane
normqL=normalized queue left lane
normqM=normalized queue left lane
normqR=normalized delay right lane

Table B33. ANOVA test for delay: Hollister Mid-day Before

SUMMARY

Groups	Count	Sum	Average	Variance	Fisher's LSD:	1.16
					Diff. from L	Diff. from M
normdL	51	215.6940	4.2293	2.9322		
normdM	51	258.7481	5.0735	9.7539	0.8442	
normdR	51	130.7757	2.5642	7.3773	1.6651	2.5093

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	166.2855	2	83.1427	12.4320	0.0000	3.0564
Within Groups	1003.1676	150	6.6878			
Total	1169.4531	152				

Test Conclusion: Reject Ho, conclude at least one of the means are different

Fishers LSD conclusion: Right Lane delay significantly lower than delay in middle and left lanes.

Table B34. ANOVA test for queue: Hollister Mid-day Before

Queue

SUMMARY

Groups	Count	Sum	Average	Variance	Fisher's LSD:	0.165
					Diff. from L	Diff. from M
normqL	51	46.8844	0.9193	0.0641		
normqM	51	55.8561	1.0952	0.2219	0.1759	
normqR	51	24.7971	0.4862	0.1204	0.4331	0.6090

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	10.0196	2	5.0098	36.9789	0.0000	3.0564
Within Groups	20.3215	150	0.1355			
Total	30.3411	152				

Test Conclusion: Reject Ho, conclude at least one of the means are different

Fishers LSD conclusion: Right Lane queue significantly lower than queue in middle and left lanes.

note:

normdL=normalized delay left lane	normqL=normalized queue left lane
normdM=normalized delay middle lane	normqM=normalized queue left lane
normdR=normalized delay right lane	normqR=normalized delay right lane

Table B35. ANOVA test for delay: Hollister Mid-day After

SUMMARY

Groups	Count	Sum	Average	Variance	Fisher's LSD:	0.971
					Diff. from L	Diff. from M
normdL	144	685.9304	4.7634	5.0394		
normdM	144	849.7420	5.9010	9.1927	1.1376	
normdR	144	726.0271	5.0419	26.0343	0.2784	0.8591

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	101.2670	2	50.6335	3.7724	0.0238	3.0168
Within Groups	5758.1135	429	13.4222			
Total	5859.3805	431				

Test Conclusion: Reject Ho, conclude at least one of the means are different

Fishers LSD conclusion: Middle lane delay significantly higher than left lane delay

Table B36. ANOVA test for queue: Hollister Mid-day After

Queue

SUMMARY

Groups	Count	Sum	Average	Variance	Fisher's LSD:	0.117
					Diff. from L	Diff. from M
normqL	144	127.6511	0.8865	0.0940		
normqM	144	160.6398	1.1156	0.2327	0.2291	
normqR	144	131.6438	0.9142	0.2555	0.0277	0.2014

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	4.5022	2	2.2511	11.5984	0.0000	3.0168
Within Groups	83.2640	429	0.1941			
Total	87.7662	431				

Test Conclusion: Reject Ho, conclude at least one of the means are different

Fishers LSD conclusion: Middle Lane queue significantly higher than queue in right and left lanes.

note:

normdL=normalized delay left lane
normdM=normalized delay middle lane
normdR=normalized delay right lane

normqL=normalized queue left lane
normqM=normalized queue left lane
normqR=normalized delay right lane

Table B37. ANOVA test for delay: West 34th PM Before

SUMMARY

Groups	Count	Sum	Average	Variance
normdL	44	138.1992	3.1409	15.1725
normdM	44	105.0825	2.3882	0.3484
normdR	44	120.2316	2.7325	0.3155

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	12.4928	2	6.2464	1.1833	0.3096	3.0664
Within Groups	680.9652	129	5.2788			
Total	693.4580	131				

Test Conclusion: Do not reject Ho, conclude means are same

Table B38. ANOVA test for queue: West 34th PM Before

SUMMARY

					Fisher's LSD:	0.141
Groups	Count	Sum	Average	Variance	Diff. from L	Diff. from M
normqL	44	36.2032	0.8228	0.1924		
normqM	44	44.9433	1.0214	0.0374	0.1986	
normqR	44	46.7474	1.0624	0.0248	0.2396	0.0410

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	1.4456	2	0.7228	8.5184	0.0003	3.0664
Within Groups	10.9463	129	0.0849			
Total	12.3919	131				

Test Conclusion: Reject Ho, conclude at least one of the means are different

Fishers LSD conclusion: Left Lane queue significantly lower than queue in middle and right lanes.

note:
normdL=normalized delay left lane
normdM=normalized delay middle lane
normdR=normalized delay right lane
normqL=normalized queue left lane
normqM=normalized queue left lane
normqR=normalized delay right lane

Table B39. ANOVA test for delay: West 34th PM After

Delay

SUMMARY

Groups	Count	Sum	Average	Variance
normdL	85	224.9829	2.6469	1.3541
normdM	85	213.1081	2.5072	0.8677
normdR	85	239.4838	2.8175	1.5819

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	4.1057	2	2.0529	1.6191	0.2001	3.0316
Within Groups	319.5163	252	1.2679			
Total	323.6221	254				

Test Conclusion: Do not reject Ho, conclude means are same

Table B40. ANOVA test for queue: West 34th PM After

SUMMARY

					Fisher's LSD:	0.102
Groups	Count	Sum	Average	Variance	Diff. from L	Diff. from M
normqL	85	65.6321	0.7721	0.0827		
normqM	85	71.6089	0.8425	0.0706	0.0703	
normqR	85	76.3515	0.8983	0.1083	0.1261	0.0558

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	0.6789	2	0.3395	3.8923	0.0216	3.0316
Within Groups	21.9772	252	0.0872			
Total	22.6561	254				

Test Conclusion: Reject Ho, conclude at least one of the means are different

Fishers LSD conclusion: Left Lane queue significantly lower than queue in middle and right lanes.

note:

normdL=normalized delay left lane | normqL=normalized queue left lane
normdM=normalized delay middle lane | normqM=normalized queue left lane
normdR=normalized delay right lane | normqR=normalized delay right lane

TEST FOR DIFFERENCES IN QUEUES AND DELAYS *BEFORE* AND *AFTER* TIME- OF-DAY LANE ASSIGNMENT CHANGES

For each data set, the mean and standard deviation were calculated and used to test whether the mean values for queue length and average delay were equal across all lanes on an approach or for each individual lane. The t-test was used to determine if a significant change was found in delay or queue length from *before* to *after* TOD implementation. The data sets were tested for equal variances and the appropriate t-test carried out. The null hypothesis for the t-test was:

Ho: the mean values of normalized average delay (or normalized average queue length) for all lanes on the approach are equal for *before* and *after* conditions
H1: the mean values of normalized average delay (or normalized average queue length) for all lanes on the approach are not equal for *before* and *after* conditions

Level of significance = 0.025 ($\alpha/2$ for a two-tailed t-test)
Reject null hypothesis if $t_{observed} > t_{critical}$

Table B41.
t-Test: Two-Sample Assuming Equal Variances
Delays on Approach

	Before	After
Mean	1.3203	1.2237
Variance	0.2529	0.2229
Observations	60	180
Pooled Variance	0.2304	
Hypothesized Mean Difference	0	
df	238	
t Stat	1.3506	
P(T<=t) one-tail	0.0890	
t Critical one-tail	1.6513	
P(T<=t) two-tail	0.1781	
t Critical two-tail	1.9700	
Test Conclusion:	Do not reject Ho	

Table B42.
t-Test: Two-Sample Assuming Unequal Variances
Delays Left Lane

	Before	After
Mean	4.9875	4.2413
Variance	19.5103	4.8915
Observations	60	180
Hypothesized Mean Difference	0	
df	69	
t Stat	1.2571	
P(T<=t) one-tail	0.1065	
t Critical one-tail	1.6672	
P(T<=t) two-tail	0.2130	
t Critical two-tail	1.9949	
Test Conclusion:	Do not reject Ho	

Table B43.
t-Test: Two-Sample Assuming Equal Variances
Delays Middle Lane

	Before	After
Mean	4.5656	4.2800
Variance	6.6669	14.0774
Observations	60	180
Pooled Variance	12.2404	
Hypothesized Mean Difference	0	
df	238	
t Stat	0.5477	
P(T<=t) one-tail	0.2922	
t Critical one-tail	1.6513	
P(T<=t) two-tail	0.5844	
t Critical two-tail	1.9700	
Test Conclusion:	Do not reject Ho	

Table B44.
t-Test: Two-Sample Assuming Equal Variances
Delays Right Lane

	Before	After
Mean	3.7931	4.5607
Variance	20.3330	82.4038
Observations	59	180
Pooled Variance	67.2135	
Hypothesized Mean Difference	0	
df	237	
t Stat	-0.6241	
P(T<=t) one-tail	0.2666	
t Critical one-tail	1.6513	
P(T<=t) two-tail	0.5331	
t Critical two-tail	1.9700	
Test Conclusion:	Do not reject Ho	

Table B45.
t-Test: Two-Sample Assuming Equal Variances
Queues on Approach

	Before	After
Mean	0.8011	0.7856
Variance	0.0654	0.0652
Observations	60	180
Pooled Variance	0.0652	
Hypothesized Mean Difference	0	
df	238	
t Stat	0.4083	
P(T<=t) one-tail	0.3417	
t Critical one-tail	1.6513	
P(T<=t) two-tail	0.6834	
t Critical two-tail	1.9700	
Test Conclusion:	Do not reject Ho	

Table B46.
t-Test: Two-Sample Assuming Unequal Variances
Queues Left Lane

	Before	After
Mean	0.9622	0.8588
Variance	0.4540	0.1207
Observations	60	180
Hypothesized Mean Difference	0	
df	70	
t Stat	1.1397	
P(T<=t) one-tail	0.1291	
t Critical one-tail	1.6669	
P(T<=t) two-tail	0.2583	
t Critical two-tail	1.9944	
Test Conclusion:	Do not reject Ho	

Table B47.
t-Test: Two-Sample Assuming Equal Variances
Queues Middle Lane

	Before	After
Mean	0.9607	0.8977
Variance	0.1899	0.3608
Observations	60	180
Pooled Variance	0.3184	
Hypothesized Mean Difference	0	
df	238	
t Stat	0.7484	
P(T<=t) one-tail	0.2275	
t Critical one-tail	1.6513	
P(T<=t) two-tail	0.4550	
t Critical two-tail	1.9700	
Test Conclusion:	Do not reject Ho	

Table B48.
t-Test: Two-Sample Assuming Equal Variances
Queues Right Lane

	Before	After
Mean	0.5954	0.8060
Variance	0.2047	0.4481
Observations	59	180
Pooled Variance	0.3885	
Hypothesized Mean Difference	0	
df	237	
t Stat	-2.2524	
P(T<=t) one-tail	0.0126	
t Critical one-tail	1.6513	
P(T<=t) two-tail	0.0252	
t Critical two-tail	1.9700	
Test Conclusion:	Reject Ho	

Ho: mean before - mean after = 0
H1: mean before - mean after unequal to 0
use two-tailed test
reject Ho if abs val tcalc > tcrit

Tables B41-B48. t-Test results for Queues and Delays - Mangum Mid-day

Table B49.
t-Test: Two-Sample Assuming Equal Variances
Delays on Approach

	Before	After
Mean	0.9045	2.4266
Variance	0.0835	0.6503
Observations	40	120
Pooled Variance	0.5104	
Hypothesized Mean Difference	0	
df	158	
t Stat	-11.6689	
P(T<=t) one-tail	0.0000	
t Critical one-tail	1.6546	
P(T<=t) two-tail	0.0000	
t Critical two-tail	1.9751	
Test Conclusion:	Reject Ho	

Table B50.
t-Test: Two-Sample Assuming Equal Variances
Delays Left Lane

	Before	After
Mean	3.1933	10.6988
Variance	2.1543	43.6886
Observations	40	120
Pooled Variance	33.4365	
Hypothesized Mean Difference	0	
df	158	
t Stat	-7.1094	
P(T<=t) one-tail	0.0000	
t Critical one-tail	1.6546	
P(T<=t) two-tail	0.0000	
t Critical two-tail	1.9751	
Test Conclusion:	Reject Ho	

Table B51.
t-Test: Two-Sample Assuming Equal Variances
Delays Middle Lane

	Before	After
Mean	3.4434	10.3959
Variance	2.8111	39.1938
Observations	40	120
Pooled Variance	30.2132	
Hypothesized Mean Difference	0	
df	158	
t Stat	-6.9279	
P(T<=t) one-tail	0.0000	
t Critical one-tail	1.6546	
P(T<=t) two-tail	0.0000	
t Critical two-tail	1.9751	
Test Conclusion:	Reject Ho	

Table B52.
t-Test: Two-Sample Assuming Unequal Variances
Delays Right Lane

	Before	After
Mean	2.6573	4.2907
Variance	37.3300	9.6422
Observations	40	120
Hypothesized Mean Difference	0	
df	46	
t Stat	-1.6224	
P(T<=t) one-tail	0.0558	
t Critical one-tail	1.6787	
P(T<=t) two-tail	0.1116	
t Critical two-tail	2.0129	
Test Conclusion:	Do not reject Ho	

Ho: mean before - mean after = 0
H1: mean before - mean after unequal to 0
use two-tailed test
reject Ho if abs val tcalc > tcrit

Table B53.
t-Test: Two-Sample Assuming Equal Variances
Queues on Approach

	Before	After
Mean	0.6206	1.0477
Variance	0.0296	0.0996
Observations	40	120
Pooled Variance	0.0823	
Hypothesized Mean Difference	0	
df	158	
t Stat	-8.1525	
P(T<=t) one-tail	0.0000	
t Critical one-tail	1.6546	
P(T<=t) two-tail	0.0000	
t Critical two-tail	1.9751	
Test Conclusion:	Reject Ho	

Table B54.
t-Test: Two-Sample Assuming Equal Variances
Queues Left Lane

	Before	After
Mean	0.8074	1.4128
Variance	0.0656	0.4822
Observations	40	120
Pooled Variance	0.3793	
Hypothesized Mean Difference	0	
df	158	
t Stat	-5.3832	
P(T<=t) one-tail	0.0000	
t Critical one-tail	1.6546	
P(T<=t) two-tail	0.0000	
t Critical two-tail	1.9751	
Test Conclusion:	Reject Ho	

Table B55.
t-Test: Two-Sample Assuming Equal Variances
Queues Middle Lane

	Before	After
Mean	0.7486	1.3148
Variance	0.0617	0.5075
Observations	40	120
Pooled Variance	0.3975	
Hypothesized Mean Difference	0	
df	158	
t Stat	-4.9191	
P(T<=t) one-tail	0.0000	
t Critical one-tail	1.6546	
P(T<=t) two-tail	0.0000	
t Critical two-tail	1.9751	
Test Conclusion:	Reject Ho	

Table B56.
t-Test: Two-Sample Assuming Equal Variances
Queues Right Lane

	Before	After
Mean	0.3187	0.7148
Variance	0.1490	0.2460
Observations	40	120
Pooled Variance	0.2221	
Hypothesized Mean Difference	0	
df	158	
t Stat	-4.6045	
P(T<=t) one-tail	0.0000	
t Critical one-tail	1.6546	
P(T<=t) two-tail	0.0000	
t Critical two-tail	1.9751	
Test Conclusion:	Reject Ho	

Tables B49-B56. t-Test results for Queues and Delays - Hollister AM

Table B57.
t-Test: Two-Sample Assuming Equal Variances
Delays on Approach

	Before	After
Mean	1.2505	1.6003
Variance	0.1906	0.3834
Observations	51	144
Pooled Variance	0.3335	
Hypothesized Mean Difference	0	
df	193	
t Stat	-3.7177	
P(T<=t) one-tail	0.0001	
t Critical one-tail	1.6528	
P(T<=t) two-tail	0.0003	
t Critical two-tail	1.9723	
Test Conclusion:	Reject Ho	

Table B58.
t-Test: Two-Sample Assuming Equal Variances
Delays Left Lane

	Before	After
Mean	4.2293	4.7634
Variance	2.9322	5.0394
Observations	51	144
Pooled Variance	4.4935	
Hypothesized Mean Difference	0	
df	193	
t Stat	-1.5463	
P(T<=t) one-tail	0.0618	
t Critical one-tail	1.6528	
P(T<=t) two-tail	0.1237	
t Critical two-tail	1.9723	
Test Conclusion:	Do not reject Ho	

Table B59.
t-Test: Two-Sample Assuming Equal Variances
Delays Middle Lane

	Before	After
Mean	5.0735	5.9010
Variance	9.7539	9.1927
Observations	51	144
Pooled Variance	9.3381	
Hypothesized Mean Difference	0	
df	193	
t Stat	-1.6618	
P(T<=t) one-tail	0.0491	
t Critical one-tail	1.6528	
P(T<=t) two-tail	0.0982	
t Critical two-tail	1.9723	
Test Conclusion:	Do not reject Ho	

Table B60.
t-Test: Two-Sample Assuming Equal Variances
Delays Right Lane

	Before	After
Mean	2.5642	5.0419
Variance	7.3773	26.0343
Observations	51	144
Pooled Variance	21.2009	
Hypothesized Mean Difference	0	
df	193	
t Stat	-3.3022	
P(T<=t) one-tail	0.0006	
t Critical one-tail	1.6528	
P(T<=t) two-tail	0.0011	
t Critical two-tail	1.9723	
Test Conclusion:	Reject Ho	

Table B61.
t-Test: Two-Sample Assuming Equal Variances
Queues on Approach

	Before	After
Mean	0.8114	0.9304
Variance	0.0354	0.0662
Observations	51	144
Pooled Variance	0.0583	
Hypothesized Mean Difference	0	
df	193	
t Stat	-3.0253	
P(T<=t) one-tail	0.0014	
t Critical one-tail	1.6528	
P(T<=t) two-tail	0.0028	
t Critical two-tail	1.9723	
Test Conclusion:	Reject Ho	

Table B62.
t-Test: Two-Sample Assuming Equal Variances
Queues Left Lane

	Before	After
Mean	0.9193	0.8865
Variance	0.0641	0.0940
Observations	51	144
Pooled Variance	0.0863	
Hypothesized Mean Difference	0	
df	193	
t Stat	0.6860	
P(T<=t) one-tail	0.2468	
t Critical one-tail	1.6528	
P(T<=t) two-tail	0.4935	
t Critical two-tail	1.9723	
Test Conclusion:	Do not reject Ho	

Table B63.
t-Test: Two-Sample Assuming Equal Variances
Queues Middle Lane

	Before	After
Mean	1.0952	1.1156
Variance	0.2219	0.2327
Observations	51	144
Pooled Variance	0.2299	
Hypothesized Mean Difference	0	
df	193	
t Stat	-0.2603	
P(T<=t) one-tail	0.3975	
t Critical one-tail	1.6528	
P(T<=t) two-tail	0.7949	
t Critical two-tail	1.9723	
Test Conclusion:	Do not reject Ho	

Table B64.
t-Test: Two-Sample Assuming Equal Variances
Queues Right Lane

	Before	After
Mean	0.4862	0.9142
Variance	0.1204	0.2555
Observations	51	144
Pooled Variance	0.2205	
Hypothesized Mean Difference	0	
df	193	
t Stat	-5.5934	
P(T<=t) one-tail	0.0000	
t Critical one-tail	1.6528	
P(T<=t) two-tail	0.0000	
t Critical two-tail	1.97233021	
Test Conclusion:	Reject Ho	

Ho: mean before - mean after = 0
H1: mean before - mean after unequal to 0
use two-tailed test
reject Ho if abs val tcalc > tcrit

Tables B57-B64. t-Test results for Queues and Delays - Hollister Mid-day

Table B65.
t-Test: Two-Sample Assuming Equal Variances
Delays on Approach

	Before	After
Mean	0.8730	0.8608
Variance	0.0435	0.0738
Observations	44	85
Pooled Variance	0.0635	
Hypothesized Mean Difference	0	
df	127	
t Stat	0.2608	
P(T<=t) one-tail	0.3973	
t Critical one-tail	1.6569	
P(T<=t) two-tail	0.7947	
t Critical two-tail	1.9788	
Test Conclusion:	Do not reject Ho	

Table B66.
t-Test: Two-Sample Assuming Unequal Variances
Delays Left Lane

	Before	After
Mean	3.1409	2.6469
Variance	15.1725	1.3541
Observations	44	85
Hypothesized Mean Difference	0	
df	47	
t Stat	0.8225	
P(T<=t) one-tail	0.2075	
t Critical one-tail	1.6779	
P(T<=t) two-tail	0.4149	
t Critical two-tail	2.0117	
Test Conclusion:	Do not reject Ho	

Table B67.
t-Test: Two-Sample Assuming Equal Variances
Delays Middle Lane

	Before	After
Mean	2.3882	2.5072
Variance	0.3484	0.8677
Observations	44	85
Pooled Variance	0.6919	
Hypothesized Mean Difference	0	
df	127	
t Stat	-0.7698	
P(T<=t) one-tail	0.2214	
t Critical one-tail	1.6569	
P(T<=t) two-tail	0.4429	
t Critical two-tail	1.9788	
Test Conclusion:	Do not reject Ho	

Table B68.
t-Test: Two-Sample Assuming Equal Variances
Delays Right Lane

	Before	After
Mean	2.7325	2.8175
Variance	0.3155	1.5819
Observations	44	85
Pooled Variance	1.1531	
Hypothesized Mean Difference	0	
df	127	
t Stat	-0.4258	
P(T<=t) one-tail	0.3355	
t Critical one-tail	1.6569	
P(T<=t) two-tail	0.6710	
t Critical two-tail	1.9788	
Test Conclusion:	Do not reject Ho	

Ho: mean before - mean after = 0
H1: mean before - mean after unequal to 0
use two-tailed test
reject Ho if abs val tcalc > tcrit

Table B69.
t-Test: Two-Sample Assuming Equal Variances
Queues on Approach

	Before	After
Mean	0.9711	0.8236
Variance	0.0269	0.0527
Observations	44	85
Pooled Variance	0.0440	
Hypothesized Mean Difference	0	
df	127	
t Stat	3.7850	
P(T<=t) one-tail	0.0001	
t Critical one-tail	1.6569	
P(T<=t) two-tail	0.0002	
t Critical two-tail	1.9788	
Test Conclusion:	Reject Ho	

Table B70.
t-Test: Two-Sample Assuming Equal Variances
Queues Left Lane

	Before	After
Mean	0.8228	0.7721
Variance	0.1924	0.0827
Observations	44	85
Pooled Variance	0.1198	
Hypothesized Mean Difference	0	
df	127	
t Stat	0.7879	
P(T<=t) one-tail	0.2161	
t Critical one-tail	1.6569	
P(T<=t) two-tail	0.4322	
t Critical two-tail	1.9788	
Test Conclusion:	Do not reject Ho	

Table B71.
t-Test: Two-Sample Assuming Equal Variances
Queues Middle Lane

	Before	After
Mean	1.0266	0.8425
Variance	0.0370	0.0706
Observations	43	85
Pooled Variance	0.0594	
Hypothesized Mean Difference	0	
df	126	
t Stat	4.0363	
P(T<=t) one-tail	0.0000	
t Critical one-tail	1.6570	
P(T<=t) two-tail	0.0001	
t Critical two-tail	1.9790	
Test Conclusion:	Reject Ho	

Table B72.
t-Test: Two-Sample Assuming Equal Variances
Queues Right Lane

	Before	After
Mean	1.0624	0.8983
Variance	0.0248	0.1083
Observations	44	85
Pooled Variance	0.0801	
Hypothesized Mean Difference	0	
df	127	
t Stat	3.1245	
P(T<=t) one-tail	0.0011	
t Critical one-tail	1.6569	
P(T<=t) two-tail	0.0022	
t Critical two-tail	1.978819455	
Test Conclusion:	Reject Ho	

Tables B65-B72. t-Test results for Queues and Delays - West 34th PM