



OHIO DEPARTMENT OF TRANSPORTATION

The following user manual and related spreadsheet tool was originally developed by Cleveland State University as part of research completed under SJN 134719. ODOT has since made updates and revisions to the documents and will continue to update them as necessary.

LANE CLOSURE QUEUE ANALYSIS TOOL USER MANUAL

The lane closure queue analysis tool is based on the 2010 Highway Capacity Manual formulation for short term work zone capacity. This user manual presents the logic contained within the spreadsheet tool and guidance for selecting input values. It is expected that users will be able to use the tool by following the directions and comments contained within the spreadsheet itself. This user manual also includes an evaluation of the HCM capacity formulation for use in Ohio, by comparing capacities observed at Ohio work zones during the 2013 and 2014 construction seasons and the capacities observed in Texas used to establish the 2010 HCM base capacity for freeway work zones.

Lane Closure Queue Analysis Tool

The lane closure queue analysis tool is a deterministic tool that evaluates the imbalance between hourly traffic volumes (i.e. demand) and hourly capacity values (i.e. supply). The tool calculates the expected number of vehicles in queue, queue length, and queue delay for up to 24, 1 hour time intervals. The formation and dissipation of the queue is also presented graphically.

The lane closure queue analysis tool was developed in Microsoft Excel. The workbook contains three worksheets:

1. **Q** sheet which is the main input and calculation sheet;
2. **AADT** sheet which allows the user to define the hourly and directional distributions to convert AADT information to hourly volumes; and
3. **NAMES** sheet which is a hidden sheet that contains the data for drop-down lists presented on the **Q** sheet.

As shown on Figure 1, the layout of the **Q** sheet has been designed to fit on a single 8.5" x 11" sheet of paper, in landscape orientation. The layout includes the following six blocks and one output graph:

1. *PROJECT INFORMATION*;
2. *TRAFFIC VOLUME DATA*;
3. *PRE-LANE CLOSURE CONDITION*;
4. *LANE CLOSURE CONDITION*;
5. *QUEUE INFORMATION*;
6. *DETERMINISTIC QUEUE ANALYSIS*.

Traffic Volume Data

In the **TRAFFIC VOLUME DATA** block shown on Figure 3, the user selects the type of volume data to be used for the analysis. In a drop-down list (Cell G14), the user has the choice of selecting hourly or AADT.

- If hourly is chosen, the user enters the estimated hourly volumes in Column B in the **DETERMINISTIC QUEUE ANALYSIS** block for up to 24, 1 hour time intervals.
- If AADT is chosen, the user enters the AADT (two directional) value in Cell G18 and selects the hourly distribution (Cell G20) and direction of travel (Cell G21) from the drop-down lists.
 - The AADT hourly and directional distributions are defined on the **AADT** sheet shown on Figure 4.
 - To define a unique distribution, AADT data is available from ODOT's Transportation Information Mapping System (TIMS).
 - If the total hourly distribution percentages on the **AADT** sheet are not equal to 100%, an error message is returned.
 - The user can enter a one directional AADT value so long as the defined directional percentage for a single direction are entered as 100% for each of the one hour time intervals on the **AADT** sheet.
 - On the **AADT** sheet, the directional percentages are entered for the Upstation direction and the values for the Downstation percentage are automatically calculated.
 - The **AADT** sheet has been setup to allow ODOT to define default hourly and directional distributions for urban and rural roadways.
- Based on the selections, Columns C through F in the **DETERMINISTIC QUEUE ANALYSIS** block are populated.

TRAFFIC VOLUME DATA	
Type of volume data to be used for analysis	Hourly
For hourly based evaluation:	
1) Enter estimated hourly volumes (column B)	
For AADT based evaluation:	
1) Enter Average Annual Daily Traffic value	
2) Select type of hourly and directional distributions	
Hourly distribution	
Direction of travel	
3) Enter/review distribution values on AADT sheet	
Enter base proportion of trucks and buses, P_T (%)	4.0
Adjust base P_T (%) value for each time interval (column G)	
Diversion threshold (passenger cars per hour)	1000
Enter the percent of the hourly passenger car volume over the diversion threshold expected to divert (column K)	

Figure 3. Traffic volume data block

TIME INTERVAL	DEFINED FACTORS BY USER			ODOT DEFAULT VALUES*					
	Hourly Distribution %	Directional Distribution		Hourly Distribution %	Directional Distribution		Hourly Distribution %	Directional Distribution	
		Upstation %	Downstation %		Upstation %	Downstation %		Upstation %	Downstation %
0:00-1:00				0.9	50	50	1.2	50	50
1:00-2:00				0.6	50	50	0.8	50	50
2:00-3:00				0.4	50	50	0.7	50	50
3:00-4:00				0.5	50	50	0.9	50	50
4:00-5:00				0.9	50	50	1.3	50	50
5:00-6:00				2.4	50	50	2.8	50	50
6:00-7:00				5	50	50	5.3	50	50
7:00-8:00				7.3	50	50	6.6	50	50
8:00-9:00				6.3	50	50	5.8	50	50
9:00-10:00				5.1	50	50	5.2	50	50
10:00-11:00				4.9	50	50	5	50	50
11:00-12:00				5.2	50	50	5.1	50	50
12:00-13:00				5.5	50	50	5.4	50	50
13:00-14:00				5.6	50	50	5.5	50	50
14:00-15:00				6.3	50	50	6.1	50	50
15:00-16:00				7.3	50	50	7	50	50
16:00-17:00				7.8	50	50	7.8	50	50
17:00-18:00				7.8	50	50	7.7	50	50
18:00-19:00				5.8	50	50	5.6	50	50
19:00-20:00				4.2	50	50	4	50	50
20:00-21:00				3.5	50	50	3.4	50	50
21:00-22:00				2.9	50	50	2.9	50	50
22:00-23:00				2.2	50	50	2.2	50	50
23:00-24:00				1.6	50	50	1.7	50	50
total	0			100			100		

Figure 4. AADT sheet for hourly and directional distributions

For hourly based or AADT based evaluations, the user enters the base proportion of truck and buses, P_T in Cell G23. The user has the option to increase or decrease the proportion of trucks and buses for each 1 hour time interval by entering adjustment values in Column G of the *DETERMINISTIC QUEUE ANALYSIS* block. The adjustments are applied to the base value to arrive at the total P_T for each time interval, as shown in Column H. The input is checked to ensure that the resulting total P_T is between zero and 100.

The total P_T value is used in combination with the passenger car equivalent (PCE) for trucks and buses, E_T defined in the *PRE-LANE CLOSURE CONDITION* block to calculate the heavy vehicle adjustment factor, f_{HV} as follows:

$$f_{HV} = \frac{1}{1 + P_T(E_T - 1)}$$

The resulting heavy vehicle adjustment factor values populate Column I of the *DETERMINISTIC QUEUE ANALYSIS* block.

The volumes for analysis, shown in Column J of the *DETERMINISTIC QUEUE ANALYSIS* block, are calculated as the hourly or AADT based volumes divided by the heavy vehicle adjustment factor. This column will remain blank if the type of volume data has not been selected from the drop down list in Cell G14.

- If AADT is selected, the volumes for analysis are based on the AADT based volumes in Column F.
- If hourly is selected the volumes for analysis are based on the estimated hourly volumes in Column B.
- Note that the volumes for analysis are in passenger cars per hour (pcph).

For hourly based or AADT based evaluations, the user also enters the diversion threshold, which is the volume of traffic over which vehicles are expected to divert onto other routes. This value is entered into Cell G25. The user then enters the percentage of traffic over the threshold which is expected to divert in Column K of the *DETERMINISTIC QUEUE ANALYSIS* block for each of the 1 hour time intervals. The work zone volumes (Column L) are then populated based on the volumes for analysis (Column J) and the diversion volumes. For consistency with prior ODOT queue analysis processes, a value of 1,000 pcph has been entered.

Pre-lane Closure Condition

In the *PRE-LANE CLOSURE CONDITION* block shown in Figure 5, the user defines the roadway conditions prior to the proposed lane closure. These conditions include the number of lanes in one direction, type of terrain, lane width, right side lateral clearance, and total (i.e. entrance and exit) ramp density.

PRE-LANE CLOSURE CONDITION	
Number of lanes (one direction), N	3 lanes
Type of terrain	Level
Passenger car equivalent for 1 truck or bus, E _T	1.5
Base free flow speed (BFFS)	75.4 mph
Adjustment for lane width, f _{LW}	0 mph
Width of lanes (min 10 ft)	12 ft
Adjustment for lateral clearance, f _{LC}	1.6 mph
Lateral clearance on the right side (max 6 ft)	2 ft
Adjustment for ramp density	0 mph
Number of ramps within ±3 miles (max 6)	0
User defined adjustment	20 mph
Calculated free flow speed (FFS)	53.8 mph
2010 HCM basic freeway segment capacity	2250 pcphpl

Figure 5. Pre-lane closure condition block

The user enters the number of lanes in one direction in Cell O2. The input must be a positive whole number.

The type of terrain is selected from a drop-down list in Cell O3. The selection of a level, rolling, or mountainous terrain results in a 1.5, 2.5 or 4.5 PCE for one truck or bus respectively, as per the 2010 HCM. The resulting PCE is populated in Cell O4. The PCE is used in the calculation of the heavy vehicle adjustment factor, as previously described in the Traffic Volume Data section.

The capacity of the pre-lane closure condition is assumed to be the base capacity of the basic freeway segment. According to the 2010 HCM, the capacity can be inferred from the free flow speed (FFS) of the facility as follows:

- 2400 pcphpl for FFS of 75 mph and 70 mph;
- 2350 pcphpl for FFS of 65 mph;
- 2300 pcphpl for FFS of 60 mph; and
- 2250 pcphpl for FFS of 55 mph.

If the free flow speed of the segment is not known, it is estimated by Equation 11-1 of the 2010 HCM:

$$FFS = 75.4 - f_{LW} - f_{LC} - 3.22TRD^{0.84}$$

where

f_{LW} = adjustment for lane width, mph

f_{LC} = adjustment for lateral clearance on the right side of the road, mph

TRD = total (i.e. entrance and exit) ramp density, measured 3 miles upstream and 3 miles downstream of the midpoint of the freeway segment, mph.

The user enters the lane width in Cell O7. Lane widths greater than or equal to 12 ft do not impact the free flow speed. For lane widths greater than or equal to 11 ft but less than 12 ft, the free flow speed is reduced by 1.9 mph, and for lane widths greater than or equal to 10 ft but less than 11 ft, a 6.6 mph reduction is applied. The resulting lane width adjustment is populated in Cell O6.

The user enters the right-side lateral clearance in cell O9. The lateral clearance is the perpendicular distance (ft) from the outer lane line of the outer lane to the nearest obstruction. The adjustments for the right-side lateral clearance differ depending upon the size of the lateral clearance and the number of lanes in one direction. The HCM values for the lateral clearance adjustments are shown in Table 1. The resulting adjustment is populated in Cell O8.

Table 1. Speed adjustment values (mph) for right-side lateral clearance

Right-side lateral clearance	Lanes in one direction			
	2	3	4	≥5
≥6	0.0	0.0	0.0	0.0
5	0.6	0.4	0.2	0.1
4	1.2	0.8	0.4	0.2
3	1.8	1.2	0.6	0.3
2	2.4	1.6	0.8	0.4
1	3.0	2.0	1.0	0.5
0	3.6	2.4	1.2	0.6

The user enters the total number of ramps (i.e. entrance and exit) within 3 miles upstream and 3 miles downstream of the midpoint of the freeway segment being evaluated in Cell O11. There is a maximum allowable value of 6 ramps. The adjustment for the ramp density is populated in Cell O10.

If the free flow speed of the segment is known, then a user defined adjustment in miles per hour can be entered (Cell O12) to adjust the calculated free flow speed (Cell O13). This adjustment is applied as a reduction to the calculated free flow speed (mph). This adjustment can also be used to reflect the impact of a work zone speed zone under the pre-lane closure condition.

Based on the calculated free flow speed (Cell O13), the 2010 HCM basic freeway segment capacity is populated in Cell O14. Note that the capacity is in passenger cars per hour per lane.

Lane Closure Condition

The **LANE CLOSURE CONDITION** block shown in Figure 6, describes the conditions within the work zone with the proposed lane closure. Since conditions can change within a 24 hour period, the entries for the number of lanes closed (N_{closed}), and capacity adjustments are made in Columns M, O, and P in the **DETERMINISTIC QUEUE ANALYSIS** block for each 1 hour time interval. Columns N and Q are then populated with the resulting number of lanes open (N_{open}) and capacity with N_{closed} (pcph) values respectively.

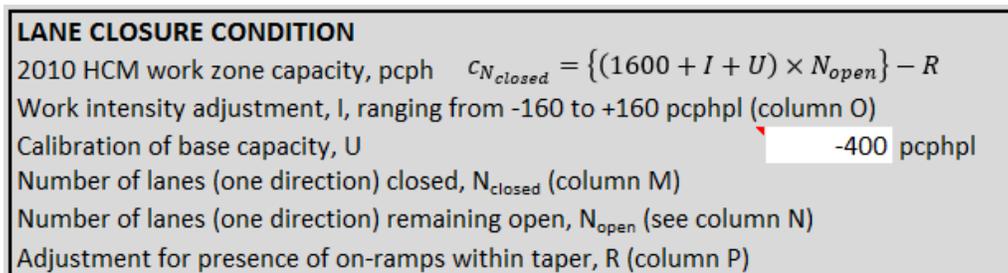


Figure 6. Lane closure condition block

The capacity of the lane closure condition ($c_{N_{closed}}$) is based on the 2010 HCM short-term work zone capacity however the formulation is modified somewhat. The heavy vehicle adjustment factor is not included so that the calculated work zone capacity is in passenger cars per hour. In addition, a user defined adjustment, U is added to allow for the calibration to local/regional/state conditions. The resulting formulation is as follows:

$$c_{N_{closed}} = \{(1600 + I + U) \times N_{open}\} - R$$

where

- 1600 = base capacity in pcphpl
- I = adjustment for the type, intensity, and proximity of work activity, pcphpl
- U = user defined adjustment, pcphpl
- N_{open} = number of open lanes through the work zone
- R = adjustment for on-ramps, pcphpl

The base capacity was proposed by Krammes and Lopez (1992, 1994) who found the overall average of the capacities observed during 33 studies with 5 different lane closure configurations was 1600 pcphpl. The range of observed capacities fell within $\pm 10\%$ of this average value. Therefore, the guidance they provided was to adjust the base capacity by $\pm 10\%$ for significantly more minor or more major work activities. This guidance is echoed in the 2010 HCM, which describes the base capacity as reflecting “normal” intensity work activity and the $\pm 10\%$ adjustment for the type, intensity and proximity of work activity is applied to reflect more or less intensive work activities. The actual relationship between the intensity of work activity and capacity was not quantified.

Work zone capacity data from Texas and California were previously examined by Dudek and Richards (1981) to show that the observed work zone capacity (or capacity

rates) differs by the type of work and lane configuration. The lane configurations are described by [A, B] where A is the total number of lanes in one direction and B is the number of lanes open in one direction during the lane closure. As shown in Table 2, the capacity tended to increase with the number of open lanes. Median barrier/guardrail repair or installation had the highest observed capacity while bridge repair work had the lowest, general speaking. One exception to this pattern was the moderate to high capacities observed for single open lane bridge repair operations.

Table 2. Capacity (vph) across work activity and lane configuration

Type of work	Lane configuration				
	[3, 1]	[2, 1]	[5, 2]	[3 or 4, 2]	[4, 3]
Median barrier/guardrail repair or installation		1500 ²		3200 ² 2940 ¹	4800 ² 4570 ¹
Pavement repair	1050 ¹	1400 ²		3000 ² 2900 ¹	4500 ²
Resurfacing, asphalt removal	1050 ¹	1200 ² 1300 ¹	2750 ¹	2600 ² 2900 ¹	4000 ²
Striping, slide removal		1200 ²		2600 ²	4000 ²
Pavement markers		1100 ²		2400 ²	3600 ²
Bridge repair	1350 ¹	1350 ¹		2200 ²	3400 ²

1 average capacities observed in Texas (Dudek and Richards, 1981)

2 capacity rates observed in California (Kermode and Myra, 1970)

Batson et al (2009) expanded upon the type of work examples of Dudek and Richards (1981) to describe the intensity of the work, as shown in Table 3. However, the lightest intensity work was used as the baseline for capacity reductions, which does not coincide with the average value rationale of Krammes and Lopez (1992, 1994) for selecting the 1600 pcphpl base capacity.

Table 3. Intensity across work activity

Intensity	Capacity reduction	Type of work
Lightest	0	Guardrail repair/installation, median cleanup
Light	100	Pothole repair, bridge deck patching, bridge deck inspection and maintenance, barrier wall erection
Moderate	200	Resurfacing/asphalt removal, paving (w/light equipment activity), milling (w/light equipment activity)
Heavy	300	Striping/slide removal, paving (w/heavy equipment activity), milling (w/heavy equipment activity)
Very Heavy	400	Pavement marking, final striping, concrete paving (w/heaving equipment activity), bridge widening (w/light equipment activity)
Heaviest	500	Bridge repair, bridge widening (w/heavy equipment activity)

A more quantitative approach to define intensity was done by Benekohal et al. (2004). They collected data at 11 work zones on Interstate highways in Illinois, 3 of which were short term and found that the number of workers and amount of construction equipment near the open travel lane were the main factors contributing to the intensity of the work activity and defined a work intensity ratio, WI as:

$$WI = \frac{w + e}{p}$$

where

w = number of workers in active work area (varies from 0 to a maximum of 10);

e = amount of equipment in active work zone (varies from 0 to a maximum of 5);

and

p = distance between active work area and open lane (ft) (from 1 to a maximum of 9 ft)

While a certain amount of confidence can be gained by using a quantitative approach, the calculation of the work intensity ratio requires specific values for the number of workers, amount of equipment, and distance between the active work area and the open lane, which would not likely be available when the proposed lane closure is being considered. Additionally the relationship between the work intensity ratio and the reduction in the work zone capacity would need to be calibrated for Ohio.

Overall, the capacity trends observed for work intensity, along with the work intensity ratio formulation provide some coarse guidance for the selection of the intensity adjustment.

- Lightest to light intensity activities where high capacities have been observed should have positive intensity adjustment values (e.g. +80 pcphpl, +160 pcphpl).
- Heavy to heaviest intensity activities, where low capacities have been observed should have negative intensity adjustment values (e.g. -80 pcphpl, -160 pcphpl).
- Further discussion on adjusting the base capacity for Ohio conditions is given in the validation and calibration section of the final research report (<http://cdm16007.contentdm.oclc.org/cdm/ref/collection/p267401ccp2/id/13142>).

The adjustment for on-ramps (Column P) accounts for the reduction in the main line traffic that can be serviced because of on-ramps within the taper area approaching the lane closure or within 500 ft downstream. The reduction is contingent upon the on-ramp volume and should not exceed one-half the single lane capacity of the main line.

A calibration of base capacity value (Cell O19) has also been added to the capacity formulation to represent local/district/regional/state differences from the HCM base capacity of 1600 pcphpl, separate from the intensity adjustment or the adjustment for the presence of on-ramps.

Key findings drawn from the literature are provided below as guidance for considering the impact of various factors not included in the queue analysis.

- Lane width
 - The HCM (TRB 2010) includes lane width adjustment for basic freeway sections.
 - At one work zone in Ohio, which was first configured as a [2, 1] left lane closure and later configured as a [2, 1] right lane closure, Schnell et al.

(2002) observed a difference in capacities. The open lane during the left lane closure was 10 ft wide and had a capacity of 866 vph while the open lane during the right lane closure was 12 ft wide and had a capacity of 1,098 vph, evidence that the narrower lane width reduced capacity.

- At 11 (3 short term and 8 long term) work zones on Interstate highways in Illinois, Chitturi and Benekohal (2005) observed the free flow speeds of trucks to be less than the free flow speeds of passenger cars. They found that reduced lane widths reduced the speeds of both passenger cars and trucks and that the speed reduction was considerably more than the reductions for basic freeway sections given in the HCM. Additionally, the reduction was more pronounced for trucks.
- Number of lanes
 - The HCM (TRB 2010) right side lateral clearance adjustment values for basic freeway segment, as shown in Table 1, differ depending upon the size of the lateral clearance and the number of lanes in one direction. Therefore it is reasonable to expect that the impact of the proximity of the work activities differs depending upon the number of lanes that remain open in one direction during the lane closure. The lane closer to the work activity will be more greatly influenced than those further away.
 - Dudek and Richards (1981) showed that the observed work zone capacity (or capacity rates) differs by lane configuration. As shown on Table 2, the capacity per lane increases with more open lanes in one direction during the lane closure. Generally speaking, the capacities of multi open lane configurations were 100 vphpl more than that of single open lane configurations, with the same work activity.
- Built environment
 - The HCM (TRB 2010) suggests applying a driver population factor to the flow rate for basic freeway segments when the driver population is different than the commuter or regular user traffic, such as recreational traffic.
 - Dixon et al. (1996) collected traffic data at 24 freeway work zones in North Carolina, compared the observed capacities between 4 rural and 4 urban work zones, and found the average capacity of the rural sites to be less than that of the urban sites. The difference was considered to be due to driver type and familiarity with the road, as commuters were the main users of the urban freeways and the rural freeways serviced a lot of through traffic. However, the urban data sets were collected during nights and weekends while the rural data sets were collected during weekends, so the time of day and day of week may be confounding factors in their analysis.
- Lighting
 - Dixon et al. (1996) examined the differences in observed daytime and nighttime capacities for a [2-1] configured urban freeway work zone in North Carolina. The daytime capacity of 1,644 vph was found to be similar to the nighttime capacity of 1,637 vph. Taking into account the percentage of heavy vehicles, the daytime capacity of 1,696 pcph still compares well to the nighttime capacity of 1,741 pcph. Whether or not these are statistically different cannot be determined from the single observations.

The demand and supply data are used to calculate the formation and dissipation of the queue under four conditions, such that:

- No lane closure, no diversion condition is calculated using the 2010 HCM basic freeway segment capacity (Cell O14) and the volumes for analysis (Column J);
- No lane closure, with diversion condition is calculated using the 2010 HCM basic freeway segment capacity (Cell O14) and the work zone volume (Column L);
- Lane(s) closed, no diversion is calculated using the capacity with N_{closed} (Column Q) for time intervals with lane(s) closed and the 2010 HCM basic freeway segment capacity (Cell O14) for time intervals with all lanes open, along with the volumes for analysis (Column J); and
- Lane(s) closed, with diversion is calculated using the capacity with N_{closed} (Column Q) for time intervals with lane(s) closed and the 2010 HCM basic freeway segment capacity (Cell O14) for time intervals with all lanes open, along with the work zone volume (Column L).

The number of passenger cars in queue, N_Q is calculated for each 1 hour time interval, as the difference between the cumulative number entering the work zone, N_{in} and the cumulative number exiting, N_{out} , summed from the beginning of the first time interval.

$$N_Q = \sum_t (N_{in} - N_{out})$$

The resulting number of equivalent passenger cars in queue for each time interval is populated in Columns R, U, X, and AA for the four conditions respectively.

The length of the queue in miles, Q for each interval is calculated, as:

$$Q_t = \frac{hN_Q}{5280N}$$

where

N_Q = number of equivalent passenger cars in queue

h = is the average minimum headway of passenger cars in queue, ft (Cell O25)

N = is the number of open lanes upstream of the work zone which is also the number of lanes in the pre-lane closure condition (Cell O3).

The resulting queue length for each time interval is populated in Columns S, V, Y and AB for the four conditions respectively. The cells are shaded based on a comparison of the queue length values and the thresholds of Policy No. 21-008(P) as follows:

- Queues less than or equal to 0.75 miles are acceptable and are shaded green;
- Queues longer than 0.75 miles are unacceptable and are shaded red.

The resulting queue lengths are also graphed with respect to the end of the time interval. The data points are formatted as follows:

- No lane closure, no diversion condition plotted as green triangles;
- No lane closure, with diversion condition plotted as purple circles;
- Lane(s) closed, no diversion condition plotted as red triangles; and
- Lanes(s) closed, with diversion condition plotted as blue circles.

The area under each graph represents the total delay in passenger car hours. The delay for each hour time interval is calculated and populated in Columns T, W, Z, and AC. The total delay is populated in Row 59 for the four conditions.

The total delay is broken into passenger car (PC) delay and truck and bus (T&B) delay based on the proportion of trucks and buses in the queue. The results populate Rows 60 and 61 for the four conditions.

The average delay is calculated as the total delay divided by the number of vehicles travelling through the work zone. For the no diversion conditions, the sum of the volumes for analysis values (Column J) is used. For the with diversion conditions, the sum of the work zone volumes values (Column L) is used. The results populate Row 62.