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Research Paper

METHODOLOGY TO OPTIMIZE A WORK ZONE QUEUE ESTIMATION TOOL

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One tool employed by various state transportation departments for traffic queue prediction, given the specifics of a proposed freeway work zone, is the Excel-based “Lane Rental Model” developed at the Oklahoma Department of Transportation (OkDOT), using the 1994 Highway Capacity Manual (HCM) lane capacity tables. Preliminary testing of the OkDOT tool confirmed lack of accuracy. Logic errors were corrected to form a baseline, and two other versions were created using the lane capacity model of HCM 2000: an HCM 2000 version using work intensity effects of -160 to +160 passenger cars per hour per lane (pcphpl); and an HCM 2000 hybrid version using work intensity penalties of -500 to 0 pcphpl. Using a diverse set of 32 actual freeway work zone lane closure descriptions as the “test data bank,” we compared predictions produced by the three versions of the OkDOT spreadsheet tool with the actual Maximum Queue Length (MQL) observed in the field. The HCM 2000 hybrid version with passenger car equivalent PCE = 2.1 for heavy vehicles is highly accurate, and minimized the overall error in predicting MQL. The “empirical optimization” methodology used to reach this conclusion is the major contribution.

Keywords: Highway and Transportation Engineering, Empirical Optimization, Highway Work Zone, Traffic Queuing, Temporary Work Zone, Work Zone Capacity, Work Zone Lane Closure

INTRODUCTION

Those who plan temporary highway work zones require accurate software to predict under which conditions queues might form, how long they might persist, and queue length profiles. To the extent possible, such planners should schedule work to avoid the creation of queues that cause inconvenience to the traveling public and commercial users.

Many models have been developed and built into software tools for the purpose of work zone queue prediction. They use different

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logics and different methodologies, but the goal remains the same—to reduce negative effects caused by work zone activities. In our research, we modified and tested a spreadsheet tool, grounded in the work zone lane capacity tables found in the 1994 Highway Capacity Manual (HCM), which was designed to predict queue formation and dissipation caused by short-term work zones. The original version developed by the Oklahoma Department of Transportation (OkDOT), which operates in Microsoft Excel, is based on a deterministic queuing analysis and a simple input/output model, which has been for several years an accepted tool in design and maintenance divisions of the Alabama Department of Transportation (ALDOT), and its local district engineering offices.

The purpose of this article is to describe our modification and testing method to optimize the performance of this spreadsheet tool in predicting queue formation and lengths. The final tool was an improved queue prediction tool to be used in short-term work zone planning. To achieve this tool, we first checked the underlying logic and formulas of the OkDOT spreadsheet tool, corrected some minor errors, thereby creating a revised HCM 1994 baseline. In this article, we describe the creation of two modifications of the baseline model, grounded in the HCM 2000 work zone lane capacity formula, as potentially more accurate versions. We studied in detail the work zone test data bank and the performance of these three alternatives applied to 32 test cases, the “empirical optimization” methodology, and identified the alternative with the best queue prediction performance, which the researchers recommended to ALDOT. The optimized spreadsheet tool and a detailed user’s guide were subsequently delivered to ALDOT, and can be obtained from the lead author.

HCM-based Queue Estimation Tool

Based on the classification scheme of Sankar and Jeannotte (2006), the OkDOT model is a Highway Capacity Manual-based, analytical/ deterministic tool. HCM procedures are closed-form, macroscopic, deterministic, and static analytical procedures that estimate capacity and performance measures to determine the level of service (Sankar and Jeannotte, 2006). An explanation of these descriptors follows:

- Closed-form means that the tools are not iterative. After users input data and parameters, the tool conducts a sequence of analytical steps and produces a single answer.
- Macroscopic means that inputs and outputs deal with average performance during a 15-min or a one-hour analysis period.
- Deterministic means that for any given set of inputs, the yield is always the same.
- Static means that the tools predict average operating conditions over a fixed time period and do not deal with transitions in operations from one state to another.

Other well-known HCM-based analytical/ deterministic tools are QuickZone (Mitretek, 2001; and Maryland DOT, 2006) and WZCAT (Lee and Noyce, 2007), both of which were also implemented in Excel, and QUEWZ (Memmott and Dudek, 1984) which was implemented in DOS. In the OkDOT tool, QuickZone, and QUEWZ, queue analysis is conducted using input-output analysis technique presented in Chapter 6 of HCM 1994. The number of vehicles in queue is estimated as the difference between demand and the work zone capacity. Demand can either be inputted by users as hourly traffic volume or can be calculated from inputs like Annual Average Daily Traffic (AADT) on the roadway, the day of the week when lane closure will be in effect, and the general location of the freeway (urban or rural). Work zone capacity is estimated using the HCM model for short-term when work activity is present.

Work Zone Capacity Estimation

Work zone capacity is the principal determinant in work zone traffic queuing study; however, an agreement on its definition and its criteria to measure work zone capacity has yet to be reached. We briefly review the various definitions, then indicate the one selected here. In a study conducted in California (Kermode and Myyra, 1970), capacity was measured in traffic volumes (vehicles/hour) during a lane closure with congested conditions. The researchers averaged two consecutive three-minute counts separated by one minute, then multiplied the average by 20 to determine the hourly capacity. In a series of work zone studies conducted by the Texas Transportation Institute (TTI) during the late 1970s and the early 1980s (Dudek and Richards, 1981), work zone capacity was measured in hourly traffic volume under congested traffic conditions. The capacity measured in this way was actually the mean queue-discharge rate at a freeway bottleneck. In a study conducted in North Carolina, in the 1990s (Dixon *et al.*, 1996), work zone capacity was measured in traffic volume immediately before queuing began. The researchers defined work zone capacity as the flow rate at which traffic behavior quickly changed from uncongested conditions to queued conditions. In an Indiana study (Jiang, 1999), the capacity was measured in volume at the time when the speed dropped sharply. In this study, the work zone capacity was defined as the traffic flow rate just before a sharp drop in speed followed by a sustained period of low vehicle speed and fluctuating traffic flow rate. In an Illinois study (Benekohal *et al.,* 2003), work zone capacity was defined as full-hour volumes counted at lane closures with upstream queue, expressed in hourly traffic volume from the maximum five-minute flow rate.

Some researchers made efforts to clarify the definition of work zone capacity. One of such efforts was done by Persaud and Hurdle (1991). They examined several different capacity definitions with a combination of philosophical arguments, theory, and data. Four categories of capacity definitions were examined: maximum flow, specified percentile flow, mean flow, and expected maximum flow. They found that defining capacity as the mean queue-discharge rate was the most suitable way.

The capacity values for short-term freeway lane closures given by Highway Capacity Manual (1994) were based on the data collected by TTI for urban freeways in Texas during the late 1970s and the early 1980s (Dudek and Richards, 1981). The capacity values were measured in hourly traffic volumes, presented in tables based on average volume for each lane closure configuration.

In an effort to revise QUEWZ, TTI researchers (Krammes and Lopez, 1994) updated capacity values for short-term freeway work zone lane closures using data collected at 33 work zone sites in Texas between 1987 and 1991 for three-to-one, two-to-one, four-to-two, five-to-three, and four-to-three work zone lane configurations. All the work zones were of short-term and most of them were of maintenance activities. The capacity was measured at the point of intersection of transition area and the activity area. The study found that the observed capacities for three-to-one and two-to-one work zone lane configurations were significantly higher than that given in HCM 1994, and recommended a base capacity value of 1,600 passenger cars per hour per lane (pcphpl) for all short-term freeway lane closure configurations. Several adjustments were made to the base capacity value when applying it to specific work zones. The adjustments considered intensity of work activity, effect of heavy vehicles, and presence of ramps. The detailed work zone lane capacity equations of Krammes and Lopez (1994) appear as equations 1 and 2 in the description of the HCM 2000 version of the queue estimation software, in the next section of the article.

A North Carolina study conducted by Dixon *et al.* (1996) identified 24 short-term lane closures at freeway work zones and collected data for capacity analysis at these sites using Nu-Metrics counters and classifiers. The data was collected from summer 1994 to spring 1995 on sites with different work zone lane closure configurations. It was found that the intensity of work activity and the type of study site (rural or urban) strongly affected the work zone capacity. The researchers recommended using capacity values of approximately 1,200 vehicles per hour per lane (vphpl) at the active work location in rural two-lane to one-lane work zones with heavy work, and 1,500 vphpl for corresponding urban work zones.

The widely used Highway Capacity Manual 2000 provides a base capacity of 1,600 pcphpl for short-term work zones of any layout and uses the model suggested by Krammes and Lopez (1994) for work zone capacity estimation. The base value can be modified with the use of adjustment factors for specific work zone lane closure configurations. Adjustment factors include work intensity, percentage of heavy vehicles, proximity of ramps, and lane width. According to Edara and Cottrell (2007), the HCM 1994 capacity charts significantly under-predict the capacity values at short-term freeway work zones; however, it is possible to obtain realistic work zone lane capacity values from equations in HCM 2000. Hence, the two modified versions of the OkDOT baseline which we created and tested are based on HCM 2000 lane capacity equations, with the only difference being how increasing work zone intensity penalizes capacity.

OKDOT Lane Rental Model in use at ALDOT

OkDOT spreadsheet was named as ODOT Lane Rental Model by its developers. To distinguish from Ohio Department of Transportation, we use OkDOT to abbreviate Oklahoma Department of Transportation. The original spreadsheet was created by Karl Zimmerman, Oklahoma Department of Transportation, 1997. The spreadsheet was modified by Richard Jurey, Federal Highway Administration, in June 2000 and again in January 2001. The January 2001 version (with minor errors corrected) is the baseline version used in our research, from which we developed two alternative versions.

The OkDOT queue prediction Excel spreadsheet can be used:

- To determine whether a queue will form or not under forced-flow conditions at a work zone, at a given hour of the day.
- To estimate the length of the queue in the startup hour and each subsequent hour until the queue dissipates. Hence, maximum queue length can be predicted.
- To identify work periods (e.g., 9 am-3 pm, 9 pm-5 am) when no queue should form, given the nature of the lane closures, the AADT, and other inputs.
- To compute the additional costs experienced by road users due to the lane closure.

The complete details on the OkDOT queue prediction model, and minor modifications to create the so-called baseline model for our testing, and the two versions based on HCM 2000, may be found in Batson *et al*. (2009). We present a brief overview here.

The OkDOT spreadsheet relies on a deterministic model to calculate queue formation and dissipation. When the volume exceeds the capacity, delay and congestion occur. A queue is formed and continues to grow until the traffic volumes are lower than the capacity. At that point the queue begins to dissipate. The calculation is conducted at ten minute periods. The model takes the previous ten-minute queued volume, adds the additional inflow for the current ten minute period, and then subtracts the work zone's processing capacity during the ten minute period.

The spreadsheet converts all traffic into an equivalent number of passenger cars with a fixed conversion factor of two (2.0) passenger cars per heavy vehicle. This conversion is done before allocating daily traffic volume to hourly traffic volumes; therefore, the calculation is based on passenger cars, and 6.1 m (20 feet) is built into the model as the distance occupied by one passenger car in a queue. Calculation formulas (Table 1) are provided for readers who are interested in the underlying formulas for queue computation and relations between inputs and outputs.

The OkDOT spreadsheet is based on the following assumptions:

- A fixed cyclical day: The single-day information the model is given is calculated in a loop starting at the end of the 3:50 am ten-minute period (time point 4:00 am), and assumes that the same information applies for the next day. A result of this assumption is that any queue which still exists at the end of the 3:50 am period is immediately dropped to zero.
- Queues in all lanes have the same length: It is assumed that drivers will maneuver as they join queued traffic in a balanced manner. This assumption is the basis for the formula Queue Length = (Queue at Slice End/Original # of Lanes) * (0.0038), where 0.0038 is the ratio of one car length to the length of a mile (20/5280 in feet). There are two sub-assumptions: the first one is that the arriving drivers will choose the shortest

Table 1: Queue input/output and computational formulas in OkDOT spreadsheet

	Category	Parameter	Note or Formula
Input Data	Basic work zone information	Analysis Code	Interstate/Arterial; Urban/Rural
		Direction	Inbound/Outbound
		Original # of Lanes	One direction
		# of Lanes Closed at each hour	One direction
	Available from historical source or observation	AADT	Both directions
		Percent of Trucks	Trucks mean heavy vehicles
		Free Flow Speed	Flow speed when there is no work zone
		Max Queue Length	If there is no limitation, set a large number
	Subjective determined	Confidence Level	Conservative level of the user
Process Data	Not visible to users	Queue at Slice End limited by Max Queue Length Limit	= (Max Queue Length Limit* Original # of Lanes)/ (20/5280)
Output Data	Process Output	Factor K	Allocate daily traffic volume to each hour
		Factor D	Allocate each hour traffic volume to different direction
		Passenger Cars per day(1)	= AADT*(1+ Percent of Trucks)
		Basic Lane Capability	• If Free Flow Speed is>=70, Basic Lane Capacity=2400; • Else if FFS>=65, BLC=2350; • Else if FFS>=60, BLC=2300; • Else BLC=2250.
		1 hour Capacity Limit(2)	• If Original # of Lanes is 2 (3, 4), # of Lanes Closed is 0, Capacity= 2 (3, 4)* Passenger Cars per day; • If # of Lanes Closed is 1 (2), Capacity is calculated based on 1998 Highway Capacity Manual; • If # of Lanes Closed is 3, Capacity is copied from 3 lanes with 2 lanes closed
		10 min Capacity Limit	= 1 hour Capacity Limit /6

Table 1 (Cont.)

	Category	Parameter	Note or Formula
		10 min Volume	= [Passenger Cars per day* (Factor K/100)* Factor D] /6
	Final Output	Queue Length	= (Queue at Slice End/Original # of Lanes) * (20/5280)
		Queue at Slice End	= Minimum { Maximum{Queue at Slice End in the beginning of current interval+10 min Volume-10 min Capacity Limit, 0}, Queue at Slice End limited by Max Queue Length Limit}

(1) The deduction for passenger cars per day (the model assumes passenger car equivalence equals to 2), giving

Passenger Cars per day
= AADT*(1-Percent of Trucks)*1+ AADT*Percent of Trucks* PCE
= AADT*(1-Percent of Trucks)*1+AADT*Percent of Trucks*2
=AADT*(1+Percent of Trucks)

(2) Work zone capacity is estimated depending on work zone characteristics from charts specified in HCM 1998, which is the same as HCM 1994.

lane in queue, keeping the length in each open lane essentially equal; the second one is that the taper will not affect the length of cars in queue, which is not the actual case, but seems to be an acceptable approximation.

- Passenger Car Equivalent (PCE) per truck is two (2.0).
- Average lane space occupied by queued passenger cars is 6.1 m (20 feet).
- Within an hour, the traffic volume for each of the ten minute periods is equal.

Weaknesses of the Queue Estimation Method in the OkDOT Lane Rental Model.

Firstly, the outputs are presented in a tabular form only; which does not give users an intuitive impression of queue development and lengths, queue lengths over time, and queue dissipation.

Secondly, the spreadsheet allows illogical inputs. The spreadsheet does not check the rationality of inputs. The calculation gives misleading answers, even for illogical inputs. For example, a two-lane road with two lanes closed will still generate data which looks compelling.

Thirdly, confidence level is an important parameter for the OkDOT spreadsheet which directly affects work zone capacity; however, there are several problems with this input, which might cause confusion to users. Major problems with confidence level are its subjectivity and meaning. Due to the lack of instructions provided to help users decide confidence level input, the choice is very subjective and depends on user's experience and "best guess." In most cases, users are likely to choose a conservative level and thus overestimate queue formation. Instructions such as matching confidence level to several levels of work zone intensity, and describing the condition that corresponds to each level of intensity, would greatly enhance the effectiveness of the model. In alternative testing, we actually use such an approach with six intensity levels to simulate the decision of a traffic planner using the OkDOT spreadsheet and having to make a judgment on which CL to use as input. The meaning of confidence level and its effect on the predicted result remains unclear to users. The confidence level works in a way that the increase of confidence level leads to a decrease in capacity, which is illustrated in Table 2; essentially, confidence level reflects the conservatism of the user applied to this particular estimate. That is, the more conservative the user is, the higher the confidence level chosen.

Table 2: Confidence Level Impact on Capacity Reduction in Two-to-one Lane Closure

Confidence Level (CL)	Work Zone Capacity (vph)
0%	1465
20%	1419
40%	1373
60%	1328
80%	1282
100%	1236

Fourthly, the model fails to consider important factors. The model makes no adjustments for most important factors such as, work zone intensity , weather, ramps, and the work zone's design (length of taper, speed zones, signage, etc.). Some of these factors have been explicitly included in the HCM 2000 lane capacity model, while some others can be manipulated into the model to some degree via other factors; for example, weather can be reflected by using a slower speed.

Fifthly, the model fails to account for effects of driver-initiated diversions. The OkDOT spreadsheet overestimates traffic impacts of work zones due to inability to account for effects of those drivers who divert to other routes. The issue of traffic diversion is not as important for rural roadways as it is for urban high-volume roads (Ullman and Dudek, 2003). For urban work zones, these authors state and evidence also supports, that queues tend to grow but stabilize in length, even when input-output models predict that they should keep growing. Finally, work zone capacity is determined by referring to the tables of HCM 1994.

Alternative HCM-Based Queue Estimation Models for Testing

The three testing alternatives were developed by using different work zone capacity estimation models. The logic of the OkDOT baseline version goes back to the HCM 1994 method of estimating work zone capacity. While the input-output logic applied to estimate queue formation and length remains valid, improvements are available based on HCM 2000. Additionally, examination of the literature on work zone capacity impacts of work intensity led us to create a HCM 2000 hybrid version incorporating even more recent research. The theme of this section is that describing work zone intensity appropriately, and penalizing work zone capacity appropriately, is the key to better traffic queue predictions (e.g., queue start-time and maximum queue length).

OkDOT Baseline Version

The OkDOT spreadsheet (with minor errors corrected) is called the OkDOT baseline version in this report. Work zone capacity in this version is determined by Confidence Level input. As previously discussed, CL input allows the user to express a degree of conservatism in the capacity (pcphpl) of an open lane through the work zone. A low level of conservatism (say CL=20%) corresponds to a high capacity; a high level of conservatism (say CL=80%) corresponds to a low capacity. Because in the two other versions, work zone intensity is going to play a major role in determining capacity, we constructed the six-level scale in Table 3 which maps confidence level to intensity.

The wording used to describe work intensity in Table 3, and the examples given, appear in Adeli and Jiang (2003). Work intensity is a function of several factors, which the spreadsheet user has to assess in deciding which level (1-6) to use. Such factors in the literature include:

- Number and size of equipment items involved in the work.
- Number of workers present and their proximity to the open lane(s).
- Width of shoulders in the work zone, if any.
- Distance from work zone to open lane(s).
- Use of lighting (at night).
- Moving or fixed work zone.

Table 3: Confidence level interpretation in OkDOT baseline version

Level	Work Intensity (example)	Confidence Level (CL)	Capacity
1	"Lightest" (e.g., guardrail repair)	0%	1465
2	"Light" (e.g., pothole repair)	20%	1419
3	"Moderate" (e.g., resurfacing)	40%	1373
4	"Heavy" (e.g., stripping)	60%	1328
5	"Very Heavy" (e.g., pavement marking)	80%	1282
6	"Heaviest" (e.g., bridge repair)	100%	1236

- Temporary or long-term work zone (long-term work zones have higher capacity than those encountered by drivers for the first time).

Although assigning an intensity level may take some thought, our research shows that it is necessary. During our testing, we found it possible to make reasonable "calls" on intensity from fairly brief descriptions of the work which accompanied the work zone data we used in testing and validation. Of course, when in doubt in choosing between two intensity levels, the recommendation is to use the more conservative (higher) level.

HCM 2000 Version

Krammes and Lopez (1994) put forth the following model for work zone capacity, which ultimately became part of HCM (2000),

$$C = (1600 \text{ pcphpl} + I - R) * H * N \quad ...(1)$$

where, C = estimated work zone capacity (vph)

I = adjustment factor for work intensity, ranging from -160 to +160 (pcphpl)

[Note that Karim and Adeli (2003) suggested a three-level I-scale of Low = +160, Medium = 0, and High = -160 (e.g., a 10% penalty for high intensity work). However, the six-level I-scale shown in Table 4 and originated by Dudek and Richards (1981) was used in our testing.]

R = adjustment value for "presence of an entrance ramp near the starting point of the lane closure," that is in the advance warning area. R = 0 if no ramp is present, and R = 160 pcphpl if entrance ramp is present (following the logic that entering traffic causes turbulence in the traffic flow approaching the work zone, indirectly reducing the work zone lane capacity 10%).

Table 4: Work Zone Intensity (I) Scale Applied in HCM 2000 Version

Level	Work Intensity	I (pcphpl)
1	"Lightest" (e.g., guardrail repair)	+160
2	"Light" (e.g., pothole repair)	+100
3	"Moderate" (e.g., resurfacing)	+40
4	"Heavy" (e.g., stripping)	-40
5	"Very Heavy" (e.g., pavement marking)	-100
6	"Heaviest" (e.g., bridge repair)	-160

H = adjustment factor for heavy vehicles =

$$100 / [100 + P*(E-1)] \quad ...(2)$$

where,

P = percentage of heavy vehicles

E = passenger car equivalent for heavy vehicles (values ranging from 2.0 to 2.5 are recommended, depending on terrain; the OkDOT baseline value is 2.0, because Oklahoma is predominately flat)

N = number of lanes open through the work zone.

HCM 2000 Hybrid Version

A University of Maryland research team (Kim *et al.,* 2001) developed an alternative work zone capacity estimation model based on multiple linear regressions applied to twelve sets of measured work zone capacity data from Maryland. The six variables they chose as predictors, and the limitations of the twelve work zones used, eliminated the model from consideration. However, a set of data from

Kermode and Myyra (1970) mentioned in Kim *et al.* (2001) led us to create the HCM 2000 hybrid version of the OkDOT spreadsheet. This third version uses the HCM 2000 work zone capacity model exactly as described above, except that the work intensity I is rescaled as shown in Table 5. This scale essentially stiffens the work zone lane capacity penalty for the most intense work from a maximum of 160 to 500 pcphpl; also, the lightest intensity has a penalty of zero here, whereas in the HCM 2000 version, the lightest intensity actually *added* 160 pcphpl (10%) to the base lane capacity of 1600.

Table 5: Work Zone Intensity (I) Scale Applied in HCM 2000 Hybrid Version

Level	Work Intensity	I (penalty, pcphpl)
1	"Lightest" (e.g., guardrail repair)	0
2	"Light" (e.g., pothole repair)	-100
3	"Moderate" (e.g., resurfacing)	-200
4	"Heavy" (e.g., stripping)	-300
5	"Very Heavy" (e.g., pavement marking)	-400
6	"Heaviest" (e.g., bridge repair)	-500

To summarize: In the analysis of predictions produced by the three (or two) versions, whenever HCM 2000 version is used, the I-values (-160 to +160) in Table 4 are applied. In the HCM 2000 hybrid version, the I-values (0 to -500) in Table 5 are applied. So, I-value has a different range in the respective versions, and is in fact the only thing that differs between these two versions.

MATERIALS AND METHODS

In order to test the OkDOT spreadsheet and the alternatives, a set of real work zone "test cases" were needed. This section describes how data were collected to test and compare the three alternatives, and also gives detailed description about the datasets. The data was obtained from two sources: on-site observations at Alabama work zones and requests for cases from other states.

Alabama Data

We were committed to on-site data collection at Alabama work zones for two reasons: 1) We could control the frequency, accuracy, and extent of data collected during a temporary work zone; 2) We could develop insights into the behavior and dynamics of freeway work zone, such as: the behavior of drivers approaching the work zone, the effect of police presence on driver willingness to slow down and merge, the effect of entrance ramp traffic on open lane flow, how rapidly queues form and dissipate, and what happens when an equipment move closes down all lanes for a short period.

Data Obtained from Other States

Work zone data with queue characteristics recorded was received in the form of reports from five states: South Carolina, Illinois, South Carolina, Ohio, and Wisconsin. We will describe three of these work zone datasets in subsections below, starting with the most important, and then tabulate these datasets and the Alabama data in the summary subsection.

South Carolina Data

Dr. Wayne Sarasua at Clemson and Dr. William Davis at The Citadel led a four-year study (2001-05) of freeway highway capacity for short-term work zone lane closures in South

Carolina (Sarasua *et al.,* 2006). Phase I of this SCDOT-sponsored research was completed in May 2003, and focused on "threshold volumes" for two-to-one lane closure work zone configurations. A total of 23 work zones were observed in Phase I, and besides capacities, queue start times and maximum queue lengths were also noted. Phase 2 expanded to 12 other work zones, including three-to-two and three-to-one lane closures, and was completed in May 2005.

An interesting finding by this research team was that Passenger Car Equivalents (PCEs) differed for various speed ranges, specifically:

- Less than 23.1 km/h (15 mph), PCE for trucks = 2.47
- 23.1-48.3 km/h (15-30 mph), PCE for trucks = 2.22
- 48.3-72.4 km/h (30-45 mph), PCE for trucks = 1.90
- 72.4-96.5 km/h (45-60 mph), PCE for trucks = 1.90.

Sarasua *et al.* (2006) states "observed differences in PCE values are primarily due to acceleration and deceleration characteristics of trucks, and are further explained that for speeds less than 30 mph, vehicles are likely to travel in a forced flow state where acceleration and deceleration are cyclically surging within the traffic stream." Of course, HCM 2000 does not account for such variable PCE values; our recommendation in a later part of this article that ALDOT use PCE = 2.1 seemed a good compromise between the 1.90 they observed for speeds greater than 30 mph, and the 2.22 for speeds in the range of 15-30 mph. Speeds less than 15 mph are unusual once vehicles leave the queue and are in the work zone.

A full tabulation of the 35 South Carolina work zones will be presented in the data summary subsection to follow. It turned out that three of the sites were "rained out," hence 32 of these sites were usable as our test data. The diversity of the sites was outstanding, as illustrated in Table 6.

Table 6: Diversity of South Carolina Datasets

Descriptors		Counts
Lane closure	2-to-1	14
	3-to-2	4
	3-to-1	12
	4-to-2	1
	4-to-1	1
Direction	Inbound	14
	Outbound	18
Intensity Level	1	2
	2	7
	3	5
	4	8
	5	8
	6	2
Highway Type	Interstate Urban (IU)	27
	Interstate Rural (IR)	5

North Carolina Data

Dixon and Hummer (1996) collected capacity and delay field data from 23 North Carolina sites in the early 1990s. They found that North Carolina work zone capacities were higher than the HCM 1994 capacities by at least 10%, confirming observations of others. We contacted Dr. Hummer, and he provided us with the NC state report. Traffic demand exceeded work zone capacity at 10 sites during the observation periods; however, the report only details the queuing results for three of these 10 sites. We use these three sites in the validation phase of our research on a modified version of the OkDOT spreadsheet.

Ohio Data

Four datasets were described in an Ohio study report (Jiang and Adeli, 2003), and were labeled as Examples 1A, 1B, 2A, and 2B. These four cases were used to test “a new freeway work zone traffic delay model” which depended on only two variables: the length of the work zone segment, and the starting time of the work zone. Average hourly traffic data was the main input. We discovered that the four cases used in their model testing were “simulated” 24-h work zone traffic volume and queue vehicle count results, not real data. But, because the model they used to generate the Examples 1A, 1B, 2A, and 2B was based on HCM 2000, their tables and graphs provided an excellent way to verify the correctness of our reprogramming of the OkDOT tool to use HCM 2000 work zone lane capacity equations and input factors.

Data Summary Tables

As discussed above, the South Carolina data became our test data bank (32 of 35 sites’ data was useable); the Ohio data turned out to be simulated (not real), but helped us verify the logic in our HCM 2000 version of the OkDOT model; and, the three North Carolina work zones with queue information became (along with the three Alabama work zones) the validation data for the recommended modification to the OkDOT spreadsheet.

Table 7 describes the six “validation datasets,” three from Alabama and three from North Carolina. Table 8 describes the 35 South Carolina datasets we extracted from the research reports (Sarasua *et al.*, 2006) prepared at Clemson University; 32 of these cases became the “test data bank” employed in comparing the three versions of the OkDOT spreadsheet. As described in Table 6, these 32 cases were remarkably diverse in work zone configuration, work intensity, and inbound vs. outbound direction of flow.

Table 7: Alabama and North Carolina Datasets

Site #	Date	Start Time	End Time	Location	Code	Direction	AADT	T%	Original # of lanes	# of Lanes Closed	Closure Geometry	Type of Work	W Z Intensity	Ramp	Queue?	Max QL
AL #1	7/28/2008	18:30	21:00	I-65 NB 176	IU	Outbound	76,170 (1)	20	3	2	O’side + Ctr	Bridge deck patching-nite	3	Y	N	0
AL #2	10/27/2008	8:50	12:30	I-65 NB 317	IR	Outbound	35,930 (2)	20	2	1	Outside	Paving bridge approach	4	Y	N	0
AL #3	1/7/2009	10:00	15:50	I-65 SB 209	IR	Outbound	36,210 (3)	16.6	2	1	Outside	Bridge deck patching-day	2	N	Y	400'
NC #1	Spring 1995	8:30	11:00	I-95 NB*	IR	Inbound	40,000	26.2	2	1	Inside	Heavy with 2' clearance	6	Y	Y	0.5 mi
NC #2	Spring 1995	8:00	11:00	I-95 NB*	IR	Inbound	40,000	24.6	2	1	Outside	Heavy with 2' clearance	6	Y	Y	1.4 mi
NC #3	Spring 1995	8:30	11:00	I-95 NB*	IR	Inbound	40,000	18.8	2	1	Outside	Heavy with 2' clearance	6	N	Y	2.9 mi

Note: * Johnston County, NC, but no MP given; (1) AADT 2007 for site I-65 at mile marker 172.295 in Montgomery county; (2) AADT 2007 for site I-65 at mile marker 308.275 in Cullman county is 37,360; for site I-65 at mile marker 326.23 in Morgan county is 34,490. Mile marker 317 is between 308 and 326, use average AADT; (3) AADT 2007 for site I-65 at mile marker 210.115 in Chilton county.

Table 8: South Carolina Datasets

Site #	Date	Start Time	End Time	Location	Code	Direction	T%	Closure Geometry	Type of Work	Equip. Activity	W Z Intensity	Ramp	Taper Length
1	9/12/2001	19:15	21:15	I-85 N MPM 32	IU	Inbnd	35.67%	Inside lane of 2 closed	Median Cable Guardrail	light	Level 2	Y	863
2	9/13/2001	19:45	20:45	I-26 W MPM 54	IU	Outbnd	28.95%	Inside lane of 2 closed	Median Cable Guardrail	light	Level 2	Y	795
3	9/16/2001	19:40	21:15	I-85 S MPM 8.5	IU	Outbnd	12.75%	Inside lane of 2 closed	Median Cable Guardrail	light	Level 2	Y	600
4	9/30/2001	19:05	22:30	I-85 N MPM 0	IR	Inbnd	17.37%	Inside lane of 2 closed	Median Cable Guardrail	light	Level 2	Y	665
5	10/1/2001	9:00	18:00	I-77 N MPM 80	IU	Outbnd	15.44%	Inside 2 lanes of 4 closed	Paving (OGFC)	heavy	Level 4	Y	675, 1475, 850
6	10/3/2001	17:00	22:30	I-385 N MPM 40	IU	Outbnd	3.17%	Outside lane of 2 closed	Paving (surface)	heavy	Level 4	Y	446
7	11/5/2001	20:00	22:00	I-26 W MPM 208	IU	Outbnd	12.38%	Outside 2 lanes of 3 closed	Final striping	heavy	Level 5	Y	668, 1544, 684
8	1/31/2002	15:30	16:00	I-26 E MPM 178	IU	Inbnd	15.55%	Outside lane of 2 closed	Conc Pvmt Repair	heavy	Level 3	Y	800
9	3/11/2002	16:00	18:10	I-385 N MPM 2	IU	Inbnd	15.51%	Inside lane of 2 closed	Median Cable Guardrail	light	Level 2	Y	950
10	4/3/2002	8:30	10:30	I-26 E MPM 104	IU	Inbnd	11.32%	Inside lane 2 of 3 closed [3]	Median Cleanup	light	Level 1	Y	-
11	4/8/2002	8:42	11:10	I-26 E MPM 107	IU	Inbnd	8.94%	Inside lane of 4 closed	Median Cleanup	light	Level 1	Y	575
12	6/3/2002	19:00	21:15	I-85 S MPM 28	IU	Outbnd	31.39%	inside lane 1 of 3 closed	Paving	light	Level 3	Y	800
13	6/4/2002	19:00	20:30	I-85 S MPM 28	IU	Outbnd	27.32%	Inside lane 2 of 3 closed [3]	Rumble Strips	light	Level 3	Y	-
14	6/6/2002	19:00	19:00	I-85 S MPM 28	IU	Outbnd	26.31%	Inside lane 2 of 3 closed		light	Level 3	Y	800
15	6/7/2002			I-85 S				RAINED OUT					
16	6/13/2002	19:00	21:00	I-85 S MPM 28	IU	Outbnd	26.58%	Inside 2 lanes of 3 closed [3]		heavy	Level 5	Y	
17	6/14/2002	19:00	21:20	I-85 S MPM 28	IU	Outbnd	17.21%	Outside lane of 2 closed	Concrete Paving	heavy	Level 5	Y	-
18	6/20/2002	20:00	22:00	I-85 S MPM 28	IU	Outbnd	30.33%	Outside lane of 2 closed	Concrete Paving	heavy	Level 5	Y	800
19	7/9/2002	19:15	20:15	I-85 S MPM 02	IR	Outbnd	33.07%	Outside lane of 2 closed	Bridge Maintenance	light	Level 6	Y	
20	7/21/2002	19:03	21:08	I-85 N MPM 179	IR	Inbnd	14.04%	Outside lane of 2 closed	Bridge Maintenance	light	Level 6	Y	
21	7/22/2002	18:56	20:30	I-85 N MPM 179	IR	Inbnd	34.43%	Outside lane of 2 closed	Bridge Decil Maintenance	light	Level 6	Y	
22	8/23/2002	21:00	22:00	I-26 W	IU	Outbnd	9.60%	Outside 2 lanes of 3 closed	Concrete Paving	light	Level 4	Y	800
23	8/14/2002	19:17	21:00	I-95 N MPM165	IR	Outbnd	30.65%	Inside 1 lane of 2 closed	Barrier Wall Erection	light	Level 2	Y	800
24	10/14/2003	21:00	23:35	I-85 S MPM 54	IU	Inbnd	36.39%	Inside 2 lanes of 3 closed	Milling	heavy	Level 4	Y	
25	3/12/2004	20:15		I-85 S MPM 54	IU	Inbnd	31.70%	Inside 2 lanes of 3 closed	Paving	heavy	Level 4	Y	800, 1200, 800
26	3/17/2004	21:35	0:11	I-85 N MPM 54	IU	Outbnd	40.69%	Inside 2 lanes of 3 closed	Milling	heavy	Level 4	Y	
27	5/13/2004	20:40	22:35	I-77 N	IU	Outbnd	14.59%	Outside 1 lane of 3 closed	Bridge Widening	light	Level 5	Y	800
28	5/13/2004	16:15	18:15	I-77 S	IU	Inbnd	17.42%	Outside lane 1 of 3 closed	Bridge Widening	light	Level 5	Y	750
29	5/14/2004	16:10	18:25	I-77 S	IU	Inbnd	14.08%	Outside lane 1 of 3 closed	Bridge Widening	light	Level 5	Y	750
30	5/14/2004	6:52	8:25	I-77 N	IU	Outbnd	22.06%	Outside 1 lane of 3 closed	Bridge Widening	light	Level 5	Y	800
31	6/24/2004	19:00	19:00	I-20 W				RAINED OUT	Paving				
32	7/9/2004	21:25	22:10	I-20 W	IU	Outbnd	14.03%	Outside 2 lanes of 3 closed	Paving	heavy	Level 4	Y	
33	10/12/2004	7:15	9:00	I-26 E MPM 76	IU	Inbnd	14.89%	Outside lane of 2 closed	Milling	light	Level 3	Y	800
34	10/20/2004	20:50	23:30	I-85 S MPM 54	IU	Inbnd	14.03%	Inside 2 lanes of 3 closed	Paving	heavy	Level 4	Y	800
35	12/13/2004			I-20 MPM 70				Inside 2 lanes of 3 closed	Paving	heavy	Level 4		800

Table 8 (Cont.)

WZ Length	Weather Conditions	5min hourly max	5min hourly min	Hourly max	Hourly min	AADT(1)	5min hourly max	5min hourly min	Hourly max	Hourly min	PCE(2)	Queue?	Max QL
short	Warm, Clear	1056	648	-		50,000	1560	1044	-		2.53	none	-
short	Warm, Clear	648	324	497	445	25,000	882	492	702	640	2.47	none	-
short	Warm, Clear	1572	636	1221	767	55,000	1824	726	1414	918	2.39	few	3200
short	Warm, Clear	1440	324	1320	995	50,000	1728	534	1540	1243	2.20	continuous	>1 mile
long	Warm, Clear	1140	636	930	802	25,000	1389	765	1112	954	2.25	none	-
long	Warm, Clear	744	60	553	458	20,000	768	60	572	479	2.27	none	-
short	Cold, Clear	1308	576	1124	735	60,000	1506	666	1310	871	2.42	none	-
medium	Cool, Clear	1128	720	927	871	32,000	1416	864	1107	1059	2.32	none	-
long	Cool, Clear	696	276	565	509	20,000	918	312	689	608	2.33	none	-
short	Warm, Clear	2016	1266	1041	1041	40,000	2262	1446	1178	1178	2.16	continuous	>4500
short	Warm, Clear	1480	1044	1308	1152	40,000	1620	1152	1437	1284	2.19	none	-
	clear	1284	636	1090	820	60,000	1758	1056	1518	1217	2.40	none	-
	clear	1668	756	1251	976	60,000	2232	960	1640	1428	2.42	Discontinuous	500
	clear	1524	1008	1357	1141	60,000	2202	1428	1836	1574	2.39	Discontinuous	800 (3)
	Rain												
	Warm, Clear	1500	936	1341	1047	60,000	2100	1296	1844	1441	2.41	Discontinuous	>1 mile
long	Warm, Clear	1680	660	1504	1240	60,000	2070	768	1793	1564	2.32	continuous	>1 mile
long	Warm, Clear	1452	732	1110	916	60,000	1998	1056	1552	1331	2.40	continuous	3000
long	Warm, Clear	1236	636	672	672	35,000	1674	930	995	995	2.45	none	-
long	Warm, Clear	1032	648	903	799	40,000	1500	978	1332	1198	4.47	continuous	>1mile
long	clear	1548	384	1339	867	40,000	1830	558	1536	1065	1.55	none	-
long	clear	1104	948	920	131	70,000	1338	1110	1038	149	2.38	Discontinuous	
long	clear	1032	648	907	815	40,000	1500	924	1276	1179	2.39	Discontinuous	5000
long	Clear	1068	540	916	712	70,000	1650	870	1407	1131	2.55	continuous	3300
long	Clear	1176	540	899	838	70,000	1564	752	1347	1201	2.47	continuous	4100
long	Clear	1188	504	860	639	70,000	1734	714	1224	1092	2.39	continuous	5033
medium	Warm, Clear	1734	726	1600	1083	90,000	1945	943	1816	1324	2.23	none	-
medium	Warm, Clear	1596	936	1380	1221	50,000	2002	1165	1712	1475	2.29	continuous	5000
medium	Warm, Clear	1824	1224	1533	1356	50,000	2124	1423	1795	1594	2.23	continuous	4000
medium	Warm, Clear	1572	852	1394	1237	60,000	1912	1099	1786	1575	2.26	continuous	4167
	Rain												
long	Clear	1836	1224	1609	1343	100,000	2141	1423	1905	1578	2.28	continuous	3800
short	Warm, Clear	1464	660	1068	858	25,000	1644	846	1268	1047	2.37	discontinuous	3500
long	Warm, Clear	1836	1224	1609	1343	70,000	2130	1428	1902	1587	2.30	continuous	4000
medium	Clear												

Note: (1) AADT is estimated from hourly vehicle volume with the exception of site one, whose AADT is estimated from 5min hourly vehicle volume; (2) PCE is calculated from hourly vehicle volume and hourly pc volume with the exception of site one, whose PCE is calculated from 5min hourly volume; (3) Change is made from original data.

RESULTS

This section reports the results of testing and validation of the three work zone queue estimation alternatives. Specifically, Ohio datasets were used to verify model logic for HCM 2000 alternatives; South Carolina datasets were used to test and compare the three alternatives; finally, Alabama and North Carolina datasets were used to validate the optimal alternative.

Checking Model Logic and Test Preparation

An auxiliary tool developed prior to checking and testing against real work zone data enabled the researchers to identify the 24-h traffic volume profile to best match the actual hourly traffic volumes reported with each real dataset. Such a profile was required as input for the testing to proceed.

When milepost and direction at the work zone are available, hourly traffic volume profiles are often available online from that state's DOT. These profiles can be obtained for a particular day of the week, or averaged over the entire week for a year. Alabama data is available in these forms. The traffic planner would use the day-of-week profile, if he/she knew the exact date of scheduled work. Otherwise, an average annual profile should be used. In some of the work zone test cases described above, the researchers themselves took actual hourly traffic volumes at the same time as work zone capacity and queues were measured, and these hourly data can be used either directly (if extended over entire 24 h) or indirectly to select the most appropriate match among several candidate 24-h profiles.

When 24-h traffic volumes are available, the analysis code required in each OkDOT alternative is set to "UV" for user-defined volume, and these hourly records can be used directly as volume inputs. However, though on-site observations could be for 24 h, typically they are for a continuous period of only a few hours only, not 24 h. In this case, a computer-aided visual tool was needed and developed as part of this project to help match 24-h profiles to observed traffic volume data.

The tool was developed based on OkDOT spreadsheet and showed traffic volume pattern for sites of different type and direction. For instance, interstate urban sites have peak hours in both morning and evening; inbound sites have a higher morning peak and outbound sites have a higher evening peak. The tool helped classify work zone sites among several options and also establish the 24-h input volumes to be used in testing the three OkDOT alternatives.

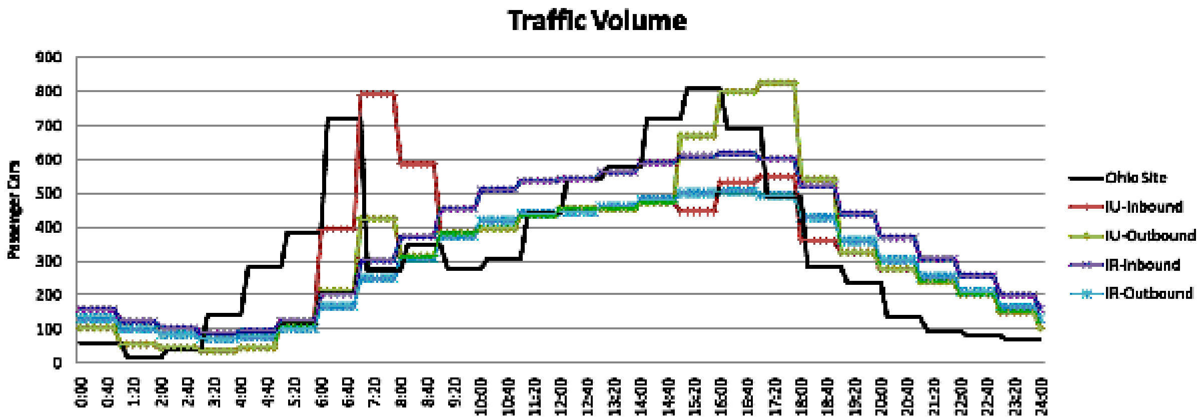
Example: Application when 24-h profile is given

Although Ohio datasets have 24-h profiles, we decide to convert data back to AADT, analysis code, and direction in order to check model logic for HCM 2000 alternatives. In this subsection, we use one of the Ohio datasets to illustrate the 24-h matching situation, as in Figure 1.

Example: Application when less than 24-h profile is given

The auxiliary tool was used in our research to determine hourly traffic volume for the North

Figure 1: Auxiliary Tool Determines Ohio Site as IU-Outbound



Carolina, South Carolina, and Wisconsin datasets. This was an important preparation step, because the South Carolina data became the main focus to test and compare the three OkDOT alternatives; and North Carolina contributed three cases to the validation. These states' datasets have traffic volumes during a data collection period, but lack traffic volumes for the rest of the day. The traffic volume pattern for data collection period is compared with the patterns available by analysis code in the OkDOT spreadsheet, and AADT that provides the best match during the data collection period of hours is used to determine what the 24-h traffic volume profile looked like at the specific site that day. We shall illustrate this process with North Carolina Site #18.

The information given in the North Carolina State report includes location I-95 NB, rural area, and traffic volume during data collection period. There is no AADT and direction (inbound or outbound) available. Table 9 contains observed 10-min traffic volumes at the work zone.

Figure 2 shows match pattern when AADT is set as 40,000. Traffic volume pattern for IR-Inbound and IR-Outbound are similar; with the difference that inbound volume is larger than outbound volume during the hours in which data was collected. Direction is chosen as inbound, which matches the maximum observed traffic volume better. The entire 24-h IR-Inbound pattern with AADT = 40,000 was used in runs associated with this site.

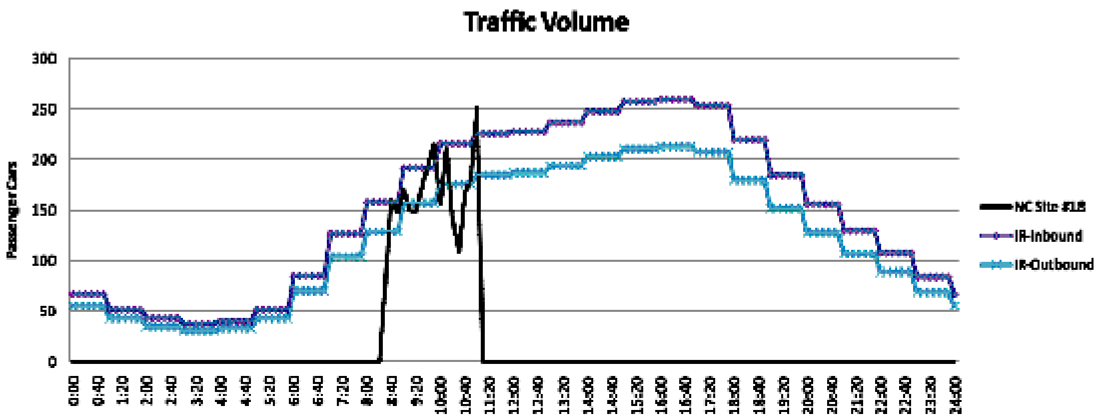
Table 9: North Carolina Site # 18

Time	Traffic volume	Time	Traffic volume
8:30	74	9:50	215
8:40	160	10:00	156
8:50	148	10:10	211
9:00	171	10:20	142
9:10	150	10:30	110
9:20	149	10:40	167
9:30	174	10:50	180
9:40	195	11:00	251

Checking Model Logic for HCM 2000 Alternatives

Before testing and comparing the three alternatives, the logic for the two modified alternatives was checked and verified using Ohio datasets. Inserting HCM 2000 logic into the OkDOT spreadsheet tool to create the HCM 2000 alternatives was a significant

Figure 2: Auxiliary Tool Used to Determine NC Site was IR-Inbound with AADT = 40,000



change. Therefore, we wanted to verify that this change was producing comparable results to some other computerized HCM 2000 tool. We chose to use four test cases described in the article by Jiang and Adeli (2003). They ran a computerized version of HCM 2000 capacity estimation and recorded their results in tables and graphs. We ran our HCM 2000 alternatives on the same four test cases, and produced virtually identical queue profiles over a 24-h period. Test cases were: Example 1A has ADT = 1000 vph with a maximum traffic flow of 2430 at 16:00; Example 1B has ADT = 2000 vph with a maximum traffic flow of 4840 at 16:00. The work zone configuration is two lanes reduced to one open lane. The maximum number of queued vehicles in Example 1A is 1220 at 16:00, with a queue existing from 12:00 to 18:00. The maximum number of queued vehicles in Example 1B is 3640 at 16:00, with a queue existing from 5:00 until 20:00.

We use Example 1B to illustrate our checking process and results; the other examples are similar. In our runs of Example 1B, we used the "best match" IU outbound with AADT = 96,000, whereas Ohio State researchers used an "anticipated traffic flow" as input. We first ran the OkDOT HCM 2000 version at I = -160, 0, and 160. As depicted in Figure 3, I = -160 comes closest to their simulated number of vehicles in queue. Note that when we set I = -400, our model output overlaps their model output. It turns out that the Ohio State researchers were using 1200 pcphpl as the nominal work zone lane capacity, so when we set I = -400 in our model, our output matches theirs, as it should if our model is programmed correctly.

In conclusion, to best match Ohio results using HCM 2000 alternatives, an intensity level penalty of I = -400 was needed; that is, work zone intensity penalties larger than -160 should be permitted in our search for the best overall work zone queue length prediction model—precisely what the HCM 2000 hybrid provides.

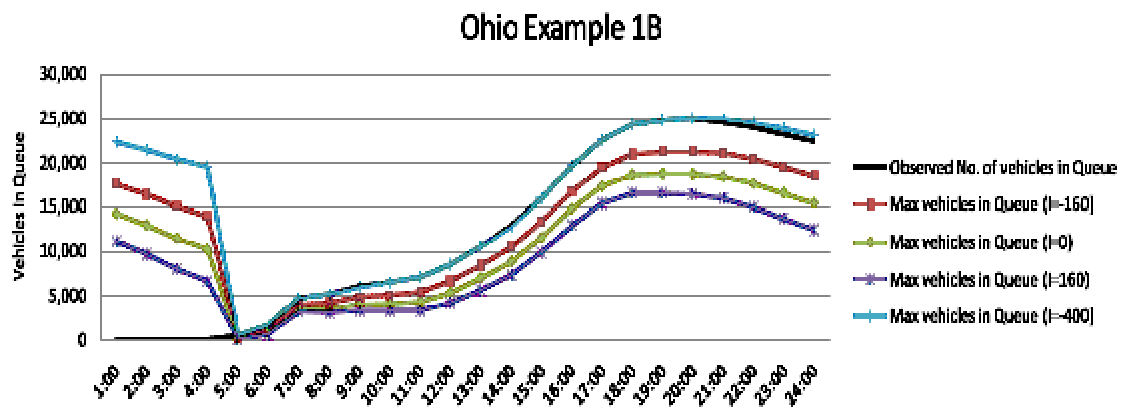
Testing Results using 32 South Carolina Work Zones

This subsection describes extensive testing of the three OkDOT alternatives in their ability to accurately predict two metrics:

- Maximum Queue Length (MQL)
- Queue Start Time (QST)

Across a diverse mix of 32 work zones where data was obtained from researchers in

Figure 3: Comparison of OkDOT Spreadsheet HCM 2000 Version Predictions with Output of a Similar Ohio State Model



South Carolina (Sarasua *et al.,* 2006). Maximum queue length is considered first, and the respective model alternatives were run at baseline settings, then calibrated to identify the optimal settings of controllable parameters for each work zone:

- CL and PCE for OkDOT baseline version.
- I and PCE for HCM 2000 and HCM 2000 hybrid versions.

Additional analyses as documented below led to the conclusion that the HCM hybrid version is the most accurate of the three at predicting MQL and QST. The best level of PCE with HCM 2000 hybrid is determined to be 2.1.

South Carolina Datasets Description

When using South Carolina datasets, we spent considerable time locating each site on a SC highway map with mileposts, and this location helped us classify each site as IR vs. IU, and outbound vs. inbound to the closet metropolitan area. A level (1-6) of work zone intensity shown in Table 10 was determined based on work zone descriptions given by Sarasua *et al.* (2006).

It was determined from map study that each work zone did have an entrance ramp within one mile of the taper and of the work zone, that is, in the advanced warning area. The AADT was estimated from the volume of traffic observed during the hours of operation of each of these temporary work zones. Passenger Car Equivalent (PCE) was calculated from hourly vehicle volume and hourly passenger car volume; these traffic volumes were directly observed by SC researchers on-site. Queue length in the SC dataset is measured in feet (0.3048 m), except as noted. When the notation >1 mile appeared in four instances, we treated MQL as exactly 1 mile (1.609 km). Finally, in six instances we modified the SC data, because we had evidence from our initial model runs at those six sites that typographical errors were made in data description. We made such modifications based on our model runs and comparisons with their results at similar sites.

Method of Prediction Error Analysis and Calibration

Each of the j =1, ..., 32 South Carolina datasets was submitted to the method of error analysis and model calibration described in Table 11.

Table 10: Confidence Level (CL) and Intensity Level (I) for the 32 South Carolina Work Zones

SC Work Zone	WorkIntensity Level CL (%)	OkDOT I (-160,160)	HCM 2000 I (-500,0)	HCM 2000 Hybrid
1	2	20	100	-100
2	2	20	100	-100
3	2	20	100	-100
4	2	20	100	-100
5	4	60	-40	-300
6	4	60	-40	-300
7	5	80	-100	-400
8	3	40	40	-200
9	2	20	100	-100
10	1	0	160	0
11	1	0	160	0
12	3	40	40	-200
13	3	40	40	-200
14	3	40	40	-200
15	NA	NA	NA	NA
16	5	-100	-100	-400
17	5	-100	-100	-400
18	5	-100	-100	-400
19	6	-160	-160	-500
20	6	-160	-160	-500
21	2	100	100	-100
22	4	-40	-40	-300

The calibration analysis was performed to see if there were any obvious trends or tendencies that suggested some other values of baseline parameters (e.g., PCE at a level other than 2.0) that might improve accuracy. In all error analysis (QST and MQL), note that we use the error measurement "difference" defined to be:

$$\text{Difference} = \text{Observed} - \text{Predicted} \quad \text{...(3)}$$

Taking the HCM 2000 hybrid version applied to site 4 as an example, the observed queue was formed after 19:05 and the maximum queue length was >5280 ft (1609 m). The baseline run for HCM 2000 hybrid had the queue formed at 19:00 and developed to a maximum length of 3260 ft (1103 m). QST difference +:05 means the predicted queue was formed 5 min earlier than the observed queue; MQL difference 2020 ft (616 m) means the maximum predicted queue was 2020 ft

Table 10 (Cont.)

SC Work Zone	Work Intensity Level	OkDOT CL (%)	HCM 2000 I (-160,160)	HCM 2000 Hybrid I (-500,0)
23	2	100	100	-100
24	4	-40	-40	-300
25	4	-40	-40	-300
26	4	-40	-40	-300
27	5	-100	-100	-400
28	5	-80	-100	-400
29	5	80	-100	-400
30	5	-80	-100	-400
31	NA	NA	NA	NA
32	4	60	-40	-300
33	3	40	40	-200
34	4	-60	-40	-300
35	NA	NA	NA	NA

shorter than observed queue. In the optimal run, QST difference was still +:05, while MQL difference was reduced to -200 ft, which means the maximum predicted queue length was 200 ft longer than the observed queue.

Table 11: Method to Find Best Version of OkDOT Spreadsheet Alternatives
Consider work zone j
Run each version of three model alternatives with inputs as indicated by work zone configuration, traffic volumes, percent heavy vehicles, work intensity, etc. and get predicted queue start time and maximum queue length.
For each of these baseline runs: Compare predicted queue start time (QST) and maximum queue length (MQL) with actual values from observers, and record difference (observed - predicted).
Through trial and error, find combinations of changes in each version that makes predictions come closest to actual QST and MQL. Record these changes and the resulting improved “differences”.
Go to work zone j + 1. At j = 32, end.

Analysis and Calibration Results

Table 12 reports the results of baseline prediction error analysis, optimal calibration analysis, and the optimal definition of parameters with which the optimal prediction was achieved. Some of the optimal definitions are baseline (e.g., whenever PCE = 2.0) but others are not. Note that occasionally, the term “miss” is recorded under QST or MQL, for either the baseline run or the optimized run. The entry “miss” means that either a queue occurred, but none was predicted; or, a queue was predicted, but none occurred. The former prediction error “miss” is more serious from the point of view of the mobility planner. We will analyze these misses later in this section.

Table 13 summarizes the results from Table 12 for the metric Maximum Queue Length (MQL). Note that 20 of the 32 work zones had queues; the other 12 did not. At the bottom of the table, appear lines for: total error (sum of errors), average error across all 32 work zones, and average error across the 20 work zones with queues. It is clear that the HCM 2000 hybrid version produces the smallest average error for all 32 work zones or the 20 with queues. In fact, HCM hybrid is roughly twice as good as the HCM 2000 version at minimizing prediction error. Furthermore, at their optimized settings, HCM 2000 hybrid provided the best estimate of queue length in 70% of the cases; OkDOT baseline was most accurate for 30% of the 20 cases with queues. HCM 2000 hybrid predicted a queue when none formed 33% of the 12 cases; when optimized, it predicted no queue would form in all 12 such cases, a 100% performance. Finally, there were three cases (sites 28, 29, and 30) with really odd queue lengths for their situational description. If these three "outliers" are removed from the dataset, HCM 2000 hybrid predicts the actual length within an average error of 333 feet over all 29 cases, and within 568 feet for the 17 with queues; that is, within 33 and 57 vehicles respectively. Optimized HCM 2000 hybrid actually has an average error of less than one car length, but these optimized settings were settings that may not have exactly matched the work zone description and traffic parameters a planner would be using.

Turning now to Queue Start Time (QST), consider Table 14 which summarizes the QST results from Table 12. The average QST error for all three models was less than five minutes. In part, this is an artifact of the way work zone data was reported, and the way the three OkDOT alternatives report a queue start time (to the nearest hour, only). The label "miss" used in Table 12 was explained earlier. To clarify, we define:

- Miss 1: There was a queue, but none was predicted
- Miss 2: There was no queue, but one was predicted.

As we stated earlier, Miss 1 is a more serious predictive error, and the conservative mobility planner would rather make a type 1 error than a type 2 error; or, at least balance these errors. As can be seen at the bottom of Table 14, HCM 2000 hybrid does the best job of minimizing the total number of misses, and the number of "Miss 1" instances, across the 32 South Carolina work zones.

As it became apparent that the HCM 2000 hybrid version would be the recommended alternative, we reviewed the "optimal settings" found in Table 12 to see if any fine tuning could be done to improve the predictive ability of the HCM 2000 hybrid with baseline settings, in particular using the Passenger Car Equivalent (PCE) value of 2.0 assumed. We noted quite a few instances where PCE = 2.5 was optimal for HCM 2000 hybrid. The highway capacity manual actually states that PCE values from 2.0 to 2.5 should be considered, the higher values however being more representative in mountainous terrain. Other researchers have suggested that PCE values of 2.5 apply when traffic speed has dropped into the range of 0 - 20 mph, because in such stop and start conditions, trucks do require more spacing than at moderate speeds of 20 - 50 mph.

We decided to conduct a parametric analysis of the MQL prediction performance of the HCM 2000 hybrid version, using PCE values of 2.0 (baseline), 2.2, and 2.4. The results of this parametric analysis are shown in Table 15. Just as in the MQL analysis above, we calculated average error for all work zones, then only for work zones with queues. In addition, we calculated the standard deviation of error in case confidence intervals were to be constructed. Also, we considered a reduced set of work zones—first eliminating sites 28, 29, and 30; then eliminating sites 23,

Table 12: SC Queue Length Analysis

Work Zone	Queue Start Time (QST)	Max. Queue Length (MQL)	Model Run	OkDOT Prediction				HCM 2000 Prediction				HCM 2000 Hybrid Prediction			
				QST	Diff	MQL	Diff	QST	Diff	MQL	Diff	QST	Diff.	MQL	Diff.
Site 1	none	-	Baseline[1]	none	-	0	0	none	-	0	0	19:00	miss	580	-580
			Optimal	none	-	0	0	none	-	0	0	none	-	0	0
			Optimal Definition	CL=20% and PCE=2.0				I=100 and PCE=2.0				I=0 and PCE=2.0 or I= -100 and PCE=1.8			
Site 2	none	-	Baseline[1]	none	-	0	0	none	-	0	0	none	-	0	0
			Optimal	none	-	0	0	none	-	0	0	none	-	0	0
			Optimal Definition	CL=20% and PCE=2.0				I=100 and PCE=2.0				I= -100 and PCE=2.0			
Site 3	after 19:40	3200'	Baseline[1]	none	miss	0	3200	none	miss	0	3200	none	miss	0	3200
			Optimal	19:00	+40	1140	−2060	19:00	+40	700	2500	19:00	+40	3160	-40
			Optimal Definition	CL=20% and PCE=2.5				I= -160 and PCE=2.5				I= -350 and PCE=2.5			
Site 4	after 19:05	>5280'	Baseline[1]	19:00	+05	2130	3150	19:00	+05	920	4360	19:00	+05	3260	2020
			Optimal	19:00	+05	5270	+10	19:00	+05	5480	-200	19:00	+05	5480	-200
			Optimal Definition	CL=50% and PCE=2.5				I= -100 and PCE=2.5				I= -100 and PCE=2.5			
Site 5	none	-	Baseline[1]	none	-	0	0	none	-	0	0	none	-	0	0
			Optimal	none	-	0	0	none	-	0	0	none	-	0	0
			Optimal Definition	CL=60% and PCE=2.0				I= -40 and PCE=2.0				I= -300 and PCE=2.0			
Site 6	none	-	Baseline[1]	none	-	0	0	none	-	0	0	none	-	0	0
			Optimal	none	-	0	0	none	-	0	0	none	-	0	0
			Optimal Definition	CL=60% and PCE=2.0				I= -40 and PCE=2.0				I= -300 and PCE=2.0			
Site 7	none	-	Baseline[1]	20:00	miss	934	-934	none	-	0	0	20:00	miss	947	-947
			Optimal	none	-	0	0	none	-	0	0	none	-	0	0
			Optimal Definition	CL=40% and PCE=2.0				I= -100 and PCE=2.0				I= -200 and PCE=2.0			
Site 8	none	-	Baseline[1]	none	-	0	0	none	-	0	0	none	-	0	0
			Optimal	none	-	0	0	none	-	0	0	none	-	0	0
			Optimal Definition	CL=40% and PCE=2.0				I=40 and PCE=2.0				I= -200 and PCE=2.0			
Site 9	none	-	Baseline[1]	none	-	0	0	none	-	0	0	none	-	0	0
			Optimal	none	-	0	0	none	-	0	0	none	-	0	0
			Optimal Definition	CL=20% and PCE=2.0				I=100 and PCE=2.0				I= -100 and PCE=2.0			

Table 12 (Cont.)

Work Zone	Queue Start Time (QST)	Max. Queue Length (MQL)	Model Run	OkDOT Prediction				HCM 2000 Prediction				HCM 2000 Hybrid Prediction			
				QST	Diff	MQL	Diff	QST	Diff	MQL	Diff	QST	Diff	MQL	Diff
Site 10	after 8:30	>4500'	Baseline[1]	none	miss	0	4500	none	miss	0	4500	16:00	+30	1401	3099
			Optimal	16:00	+30	4289	+211	16:00	+30	4762	-262	16:00	+30	4842	-342
			Optimal Definition	CL=60% and PCE=2.5				I= -160 and PCE=5.0				I= -400 and PCE=2.0			
Site 11	none	-	Baseline[1]	none	-	0	0	none	-	0	0	none	-	0	0
			Optimal	none	-	0	0	none	-	0	0	none	-	0	0
			Optimal Definition	CL=0% and PCE=2.0				I=160 and PCE=2.0				I=0 and PCE=2.0			
Site 12	none	-	Baseline[1]	none	-	0	0	none	-	0	0	none	-	0	0
			Optimal	none	-	0	0	none	-	0	0	none	-	0	0
			Optimal Definition	CL=40% and PCE=2.0				I=40 and PCE=2.0				I= -200 and PCE=2.0			
Site 13	after 19:00	500	Baseline[1]	none	miss	0	500	19:00	0	654	-154	19:00	0	2908	-2408
			Optimal	19:00	0	507	-7	19:00	0	537	-37	19:00	0	560	-60
			Optimal Definition	CL=0% and PCE=1.7				I=40 and PCE=1.95				I=0 and PCE=1.85			
Site 14	after 19:00	800	Baseline[1]	19:00	0	2301	-1501	19:00	0	860	-60	19:00	0	2165	-1365
			Optimal	19:00	0	667	133	19:00	0	860	-60	19:00	0	840	-40
			Optimal Definition	CL=0% and PCE=1.9				I=40 and PCE=2.0				I=0 and PCE=2 or I= -100 and PCE=1.8			
Site 15	no data abailable		Baseline[1]												
			Optimal												
			Optimal Definition												
Site 16	after 19:00	>5280'	Baseline[1]	19:00	0	5423	-143	19:00	0	1507	3773	19:00	0	5456	-176
			Optimal	19:00	0	5423	-143	19:00	0	5056	224	19:00	0	5216	+74
			Optimal Definition	CL=80% and PCE=2.0				I= -160 and PCE=2.7				I= -400 and PCE=1.95			
Site 17	after 19:00	>5280'	Baseline[1]	19:00	0	1700	3580	19:00	0	1120	4160	19:00	0	6240	-960
			Optimal	19:00	0	4020	1260	19:00	0	3140	2140	19:00	0	5420	-140
			Optimal Definition	CL=100% and PCE=2.5				I= -160 and PCE=2.5				I= -400 and PCE=1.85			
Site 18	after 20:00	3000'	Baseline[1]	20:00	0	860	2140	20:00	0	280	2720	20:00	0	4700	-1700
			Optimal	20:00	0	2860	140	20:00	0	2900	100	20:00	0	3000	0
			Optimal Definition	CL=80% and PCE=2.5				I= -160 and PCE=2.5				I= -400 and PCE=1.7 or I= -300 and PCE=2.05			

Table 12 (Cont.)

Work Zone	Queue Start Time (QST)	Max. Queue Length (MQL)	Model Run	OkDOT Prediction				HCM 2000 Prediction				HCM 2000 Hybrid Prediction			
				QST	Diff.	MQL	Diff.	QST	Diff.	MQL	Diff.	QST	Diff.	MQL	Diff.
Site 19	none	-	Baseline[1]	none	-	0	0	none	-	0	0	19:00	miss	1160	-1160
			Optimal	none	-	0	0	none	-	0	0	none	-	0	0
			Optimal Definition	CL=100% and PCE=2.0				I= -160 and PCE=2.0				I= -400 and PCE=1.95			
Site 20	after 19:03	>5280'	Baseline[1]	19:00	:03	300	4980	none	miss	0	5280	19:00	:03	4540	740
			Optimal	19:00	:03	1080	4200	19:00	:03	640	4640	19:00	:03	5260	20
			Optimal Definition	CL=100% and PCE=2.5				I= -160 and PCE=2.5				I= -500 and PCE=2.25			
Site 21	none	-	Baseline[1]	19:00	miss	1210	-1210	none	-	0	0	19:00	miss	1540	-1540
			Optimal	none	-	0	0	none	-	0	0	none	-	0	0
			Optimal Definition	CL=40% and PCE=1.7 or CL=20% and PCE=1.8				I=100 and PCE=2.0				I=0 and PCE=1.85			
Site 22	after 21:00	250	Baseline[1]	21:00	0	173	72	none	miss	0	250	21:00	0	120	130
			Optimal	21:00	0	253	-3	none	miss	0	250	21:00	0	240	10
			Optimal Definition	CL=60% and PCE=2.1				I= -160 and PCE=2.0				I= -300 and PCE=2.15			
Site 23	after 19:17	5000'	Baseline[1]	none	miss	0	5000	none	miss	0	5000	none	miss	0	5000
			Optimal	19:00	:17	900	4100	19:00	:17	460	4540	19:00	:17	5140	-140
			Optimal Definition	CL=100% and PCE=2.5				I= -160 and PCE=2.5				I= -500 and PCE=2.4			
Site 24	21:00	3300'	Baseline[1]	21:00	0	2748	552	21:00	0	307	2993	21:00	0	2641	659
			Optimal	21:00	0	3188	112	21:00	0	3135	165	21:00	0	3322	-22
			Optimal Definition	CL=60% and PCE=2.1				I= -160 and PCE=2.5				I= -300 and PCE=2.15			
Site 25	20:15	4100'	Baseline[1]	20:00	:15	3215	885	20:00	0	1427	2673	20:00	0	3162	938
			Optimal	20:00	:15	3975	125	20:00	0	3508	592	20:00	0	3922	178
			Optimal Definition	CL=60% and PCE=2.2				I= -160 and PCE=2.5				I= -300 and PCE=2.3			
Site 26	21:35	5033'	Baseline[1]	21:00	:35	3268	1765	21:00	:35	587	4446	21:00	:35	3162	1871
			Optimal	21:00	:35	4909	124	21:00	:35	3975	1058	21:00	:35	5043	-10
			Optimal Definition	CL=60% and PCE=2.3				I= -160 and PCE=2.5				I= -300 and PCE=2.35			
Site 27	none	-	Baseline[1]	none	-	0	0	none	-	0	0	none	-	0	0
			Optimal	none	-	0	0	none	-	0	0	none	-	0	0
			Optimal Definition	CL=80% and PCE=2.0				I= -100 and PCE=2.0				I= -400 and PCE=2.0			

Table 12 (Cont.)

Work Zone	Queue Start Time (QST)	Max. Queue Length (MQL)	Model Run	OkDOT Prediction				HCM 2000 Prediction				HCM 2000 Hybrid Prediction			
				QST	Diff	MQL	Diff.	QST	Diff	MQL	Diff	QST	Diff.	MQL	Diff
Site 28	16:15	5000'	Baseline[1]	none	miss	0	5000	none	miss	0	5000	16:00	:15	0	5000
			Optimal	none	miss	0	5000	none	miss	0	5000	16:00	:15	3695	1305
			Optimal Definition	CL=100% and PCE=2.5				I= -160 and PCE=2.5				I= -500 and PCE=2.5			
Site 29	16:10	4000'	Baseline[1]	none	miss	0	4000	none	miss	0	4000	none	miss	0	4000
			Optimal	none	miss	0	4000	none	miss	0	4000	16:00	:10	2535	1465
			Optimal Definition	CL=100% and PCE=2.5				I= -160 and PCE=2.5				I= -500 and PCE=2.5			
Site 30	6:52	4167	Baseline[1]	none	miss	0	4167	none	miss	0	4167	none	miss	0	4167
			Optimal	none	miss	0	4167	none	miss	0	4167	7:00	-:08	1788	2379
			Optimal Definition	CL=100% and PCE=2.5				I= -160 and PCE=2.5				I= -500 and PCE=2.5			
Site 31	no data abailable		Baseline[1]												
			Optimal												
			Optimal Definition												
Site 32	21:25	3800'	Baseline[1]	21:00	:25	6190	2390	21:00	:25	2615	1185	21:00	:25	6083	-2283
			Optimal	21:00	:25	3809	-9	21:00	:25	3695	105	21:00	:25	3695	105
			Optimal Definition	CL=20% and PCE=2.0				I= -100 and PCE=2.1				I= -100 and PCE=2.1			
Site 33	7:15	3500'	Baseline[1]	7:00	:15	610	2890	none	miss	0	3500	7:00	:15	1940	1560
			Optimal	7:00	:15	2880	620	7:00	:15	2440	1050	7:00	:15	3600	-100
			Optimal Definition	CL=100% and PCE=2.5				I= -160 and PCE=2.5				I= -300 and PCE=2.35			
Site 34	20:50	4000'	Baseline[1]	21:00	-:10	494	3506	none	miss	0	4000	21:00	-:10	440	3560
			Optimal	21:00	-:10	3135	855	21:00	-:10	4	3996	21:00	-:10	3308	692
			Optimal Definition	CL=100% and PCE=2.5				I= -160 and PCE=2.5				I= -500 and PCE=2.5			
Site 35	no data abailable		Baseline[1]												
			Optimal												
			Optimal Definition												

(1) Baseline Input: PCE is set as default value 2.0 and Confidence (CL) in OkDOT model, Intensity (I) in HCM 2000 and HCM 2000 Hybrid models are set by work zone description

Table 13: Maximum Queue Length Prediction Error for 32 SC Work Zones (20 with queues)

SC Work Zone	OKDOT		HCM 2000		HCM 2000 Hybrid		Maximum Queue Length
	Baseline	Optimal	Baseline	Optimal	Baseline	Optimal	
1	0	0	0	0	-580	0	
2	0	0	0	0	0	0	
3	3200	2860	3200	2500	3200	40	3200'
4	3150	10	4360	-200	2020	-200	5280'
5	0	0	0	0	0	0	
6	0	0	0	0	0	0	
7	-934	0	0	0	-947	0	
8	0	0	0	0	0	0	
9	0	0	0	0	0	0	
10	4500	211	4500	-262	3099	-342	4500'
11	0	0	0	0	0	0	
12	0	0	0	0	0	0	
13	560	-7	-154	-37	-2108	-60	500'
14	-1501	133	-60	-60	-1365	-40	800'
15	NA	NA	NA	NA	NA	NA	
16	-143	-143	3773	224	-176	74	5280'
17	3580	1260	4160	2140	-960	-140	5280'
18	2140	140	2720	100	-1700	0	3000'
19	0	0	0	0	-1160	0	
20	4980	4200	5280	4640	740	20	5280'
21	-1210	0	0	0	-1540	0	
22	72	-3	250	250	130	10	250'
23	5000	4100	5000	4540	5000	-140	5000'
24	552	112	2993	165	659	-22	3300'
25	885	125	2673	592	938	178	4100'
26	1765	124	4446	1058	1871	-10	5033'
27	0	0	0	0	0	0	
28	5000	5000	5000	5000	5000	1305	5000'
29	4000	4000	4000	4000	4000	1465	4000'
30	4167	4167	4167	4167	4167	2379	4167'
31	NA	NA	NA	NA	NA	NA	
32	2390	-9	1185	105	-2283	105	3800'
33	2890	620	3500	1060	1560	-100	3500'
34	3506	865	4000	3996	3560	692	4000'
35	NA	NA	NA	NA	NA	NA	
Total Error	48549	27765	64993	33978	22825	5214	
Average (n 32)	1517.2	867.7	2031	1061.8	713.3	162.9	
Average (n 20)	2427.5	1388.3	3249.7	1698.9	1141.3	260.7	
	Best estimate 6/20 – 30% of queues				Best estimate 14/20 – 70% of queues		
Predicted Queue when none formed					4/12 = 33%	0/12 = 0%	
Total without sites 28,29, & 30 ---------------------------------->					9656	65	
Average (n=29)					333	2.2	
Average (n=17)					568	3.8	

Table 14: Queue Start Time (QST) Prediction Error (minutes) with Models at Baseline Settings

SC Work Zone	OkDOT	HCM 2000	HCM 2000 Hybrid
1	0	0	miss 2
2	0	0	0
3	miss 1	miss 1	miss 1
4	5	5	5
5	0	0	0
6	0	0	0
7	miss 2	0	miss 2
8	0	0	0
9	0	0	0
10	miss 1	miss 1	30
11	0	0	0
12	0	0	0
13	miss 1	0	0
14	0	0	0
15	NA	NA	NA
16	0	0	0
17	0	0	0
18	0	0	0
19	0	0	miss 2
20	3	miss 1	3
21	miss 2	0	miss 2
22	0	miss 1	0
23	miss 1	miss 1	miss 1
24	0	0	0
25	15	0	0
26	35	35	35
27	0	0	0
28	miss 1	miss 1	15
29	miss 1	miss 1	miss 1
30	miss 1	miss 1	miss 1
31	NA	NA	NA
32	25	25	25
33	15	miss 1	15
34	-10	miss 1	-10
35	NA	NA	NA
Average	88/23=3.8 min 7 miss 1 2 miss 2	65/22=3.0 min 10 miss 1 0 miss 2	118/24=4.9 min 4 miss 1 4 miss 2

miss 1: there was a queue, but none was predicted
miss 2: there was no queue, but one was predicted

Table 15: Maximum Queue Length Prediction Error (Feet) in Hcm 2000 Hybrid Model With Intensity as Assigned By Site, and PCE as Indicated in Column

SC Work Zone	PCE=2.0 (Baseline)	PCE=2.2	PCE=2.4
1	-580	-1300	-2080
2	0	0	0
3	3200	3200	3200
4	2020	1180	280
5	0	0	0
6	0	0	0
7	-947	-1134	-1414
8	0	0	0
9	0	0	0
10	3099	2859	2659
11	0	0	0
12	0	0	0
13	-2408	-3209	-4049
14	-1365	-1775	-2215
15	NA	NA	NA
16	-176	-976	-1777
17	-960	-2040	-3180
18	-1700	-2900	-4040
19	-1160	-1700	-2620
20	740	200	-400
21	-1540	-2320	-3500
22	130	-30	-150
23	5000	5000	5000
24	659	-302	-1222
25	938	418	-102
26	1871	751	-290
27	0	0	0
28	5000	4867	4373
29	4000	4000	4000
30	4167	4167	3954
31	NA	NA	NA
32	-2283	-2843	-3364
33	1560	1200	840
34	3560	3360	3160
35	NA	NA	NA
Total Error	22825	10673	-2937
Average (n=32)	713.3	333.5	-91.8
Std. Dev.(n=32)	2073	2259	2495
Average (n=20)	1353	856	334
Std. Dev.(n=20)	2383	2674	2952
Eliminating sites 28,29,30			
Average (n=29)	333	-81	-526
Std. Dev.(n 29)	1771	1932	2191
Average (n=17)	817	241	-332
Std. Dev.(n=17)	2162	2404	2683
Eliminating sites 23,28,29, 30			
Average (n=28)	166	-263	-724
Std. Dev.(n 28)	1555	1697	1952
Average (n=16)	555	-57	-666
Std. Dev.(n=16)	1936	2136	2380

Figure 4: HCM 2000 Hybrid Model with Intensity Assigned by Site and PCE as Indicated: 32 Total SC Sites, 20 with Queues

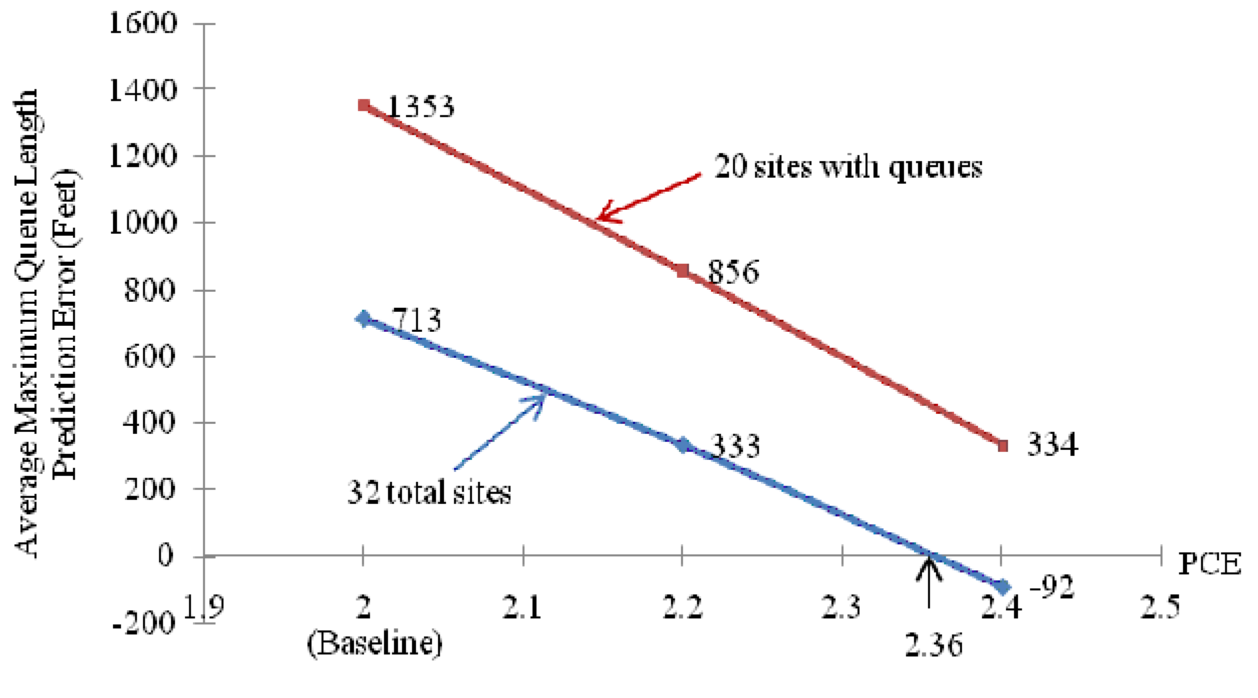


Figure 5: HCM 2000 Hybrid Model with Intensity Assigned by Site and PCE as Indicated: 29 Total SC Sites, 17 with Queues (Sites 28, 29, 30 Eliminated)

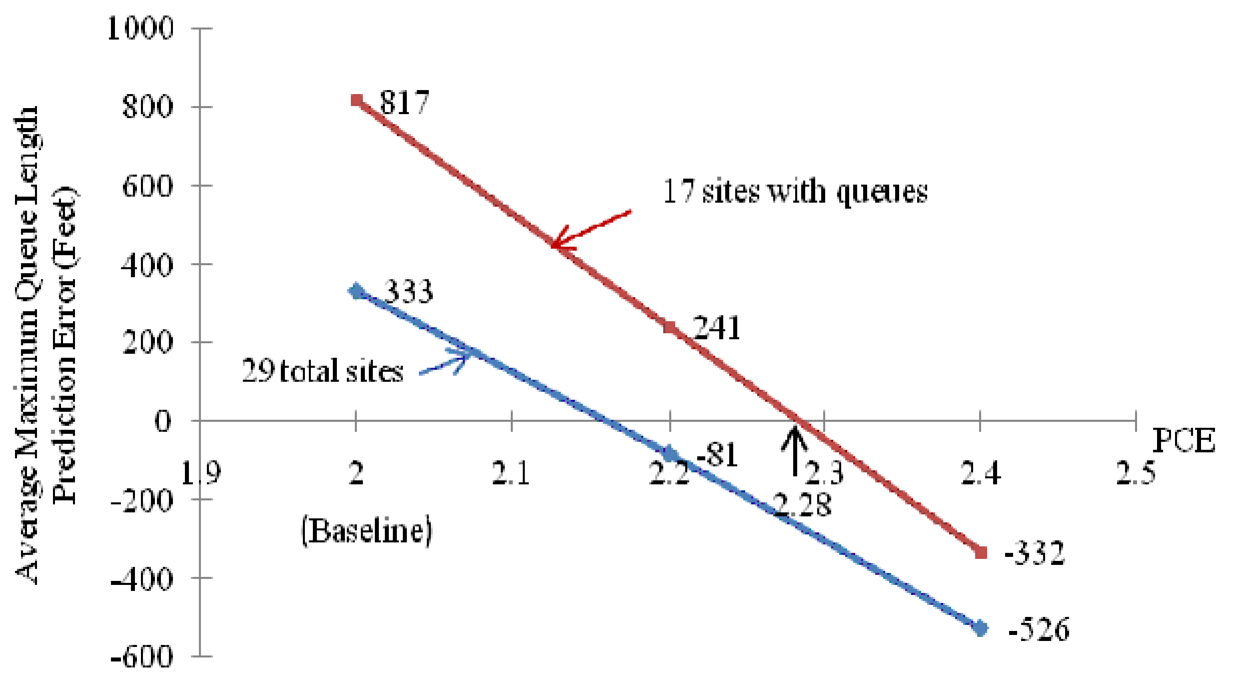


Figure 6: HCM 2000 Hybrid Model with Intensity Assigned by Site and PCE as Indicated: 28 Total SC Sites, 16 with Queues (Sites 23, 28, 29, 30 Eliminated)

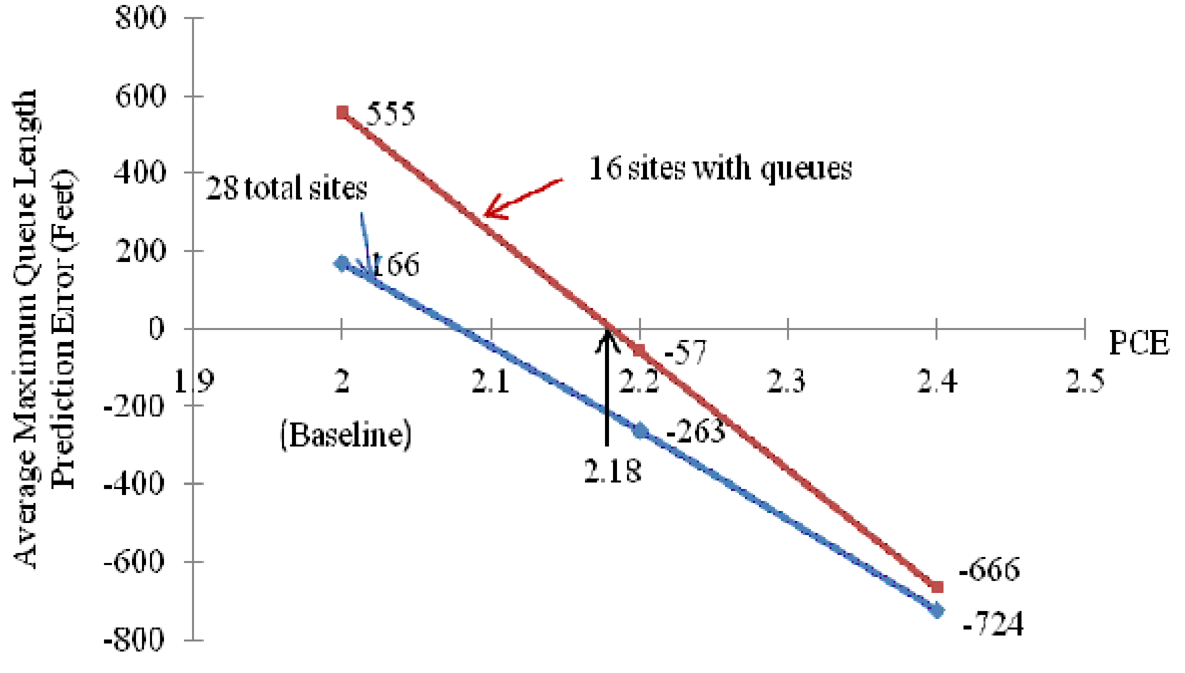


Figure 7: CI Plots on Mean Queue Length Prediction Error with Sites 23, 28, 29, 30 Deleted

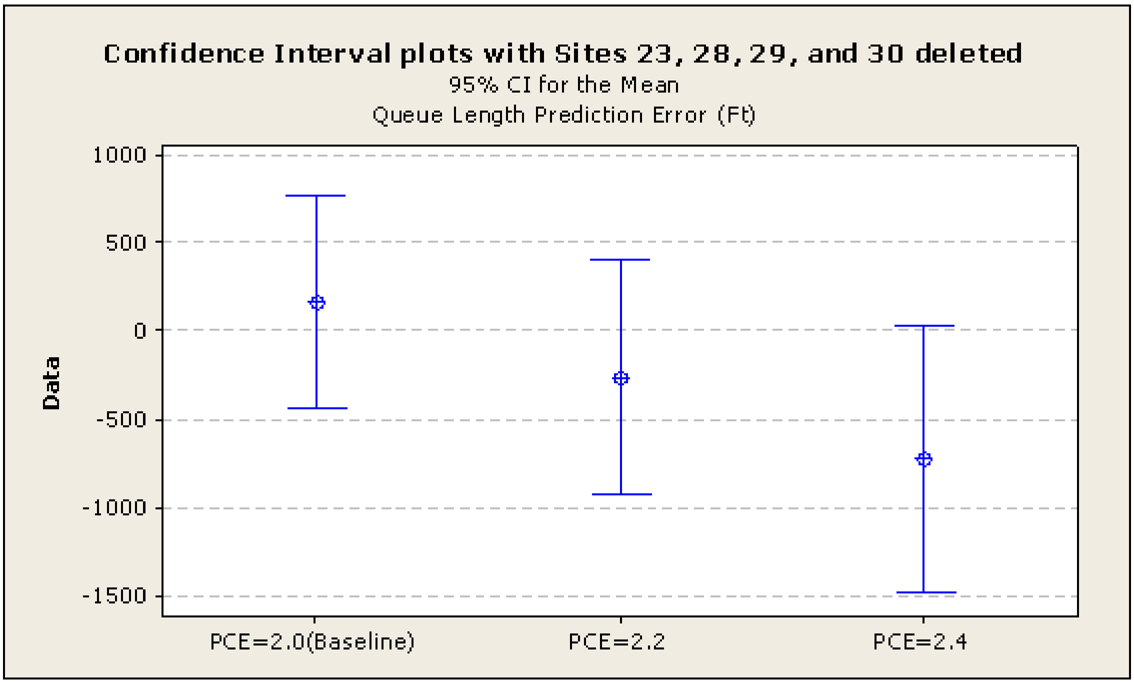
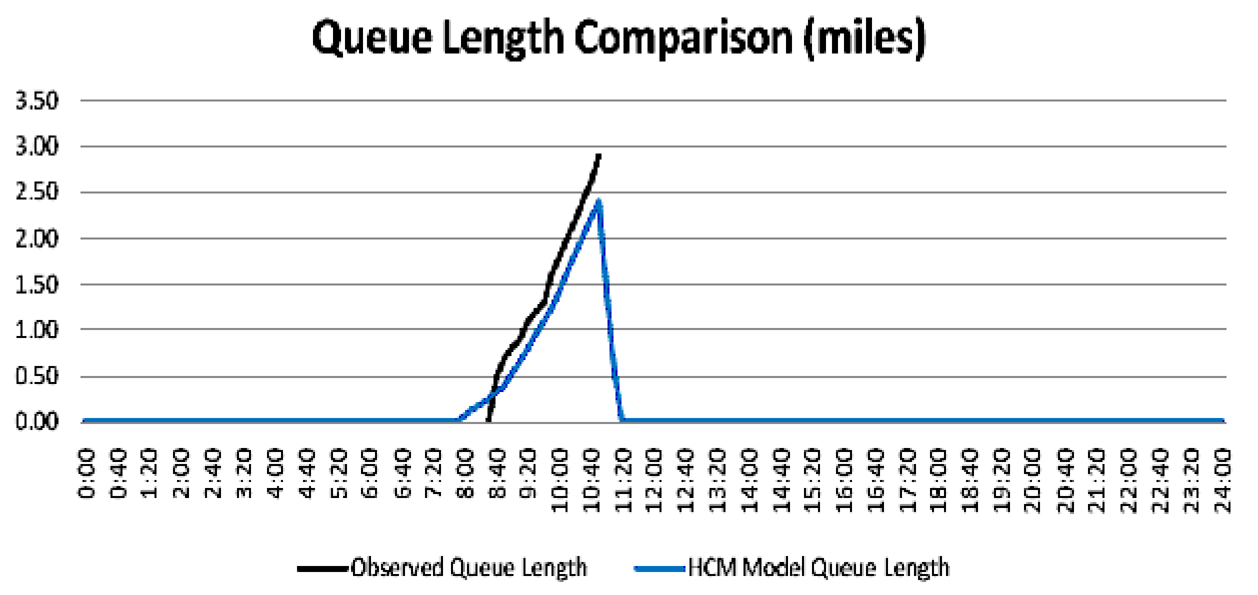


Table 16: Validation Queue Length Analysis

Work Zone	Queue Start Time (QST)	Max. Queue Length (MQL)	Model Run	HCM 2000 Hybrid Prediction			
				QST	Diff.	MQL	Diff.
AL 1	none	0	Baseline	18:00	miss	3335	-3335
			Comment	Predicts 0.63 mi queuewhen none forms			
AL 2	none	0	Baseline	none	–	0	0
			Comment	Accurately predicts no queue forms			
AL 3	15:20	400'	Baseline	none	miss	0	400
			Comment	Predicts no queue (just barely) when 400' queue forms			
NC 1	9:40	1.55 mi	Baseline	9:00	:40	12700	-4501
			Comment	Over-predicts max,but pattern is correct			
NC 2	8:30	1.4 mi	Baseline	8:00	:30	14880	-7488
			Comment	Over-predicts max,but pattern is correct			
NC 3	8:35	2.9 mi	Baseline	8:00	:30	12660	2652
			Comment	Under-predicts max,but pattern is correct			

Figure 8: HCM 2000 Hybrid Closely Predicts Queue Growth at NC WZ #3



28, 29, and 30. The problem at these four work zones is that all three models failed to predict queue formation, whereas the work site data showed a queue forming; furthermore, these four had the largest prediction errors (1291-1524 m = 4000-5000 ft) of the 32 work zones. The appropriate term for such data that appears different in character from the vast majority, is "outlier."

While it appears from Table 15 that PCE = 2.4 might be best from an average error viewpoint (actually, Figure 4 points to 2.36 as best), the elimination of sites 28, 29, and 30 as outliers points to PCE = 2.2 (actually 2.16 according to Figure 5) as best. Finally, when site 23 is eliminated as well, PCE = 2.0 produces the smallest average error considering the remaining 16 sites with queues (see Figure 6). A plot showing 95% confidence interval on the mean prediction error with four outliers eliminated (Figure 7) shows PCE = 2.1 matches up well with zero average prediction error for the 28 runs, with reasonable uncertainty in the average error for an infinite number of cases of character similar to these runs.

Testing Conclusion

Based on the analysis and evaluation above, we conclude that the optimal alternative is the HCM 2000 hybrid version because it minimized error in predicting actual MQL at the 32 SC work zones, and minimized the error of not predicting a queue, when one actually formed. Additional testing revealed a PCE = 2.1 minimized error in MQL among typical PCE values in the range [2.0, 2.5].

Optimal Alternative Validation

To validate the optimal alternative, we used data reported from the six work zones from Alabama and North Carolina (Table 7) as our validation datasets. We ran HCM 2000 hybrid with PCE =2.1 using the description data for each of these six work zones. The results of these runs are shown in Table 16. For the three Alabama work zones, HCM 2000 hybrid with PCE = 2.1 accurately predicted no queue would form at AL 2, missed a very short queue that formed at AL 3, and predicted a 0.63 mile (1 km) queue that would form at AL 1, when no queue was observed. This conservative behavior at AL 1 and essentially accurate prediction at AL 2 and AL 3 are what should be expected. All three of North Carolina work zone predictions resulted in queue patterns (start, build up, and decline to end) that matched the actual data, but over-predicted queue length in the first two cases and slightly under-predicted queue length in NC 3, as shown in Figure 8. This final figure also illustrates the queue profile graphic inserted in the modified spreadsheets we created and tested in this research.

CONCLUSION

The goal of our research was to optimize the accuracy of an existing queue prediction spreadsheet tool, the OkDOT Lane Rental Model. Directed by this goal, we analyzed the underlying logic and principal variables of the OkDOT tool, and corrected minor errors to form a baseline. We also examined many of the work zone queue prediction tools available in the US. We identified the optimization opportunity to be the insertion of work zone capacity equations reflective of actual site conditions, to replace HCM 1994 capacity tables. Two software alternatives were created, the HCM 2000 version and the HCM 2000 hybrid version, using different work intensity penalties. Then we tested the three alternatives using a diverse collection of work zone datasets, and chose the HCM 2000 hybrid as the optimal alternative. Finally, we validated the HCM 2000 hybrid and assured that its performance was a great improvement over the baseline. A graphical queue profile was added to enhance the tabular output of the tool.

The strength of our research is that it was conducted in a systematic way, following a well-designed methodology. The adjustments we made to the OkDOT tool used the widely accepted HCM 2000 capacity estimation equation and replaced the nebulous user input "confidence level" factor with specific adjustment factors for work zone intensity, proximity to ramps, and percent heavy vehicles in the traffic flow. The limitation of the research is that although the conclusion is based on testing a large and diverse mix of datasets, it is still perilous to reach a generalization for all conditions; for instance, our recommended model did not perform well when tested on urban interstates. This limitation also provides a future research idea—a more comprehensive tool could be created by studying more cases obtained from a vast variety of conditions, and specializing the model to those situations. The main contribution of the research reported here is the empirical optimization methodology used, which we believe can be adapted to other traffic prediction improvement studies.

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