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Microsimulation of Freeway Work Zones to Assess Flow and Capacity

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Abstract

This research applied microscopic traffic simulation to freeway work zones to further understand the relationship between traffic variables and capacity. There are two distinct forms of capacity depending upon the flow regime: capacity while traffic is free flowing and capacity while traffic is queued. Actual work zones from the Milwaukee freeway systems were varied by simulation to obtain relationships between capacity and truck volume, lane distribution, ramp location, ramp volumes, grade and merging schemes. Capacity was found to be a random variable, even when all prevailing conditions are held constant, because of stochastic variations in vehicle mix, lane distribution and driver behavior. Capacity was found to be significantly affected by prevailing conditions of grade, vehicle mix, and the lane distribution of trucks.

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Final Report

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INTRODUCTION

The capacity of a work zone is an important input to a traffic engineer's design, as it has a strong effect on the work zone's throughput and the potential for formation of queues. Previous studies, such as the Highway Capacity Manual (HCM) (Transportation Research Board, 2000) suggest that work zone capacity is influenced by factors such as the intensity of work zone activity, environmental conditions, vehicle mix, geometric conditions and whether a lane closure is long-term or short term. Work zone capacity is an important variable for computer models that estimate work zone traffic impacts.

The HCM defines freeway capacity as "the maximum sustained 15-min flow rate, expressed in passenger cars per hour per lane, that can be accommodated by a uniform freeway segment under prevailing traffic and roadway conditions in one direction of flow." This definition has not always been followed in studies of work zone capacity because it does not differentiate between conditions with and without a queue. For work zones there are two relevant flow regimes for the measurement of "capacity":

Regime 1. Relatively free flow conditions, perhaps with reduced speeds; and
Regime 2. Queued conditions, exhibiting stop and go speeds.

The values of "capacity" differ substantially between these two regimes. Regime 1 is particularly relevant to traffic mitigation efforts to avoid queue formation, and regime 2 is particularly relevant for the management of queues, for estimating the length of queues or for understanding the amount of delay when upstream flow rates are consistently above the capacity of the work zone. The Highway Capacity Manual (TRB, 2000) in its discussion of work zones favors the regime 1 definition, which might involve intermittent queuing due to uneven flow rates.

A given work zone under a specific set of flows has a single chokepoint that controls the work zone's capacity. It is not always easy to find that chokepoint, especially when there are multiple lane closures or ramps within the work zone or just downstream. Conditions downstream of the chokepoint will have comparatively little impact on capacity. Conversely, upstream conditions can significantly affect the capacity because of traffic distribution across lanes and turbulence caused by merging and weaving.

Capacity can be ascertained for specific work zones, after the fact, by analysis of detector data. Forecasting the capacity of a work zone requires some form of a model, ranging from a one-line equation from the Highway Capacity Manual to an elaborate microscopic traffic simulation. Although building a microscopic traffic simulation of a work zone is not technically difficult with packaged software, an effort must still be made to calibrate the model to local data because national default parameters are not available. Furthermore, many traffic engineers do not have ready access to a traffic simulation software package.

Some attributes of work zones are known to affect driver's speeds. These same attributes may also affect capacity, but speed and capacity of freeways are known to be only weakly related (see the Highway Capacity Manual, Chapter 23 for details). Capacity is a function of free flow speed on freeways and varies only between 2250 pcphpl (passengers cars per hour per lane) on 55 mph facilities to 2400 pcphpl on 70 mph facilities, under ideal conditions. Thus, it is important to clearly differentiate between those attributes that primarily affect speed and those attributes that primarily affect capacity.

This report calibrates a microscopic traffic simulation package, CORSIM, on two work zones. Then, the configurations of the work zones, as represented in the software, are changed to provide recommendations as to how capacity might vary under different scenarios. In addition, recommendations are made as to how to perform a microscopic traffic simulation to assess the capacity of work zones.

BACKGROUND ON CORSIM

CORSIM is a well-respected microscopic traffic simulation model that was developed by the Federal Highway Administration. CORSIM was selected for this study primarily because of the availability of its source code. The source code was deemed necessary because of the unusual nature of this application. While this project did not actually modify the source code, it was invaluable to understanding the precise effect of parameter changes on the simulated driver behavior. CORSIM is actually a combination of two distinctly different traffic models: FRESIM for freeways and NETSIM for surface arterials. Only FRESIM was used in this study.

CORSIM has been previously used by many traffic engineers to model work zones. However, the few attempts to validate the results have met with only mixed success. For example, Schnell and Aktan evaluated CORSIM on three separate work zones. CORSIM with default parameters was able to closely match delays in two work zones, but was unable to be calibrated correctly for a third work zone, where it "significantly underestimates the associated work zone delays". CORSIM's parameters could not be adjusted successfully in this one case.

CORSIM tracks individual vehicles in the traffic stream as they interact with each other, road geometry and traffic control devices. CORSIM assigns random behaviors to drivers of vehicles, which are also randomly generated at entry points at a desired mean flow rate. The critical relationship in CORSIM for correctly simulating work zones is the Pitt car-following model (FHWA, 2001).

$$H = L + P_j v_t + P_{11} + bP_j \left(u_t - v_t\right)^2 \qquad (1)$$

where

H = spacing between vehicles (feet);
L = length of leading vehicle (feet);

P_j = driver sensitivity factor for follower of behavior j (seconds), j = 1…10;
P_{11} = car-following constant (feet);
v_t = speed of following vehicle at time t (feet/second);
u_t = speed of leading vehicle at time t (feet/second); and
b = 0.1 when $u_t < v_t$ and 0 otherwise.

The minimum spacing between vehicles is seen to be $L + P_{11}$, regardless of driver characteristics. While P_{11} can have an effect on the capacity when vehicles are moving slowly, it would have comparatively little effect on capacity under free flow conditions. The main way to affect capacity under most traffic conditions is the set of driver sensitivity factors, of which there are ten in CORSIM, P_1 to P_{10}. The default values of the driver sensitivity factors for CORSIM range from 0.35 to 1.25 seconds, as listed in Appendix A. Sensitivity factors are randomly assigned to drivers. It can be seen in Equation 1 that increases in the driver sensitivity factors would tend to increase spacing at a given speed and thereby reduce capacity.

In addition, CORSIM allows for the possibility of an incident in the traffic stream. Incidents can be full lane blockages or just distractions for drivers. For distractions, which are particularly relevant to simulations of work zones as they can occur outside the travel lanes, CORSIM allows the user to set a “rubberneck” factor, which has the effect of increasing spacing between vehicles. CORSIM simply divides the Pitt driver sensitivity factors by one minus the rubberneck factor. That is, P_j in Equation 1 is found by:

$$P_j = P_j^* \big/ 1 - \eta \qquad (2)$$

where

P_j = Pitt driver sensitivity factor for driver type j, j = 1…10;
P_j^* = Original Pitt driver sensitivity factor for driver type j; and
η = rubberneck factor.

An incident can be placed anywhere on a link (road segment). Each lane can have its own factor. The rubberneck factor is also the simplest way to model lane-width reductions, work zone intensity, rough pavement and other non-visual effects occurring at a single chokepoint. There does not seem to be any consistency in past studies about how the rubberneck factor has been used to model work zones. Vadakpat and Dixon found that at rubberneck factor of 0.5 (with all other parameters unchanged from the default) worked well for their North Carolina work zone (2 lanes reduced to 1 lane). Elefteriadou, et al. (2007) suggested a rubberneck factor of 0.056 for a capacity reduction of 7% as suggested by Al-Kaisy and Hall (2003) from their studies of work zones. Experience with CORSIM indicates that the precise “incident” location, relative to ramps and lane closures, has a significant effect on work zone capacity and delay.

Further, CORSIM has a set of parameters related to lane changing that could affect simulated work zone capacity. The lane change gap acceptance parameter is set globally for a network and has a default value of 3 seconds. Another parameter is the fraction of “drivers yielding the right-of-way to lane-changing vehicles attempting to merge ahead”, which has a default value of 0.20. These parameters would likely vary by locale and would depend upon driver aggressiveness and courtesy. Adjustments to these parameters can help eliminate unrealistically long queues in the closed lane when vehicles, particularly trucks, do not have adequate gaps for lane changing. Overly long queues of trucks in the closed lane can have an undesirable positive effect on capacity within the model because these longer, low-accelerating vehicles are being filtered out of the downstream traffic. CORSIM does not provide as output the vehicle mix on any link, so any such filtering that disturbs the vehicle mix must be avoided.

Many states, such as Wisconsin, ask drivers to merge early into the open lanes, joining the back of any queue that might have formed. Therefore, it is important within CORSIM to warn the simulated drivers of a lane closure well upstream of the rear end of any queue. Such a warning will also help eliminate long queues in the closed lane and promote realistic driver behavior near the back of the queue.

It should be noted that neither the set of driver sensitivity factors nor the rubberneck factor has a direct effect on speed. Speeds can be reduced from free speed as simulated drivers decelerate to maintain their spacing, as given by Equation 1.

CORSIM can handle common freeway geometries, including on-ramp, off-ramps, auxiliary lanes and lane drops. However, the FRESIM part of CORSIM does not give the ability to vary lane widths.

Flow data are given to the FRESIM part of CORSIM in the form of an origin-destination table. The percentage of heavy vehicles is constant at any given origin.

While CORSIM can be used to investigate the length of a queue ahead of any work zone, it is necessary to give CORSIM very precise upstream flow rates. CORSIM does not have the ability to forecast the amount of traffic actually using the work zone or diverting from the work zone.

CASE STUDIES

Finding suitable cases from historical work zones is difficult because critical data are often missing from technical reports. Reports fail to mention such items as the exact locations of ramps relative to the work zone taper, length of taper, exact lane width, lateral clearances to barriers or barrels, upstream lane distribution of traffic, curvature, pavement condition and traffic flow rates upstream of the taper.

For the current study CORSIM parameters were preliminarily adopted from a carefully calibrated model for an evening peak hour in Houston, TX (Schultz and Rilett, 2004). Driver sensitivity factors ranged from 0.30 to 1.46 seconds. These parameters, being for the most part larger than the CORSIM's defaults, will cause capacities to be somewhat lower than would be achieved with the default parameters.

True capacity is determined in software for any work zone by increasing upstream volumes until downstream flows have achieved their maximum values. Capacity itself is a random variable, because of natural unevenness of flows and randomness of drivers. Finding capacity is a trial and error process, involving multiple runs with different random number seeds, so an exact solution is not possible. So that it is possible to closely determine when "capacity" has been reached, the following criteria have been established.

- Regime 1. Flow downstream of the chokepoint reaches a maximum while speeds average approximately 35 mph at the chokepoint. Density is between 45 and 50 vehicles per lane-mile upstream of the chokepoint and approximately 45 vehicles per lane-mile within the work zone.

- Regime 2. Speeds are, on average, lower than 15 mph just upstream of the chokepoint, with queues greater than 10 vehicles per lane over substantial intervals of time. Density is greater than 80 vehicles per lane-mile upstream of the chokepoint and also approximately 45 vehicles per lane-mile within the work zone.

Simulations are allowed a long warm-up time of 10 minutes so that steady state conditions have been achieved. Capacity values are averaged over a 15 minute period of time, consistent with the HCM's definition.

Milwaukee Work Zone Field Characteristics

Data about two Milwaukee freeway work zones were obtained and analyzed by a team at Marquette University (Dehman, 2007). The data pertain to both regime 1 and regime 2 and to both weekday and weekend traffic. These data are summarized on Tables 1 to 4. A data point consists of average traffic conditions over a 15 minute interval of time. Data identified as regime 1 actually were obtained from a full hour of traffic prior to the start of queuing and after the queue dissipates. It is important to note that Work Zone 1 volumes were taken 150 feet *downstream* of the taper, while Work Zone 2 volumes were taken 800 feet *upstream* of the taper. Thus, Work Zone 2 capacity estimates are not as reliable as Work Zone 1 estimates.

Marquette's Work Zone 1 was northbound on US 45 just north of the Zoo Interchange with I-94 in the west-central portion of Milwaukee County (Figure 1). This work zone actually consisted of two tapers, but the taper from three lanes to two lanes controlled the capacity of the work zone. The left-most lane was closed with the right-most two lanes remaining open. The work zone had three upstream traffic sources from the interchange. Through vehicles (from I-894) contributed just about ½ of the work zone flow; left entering vehicles contributed about 1/3 of the work zone flow; and right entering vehicles (closest of the work zone) contributed about 1/6 of the work zone flow. There was an off-ramp between the two tapers.

Marquette's Work Zone 2 was northbound on I-894 just south of Work Zone 1 within the same Zoo Interchange, with traffic heading toward US 45 (Figure 2). The work zone removed the right-most of two lanes. There was only one pertinent upstream source of traffic. There was an interchange on-ramp downstream of the taper, but traffic from this on-ramp did not affect the capacity of the work zone.

Heavy vehicle percentages were reported by the Marquette study averaged 13% for week-day traffic at both sites, although comparisons with other vehicle classification data suggest that these percentages may be too high (see Appendix B) because of inaccuracies inherent in the detection technique, side-fire radar (Zwahlen, et al., 2005).

TABLE 1 Marquette Work Zone 1, Queued Conditions, Regime 2, Weekdays

	N	Minimum	Maximum	Mean	Std. Dev.
Occupancy % (upstream)	371	45.0	59.2	50.5	2.85
Volume vph (two lanes)	371	2528.0	4400.0	3792.5	262.41
Speed mph (upstream)	371	6.0	14.8	9.5	1.49

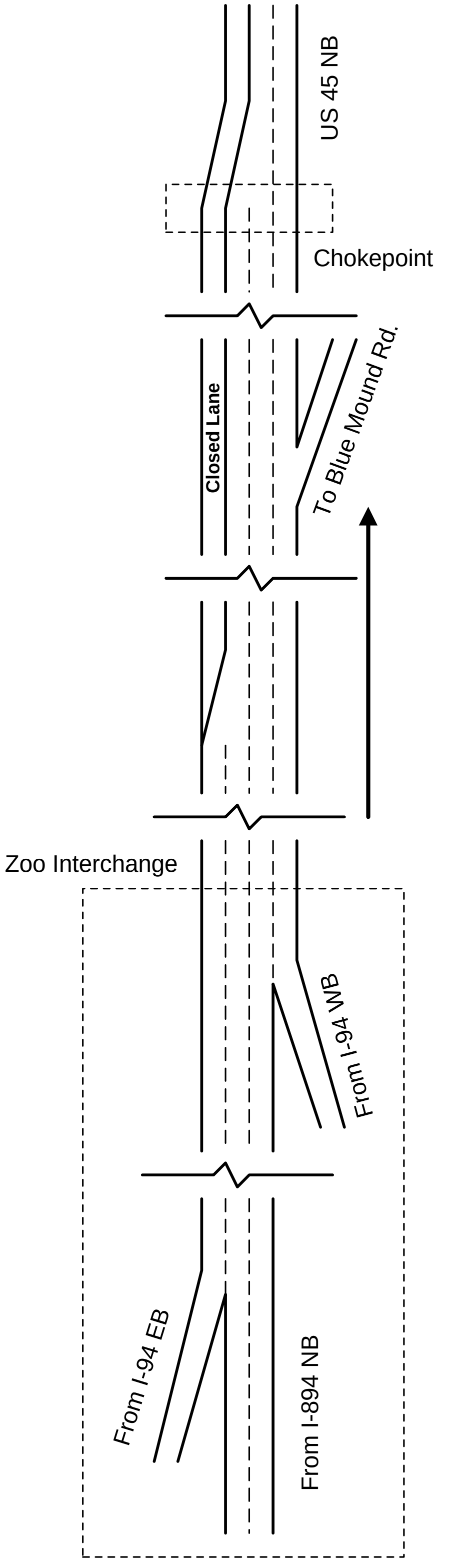

FIGURE 1 Marquette Work Zone 1

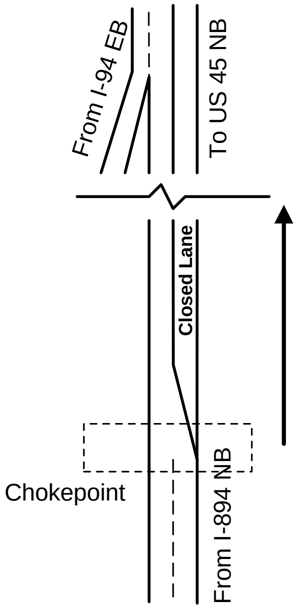

FIGURE 2 Marquette Work Zone 2

TABLE 2 Marquette Work Zone 1, Free Flow Conditions, Regime 1, Weekdays

	N	Minimum	Maximum	Mean	Std. Dev.
Occupancy % (upstream)	43	11.1	53.5	29.4	15.86
Volume vph (two lanes)	43	3420.0	4352.0	3949.9	216.28
Speed mph (upstream)	43	7.5	58.2	34.1	20.61

TABLE 3 Marquette Work Zone 1, Queued Conditions, Regime 2, Weekends

	N	Minimum	Maximum	Mean	Std. Dev.
Occupancy % (upstream)	25	20.8	43.1	33.0	6.31
Volume vph (two lanes)	25	3464.0	4356.0	3973.3	220.29
Speed mph (upstream)	25	10.1	37.1	19.6	7.99

TABLE 4 Marquette Work Zone 2, Queued Conditions, Regime 2, Weekdays

	N	Minimum	Maximum	Mean	Std. Dev.
Occupancy % (upstream)	18	45.4	56.8	47.8	2.66
Volume vph (one lane)	18	1244.0	1908.0	1562.2	142.13
Speed mph (upstream)	18	7.9	10.4	8.9	0.61

It is interesting that there is a very large range of values for all of these traffic variables. Of particular importance is the variation in volume, because capacity is most typically defined as the maximum volume under prevailing conditions. Therefore, these data do not suggest a single value for capacity. There are at least three possible explanations for the variation:

- Prevailing conditions, as defined in the Highway Capacity Manual, may have changed substantially during data collection;
- Upstream flow rates may have dipped below capacity conditions during some intervals; or
- Stochastic variations in traffic (vehicle mix, driver behavior, short-term flow rate variations, etc.) may have caused large variations in capacity.

The last explanation is particularly intriguing because it implies that there may not be a single value for freeway work zone capacity under a given set of conventional HCM prevailing conditions. Rather, the capacity can vary substantially because of random properties of the traffic stream. This concept has been explored by Brilon, Geistefeldt, and Zurlinden (2007) for general freeway capacity.

The regime 2 data were taken when queues were unambiguously present, so the mean value of volume is the most likely estimate of the capacity, given the usual statistical assumptions. However, the regime 1 data on Table 2 includes intervals of time when volumes were below capacity conditions. Given the regime 2 data points (43) relative to the number of days and direct observations of the variation in volumes (before and after queuing occurred), capacity is taken for the purposes of the CORSIM calibration to be at the 75th percentile of measured flow rates. Recent research indicates that field-determined capacities behave according to the Weibull probability distribution (Brilon, Geistefeldt, and Zurlinden, 2007):

$$F(q) = 1 - e^{-\left(\frac{q}{\beta}\right)^{\alpha}}$$

which has a mean, E(q) of:

$$E(q) = \beta * \Gamma\left(1 + \frac{1}{\alpha}\right)$$

and a variance σ^2 of:

$$\sigma^2(q) = \beta^2 \left\{ \Gamma\left(1 + \frac{2}{\alpha}\right) - \left[\Gamma\left(1 + \frac{1}{\alpha}\right)\right]^2 \right\}$$

In these equations q is the measured volume and α and β are distribution function parameters. The distribution function parameters can be estimated by using the method of moments. This estimation results in a 75th percentile capacity value of 4104 vehicles per hour per two open lanes ($\alpha = 22.72$; $\beta = 4045.2$).

Weekday and weekend capacity in passenger car equivalents (PCE), using HCM adjustments, under queued (regime 1) conditions are approximately the same, according to the Marquette study.

Upstream lane distribution was not reported in the Marquette data, so it is not possible to determine if drivers were trying to merge early (prior to the end of the queue) or merge late when queues were present. For most tests, no attempt was made to force either an “early merge” or “late merge” behavior on simulated drivers. The sensitivity of capacity to an “early merge” strategy is dealt with as a separate test in this report.

SIMULATION DESIGN AND RESULTS

Not every aspect of work zone geometric design or traffic control can be reliably simulated. The experimental design addresses those aspects that have a large impact on capacity and fall within the theoretical capabilities of a microscopic traffic simulation package. The experimental design reflects the need to consider stochastic variations in traffic.

Step 1. Develop base case simulations of work zones. The first step is to develop a CORSIM network and calibrate CORSIM parameters so as to achieve results consistent with field data under both regime 1 and regime 2. Multiple runs are required to account for statistical variation in traffic conditions. Capacity is determined under regime 2 by creating a sufficiently large upstream volume to just cause the formation of a queue that lasts for a full 15 minutes. Capacity is determined under regime 1 by creating a sufficiently large upstream volume so that maximum flow is obtained but queuing is at most intermittent, i.e., less than 3 minutes of a 15 minute time interval. Simulations are repeated many times to obtain stable results.

Step 2. Vary the prevailing conditions and determine the capacity. Similar to step 1, capacity is determined for each regime by varying the upstream volume until queue formation starts or until queues are present for an extended period of time. Prevailing conditions are:

- Percentage of heavy vehicles
- Grade
- Ramp location relative to closed lanes (left or right)
- Ramp distance upstream of the taper
- Upstream lane distribution, particularly trucks
- Upstream ramp volume
- Number of closed lanes
- Merging scheme

Aspects of work zone geometric design or traffic control that cannot be reliably simulated with CORSIM include lane width, length of taper, location of warning signs, curvature, and distance to lateral obstructions. Multiple simulation runs are required for each condition to wash-out statistical variations and to obtain stable results.

To the extent possible sensitivity tests should be performed on actual work zones configurations; however, some tests require substantial geometric changes, which cannot be readily performed on the work zones from the Marquette study without modification.

Step 3. Summarize the results, keeping in mind random events within the traffic stream. There is less statistical variance across simulations than for field data, but small differences between simulations may not be statistically significant. Only significant effects should be summarized.

Calibration of CORSIM

Networks were built using standard CORSIM procedures. A short link was introduced just downstream from each taper, so that downstream flow rates could be readily observed.

Calibration consisted of both parameter and network changes. New parameters were established on the regime 1 network and then validated against the regime 2 networks. In order to simplify the process, calibration focused mainly on the Pitt model parameters. Matching the capacity for regime 1 required reductions from the values obtained from Houston. The final Pitt parameters are shown in Appendix A.

Two other parameter changes were made to correct obvious issues in trial simulations. First, visual observations of trial traffic simulations revealed some unrealistic difficulties by drivers making lane changes just upstream of the taper. Better realism was obtained by slightly increasing the “percent of drivers yielding the right of way” parameter. Second, because of the large volume of upstream traffic needed to reach capacity at Marquette Work Zone 1, the “minimum separation for generation of vehicles” (minimum headway between vehicles at entry points) was reduced from CORSIM’s defaults.

The calibration process for regime 1 involved simultaneously increasing upstream volumes at all entry points to the network while decreasing the Pitt model parameters. This trial-and-error process stopped when the target values of downstream flow and upstream density were obtained for a single run. One hundred runs were then made with different random number seeds to confirm the stability of the results. The average capacity value over these 100 runs was 4108 vehicles per hour with a standard deviation of 61 vehicles per hour and a standard error of the mean of 6.1 vehicles per hour. The simulated capacity disagreed with field measurements by only 0.1%. Average simulated density for the link just upstream of the taper was 47 vehicles per lane-mile, somewhat higher the break point between LOS E and LOS F, 45 passenger cars per lane-mile, in the 2000 Highway Capacity Manual.

Validating the parameters on regime 2 involved increasing the upstream volumes in a single simulation until queues formed at the taper early in the simulation. One hundred separate runs were then made with different random number seeds. The average simulated downstream flow rate was 3896 vehicles per hour or about 3% larger than the field-measured regime 2 average flow rate in Marquette Work Zone 1. The simulated standard deviation of the volumes for regime 2 runs was 64 vph or 2.6%. Average simulated density for the link just upstream of the taper was 102 vehicles per lane-mile, indicating the consistent presence of queues.

Because the capacities for Marquette Work Zone 2 were measured substantially upstream of the taper and may have been affected by varying queue lengths, a precise comparison is not possible. When using the modified CORSIM parameters, the estimated downstream flow rate averaged 1960 vehicles per hour across 100 simulations with a standard deviation of 118 vph. This volume is well above the values summarized in Table 4.

Other work zone capacity estimates were recently developed by Lee and Noyce (2007) for roughly the same Wisconsin driver population as the Marquette study. These particular work zones were not described well enough by the authors for simulation purposes, and the capacities were also established by measuring volumes upstream of the taper.[1] However, the authors stated that detectors were further downstream than the back of the queue during their measurements. Capacity values were given for regime 2, queued conditions. Table 5 contains data for those work zones with one open lane. Considering the higher heavy vehicle percentages, which were obtained through a manual classification count, the average values from this table would also fall near the lower range of field data from Marquette Work Zone 2.

TABLE 5 Capacity Values for Milwaukee Area Work Zones, One Open Lane, Regime 2

	Lee-Noyce Work Zone 1	Lee-Noyce Work Zone 2
# of Open Lanes	1	1
WZ Capacity-Max (vph)	1223	1579
WZ Capacity-Min (vph)	985	1060
WZ Capacity-Mean (vph)	1134	1279
Heavy Vehicle Percentage	16%	15%

These comparisons suggest that CORSIM, as calibrated, is sufficiently realistic for work zones with two open lanes, but cannot handle work zones with just one open lane without further parameter changes. Trials with CORSIM indicate that a 20% rubbernecking factor is necessary to achieve the average capacity that is slightly less (1492 vehicles per hour) than the average for Marquette's Work Zone 2.

The calibration exercise also revealed that there is less dispersion in the data from CORSIM than from field measurements. The greater dispersion in field data implies that there

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[1] The lead author, Changyoung Lee, was asked through personal correspondence for additional information that would further describe the work zones. The lead author stated that the requested information was not retained by his research team.

are sizeable variations in prevailing conditions, such as the percentage of heavy vehicles, across measurements going beyond random variations in traffic flow and driver behavior.

It is also important to note that the standard error of the mean capacity across the calibration runs ranges from 6 to 12 vehicles per hour. Thus, changes in volumes from sensitivity tests of less than about 15 vehicles per hour should be considered to be insignificant. Thus, it is important to design the sensitivity tests to achieve substantial (i.e., much greater than 15 vehicles per hour) deviations from base case volumes, if possible.

Sensitivity Tests

Heavy Vehicle Percentage

The sensitivity of capacity to heavy vehicle percentage was obtained in three cases, corresponding to the Marquette weekday measurements. In addition, it is possible to express this sensitivity in terms of passenger car equivalents, as defined in the 2000 Highway Capacity Manual. Each case involved three batches of 100 simulations, as outlined in Step 2 of the procedure, varying the heavy vehicle percentage both up and down by approximately 2% from base conditions. It is important to note that the sensitivity and the passenger car equivalent factors is dependent upon the vehicle mix, which was customized to the Milwaukee work zones (see Appendices A and B). This vehicle mix differs from CORSIM's default values and from the HPMS vehicle mix percentages as reported in the 1996 edition of the Quick Response Freight Manual (Cambridge Systematics, et al., 1996) for urban freeways. Terrain was assumed to be level. Marquette's work zones had about 8% heavy trucks.

TABLE 6 Sensitivity of Capacity to Changes in Heavy Vehicle Percentages

	Reduction in Capacity from a 1% Increase in Heavy Vehicles*	Passenger Car Equivalent Factor at 0% Grade
Work Zone 1, Regime 1	1.04%	2.04
Work Zone 1, Regime 2	0.86%	1.86
Work Zone 2, Regime 2	0.64%	1.64

*For example, a change in heavy vehicles from 8% to 9% is a 1% increase.

Overall, the values in Table 6 are reasonable. Table 6 suggests that heavy vehicles have a slightly lesser impact on capacity during regime 2 (queued conditions), even though trucks often come to a full stop near the taper. There was no indication that PCE factors varied according to the percentage of heavy trucks in the traffic stream.

The major difference between the field-measured regime 2 capacities between weekdays and weekends was attributed by the Marquette study to the number of heavy vehicles. If one were to boldly assume that the only difference between the two average capacities is the heavy vehicle percentage and that the vehicle mix is identical and that the heavy vehicles percentages were overestimated by the same factor, the calculated PCE factor is 2.17. This value is somewhat higher than the 1.86 value obtained through simulation and somewhat smaller than the 2.4 value that the Marquette study determined by referencing the 2000 Highway Capacity Manual and assuming rolling terrain. As an additional point of reference, the PCE factor for heavy vehicles under a level terrain condition in the 2000 Highway Capacity Manual is 1.5. The standard error of the simulated PCE factor estimates is approximately 0.1.

Grade

The 2000 Highway Capacity Manual states that large grades on freeways affect the PCE factors for heavy trucks, thereby causing a reduction in the number of vehicles that can be accommodated at any level of service. Simulations of Marquette's work zones indeed revealed a compounding effect between grade and heavy vehicle percentage on capacity. Table 7 shows the capacity simulated reduction for each 1% of grade (averaged across 6%, 8% and 10% heavy vehicles) and the passenger car equivalent factor at a 4% grade. Each set of prevailing conditions was simulated 100 times.

TABLE 7 Sensitivity of Capacity to Changes in Grade

	Capacity Reduction Per 1% Increase in Grade*	**Passenger Car Equivalent Factor at 4% Grade**
Work Zone 1, Regime 1	2.56%	2.55
Work Zone 1, Regime 2	1.99%	2.52
Work Zone 2, Regime 2	0.26%	1.81

*For example, a change in grade from 2% to 3% is a 1% increase.

As expected, passenger car equivalent factors are greater at 4% grade than at 0% grade. Grade had comparatively little effect on simulations of Marquette's Work Zone 2. The difference in PCE factors between regime 1 and regime 2 is negligible. At 4% grade, the simulations suggest (not shown in Table 7) that the PCE factors are slightly larger when there are more trucks in the traffic stream, regardless of the regime.

Upstream Interchange Ramps

The interchange-ramp nearest upstream from Marquette's Work Zone 1 enters on the right to a full auxiliary lane. This interchange ramp supplies 1/6ths of the upstream flow to the work zone and is located approximately 2000 feet from the downstream end of the taper to two lanes. Moving the ramp to the left (on the same side as the closed lanes), moving the ramp downstream or eliminating the ramp entirely have negligible effects on regime 1 capacity, as seen in Table 8. Keeping the ramp on the right but moving it closer had a small positive effect on capacity, perhaps because it promoted a more favorable lane distribution just ahead of the taper. Each average capacity was computed from 100 CORSIM runs and upstream flows were individually adjusted to achieve peak flow rates.

TABLE 8 Sensitivity of Capacity to Upstream Interchange Ramp, Regime 1, Marquette Work Zone 1

Work Zone and Condition	**Capacity**
Base Case with Right Interchange Ramp (2000 ft Upstream)	4108
No Right Interchange Ramp	4124
Left Interchange Ramp (2000 ft Upstream)	4125
Left Interchange Ramp (870 ft Upstream)	4127
Right Interchange Ramp (870 ft Upstream)	4231

Logically, one would not expect the location of an upstream interchange ramp to significantly affect capacity under regime 2 conditions. Table 9 lists the results of ramp conditions similar to those reported in Table 8 for regime 1. Again, the variations in capacities in this table are not easily explained and are inconsistent with the capacity variations on Table 8.

TABLE 9 Sensitivity of Capacity to Upstream Interchange Ramp, Regime 2, Marquette Work Zone 1

Work Zone and Condition	Capacity
Base Case with Right Interchange Ramp (2000 ft Upstream)	3896
No Right Interchange Ramp	3977
Left Interchange Ramp (2000 ft Upstream)	3971
Left Interchange Ramp (870 ft Upstream)	3885
Right Interchange Ramp (870 ft Upstream)	3839

Upstream Lane Distribution of Trucks

One could hypothesize that restricting trucks entirely to the right lane may have a favorable effect on capacity under regime 2, because most automobiles can avoid following a slowly accelerating truck. Under the base simulations, CORSIM realistically allows a few trucks that entered on the left to remain in a left lane through the taper. Tables 10 and 11 show the effects of truck lane-distribution on capacity under regimes 1 and 2, respectively. In each table, a new base case was created that had approximately an even distribution of upstream traffic, entering from the left and originally on the mainline. This new base case, as the original base case, gave trucks a strong preference for the right-most lane on all links. For regime 1 (Table 10) the effect of this minor redistribution was minimal; however, for regime 2, the redistribution caused a 2% increase in capacity. Truck percentages, overall, were 8% in all cases.

TABLE 10 Effect of Lane Distribution of Trucks, Regime 1, Marquette Work Zone 1

Work Zone and Condition	Capacity
Original Base Case	4108
New Base Case, No Right On Ramp, Even Entry Distribution	4101
No Right On Ramp, Trucks Have No Lane Preference	4028
No Right On Ramp, Trucks Restricted to the Right	4135
No Right On Ramp, Trucks Restricted to the Left	4023

TABLE 11 Effect of Lane Distribution of Trucks, Regime 2, Marquette Work Zone 1

Work Zone and Condition	Capacity
Original Base Case	3896
New Base Case, No Right On Ramp, Even Entry Distribution	3984
No Right On Ramp, Trucks Have No Lane Preference	3887
No Right On Ramp, Trucks Restricted to the Right	3997
No Right On Ramp, Trucks Restricted to the Left	3918

The effects on capacity of truck lane distribution are small, but interesting. It is important to recall that the work zone closed the left-most lane. It is seen that capacity is higher for both regimes, if trucks are kept together on the right and away from the closed lane. Keeping trucks together on the left, albeit an unrealistic situation, resulted in a lower capacity than normal traffic, as represented by the new base case. The fact that capacities under regime 2 were slightly higher when trucks were restricted to the left gives some credence to the hypothesis stated at the beginning of this subsection that higher capacities are achieved when trucks are kept together.

The symmetric situation to the last case in Tables 10 and 11 (that is, trucks restricted to the right with a right-lane closure) might be an interesting validation of some effects of truck lane distribution, but it could not be adequately tested with Marquette's Work Zone 1. The right lane is a continuation of an auxiliary lane from the right interchange ramp, so trucks originating upstream are already in the second lane from the right and CORSIM realistically does not insist that they move into the auxiliary lane or its continuation. Thus, there is almost no need for a truck to change lanes ahead of the taper for a right-lane closure for this work zone.

Right or Left Closed Lane, One Lane Open

It is possible that a left-lane closure might result in a different capacity for a work zone with a single open lane than the same work zone with a right-lane closure. However, tests with CORSIM under regime 2 for Marquette's Work Zone 2, revealed no significant difference between the computed capacities.

Volume from Upstream Interchange-Ramp

A large amount of traffic entering the freeway mainline, just ahead of the taper, might cause enough turbulence to reduce the capacity of the work zone. Tables 12 and 13 summarize the effects of varying the proportion of flow from an interchange-ramp. When interpreting the tables, it is important to recall that the total flow through the work zone is almost constant, as the upstream flow has been adjusted in each case to achieve capacity conditions. In order to exaggerate any effects of traffic from an on-ramp, the cases from Tables 8 and 9, representing on-ramps very close to the taper, were selected for comparison. The heavy vehicle percentage was 8% in all cases.

TABLE 12 Sensitivity of Capacity to Increased Proportion of Ramp Volume, Regime 1, Marquette Work Zone 1

Work Zone and Condition	Capacity
Left Interchange Ramp (870 ft Upstream), 1/6 of Traffic	4127
Right Interchange Ramp (870 ft Upstream)), 1/6 of Traffic	4231
Left Interchange Ramp (870 ft Upstream), 44% of Traffic	3973
Right Interchange Ramp (870 ft Upstream)), 44% of Traffic	4094

TABLE 13 Sensitivity of Capacity to Increased Proportion of Ramp Volume, Regime 2, Marquette Work Zone 1

Work Zone and Condition	Capacity
Left Interchange Ramp (870 ft Upstream)), 1/6 of Traffic	3885
Right Interchange Ramp (870 ft Upstream)), 1/6 of Traffic	3839
Left Interchange Ramp (870 ft Upstream)), 38% of Traffic	3819
Right Interchange Ramp (870 ft Upstream)), 24% of Traffic	3960

Tables 8 and 9 showed the effects of eliminating flow entirely from the on-ramp. Tables 12 shows the effects of increasing the flow from an interchange-ramp to the maximum value that still keeps the taper as the chokepoint under regime 1 and is within the capacity of the ramp itself. These maximum values were found to be between 1800 and 1870 vehicles per hour for regime 1.

For regime 2, Table 13, it was not possible to find a right-entering ramp flow rate substantially above 20% that clearly caused the chokepoint to remain at the taper. Increasing the ramp volumes under regime 2 with a right-entering ramp had a counterintuitive effect of raising the capacity. Inspections of the simulation revealed that slowing at the merge point created a favorable density of traffic for moving past the taper with many vehicles being able to avoid a complete stop. Thus, the test of varying ramp volume under regime 2 for the right-entering ramp is inclusive. For the left-entering ramp under regime 2, raising the ramp flow rate had no effect.

Early Merge

Wisconsin drivers are usually encouraged to merge early when approaching work zones. At a few work zones, WisDOT and other states have experimented with a late merge scheme where drivers are encouraged though signing to use all lanes, then to take turns when entering a single lane at the taper. A late merge scheme has the obvious benefit of more effectively using the storage capacity of all lanes upstream of a work zone. It is not possible to simulate the process of turn-taking in CORSIM, so a true “late merge” strategy cannot be tested. CORSIM naturally tends toward a late merging behavior with its default parameter settings when the network is congested, but trucks sometimes have difficulty changing lanes when close to the taper.

However, a perfect early merge can be tested by forcing all drivers to enter the network in the opened lane(s), by warning drivers well ahead about lane closures and incidents and by restricting trucks from entering the closed lane. The difference between an early merge and CORSIM’s natural merge (slightly modified for all tests in this report, as indicated earlier) is illustrated on Table 14 for Marquette Work Zone 2.

TABLE 14 Comparison between Perfect Early Merge and CORSIM’s Natural Merge and Perfect Late Merge, Regime 2, Marquette Work Zone 2

Work Zone and Condition	Capacity
Base Case, Natural Merge	1492
Perfect Early Merge	1477
Perfect Late Merge	1525

Table 14 indicates that a perfect early merge reduces capacity by a very small amount. Multiple attempts to further modify CORSIM's parameters or to add upstream "incidents" to improve cooperation between drivers with a late merge strategy did not provide any greater capacity than the base case. All cases in Table 14 have 8% heavy trucks.

A hypothetical way of improving the capacity of any work zone would be to create a metering system, well upstream of the taper, that prevents the work zone from entering regime 2 conditions. A "take-turns" scheme could provide that metering, under some peculiar circumstances, but flow rates would still be limited to regime 1 capacities.

It has been argued (Meyer, 2004) that a "take-turns" scheme could improve capacity by better organizing accelerating passenger cars and trucks. For example, consider the case of a passenger car directly behind another passenger car that is next to a truck. The release order while taking turns is car-truck-car, but the second car in the queue might have the opportunity to pass the truck, thereby creating a car-car-truck order. A car-car-truck order would assist a higher capacity for the whole traffic stream. The limiting case would be a traffic stream that perfectly orders passenger cars together and perfectly orders all trucks together. This limiting case can be reasonably tested in CORSIM and is identified as "perfect late merge" in Table 14. It can be seen that capacity can be improved by at most 3% over "perfect early merge" and by just 2% over "natural merge".

Discussion

It is important to note that simulation models are limited by design in the effects that can be tested. The cases tested in the previous subsections were chosen to be well within the capabilities of the software. Nonetheless, any test that proved insignificant could indicate two possibilities: (1) the change in condition is truly unimportant or (2) the model is incapable of discerning the difference.

Standard deviations of volumes for the same traffic conditions that produced capacity ranged between 50 vph to 120 vph across a full 15 minute time interval. High standard deviations suggest that it would be difficult to accurately predict exactly when a traffic stream will reach capacity conditions in the field.

Probability Distribution of Work Zone Capacity

Given the uncertainty of knowing the exact capacity of any work zone, even if the prevailing conditions are known precisely on average, it may be appropriate to use a conservative value of the regime 1 (relatively free flowing) capacity for planning purposes. If a conservative value is not used, then an unfavorable random fluctuation in vehicle mix or another traffic variable could cause a queue to form. Once a queue has formed, volumes would need to drop substantially to regain free flowing traffic. Furthermore, since the prevailing conditions are not known precisely, those conditions should also be selected conservatively when planning work zone traffic control.

The pooled standard deviation of a single-lane capacity for all regime 1 simulations was 52.4 vehicles per hour. Table 15 uses probability theory and the Weibull probability distribution (see earlier discussion) to extrapolate these simulation results to various numbers of lanes and various confidence levels. Table 15 has been limited to three open lanes so as to not greatly exceed the valid range of the original Marquette data.

TABLE 15 Deductions from Average Capacity to Achieve a Conservative Percentile Capacity Value for Work Zone Planning Purposes, One to Three Open Lanes

Percentile	One Lane	Two Lanes	Three Lanes
5%	97	140	169
10%	70	97	119
25%	29	40	48

For example, if a two-lane work zone has a computed average capacity of 3800 vehicles per hour, then the 10 percentile capacity is 3703 (that is, 3800 minus 97).

GUIDANCE ON THE USE OF CORSIM TO EVALUATE CAPACITY OF WORK ZONES

CORSIM is a relatively inexpensive microscopic traffic simulation model, which has the ability to realistically model many work zones. Experience with modeling the Marquette work zones leads to guidelines for analysis of work zones elsewhere.

- *Need to closely visually observe the simulation of the work zone.* One of the advantages of microscopic traffic simulation models is the ability to visually inspect individual vehicles in the traffic stream. Behavioral inaccuracies in a model are accentuated when traffic is running close to capacity. Therefore, it is essential to frequently check to see that simulated drivers are behaving reasonably. If not, there is a need to review parameter settings or to place appropriate limits on tested prevailing conditions.
- *Warm-up and simulation times.* Extensive warm up periods are required to achieve stable flow conditions. Simulation time should be sufficiently long to get a good average capacity. A 15-minute interval, consistent with the HCM, works well.
- *Need to run many separate simulations.* There can be substantial variations between runs with different random number seeds. Capacity should be taken from volume averages across many runs, such as the 100 runs used for this report. Two computer programs developed by the Advanced Traffic Analysis Center at North Dakota State University, CORSEED and COROUT, are very helpful in managing large numbers of CORSIM runs.
- *Achieving regime 2 capacity.* Regime 2, queued conditions, are easily obtained in CORSIM by creating more upstream flow than the work zone can possibly handle under relatively free flow conditions. Occasional warning messages from CORSIM that traffic is backed up beyond entry points are tolerable and are indicative of more than enough volume. Wide ranges of volumes can create regime 2 conditions. Upstream densities are typically between 100 and 150 vehicles per lane-mile.
- *Achieving regime 1 capacity.* Achieving a regime 1 capacity is more complicated than achieving a regime 2 capacity, because of the very narrow range of upstream volumes required. A two-stage iterative procedure is necessary to find upstream volumes within this range. As well as maximizing downstream volume, a desired range should be set for downstream densities, typically near density values for LOS E in the Highway Capacity Manual. First, trial upstream volumes should be set and downstream flow rates obtained for a single run. Select the upstream flow rate that gives the maximum downstream flow.

Second, check this flow rate across many runs. If average downstream densities over those many runs are not within an acceptable range, then the process must be repeated.

- *Parameter setting and calibration.* Ideally, parameters should be adjusted to match actual work zones. If this is not possible, then parameters borrowed from elsewhere can be used with caution. For CORSIM, particular attention should be paid to the Pitt car-following parameters.
- *Match the capabilities of the software to the work zone.* It is important to use any simulation model prudently, especially by assuring that the work zone is well within the capability of the software. As examples, CORSIM is insensitive to lane width (within the FRESIM module) and road curvature, so tests of these properties should be avoided.
- *Identifying the chokepoint.* For most work zones, the chokepoint will be the taper. However, if there in an on-ramp near the taper, either upstream or downstream, the chokepoint could be within the on-ramp merge area. If the chokepoint might be in an on-ramp merge area, then specific care must be exercised in setting or proportioning on-ramp flow rates. Being able to identify a single chokepoint can simplify the analysis.
- *Length of taper is implied.* A work zone taper is modeled as a “lane drop” in CORSIM. A model can vary the amount of space ahead that drivers have to react to a lane drop, but the physical length of the taper cannot be specifically entered as a variable.
- *Lane distribution of trucks is important.* A fundamental conclusion of the tests of this report is that the lane distribution of trucks is important to the measured capacities. Lane distribution just ahead of the taper can vary with the proportion of trucks in entering flows, the lane distribution of all vehicles while entering at a given node, lane changing parameters and restrictions or biases placed on truck lane selection. Particular attention should be given to assure that the lane distribution of trucks is accurate.
- *Creating a section to measure capacity.* The section of road should include any on-ramps off-ramps or interchange-ramps that might affect lane distribution just upstream of the taper. Downstream on-ramps must be included if there is a possibility of a chokepoint within its merge area. There should be a separate link just upstream and a separate link just downstream of the chokepoint for measurement purposes. The section upstream of the ramp should be long enough to accommodate a substantial queue, especially when ascertaining regime 2 capacity.
- *Placement of the “incident*”. If an “incident” is required to reduce capacity due to distractions or a severe geometry issue, then the incident should be placed just upstream of the taper or within the merge area.

CONCLUSIONS

Work zone capacity is effectively a random variable, because of moment-to-moment variations in vehicle mix and driver behaviors. This randomness goes beyond our inability to exactly know all prevailing conditions. The standard error of a single capacity estimate over a 15 minute time interval can be as high as 120 vph, depending upon the prevailing conditions.

Simulations confirm the empirical observation that there is a significant difference in capacity between regime 1 (free flow traffic) and regime 2 (queued traffic).

Based on the tests in this report, it is most likely that a chokepoint for a work zone is at a taper for a lane closure. However, it is entirely possible that the chokepoint could occur further upstream or downstream where vehicles are merging from an on-ramp. The chokepoint can be at either position (taper or merge) in the same work zone, depending upon the distribution of volume between the mainline and the on-ramp or interchange-ramp. Very complex work zones, particularly those with multiple tapers or on-ramps near a taper, should be analyzed with a suitable microscopic traffic simulation program to identify the chokepoint.

The lane distribution of trucks is important for determining work zone capacity. Capacity is highest when the vast majority of trucks are in a single lane that remains open.

Microscopic traffic simulations can be useful in calculating the capacity of many work zones, but care must be taken to keep all conditions to within the capability of the software.

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REFERENCES

1. Ahmed Al-Kaisy1 and Fred Hall, “Guidelines for Estimating Freeway Capacity at Long-Term Reconstruction Zones”, *ASCE Journal of Transportation Engineering*, Vol. 129, No. 5, 2003, pp 572-577.
2. Werner Brilon, Justin Geistefeldt, Hendrik Zurlinden, “Implementing The Concept Of Reliability For Highway Capacity Analysis”, TRB 86th Annual Meeting Compendium of Papers CD-ROM, January 21-15, 2007.
3. Cambridge Systematics, et al., “The Quick Response Freight Manual”, Federal Highway Administration, DOT-T-97-10, September 1996.
4. Amjad Dehman, “Freeway Work Zone Traffic Management And Roadway Design”, Masters Thesis, Marquette University, Department of Civil And Environmental Engineering, 2007.
5. Lily Elefteriadou, Diego Arguea, Alexandra Kondyli, and Kevin Heaslip, “Impact of Trucks on Arterial LOS and Freeway Work Zone Capacity”, Transportation Research Center, University of Florida, TRC-FDOT-54954-b-2007, July 2007.
6. Federal Highway Administration, CORSIM User’s Guide, 2001.
7. Chanyoung Lee and David A. Noyce, “Work Zone Capacity and Analysis Tool (WZCAT) Calibration/Validation”, Traffic Operations and Safety Laboratory, University of Wisconsin-Madison, Department of Civil and Environmental Engineering, January 2007.
8. Eric Meyer, “Construction Area Late Merge System (CALM)”, Midwest Smart Work Zone Deployment Initiative, www.ctre.iastate.edu/smartwz/reports/MwSWZDI-2004-Meyer-CALM_System.pdf, February 2004.
9. Thomas Schnell and Fuat Aktan, “On the Accuracy of Commercially Available Macroscopic and Microscopic Traffic Simulation Tools for Prediction of Workzone Traffic”, Federal Highway Administration, accessed online on September 4, 2007, http://ops.fhwa.dot.gov/wz/workshops/accessible/Schnell_pdf.htm.

10. Grant B. Schultz and L. R. Rilett, “Analysis of Distribution and Calibration of Car-Following Sensity Parameters in Microscopic Traffic Simulation Models”, *Transportation Research Record*, Number 1876, 2004, pp. 41-51.
11. Transportation Research Board, *Highway Capacity Manual, HCM2000*, 2000.
12. Govindarajan Vadakpat and Karen Dixon, “Calibration and Validation of CORSIM for Work Zones, *ITE Journal*, February 1999.
13. Helmut T. Zwahlen, Andrew Russ, Erdinc Oner, Meghna Parthasarathy, “Evaluation of Microwave Radar Trailers for Nonintrusive Traffic Measurements”, *Journal Transportation Research Record*, Number 1917, 2005, pp. 127-140.

APPENDIX A. CALIBRATED PARAMETERS FOR CORSIM

TABLE A1 Pitt Car Following Sensitivity Parameters

Driver	Original CORSIM	Houston	Milwaukee Work Zone Calibrated
1	1.25	1.46	1.34
2	1.15	1.23	1.11
3	1.05	1.08	0.96
4	0.95	0.97	0.85
5	0.85	0.87	0.77
6	0.75	0.76	0.64
7	0.65	0.67	0.55
8	0.55	0.55	0.43
9	0.45	0.41	0.29
10	0.35	0.30	0.18
Constant	10	10	9

Heavy Vehicle Mix
Fresim 3 = 41.7%
Fresim 4 = 7.8%
Fresim 5 = 48.5%
Fresim 6 = 2.0%

One-lane work zones receive a rubbernecking factor of 20%

APPENDIX B. HEAVY VEHICLE CLASSIFICATION COUNTS

TABLE B1 Average Daily Classification of Vehicles, NB and SB I-894 at Cleveland, South of Marquette's Work Zone 2

FHWA Vehicle Class	Year 2004	Year 2005
1 Motorcycles	0.65%	0.75%
2 Passenger Cars	80.80%	78.45%
3 Light Trucks	9.19%	11.31%
4 Buses	0.68%	0.65%
5 SU, 2 Axles, 6 tires	1.54%	1.60%
6 SU, 3 Axles	0.56%	0.53%
7 SU, 4 + Axles	0.24%	0.22%
8 Single Trailer, 4 or Less Axles	0.96%	0.98%
9 Single Trailer, 5 Axles	5.03%	5.19%
10 Single Trailer, 6 + Axles	0.11%	0.09%
11 Multi-Trailer, 5 or Less Axles	0.18%	0.20%
12 Multi-Trailer, 6 Axles	0.03%	0.03%
13 Multi-Trailer, 7 + Axles	0.03%	0.01%
Total of 5 to 7	2.24%	2.35%
Total of 8 to 10	6.10%	6.26%
Total of 11 to 13	0.24%	0.23%

Source: Wisconsin Department of Transportation

TABLE B2 Classification over Five Weekdays, NB US 45 South of Wisconsin, Near Marquette's Work Zone 1, 2003

Classes	Mon	Tues	Wed	Thu	Fri
4	1.3%	1.3%	1.3%	1.3%	1.2%
5-7	3.8%	3.8%	3.9%	3.9%	3.6%
8-13	5.3%	5.1%	5.1%	4.8%	4.6%

Source: Wisconsin Department of Transportation

TABLE B3 Classification by Time of Day (Weekdays), NB US 45 South of Wisconsin, Near Marquette's Work Zone 1, 2003

Classes	AM peak (2 hours)	PM peak (2 hours)	Adj peak (9 hours)	Off-peak
4	1.2%	1.0%	1.4%	1.0%
5-7	3.6%	2.7%	4.2%	3.6%
8-13	4.9%	3.9%	5.3%	4.8%

Source: Wisconsin Department of Transportation

TABLE B4 Classification over Five Weekdays, NB I-894 at Cleveland, South of Marquette's Work Zone 2, 2003

Classes	Mon	Tues	Wed	Thu	Fri
4	0.8%	0.9%	0.8%	0.7%	0.7%
5-7	2.7%	2.6%	2.6%	2.7%	2.5%
8-13	7.8%	7.9%	8.4%	8.2%	7.4%

Source: Wisconsin Department of Transportation

TABLE B5 Classification by Time of Day (Weekdays), NB I-894 at Cleveland, South of Marquette's Work Zone 2, 2003

Classes	AM peak (2 hours)	PM peak (2 hours)	Adj peak (9 hours)	Off-peak
4	0.7%	0.5%	1.0%	0.5%
5-7	2.4%	2.1%	3.2%	1.7%
8-13	6.6%	4.4%	7.8%	11.4%

Source: Wisconsin Department of Transportation

TABLE B6 CORSIM Heavy Vehicle Class Characteristics

Vehicle Type	Length	Description	Spit
Fresim Type 3	35	Single Unit Truck	100% of FHWA 5-7
Fresim Type 4	53	Semi-Trailer Truck, Medium Load	13.9% of FHWA 8-10
Fresim Type 5	53	Semi-Trailer Truck, Heavy Load	86.1% of FHWA 8-10
Fresim Type 6	64	Double-Bottom Truck	100% of FHWA 11-13

Source: "Simulating Trucks in CORSIM", Minnesota Department of Transportation, September 13, 2004.