
FINAL REPORT

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THE FLORIDA DEPARTMENT OF TRANSPORTATION
RESEARCH CENTER

on Project

“Impact of Lane Closures on Roadway Capacity, Phase 2”

FDOT Contract BDK77-977-18 (UF Project 93879)



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University of Florida
Transportation Research Center
Department of Civil and Coastal Engineering

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SI (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS				
Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH				
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
AREA				
in ²	square inches	645.2	square millimeters	mm ²
ft ²	square feet	0.093	square meters	m ²
yd ²	square yard	0.836	square meters	m ²
ac	acres	0.405	hectares	ha
mi ²	square miles	2.59	square kilometers	km ²
VOLUME				
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft ³	cubic feet	0.028	cubic meters	m ³
yd ³	cubic yards	0.765	cubic meters	m ³
NOTE: volumes greater than 1000 L shall be shown in m ³				
MASS				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
TEMPERATURE (exact degrees)				
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
ILLUMINATION				
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.428	candela/m ²	cd/m ²
FORCE and PRESSURE or STRESS				
lbf	poundforce	4.45	newtons	N
lbf/in ²	poundforce per square inch	6.89	kilopascals	kPa
APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH				
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
AREA				
mm ²	square millimeters	0.0016	square inches	in ²
m ²	square meters	10.764	square feet	ft ²
m ²	square meters	1.195	square yards	yd ²
ha	hectares	2.47	acres	ac
km ²	square kilometers	0.388	square miles	mi ²
VOLUME				
ml	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m ³	cubic meters	35.314	cubic feet	ft ³
m ³	cubic meters	1.307	cubic yards	yd ³
MASS				
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
TEMPERATURE (exact degrees)				
°C	Celsius	1.8C+32	Fahrenheit	°F
ILLUMINATION				
lx	lux	0.0929	foot-candles	fc
cd/m ²	candela/m ²	0.2919	foot-Lamberts	fl
FORCE and PRESSURE or STRESS				
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in ²

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

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16. Abstract This project is a follow-up to Florida Department of Transportation (FDOT) research project BD545-61, "Impact of Lane Closures on Roadway Capacity" (specifically, Part A: Development of a Two-Lane Work Zone Lane Closure Analysis Procedure and Part C: Modeling Diversion Propensity at Work Zones). In this previous project, the primary objective was to update the procedure in the Plans Preparation Manual (PPM), Volume 1, Section 10.14.7 (2006), for two-lane roadways. Field data collection was not included in the previous project; thus, the results were based strictly on simulation data from the FlagSim simulation program.			
The primary objective of this project was to update the two-lane roadway with a lane closure analysis procedure developed under the previous project, based on calibrating the FlagSim simulation program to field data. An additional aspect of this that was not considered in the BD545-61 project was to account for the effect of grade on the work zone performance measures. An additional project objective was to update the RTF estimation method developed under the BD545-61 project, as necessary, based on measured traffic demands (before and during) at work zone field sites.			
Field data were collected at three sites and used to calibrate the FlagSim program. FlagSim was then used to generate the data used to update the models contained in the analysis procedure developed under the previous project. Local area traffic demand data were also used to update the RTF estimation model.			
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EXECUTIVE SUMMARY

This project is a follow-up to Florida Department of Transportation (FDOT) research project BD545-61, “Impact of Lane Closures on Roadway Capacity” (specifically, Part A: Development of a Two-Lane Work Zone Lane Closure Analysis Procedure and Part C: Modeling Diversion Propensity at Work Zones). In this previous project, the primary objective was to update the procedure in the Plans Preparation Manual (PPM), Volume 1, Section 10.14.7 (2006), for two-lane roadways. Field data collection was not included in the previous project; thus, the results were based strictly on simulation data from the FlagSim simulation program.

Before the preceding research project, the FDOT developed an analysis procedure for two-lane roadways with a lane closure that was a relatively simple deterministic procedure, with rough approximations for work zone capacity and other important parameter values. Through the previous project (BD545-61), a new analysis procedure was developed that is sensitive to the major factors that influence work zone performance measures. However, the main limitation from the BD545-61 project was the lack of field data to use for calibrating the various simulation parameters.

Another aspect of the BD545-61 project was to develop a method to estimate the amount of traffic diversion that occurs at a work zone location. The previous analysis procedure in the PPM included the “Remaining Traffic Factor” (RTF) term. This term accounts for “The percentage of traffic that will not be diverted onto other facilities during a lane closure” (FDOT, 2006 PPM). The value to use for this input was left strictly to the analyst’s judgment, as there was no method or quantitative guidance provided. Again, since field data were not available in the BD545-61 project, a stated preference (SP) survey, via telephone, approach was used to develop a method to estimate that amount of traffic diversion that will occur at a work zone site.

The primary objective of this project was to update the two-lane roadway with lane closure analysis procedure developed under the previous project based on calibrating the FlagSim simulation program to field data. An additional aspect of this that was not considered in the BD545-61 project was to account for the effect of grade on the work zone performance measures. An additional project objective was to update the RTF estimation method developed under the BD545-61 project, as necessary, based on measured traffic demands (before and during) at field sites.

Field data were collected from three sites. Two of these sites were in fairly rural locations, which featured longer lane closure lengths and lower demand volumes. The third site was less rural in nature and featured shorter lane closures and higher demand volumes. All three sites were located in the north-central Florida region. From the field data, values for factors critical to the calibration of FlagSim were determined, such as startup lost time, saturation headway, travel speed through the work zone, flagging right-of-way changing behavior, etc.

After FlagSim was calibrated to the field conditions, it was then used to generate the data used to update the models contained in the analysis procedure developed under the previous project. Specifically, models for average work zone travel speed, average saturation headway, total queue delay, and maximum queue length were updated. The models were updated in the analysis worksheet tool.

The RTF task aimed to refine the estimation model proposed in Phase 1 using field-observed diversion data. The binary Logit model developed in Phase 1 was calibrated based on SP survey data, and SP data tend to overestimate the diversion rate in work zones. The aggregate traffic data collected in a work zone on SR-20 confirmed this phenomenon. A simplistic methodology is adopted primarily due to limitations in data availability and quality.

The constant coefficient associated with the original route is adjusted to fix the overestimation problem while retaining the preference structure of the estimated route choice model. The recalibrated model was incorporated into the RTF modeling framework proposed in Phase 1 by updating the route choice model.

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CHAPTER 1 INTRODUCTION

This project is a follow-up to Florida Department of Transportation (FDOT) research project BD545-61, “Impact of Lane Closures on Roadway Capacity” (specifically, Part A: Development of a Two-Lane Work Zone Lane Closure Analysis Procedure and Part C: Modeling Diversion Propensity at Work Zones). In this previous project, the primary objective was to update the procedure in the Plans Preparation Manual (PPM), Volume 1, Section 10.14.7 (2006), for two-lane roadways. Field data collection was not included in the previous project; thus, the results were based strictly on simulation data from the FlagSim simulation program (described in Appendix C).

Some material in this report is repeated from the previous project report to minimize the need to reference the previous report, starting with an overview of two-lane roadway lane closure configuration and operations. Two-lane roadway work zone configurations consist of a single lane that accommodates both directions of flow, in an alternating pattern, as illustrated in Figure 1.

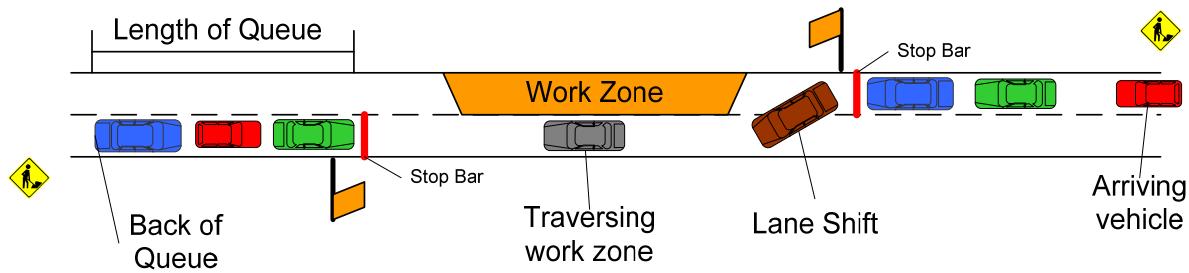


Figure 1: Two-lane work zone operated with flagging control

These work zones typically employ a flagging control person (i.e., someone who operates a sign that gives motorists instructions to stop or proceed) at both ends to regulate the flow of

traffic through the work zone. In some situations (usually where the lane closure is long or there are a large number of driveways), a lead vehicle, called a pilot car, may be required to lead the platoon of vehicles through the work zone.

Significant delay is incurred by motorists due to the lost time that accrues while the opposing direction has the right-of-way. Additionally, both directions incur lost time when there is a change in the right-of-way as the last vehicle that received the right-of-way must traverse the entire length of the work zone; therefore, all vehicles must wait until the last vehicle has passed the opposite stop location. The queue discharge process is similar to the operation of a signalized intersection, but the queue discharge rate may be lower due to driver caution and various work zone factors and activities.

Changing of the right-of-way is rarely performed in an optimal manner. Flag persons are not trained on how to switch the right-of-way in such a manner as to minimize delay, or otherwise optimize some particular performance measure (Evans, 2006). Generally, flag persons change the flow direction due to queue and cycle length. The queue at the beginning of the “green” period discharges at the saturation flow rate. After the initial queue dissipates, flag persons usually extend the green to allow for vehicles still arriving. This extension time can be lowered if there is a significant queue in the opposite direction. At this point, the flow through the work zone will drop to the arrival rate. The arrival rate can be significantly lower than the queue discharge rate on low volume roadways, thus increasing the overall average delay if vehicles are queuing at the opposite approach (Cassidy and Son, 1994).

The typical performance measures for evaluating a work zone with flagging operations are:

- Capacity – maximum vehicle throughput
- Delay – time spent not moving, or at a slower speed than desired
- Queue length – vehicle arrivals minus vehicle departures for a specified length of time

Problem Statement

Since there is not a single accepted national standard for analyzing work zone operations and estimating performance measures, such as might be provided by the Highway Capacity Manual (HCM) (TRB, 2010), transportation agencies are tasked with developing their own methods or adopt/adapt ones from existing methods. Before the preceding research project, the FDOT developed an analysis procedure for two-lane roadways with a lane closure that was a relatively simple deterministic procedure, with rough approximations for work zone capacity and other important parameter values. Through the previous project (BD545-61), a new analysis procedure was developed that is sensitive to the major factors that influence work zone performance measures. However, the main limitation from the BD545-61 project was the lack of field data to use for calibrating the various simulation parameters. While some of these parameters were set based on results of field data collection at signalized intersections from a previous FDOT research project (BD545-51, Washburn and Cruz-Casas, 2007), it is likely that there are still a number of significant differences in the queue accumulation and discharge process at two-lane roadway lane closure sites. Furthermore, the extent to which conditions within the work zone might further reduce drivers' desired speed, relative to the posted speed, was not known. Another aspect of the BD545-61 project was to develop a method to estimate the amount of traffic diversion that occurs at a work zone location. The previous analysis procedure in the PPM included the 'Remaining Traffic Factor' (RTF) term. This term accounts for "The percentage of traffic that will not be diverted onto other facilities during a lane closure." (FDOT, 2006 PPM) The value to use for this input was left strictly to the analyst's judgment, as there was no method or quantitative guidance provided. Again, since field data were not available in the BD545-61 project, a stated preference (SP) survey, via telephone, approach was

used to develop a method to estimate that amount of traffic diversion that will occur at a work zone site.

Research Objective and Supporting Tasks

The primary objective of this project was to update the two-lane roadway with lane closure analysis procedure developed under the previous project based on calibrating the FlagSim simulation program to field data. An additional aspect of this that was not considered in the BD545-61 project was to account for the effect of grade on the work zone performance measures. An additional project objective was to update the RTF estimation method developed under the BD545-61 project, as necessary, based on measured traffic demands (before and during) at field sites. The tasks that were conducted to support completion of the objectives were as follows:

- Collected work zone operations data at three lane closure sites in north-central Florida.
- Reduced and analyzed the field operations data.
- Developed models for estimating work zone travel speed and saturation headway based on the field data.
- Calibrated various FlagSim input parameters to yield a good match between simulated work zone traffic operations and field work zone operations.
- Incorporated a new truck acceleration model into FlagSim (the same model used in FDOT Project BDK77-977-15) and updated truck characteristics in FlagSim based on analysis of weigh-in-motion (WIM) data from several two-lane highway sites.
- Developed models for estimating work zone travel speed, saturation headway, queue delay, and queue length based on simulation data.
- Revised the analysis procedure spreadsheet developed under the previous project to reflect the updated models developed in this project.
- Collected local area traffic demand data at each field site, before and during the lane closure, (this was performed by FDOT staff) and analyzed the data.
- Updated the RTF estimation model based on the field site local area traffic counts.

Document Organization

The remaining chapters in this report are organized as follows. Chapter 2 provides a brief overview of the results of the preceding project as well as an overview of the original FDOT PPM procedure (this material is repeated from the BD545-61 project report). Readers interested in other research efforts and/or analysis tools applicable to two-lane roadways with a lane closure should consult Chapter 2 of the BD545-61 project report. Chapter 3 describes the field site data collection, analysis, and model development. Chapter 4 describes the simulation calibration effort, the incorporation of the effect of grade, and the development of the final models to be incorporated into the analysis spreadsheet tool. Chapter 5 provides a step-by-step overview of the analysis procedure. Chapter 6 describes the results of the RTF task.

CHAPTER 2

REVIEW OF PREVIOUS FDOT ANALYSIS METHODS

This chapter presents a summary of the original FDOT PPM analysis procedure for two-lane roadways with a lane closure and a summary of the results of the previous project (BD545-61).

Original FDOT PPM Analysis Procedure

The FDOT developed a lane closure analysis procedure for use with all road type classes. The procedure is in the Plans Preparation Manual (PPM), Volume I, Section 10.14.7 (2006). The procedure can analyze two-lane two-way work zones. In order to accommodate flagging operations, the procedure attempts to determine the peak hour volume and the restricted capacity. From these two values, the time during when lane closures can occur without creating excessive delays is determined.

This procedure's main limitation is that capacity is an input, and the given capacities were not specific to two-lane work zones. With capacity not based on a flagging work zone value, the procedure quite likely will be unable to model the field conditions accurately. Another limitation with modeling flagging operations with this procedure is that it is based on only the ratio of green time to the cycle length. This assumption does not take in to account the differences in delays of flagging operations, such as the lost time due to the traversing the work zone, startup lost time, and the variation of extended green time.

The capacity is adjusted by the work zone factor (WZF) shown in Table 1. The WZF is used instead of a calculated travel time based on a typical speed. All of the lost time is also incorporated in to the WZF. This is a simplistic adjustment to incorporate these important factors. The travel time through the work zone is an easy calculation, which would make a logical factor. One of the problems is the WZF is not adjusted by speed and is not documented by what speed the factor is based on. This is an important question, as speeds through a work

zone can be quite different for an intense construction operation like chip and seal versus a less intense operation such as shoulder work.

Table 1. FDOT PPM Analysis Method Work Zone Factor (WZF)

WZL (ft.)	WZF	WZL (ft.)	WZF	WZL (ft.)	WZF
200	0.98	2200	0.81	4200	0.64
400	0.97	2400	0.8	4400	0.63
600	0.95	2600	0.78	4600	0.61
800	0.93	2800	0.76	4800	0.59
1000	0.92	3000	0.74	5000	0.57
1200	0.9	3200	0.73	5200	0.56
1400	0.88	3400	0.71	5400	0.54
1600	0.86	3600	0.69	5600	0.53
1800	0.85	3800	0.68	5800	0.51
2000	0.83	4000	0.66	6000	0.5

The FDOT PPM lane closure analysis procedure is as follows:

1. Select the appropriate capacity (c) from the table below:

LANE CLOSURE CAPACITY TABLE

Capacity (c) of an Existing 2-Lane-Converted to 2-Way, 1-Lane=1400 veh/h

Capacity (c) of an Existing 4-Lane-Converted to 1-Way, 1-Lane=1800 veh/h

Capacity (c) of an Existing 6-Lane-Converted to 1-Way, 1-Lane=3600 veh/h

Therefore, for a two-lane highway work zone, the capacity (c) is 1400 veh/h.

2. The restricted capacity (RC) is then calculated taking into consideration the following factors:

TLW = Travel Lane Width

LC = Lateral Clearance. This is the distance from the edge of the travel lane to the obstruction (e.g., Jersey barrier)

WZF = Work Zone Factor. This factor is proportional to the length of the work zone. It is only used in the procedure for two-lane two-way work zones.

OF = Obstruction Factor. This factor reduces the capacity of the travel lane if the one of the following factors violates their constraints: TLW less than 12 ft and LC less than 6 ft.

G/C = Ratio of green time to cycle time. This factor is applied when the lane closure is through or within 600 ft of a signalized intersection.

ADT = Average Daily Trips. This value is used to calculate the design hourly volume.

The RC for roadways without signals is calculated as follows:

$$RC(\text{Open Road}) = c \times OF \times WZF \quad [1]$$

If the work zone is through or within 600 feet of a signalized intersection, then RC is determined by applying the following additional calculation.

$$RC(\text{Signalized}) = RC(\text{Open Road}) \times G/C \quad [2]$$

If Peak Traffic Volume \leq RC, there is no restriction on the lane closure. That is, if the peak traffic volume is less than or equal to the restricted capacity, the work zone lane closure can be implemented at any time during the day.

If Peak Traffic Volume $>$ RC, calculate the hourly percentage of ADT at which a lane closure will be permitted.

$$\text{Open Road\%} = \frac{RC(\text{OpenRoad})}{ATC \times D \times PSCF \times RTF} \quad [3]$$

where

ATC = Actual Traffic Counts. The hourly traffic volumes for the roadway during the desired time period.

D = Directional distribution of peak hour traffic on multilane roads. This factor does not apply to a two-lane roadway converted to two-way, one-lane.

PSCF = Peak Season Conversion Factor

RTF = Remaining Traffic Factor. The percentage of traffic that will not be diverted onto other facilities during a lane closure.

Signalized\% = (Open Road \%) \times (G/C)

Plot the 24-hour traffic, relative to capacity, to determine when a lane closure is permitted.

Revised Analysis Procedure through FDOT Project BD545-61

Overall Analysis Procedure

As described above, the original FDOT analysis procedure in the PPM is fairly simple and considers a limited number of factors. Consequently, there is a very limited range of field conditions for which this method will yield reasonably accurate results. Furthermore, the only output from the method is work zone capacity. The objective of project BD545-61 was to develop an analysis procedure for two-lane roadway work zones (with a lane closure) that was more robust, both in terms of inputs and outputs, than the FDOT's current PPM method. The FDOT also had the requirement that this new procedure still be easy to use.

A custom microscopic simulation program, FlagSim, was used to generate the data used in the development of the models contained in the new analysis procedure. Specifically, models were developed to estimate work zone travel speed, saturation headway, queue delay, and queue length, as follows.

$$\begin{aligned} \text{WorkZoneSpd}_i &= 4.608474 + 0.706381 \times \text{PostedSpd}_i + 0.000601 \\ &\quad \times \text{Min}((L \times 5280), 10560) - 0.1063336 \times HV_i \end{aligned} \quad [4]$$

where

WorkZoneSpd_i = estimated average travel speed of vehicles through the work zone for direction i (mi/h)

PostedSpd_i = the posted speed, or maximum desirable travel speed of vehicles, through the work zone for direction i (mi/h)

L = work zone length (mi)

HV_i = percentage of heavy vehicles in the traffic stream for direction i

$$h_{sat_i} = 1.92 \times \left(1 - 0.00516(\text{Min}(\text{speed}_i, 45) - 45)\right) \times \left(1 + \left(\frac{HV_i}{100}\right) \times (2.37 - 1)\right) \quad [5]$$

where

h_{sat_i} = saturation headway for direction i (s/veh)

speed_i = average travel speed downstream of stop bar for direction i (veh/h)

$$\begin{aligned}
HV_i &= \text{percentage of heavy vehicles in the traffic stream for direction } i \\
TotalQDelay_i &= -0.276980 \times (g_i / C)(\%) + 0.242061 \times (v/s)_i(\%) + 0.003387 \times C \\
&\quad + 0.148503 \times g_i - 0.001376 \times HV_i \times g_i
\end{aligned} \tag{6}$$

where

- $TotalQDelay_i$ = total queue delay for a 1-hr time period for direction i (veh-hr)
- (g_i / C) = average effective green time to average cycle length ratio for direction i (expressed as a percentage)
- $(v/s)_i$ = volume to saturation flow rate ratio for direction i (expressed as a percentage)
- C = average cycle length (sec)
- g_i = average green time for direction i (sec)
- HV_i = percentage of heavy vehicles in the traffic stream for direction i

$$\begin{aligned}
MaxQueueLength_i &= -0.616983 \times (g_i / C)(\%) + 0.598965 \times (v/s)_i(\%) + 0.0006855 \times C \\
&\quad + 0.299197 \times g_i - 0.003199 \times HV_i \times g_i
\end{aligned} \tag{7}$$

where

- $MaxQueueLength_i$ = average maximum queue length per cycle for direction i (veh/cycle)
- Other terms are as previously defined.

The analysis procedure also employs calculation elements consistent with the analysis of signalized intersections. This procedure is much more robust than the original PPM procedure, and the results match well with the simulation data. The analysis procedure was implemented into an easy-to-use spreadsheet format. Screen captures of the analysis spreadsheet are shown in Figure 2 and Figure 3.

Two-Lane, Two-Way, Work Zone Analysis Worksheet
Florida Department of Transportation
(08/19/10)

Input Variables		Measures of Effectiveness		
		Peak Direction	Off-Peak Direction	Total
Length (mi)	2.25			
Work Zone Posted Speed (mi/h)	35			
Start-Up Lost Time, per direction (sec)	15			
Heavy Vehicles (%), Peak Direction	15			
Heavy Vehicles (%), Off-Peak Direction	10			
Volume (veh/h), Peak Direction	300			
Volume (veh/h), Off-Peak Direction	250			
Average Passenger Car Queue Spacing (ft/veh)	25			
Would you like to directly specify green times?	NO			
User Defined Peak Green Time (sec)				
User Defined Off-Peak Green Time (sec)				
		Capacity (veh/hr)	401	826
			Under Capacity	Under Capacity
		Delay in Queue (min/veh)	4.50	4.54
		Work Zone Travel Time Delay (min/veh)	0.10	0.08
		Total Delay (min/veh)	4.61	4.62
		Delay in Queue (veh-hrs)	22.52	41.62
		Work Zone Travel Time Delay (veh-hrs)	0.52	0.70
		Total Delay (veh-hrs)	23.04	42.32
		Maximum Queue Length (veh/cycle)	45.4	38.8
		Maximum Queue Length (ft)	1320	1075
Estimated Parameters				
Adjusted Saturation Flow Rate (veh/h), Peak Dir	1471			
Adjusted Saturation Flow Rate (veh/h), Off-Peak Dir	1564			
Minimum Green Time (sec), Peak Direction	161			
Minimum Green Time (sec), Off-Peak Direction	126			
Minimum Cycle Length (sec)	789			
Effective Vehicle Queue Spacing (ft/veh), Peak Dir	29.1			
Effective Vehicle Queue Spacing (ft/veh), Off-Peak Dir	27.7			

Notes:

MOE values in the "Total" column reflect volume weighted (by direction) averages where appropriate
Only the values in the colored cells in the "Input Variables" section should be edited by the user

Figure 2. Analysis worksheet tool developed in FDOT project BD545-61 screen capture (1-hour analysis)

Two-Lane, Two-Way, Work Zone Analysis Worksheet
Florida Department of Transportation
(08/19/10)

Fixed Inputs												
Length (mi)	2.25			Work Zone Posted Speed (mi/h)	35			Start-Up Lost Time, per direction (sec)	15			
Average Passenger Car Queue Spacing (ft/veh)	25			Would you like to directly specify green times?	NO							
Input Values per Hour												
Hour	Adj. Set Flow (veh/h)	Min Green (sec)	Min Cycle (sec)	Tot Cap (veh/h)	Capacity	Over Cap	Over Cap	Delay (min/veh), Dir 1	Delay (min/veh), Dir 2	Delay (veh-hr), Dir 1	Delay (veh-hr), Dir 2	
Dir 1	Dir 2	Dir 1	Dir 2	Dir 1	Dir 2	Yield	Yield	Dir 1	Dir 2	Dir 1	Dir 2	
12:00 - 1:00 AM	300	250	15	60	60	1471	1554	161	126	788	801	401
1:00 - 2:00 AM	200	100	19	19	60	1404	1404	46	650	750	370	379
2:00 - 3:00 AM	200	100	18	18	60	1420	1420	91	645	768	304	304
3:00 - 4:00 AM	200	100	17	17	60	1437	1437	89	642	778	369	369
4:00 - 5:00 AM	200	100	16	16	60	1454	1454	88	644	639	783	394
5:00 - 6:00 AM	300	200	15	15	60	1471	1471	106	766	798	399	399
6:00 - 7:00 AM	600	450	14	14	60	1489	1489	300	284	1392	809	405
7:00 - 8:00 AM	700	550	13	13	60	1507	1507	300	264	2943	820	410
8:00 - 9:00 AM	600	500	12	12	60	1525	1525	300	273	1791	831	416
9:00 - 10:00 AM	500	450	12	12	60	1542	1542	300	292	1791	831	416
10:00 - 11:00 AM	200	100	0	60	60	1787	1887	65	33	502	949	496
11:00 - 12:00 PM	200	100	15	15	60	1471	1471	86	49	636	798	399
12:00 - 1:00 PM	200	100	16	16	60	1454	1454	88	46	636	788	304
1:00 - 2:00 PM	200	100	17	17	60	1437	1437	89	46	642	778	389
2:00 - 3:00 PM	200	100	18	18	60	1420	1420	91	46	646	768	384
3:00 - 4:00 PM	200	100	17	17	60	1437	1437	89	45	642	778	389
4:00 - 5:00 PM	500	450	16	16	60	1454	1454	300	264	1463	708	394
5:00 - 6:00 PM	700	550	15	15	60	1471	1471	300	254	3364	798	399
6:00 - 7:00 PM	600	500	14	14	60	1489	1489	300	273	1930	809	405
7:00 - 8:00 PM	450	400	15	15	60	1471	1471	300	282	1197	798	399
8:00 - 9:00 PM	200	100	16	16	60	1454	1454	88	44	636	788	304
9:00 - 10:00 PM	200	100	17	17	60	1437	1437	89	45	642	778	389
10:00 - 11:00 PM	200	100	18	18	60	1420	1420	91	46	646	768	384
11:00 - 12:00 PM	200	100	19	19	60	1404	1404	93	46	650	798	390

Figure 3. Analysis worksheet tool developed in FDOT project BD545-61 screen capture (24-hour analysis)

While it was felt that the results of this project (BD545-61) provided significant improvements over the existing FDOT PPM procedure, there were several areas that were identified that could benefit from additional research, as follows:

- One obvious limitation to the results of this project is the lack of field data for verification/validation of several aspects of the simulation program. Although certain parameter values used in the simulation program were compared for consistency to field data values obtained from the Cassidy and Son research (1994), most of their field sites utilized a pilot car; thus, their parameter values may not be directly comparable to sites that do not use a pilot car. Field data should be collected at several sites, under only flagging control, to confirm the following factors:
 - Saturation flow rates and/or capacities
 - What are typical values, and how do they differ due to traffic stream composition?
 - Are they different by direction, e.g., due to the required lane shift in one direction?
 - Travel speeds through the work zone
 - Are they related to, or independent of, posted speed limits?
 - Are they different by direction due to the lane crossover at the beginning of the work zone? Son (1994) states from their literature review that vehicles in the blocked travel direction usually have lower speeds than the opposite direction.
 - Startup lost time
 - What are typical values?

- Are they different by direction?
- Flagging methods
 - Is a gap-out strategy ever applied, and if so, how?
 - Is a maximum green time used, and if so, what value?
 - Is a green time extension used, and if so, what value?

Remaining Traffic Factor (RTF) Task

When estimating the hourly traffic demand, the FDOT PPM procedure applies a "Remaining Traffic Factor" (RTF) to the observed hourly traffic demand without the lane closure. The RTF accounts for possible traffic diversion during the lane closure. However, no guidance has been offered on how to obtain the value of the RTF in the PPM.

The purposes of this research task were twofold. First, diversion behaviors at work zones were modeled in a discrete choice modeling framework. A stated preference survey was carried out to obtain the data on drivers' diversion propensity from work zones. By calibrating a Logit model with the data, we identified three major factors that influence drivers' diversion decisions, namely, travel time, work zone location, and weather condition. For other factors, such as trip purpose and drivers' social economic characteristics, we found no evidence that they are important in drivers' decision making about diversion at work zones. The calibrated model provides us with more insight on drivers' work zone diversion behaviors and may be used to forecast diversion rates or be incorporated into a work zone traffic analysis tool.

Second, we proposed two procedures, namely open-loop and closed-loop, to apply the calibrated binary Logit model to estimate the RTF. The former directly applies the choice model without considering the feedback of remaining and diverted flows on travel times. It may be more appropriate to be used for a short-term work zone lane closure. The latter applies the notion of equilibrium to maintain the consistency between travel times and flows at different routes. Therefore, it may better replicate the situation at a long-term work zone. Based on the

combinations of the weather condition and work zone location, four Fisk's stochastic user equilibrium models have been formulated, which can be solved by the Excel solver to compute the RTF. An Excel tool was developed to facilitate the computation, screen captures of which are shown below in Figure 4 and Figure 5.

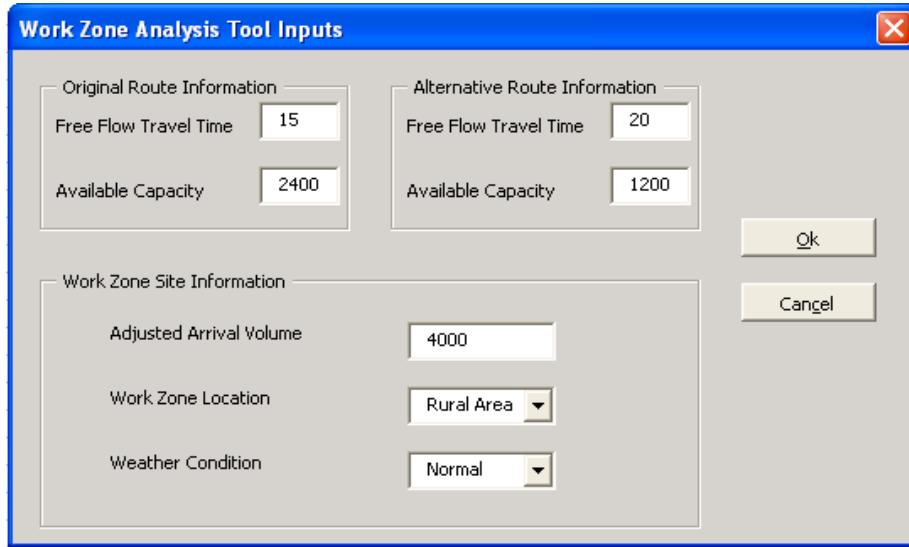


Figure 4. RTF estimation spreadsheet tool developed in FDOT project BD545-61 screen capture (1)

	A	B	C	D	E	F	G	H	I	J
Calculation of Remaining Traffic Factor for FDOT's Lane Closure Analysis of Work Zone										
Input										
Original Route					Work Zone Location					
5	Free-flow travel time	15	min		Rural Area	*				
6	Capacity with work zone	2400	vph		Urban Area					
Alternative Route					Weather Condition					
9	Free-flow travel time	20	min		Normal	*				
10	Capacity with work zone	1200	vph		Bad					
Adjusted Total Arrival										
12	4000	vph								
Output										
15	Remaining Traffic Factor	0.723		RTF	<== Press button to compute					

Figure 5. RTF estimation spreadsheet tool developed in FDOT project BD545-61 screen capture (2)

CHAPTER 3

FIELD DATA COLLECTION AND ANALYSIS

This chapter describes the data requirements for calibration of the FlagSim simulation program. This is followed by discussion on the sites where data were collected, the data collection procedure undertaken, and a brief description of the data collected at these sites. The data processing procedure is then described, and results from this processing are presented and discussed. Lastly, the work zone speed and saturation headway models developed from the field data are presented.

Data Requirements

In order to calibrate the FlagSim simulation program to field conditions, it was first necessary to identify what type of data were necessary to perform this task. Based on the simulation program internal models and possible outputs from this program, the following data parameters were identified:

- Length of lane closure
- Posted speed in work zone
- Posted speed of work zone approach
- Travel time of each vehicle through work zone for each phase
- Vehicle type of each vehicle entering the work zone per phase
- Number of vehicles entering the work zone per phase
- Average speed of vehicles in the work zone per phase
- “Green” time per phase
- Startup lost time per phase
- Queue delay per phase
- Queue length per phase

- Saturation headway per phase
- Type of flagging control used at the lane closure

These parameters collectively comprise the inputs and outputs of the FlagSim program. In addition, it was also necessary to obtain some data regarding traffic operations within the lane closure. Specifically, how traffic operations were impacted by construction taking place in the work zone.

Description of Study Sites

To facilitate the calibration of the FlagSim program, it was necessary to identify several study sites that provided different traffic characteristics and work zone conditions. Ultimately, field data were collected from three sites. Two of these sites were in fairly rural locations, which featured longer lane closure lengths and lower demand volumes. The third site was less rural in nature and featured shorter lane closures and higher demand volumes. The general location of these sites is indicated in Figure 6. Each of these sites is discussed in more detail in the following sections.

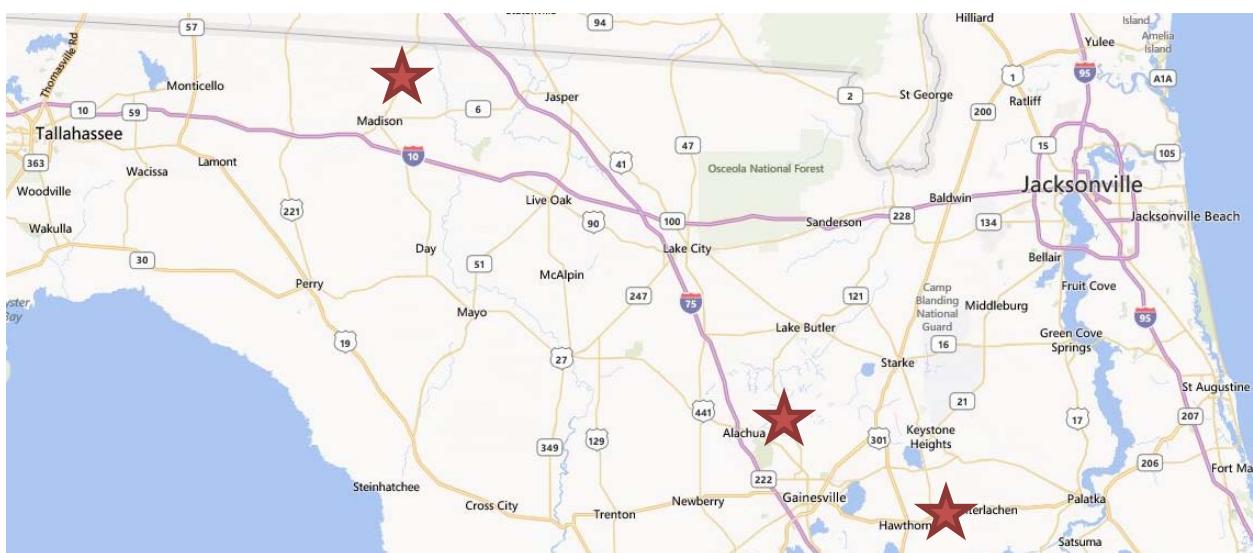


Figure 6. Work zone site locations

Site 1 Description

The first field site identified was located on SR-145 between the cities of Madison, FL and the Florida/Georgia border. This road is a frequent logging route and features a large percentage of heavy vehicles. It is more rural in nature, and the total AADT on this road was approximately 2000 in 2010. The length of lane closures on this roadway varied between 1.29 and 1.95 miles. The distance weighted average of the posted speed in these lane closures was mainly 55 mi/h, while one lane closure had an average posted speed of 60 mi/h. Construction activities consisted mainly of milling and resurfacing. Figure 7 shows a general map of the location of the construction along this road. It should also be noted that a few access roads are located along this stretch of road and had some contribution to the traffic through the lane closures. These roads primarily provide access to residential neighborhoods.

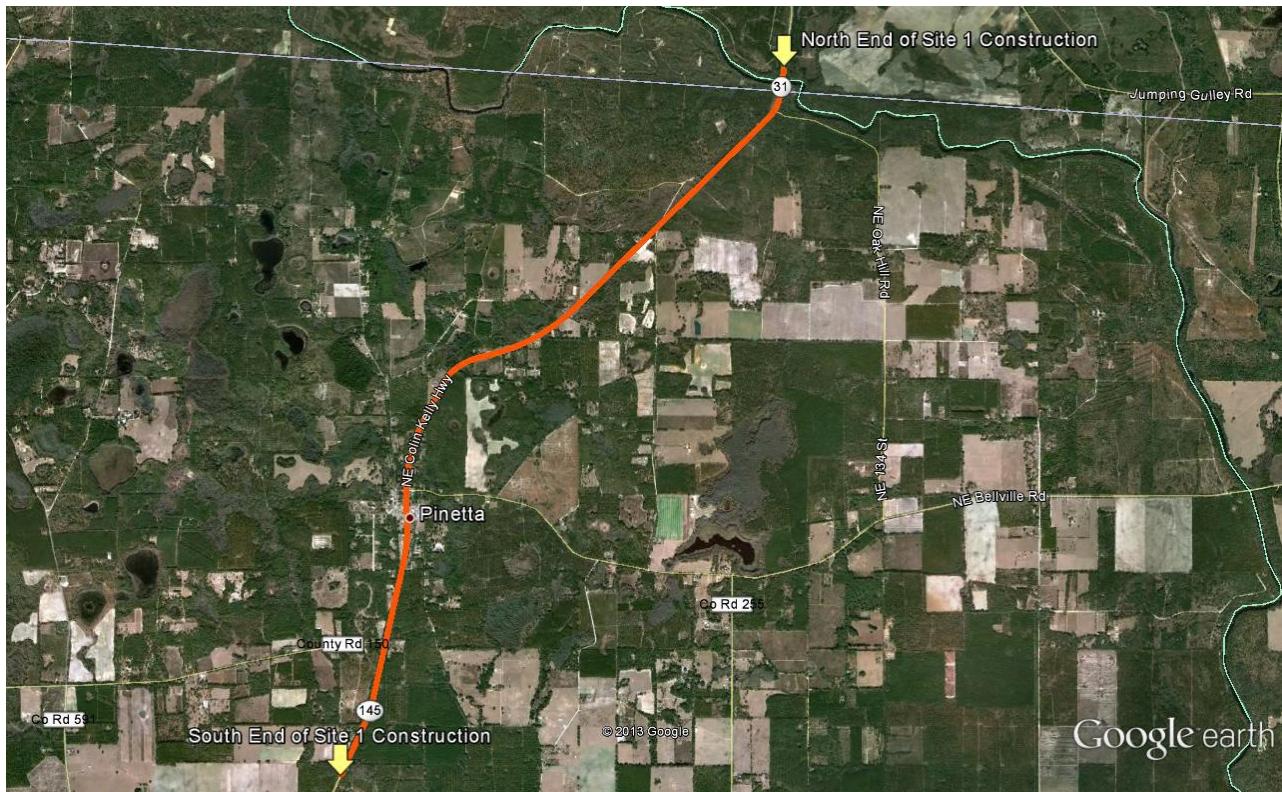


Figure 7. Extent of construction along SR-145 (site 1)

Site 2 Description

The second field site identified was located on SR-235 between the cities of Alachua, FL and La Crosse, FL. This road is more rural in nature, and the total AADT on this road was approximately 2800 in 2010. The length of lane closures on this roadway varied between 1.63 and 2.00 miles. The distance weighted average of the posted speed in these lane closures was 55 mi/h. Construction activities consisted mainly of milling and resurfacing. Occasional access roads are located along this stretch of road. These roads primarily provide access to more rural residences although a couple provided access to religious institutions. Figure 8 shows a map of where construction was being performed along this stretch of road.

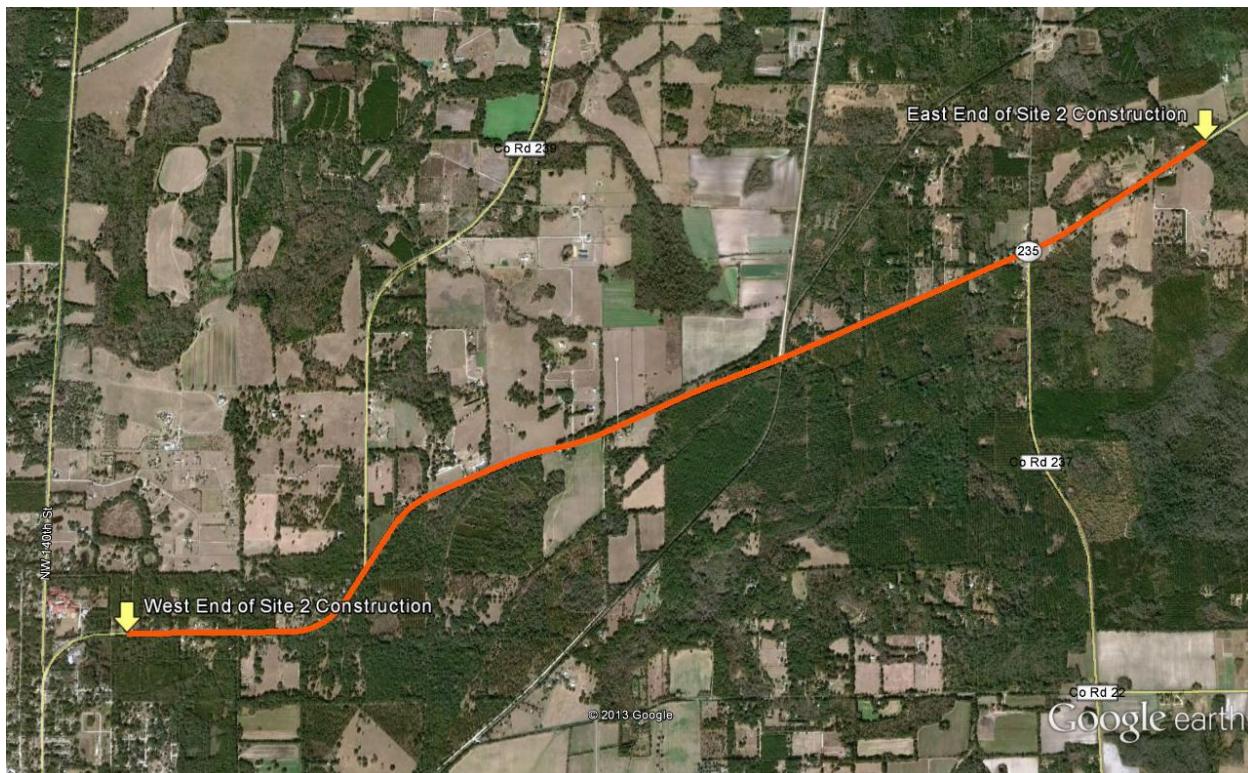


Figure 8. Extent of construction along SR-235 (site 2)

Site 3 Description

The third field site identified was located on SR-20 between the city of Hawthorne, FL and the intersection of SR-20 and SR-21. This road is heavily trafficked by commuters in the both the morning and afternoon. As a result, this road is less rural in nature during these peak periods and features larger volumes of traffic compared to sites 1 and 2. The total AADT on this road was approximately 8200 in 2010. The length of lane closures on this roadway varied between 0.74 and 1.63 miles with only one lane closure being over 1 mile. The distance weighted average of the posted speed in these lane closures was mainly 55 mi/h, while one lane closure had an average posted speed of 50 mi/h. Construction activities performed at this site primarily consisted of shoulder reconstruction and sodding. Figure 9 shows a map of the location of the construction along this road. Occasional access roads are located along this stretch of road. These roads can serve as alternate routes to the nearby city of Hawthorne and SR-21.

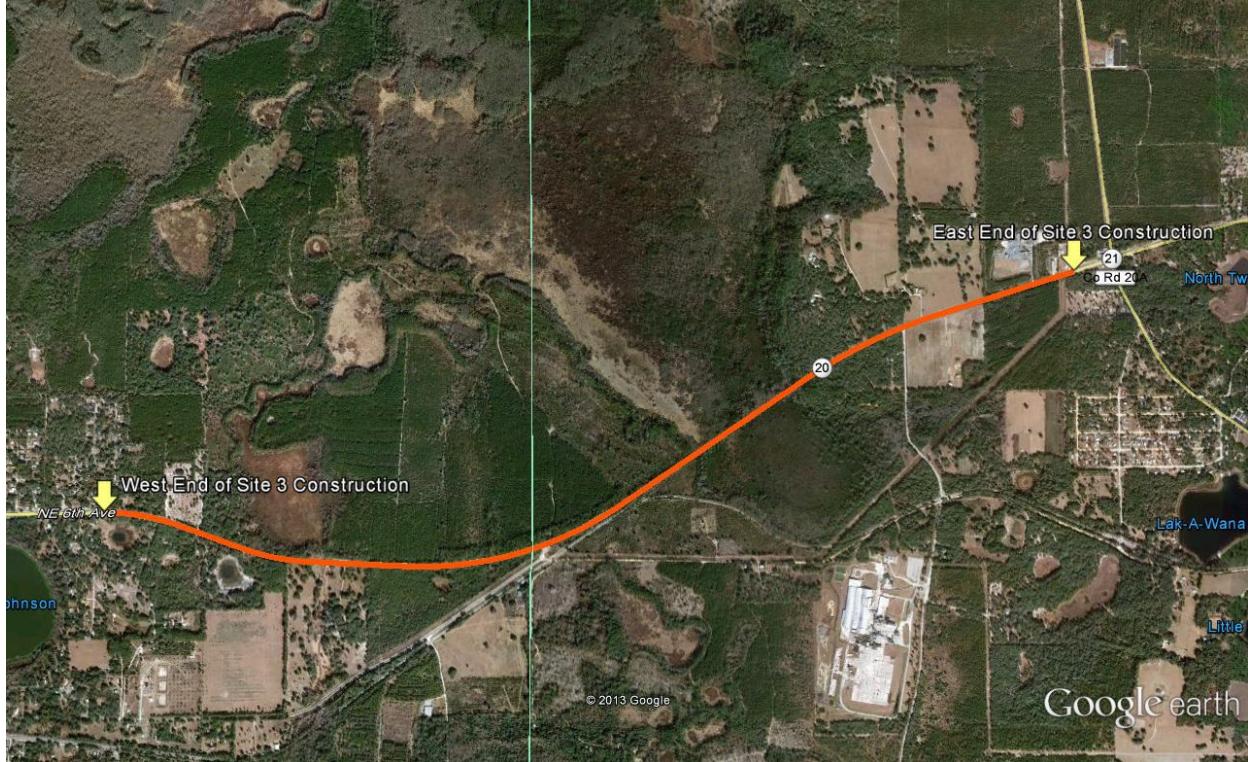


Figure 9. Extent of construction along SR-20 (site 3)

Data Collection Procedure

To obtain adequate data for calibration of the FlagSim simulation program, it was desirable to obtain approximately 4 hours of data each day for 4 different days at each of the three study sites. Due to the microscopic nature of the data required for this study, video was selected as the method by which to collect the data. For each study site, stationary cameras were placed at each end of the lane closures to observe vehicles entering and exiting the work zone, queuing at the work zone, and flagging operations. The video feed was recorded to an external hard drive recorder which was secured in a Pelican case next to the camera. Both the camera and hard drive recorder were powered by a single 12-volt battery. An example of the type of equipment and set up used to collect the data is shown in Figure 10.



Figure 10. Video camera and external hard drive recorder setup used for data collection

In addition to obtaining data at the entrances to the work zones, it was also desirable to obtain some data on the traffic operations within the lane closure. In order to obtain information about these traffic operations, an instrumented Honda Pilot was driven through the work zone along with regular traffic. This vehicle was equipped with cameras that recorded video of each trip that was made through the work zone. This video was used to obtain information about other factors within the work zone, such as available lane width, construction activity, and construction vehicle presence that may have a significant impact on vehicles' travel times through the work zone. It was desired to record approximately 12 trips through the work zone (6 in each direction) for each couple of hours of data collection at each site. Figure 11 shows the instrumented vehicle used for the data collection.



Figure 11. Instrumented Honda Pilot used to collect data inside work zone

Description of Data Obtained from Study Sites

Video from Stationary Cameras

A total of 34.5 hours of data was obtained from the three study sites. Data for site 1 were collected on 10/25/2011, 10/27/2011, and 10/28/2011. Approximately 4 hours of data was collected on 10/25/2011 and 10/27/2011, while 3 hours of data were collected on 10/28/2011.

Figure 12 shows a frame capture from one of the videos recorded at this site.



Figure 12. Entrance to work zone at site 1 on 10/25/2011

Data for site 2 were collected on 02/01/2012, 02/03/2012, 02/06/2012, 02/08/2012, and 02/09/2012. Unfortunately, the data collected on 02/01/2012 did not prove useful as it contained very minimal amounts of traffic (only 1 to 3 vehicles in queue). This very low traffic demand does not lend itself well to reliable calibration of the FlagSim program. As a result, these data

was not used for the purposes of this project. Approximately 13.5 hours of data were collected on the remaining three days at the site. Specifically, 6, 2.5, 1.5, and 3.5 hours of data were collected on 02/03/2012, 02/06/2012, 02/08/2012, and 02/09/2012, respectively. Figure 13 shows a frame capture from one of the videos recorded at this site.



Figure 13. Entrance to work zone at site 2 on 2/3/2012

Data were collected from site 3 on 01/21/2013, 01/23/2013, 01/24/2013, and 01/25/2013. Because this site featured shorter lane closures, it was necessary for the construction crew to move the location of the lane closure more frequently as the construction progressed throughout the day. As a result, the length and location of the lane closure varied throughout each day. Approximately 10 hours of data were collected at this site. Specifically, 2, 2.5, 3, and 2.5 hours

of data were collected on 01/21/2013, 01/23/2013, 01/24/2013, and 01/25/2013, respectively.

Figure 14 shows a frame capture from one of the videos recorded at this site.



Figure 14. Entrance to work zone at site 3 on 1/25/2013

Video from Instrumented Honda Pilot

A total of 117 trips were made through the various work zones at the three sites. Fifty-one trips were made at site 1, 29 trips were made at site 2, and 37 trips were made at site 3. Figure 15, Figure 16, and Figure 17 show frame captures from the in-vehicle videos recorded at sites 1, 2, and 3, respectively.



Figure 15. Video from instrumented Honda Pilot at site 1 on 10/25/2011



Figure 16. Video from instrumented Honda Pilot at site 2 on 2/9/2012



Figure 17. Video from instrumented Honda Pilot at site 3 on 1/24/2013

Data Processing

Once the data had been collected at a lane closure site, it was necessary to process these data to obtain the information needed for the calibration of FlagSim. This processing required watching the videos from both the stationary cameras as well as from the instrumented Honda Pilot. Pertinent information from these videos was recorded into Excel spreadsheets. The data items that were obtained from these two video sources are discussed in the following sections.

Before proceeding with the discussion, the following definitions are provided for several terms used throughout the remainder of this report:

- *Green time*: “Green” time, which means “go time”, is the time during which, for a given travel direction, the flag person’s paddle/sign is displaying ‘slow’. The total green time is calculated as the difference in time from when the flag person changes the paddle/sign from ‘stop’ to ‘slow’ and back to ‘stop’. The definition of this term as used in this study is consistent with the definition of ‘displayed green time’ in signalized intersection analysis.
- *Red time*: “Red” time, which means “stopped time”, is the time during which, for a given travel direction, the flag person’s paddle/sign is displaying ‘stop’. The total red time is calculated as the difference in time from when the flag person changes the paddle/sign from ‘slow’ to ‘stop’ and back to ‘slow’. The definition of this term as used in this study is consistent with the definition of ‘displayed red time’ in signalized intersection analysis.
- *Phase time*: The phase time was calculated as the green time plus the time it takes the last vehicle to enter the work zone during the displayed green to exit the work zone. More generally, this is referred to as green time plus work zone travel time. There were some cases where the flag person allowed one or more vehicles to enter the work zone after he/she turned the paddle/sign to ‘stop’. In these cases, the time that the flag person changed the flag to ‘stop’ was changed to the time that the last vehicle entered the work zone. However, this was not done in cases where the vehicle(s) that entered after the paddle/sign had been changed to ‘stop’ were associated with the construction activities (i.e., the vehicle did not exit the work zone during that phase).
- *Lost time*: As used in this study, the definition of total lost time for a phase is consistent with the definition as used in signalized intersection analysis—that is, the time during which vehicles for a given approach/direction are not moving. This lost time is typically separated into a ‘startup’ lost time component and a ‘clearance’ lost time component. The startup lost time is considered to be the difference between the time when the front bumper of the last vehicle to exit the work zone crosses the stop bar and the time when the front bumper of the first vehicle of the opposing direction enters the work zone. The

clearance lost time is considered to be the travel time through the lane closure area of the last vehicle for the opposing direction to enter the work zone, for a given phase.

- *Cycle time*: The cycle time (or length) is calculated as the difference in time from when the flag person for a given travel direction changes the paddle/sign from ‘stop’ to ‘slow’ to ‘stop’ and back to ‘slow’ again. This is equivalent to the phase time for one travel direction plus the phase time for the opposing travel direction.

Data from Stationary Camera Video

Some of the parameters outlined in the data requirements section were obtained from the stationary camera videos. An Excel spreadsheet was used to organize data for each travel direction for each day and site. An example of the type of Excel spreadsheet created for the stationary camera video data is shown in Appendix A. The data are organized for each phase observed from the video recordings. For each phase, certain information was recorded in order to obtain data for the parameters outlined in the data requirements section. This section discusses how such information was used to determine values for the parameters in the data requirements section. A discussion on what type of flagging control was employed in the field is also discussed.

Displayed paddle/sign indication change times

The time at which a flag person for a given travel direction change the displayed indication (‘slow’ or ‘stop’) was recorded. This allowed several of the above-defined time-related definitions to be calculated.

Vehicle type and work zone travel time

A record of each vehicle that entered the work zone was created. Each record contained the vehicle’s work zone entry time and work zone exit time (for those vehicles that exited the work zone). Using the work zone entry and exit times of the vehicle, the work zone travel time for the vehicle was obtained. The vehicle was also classified as either a passenger car (PC),

small truck (ST), medium truck (MT), or large truck (LT). Pictures showing how the truck categories were classified can be found in Appendix B.

Average speed of vehicles in the work zone per phase

The work zone travel times for all vehicles entering the work zone during a given phase were averaged. This average work zone travel time was then used along with the length of the lane closure to determine the average speed of vehicles through the work zone for the phase.

Number of vehicles entering the work zone per phase

The time when each flag person switched their paddle/sign was recorded. From this information and the work zone entry time for each vehicle, the number of vehicles entering the work zone for each phase could be determined. It was also possible to determine how many vehicles of each different vehicle classification (e.g., passenger car, small truck) entered the work zone during each phase.

Startup lost time

The amount of startup lost time is a function of several factors. The first delay occurs as the last vehicle exiting the work zone travels from the work zone exit point to a safe distance in order to allow the next direction of vehicles to proceed. The exiting vehicle must maneuver the lane switch area and pass the first few vehicles queued. Second, additional time is needed for the flag person to switch their paddle/sign, such as the time it takes the flag person to determine when the work zone is clear. Finally, there is lost time for the first vehicle reacting to the change of the sign, similar to vehicles' startup lost time at a signalized intersection.

The startup lost time for each phase was calculated by taking the difference between the time the first vehicle in queue entered the work zone and the time the last vehicle traveling in the opposing direction exited the work zone. If the last vehicle traveling in the opposing direction exited after the flag person changed the paddle/sign to 'slow', the startup lost time calculation

was modified. In this case, the startup lost time was calculated by taking the difference between the time the first vehicle in queue entered the work zone and the time the flag person changed the paddle/sign to ‘slow’.

The mean and standard deviation of the startup lost time was determined for each site. These values are shown in Table 2. From this table, it can be seen that the first two sites had larger means and standard deviations than the third site. This is likely a result of the longer lane closures at these sites. Since these sites were more rural in nature and had longer lane closures, the amount of time that some drivers were waiting to enter the work zone was in the order of 4 to 7 minutes. As a result, some drivers were not paying as much attention to the flag person and took a little more time to start up after the flag person changed the paddle/sign to ‘slow.’ This resulted in larger startup lost time values compared to those obtained from the third site, which had shorter lane closures and was less rural in nature.

Table 2. Startup Lost Time Values Determined for Each Site

Site #	Startup Lost Time	
	Mean (s)	Std. Dev. (s)
1	14.73	10.56
2	15.18	11.56
3	10.00	4.75

Queue length

The queue length for each phase and direction was obtained by simply counting the number of vehicles in queue prior to the flag person changing the paddle/sign to ‘slow’.

Saturation headway

The saturation headway for each phase and direction was obtained by using the work zone entry times of the first eight vehicles in queue. Specifically, this value was calculated by taking

the difference between the work zone entry times of the first and eighth vehicle in queue and dividing by the number of headways between the first and eighth vehicle.

Type of flagging control employed

After watching the videos from the stationary cameras, it seemed as though most flag persons were using a ‘distance gap out’ mechanism to judge when to switch the travel direction right-of-way. The main input for this type of flagging control in FlagSim is the mean distance gap out value. From watching the videos, it was difficult to determine the distance gaps that the flag persons were using to control their paddle/sign. Therefore, the mean distance gap out value could not be determined with much accuracy. The time gaps associated with the distance gaps that the flag persons used, however, could be easily determined from the videos. While it is unrealistic for a flag person to directly employ a ‘time gap out’ method in the field, since the flag person would have to constantly look at a timing device, the use of a time gap out flagging control would allow for the best calibration of the FlagSim program. Therefore, a time gap out flagging control was used in place of a distance gap out flagging control for calibration of the FlagSim program.

In order to use this time gap out flagging control for the FlagSim calibration, it was necessary to determine the mean and standard deviation of the time gap out values used by the flag persons. The mean time gap out value was determined using a critical gap procedure. Specifically, Raff’s critical gap method (1950) was used, which required the use of the gaps the flag persons accepted as well as rejected. This is the same method used to identify critical gap acceptance values for the unsignalized intersection analysis procedure in the HCM.

An accepted gap was calculated by taking the difference between the work zone entry times of two consecutive vehicles that entered the work zone during the same phase. Each phase contained multiple accepted gaps if more than two vehicles entered the work zone during the

phase. A rejected gap was calculated for a given phase by taking the difference between the time the first vehicle arrived at the work zone after the flag person changed the paddle/sign to ‘slow’ and the time the last vehicle in the phase entered the work zone. There was only one rejected gap per phase.

Rather than estimating the time gap out values to the nearest second, it was determined that it would be more beneficial to estimate the time gap out values to the nearest 5 seconds. This was because the actual values of the accepted and rejected gap values were only accurate within a couple of seconds, since the work zone entry times could only be obtained from the videos to the nearest second. Therefore, the accepted and rejected gap values were placed into 5 second bins between 0 and 60 seconds. Values greater than or equal to 60 seconds were placed into a separate bin, since a very small number of gaps greater than or equal to 60 seconds were accepted by the flag persons.

After the accepted and rejected gaps were placed into these bins, the critical time gap out value was determined. A graph was created to show the cumulative number of accepted gaps and rejected gaps for the different bins. From this graph the critical time gap out value was determined by looking at the point where these cumulative curves intersected. This value was used as the mean time gap out value in FlagSim. Since the critical time gap out value was only accurate within 5 seconds, it was decided that a standard deviation of 5 seconds was appropriate for the time gap out value.

Critical time gap out values were determined for each site. These values are shown in Table 3. From this table, it can be seen that the first two sites had a larger mean critical time gap out value as compared to the third site. This is likely a result of the longer lane closures and smaller traffic demands at sites 1 and 2. Because the lane closures were longer and not as many

vehicles needed to enter the work zone, the flag persons would generally allow any late arriving vehicles to enter the work zone, even if the vehicles were a good distance away from the work zone. This in turn increased some of the accepted gap values, which resulted in a larger critical gap. The graphs that were used to obtain the critical gap values for each site are shown in Figure 18, Figure 19, and Figure 20. The data used to create these plots can be found in Appendix A.

Table 3. Critical Time Gap Out Values Determined for Each Site

Site #	Critical Time Gap Out	
	Mean (s)	Std. Dev. (s)
1	30	5
2	30	5
3	25	5

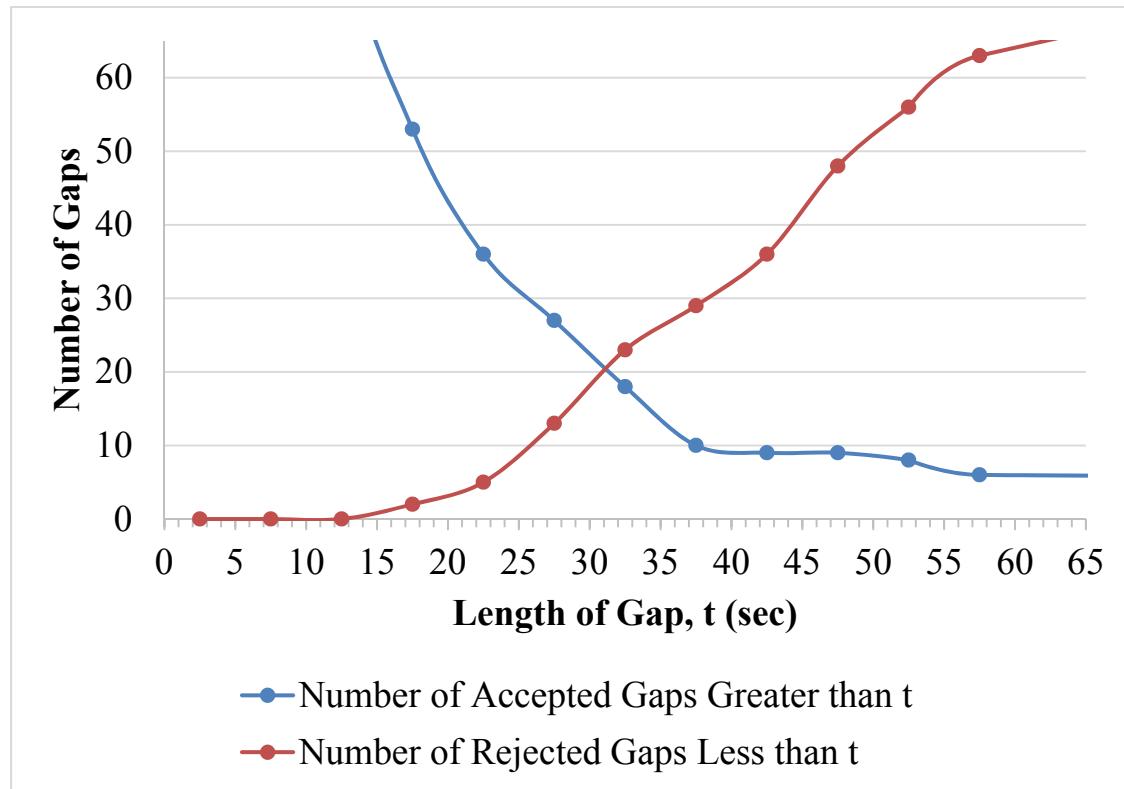


Figure 18. Critical gap for site 1

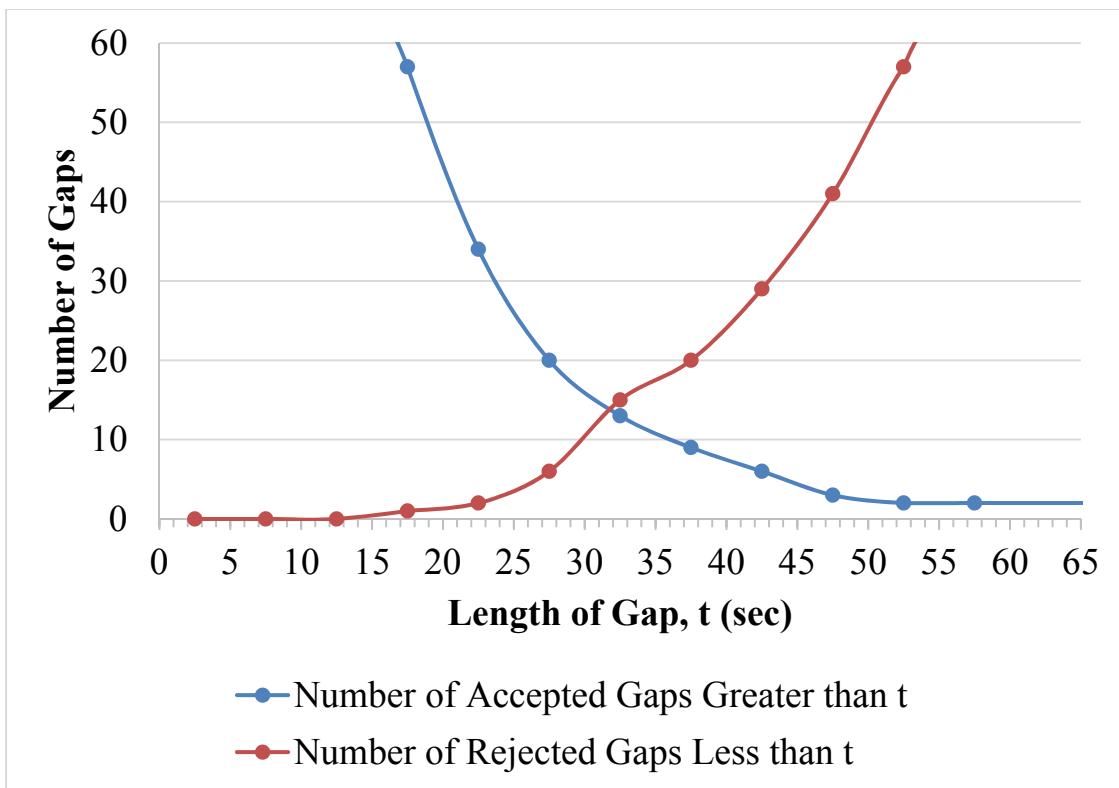


Figure 19. Critical gap for site 2

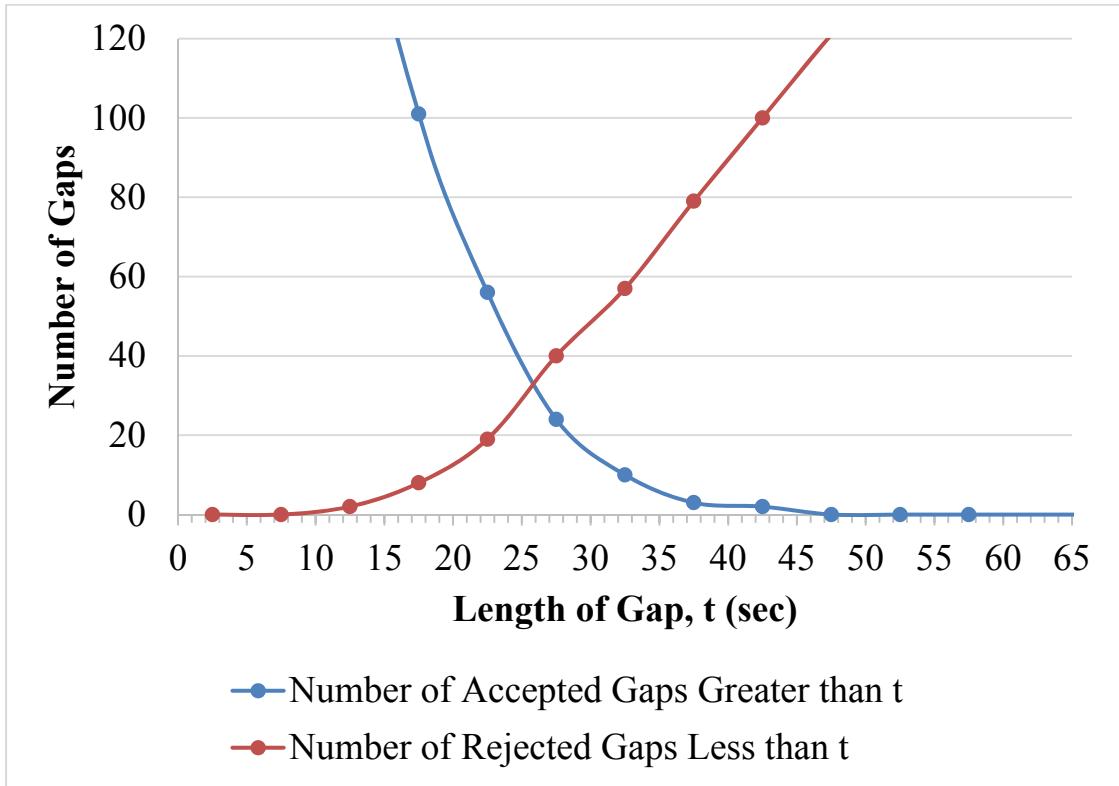


Figure 20. Critical gap for site 3

Video from Instrumented Vehicle

Video of trips made through the work zone in the instrumented Honda Pilot were used to ascertain information about different factors within the work zone that may have an impact on traffic operations in the work zone. Specifically, it was desirable to determine what factors may have an impact on vehicles' speeds through the work zone. From watching the videos, it was observed that the following factors may have influenced vehicles' speeds:

- Effective lane width – the width of the pavement available for vehicles to drive on (includes paved shoulders)
- Construction activity – level of construction activity taking place (e.g., milling and resurfacing, shoulder work, sodding)
- Construction vehicle presence – number of stationary construction vehicles parked on the closed lane in close proximity to vehicles traveling on the open lane
- Travel direction of closed lane – whether drivers will have to travel in the “opposing” lane through the work zone
- Percentage of construction vehicles entering the work zone – the percent of construction vehicles that entered the work zone during a phase but did not exit

Information about the first four factors above was determined from the instrumented Honda Pilot video. Information about the last factor, percentage of construction vehicles entering the work zone, was determined from both the stationary camera video and instrumented Honda Pilot video. An Excel spreadsheet was used to organize information about each of these factors for all recorded trips through the work zone. A screenshot of this spreadsheet can be found in Appendix A. The type of information obtained for each of these factors is discussed below in its respective section.

Effective lane width

Based on observations from the videos, it was hypothesized that as the lane width available to drivers in the work zone decreased, the average speed of vehicles in the work zone also decreased. Therefore, this effective lane width was recorded for each trip made through the work zone by the instrumented Honda Pilot. It was difficult to determine a precise numeric

value for the effective lane width from the videos, so this variable was categorized into three general levels (narrow, medium, and wide).

Narrow lane widths were assigned for lanes that had no, or a very narrow, shoulder and cones placed inside the lane. Figure 21 shows an example of a narrow effective lane width. Medium lane widths were assigned for lanes that had a small shoulder and cones placed outside the lane or on the centerline. Medium lane widths were also assigned for lanes that had a relatively wide shoulder and cones placed inside the lane. Figure 22 shows an example of a medium effective lane width. Wide lane widths were classified for a lane with a relatively wide shoulder and cones placed outside the lane or on the centerline. Wide lane widths were also assigned for lanes that had a narrow shoulder but cones placed outside the lane. Figure 23 shows an example of a wide effective lane width.

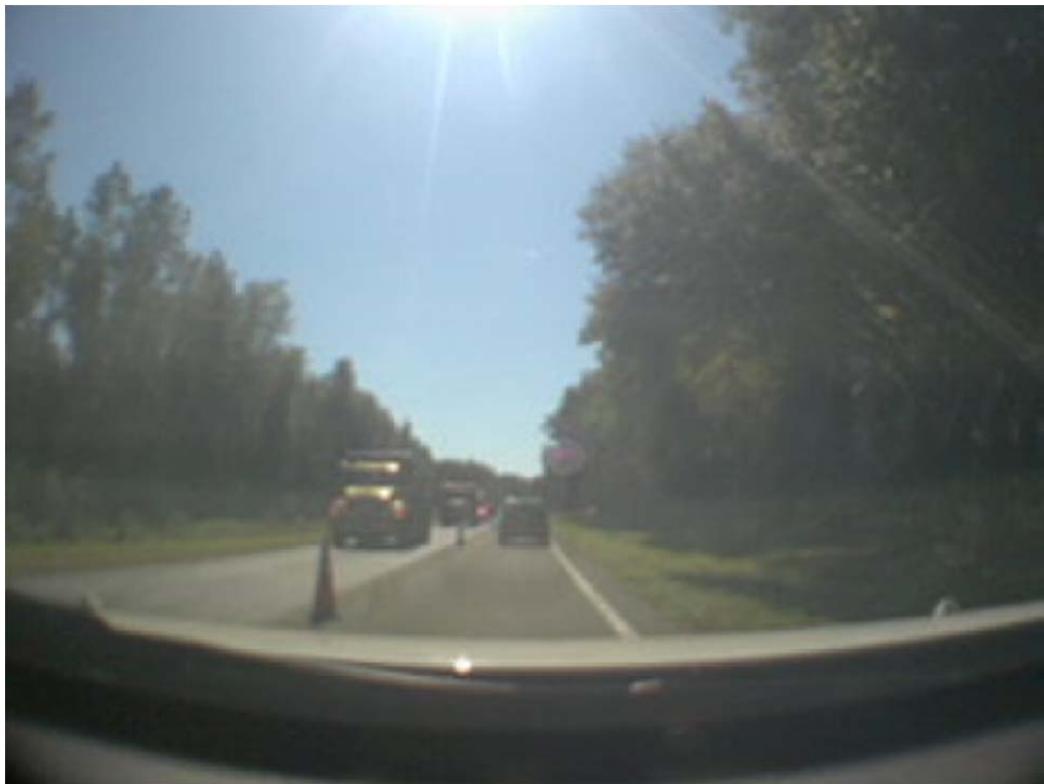


Figure 21. Example of narrow effective lane width from site 1



Figure 22. Example of medium effective lane width from site 2



Figure 23. Example of wide effective lane width from site 3

Construction activity

The construction activity in the work zone also appeared to have an effect on vehicles' speeds in the work zone. Therefore, the construction activity was recorded for each trip through the work zone. Since a numeric value was not able to be put on the construction activity, three different categorical levels were used for this variable (low, medium, and high). Low construction activity was considered for activities such as sodding, shoulder work, or any other activity that required few construction vehicles or equipment to operate close to the open travel lane. Medium construction activity was considered for activities such as milling or resurfacing or any other activity that required several construction vehicles or pieces of equipment to operate close to the open travel lane. High construction activity considered for activities such as both milling and resurfacing taking place at the same time or any other activity that required a large number of construction vehicles or equipment to operate close to the open travel lane.

Construction vehicle presence

The number of stationary construction vehicles that were in proximity to the open travel lane was also thought to have some effect on vehicles' speeds in the work zone. Since some construction vehicles (e.g., dump trucks, rolling equipment) would sit on the closed travel lane in close proximity to the open travel lane, it was thought that drivers may tend to slow down when driving past these vehicles. This could lead to lower average speeds in the work zone. The presence of construction vehicles was recorded for each trip made with the instrumented Honda Pilot. Developing a precise numeric value for this factor was not practical; thus, three different categorical levels were used (low, medium, and high). Low construction vehicle presence was defined as having very few construction vehicles in the work zone, and if there were vehicles, they were not close to the open travel lane. Medium construction vehicle presence was defined as having a few construction vehicles in the work zone. These were mainly pickup trucks or

other smaller pieces of construction equipment, but there could be a few larger construction vehicles (e.g., dump trucks). A few of these construction vehicles would be close to the open travel lane, but the majority would not. High construction vehicle presence was defined as having a large number of construction vehicles in the work zone. These vehicles would consist of larger construction vehicles (e.g., dump trucks, semi-tractor trailers), and many of these vehicles would be in close proximity to the open travel lane.

Travel direction of closed lane

If a driver is traveling on the lane that is closed, he/she will have to temporarily switch lanes and travel on the opposing lane when proceeding through the work zone. Since drivers are not accustomed to driving in the opposite lane, they may be more cautious when proceeding through the work zone. As a result, the average speed of vehicles in the work zone may be slightly lower for the travel direction with the closed lane as opposed to the direction with the open lane. The travel direction of the closed lane was recorded for each of the trips through the work zone in the Honda Pilot.

Percentage of construction vehicles entering the work zone

When watching some of the videos, vehicles associated with the construction activities (e.g., dump trucks) were seen departing from the open travel lane and moving onto the closed travel lane to help with the construction activities. Before these vehicles moved off the open travel lane and onto the closed travel lane, they usually decelerated, sometimes causing the vehicles traveling behind them to slow down. As a result, the travel times of these vehicles may have been extended due to this impedance by the construction vehicles. Information about how many of these construction vehicles entered the work zone was not able to be accurately determined from the instrumented Honda Pilot videos. Fortunately, this information could be obtained from the stationary camera video. Therefore, the construction vehicles which entered

the work zone but did not exit were identified for each phase. These vehicles were temporarily assigned a classification of CV, for construction vehicle, within the spreadsheet data logs. The percentage of construction vehicles that entered the work zone was then determined for each of the trips the Honda Pilot made through the work zone. It should be noted that most of the construction vehicles that entered the work zone and did not exit were dump trucks.

Models from Field Data

Two models were estimated from the field data—one for average travel speed through the work zone and one for the average saturation headway of vehicles discharging from a queue into the work zone.

Work Zone Speed Model

With the impact to the overall cycle length due to the lost time caused by traversing the work zone, the estimation of the work zone travel speed must be as accurate as possible. A regression analysis was performed on all of the data recorded from the Honda Pilot trips through the work zone (92 trips). The resulting model formulation is shown in Eq. 8.

$$\begin{aligned} WorkZoneSpd_i = & 0.4611 - 0.4694 \times \%HV_i - 12.9068 \times LW_Narrow - 8.2328 \times LW_Medium \\ & + 0.8501 \times PostedSpd - 1.33 \times TravelDirClosedLane - 0.0590 \times NumVeh_i \\ & - 2.5092 \times ConstAct_MedHigh + 0.5310 \times \%HV_i \times LW_Narrow + 0.2993 \times \%HV_i \times LW_Medium \end{aligned} \quad [8]$$

where

$WorkZoneSpd_i$ = average travel speed of vehicles through the work zone for phase i (mi/h)

$\%HV_i$ = percentage of heavy vehicles in the traffic stream for phase i

LW_Narrow = 1 if the effective lane width is narrow, 0 otherwise

LW_Medium = 1 if the effective lane width is medium, 0 otherwise

$PostedSpd$ = the posted speed limit through the work zone (mi/h)

$TravelDirClosedLane$ = 1 if vehicles are traveling in the direction of the closed lane (i.e., they perform a lane shift when entering and exiting work zone), 0 otherwise

$NumVeh_i$ = the number of vehicles entering the work zone for phase i

$ConstAct_MedHigh$ = 1 if the level of construction activity in the work zone is medium or high, 0 otherwise

The signs of the variables are all as expected. When interpreting coefficient signs, keep in mind that some variables appear more than once in the equation (e.g., %HV and lane widths), and that some terms are interactions (e.g., the last two terms). All of the non-intercept terms were significant at the 95% or better confidence level, except for the *NumVeh* term, which was significant at the 90% confidence level and the *ConstAct_MedHigh* term, which was significant at the 85% confidence level. The adjusted R^2 value of the model is 0.684. Given all of the variability in the field data, this moderate level of model fit was expected.

Saturation Headway Model

One of the key parameters to all of the calculations in the analysis procedure is saturation headway. This measure refers to the time headway between vehicles when departing from a standing queue when the traffic signal (or flag person's paddle/sign in this case) turns green. A regression analysis was performed on all of the phase data recorded from the field for phases that had at least 8 vehicles in queue at the start of the phase (358 phases). The resulting model formulation is shown in Eq. 9.

$$\bar{h}_{sat_i} = 2.9817 + 0.0127 \times \%ST_i + 0.0417 \times \%MT_i + 0.0487 \times \%LT_i \quad [9]$$

where

\bar{h}_{sat_i} = average saturation headway for phase i (s/veh)

$\%ST_i$ = percentage of small trucks in the traffic stream for phase i

$\%MT_i$ = percentage of medium trucks in the traffic stream for phase i

$\%LT_i$ = percentage of large trucks in the traffic stream for phase i

The signs of the variables are all as expected, and all of the terms were significant at the 95% or better confidence level. The adjusted R^2 value of the model is 0.627. Again, given all of the variability in the field data, this moderate level of model fit was expected.

CHAPTER 4

SIMULATION ANALYSIS AND RESULTS

This chapter describes the simulation aspect of this project. Because a wide range of input conditions were not obtained from the field sites described in the previous chapter, it was necessary to use simulation to be able to analyze the performance of two-lane roadways with a lane closure across a wide range of conditions (e.g., length of lane closure, traffic demand, work zone posted speed, etc.). The main purpose of the field data was to identify the appropriate values for the various settings that affect the behavior of the vehicles and flagging operations in the simulation program.

Two-lane work zones are unique in their operation. In order to model the operations reasonably accurately, a simulation program must have the following capabilities at a minimum:

- model the flagging control method used in the field
- model vehicle arrivals at the work zone
- model vehicles discharging from the stop line
- model heavy vehicles, in addition to passenger cars
- model vehicles traveling through the work zone
- record various simulation results in order to allow for the following performance measures to be calculated, such as
 - queue delay
 - travel time delay due to reduced speeds
 - queue length
 - capacity

Most, if not all, existing commercially available simulation packages do not explicitly provide for modeling work zones on two-lane roadways, nor are they easily configured for such

modeling, particularly because of the unique aspects of flagging control. The FlagSim simulation program was used for the simulation aspects of this project. This program was also used for the predecessor project to this one; however, it has undergone a number of enhancements since that time. A detailed overview of the program is provided in the Users Guide, which is included in Appendix C of this report.

Calibration

The calibration effort consisted of initially setting the various driver and vehicle parameters in FlagSim to values consistent with observations from the field data and/or other data sources. A large number of simulation runs, with a range of input conditions consistent with the range of input conditions observed in the field, were then made. The simulation results for average work zone travel speed and average saturation headway were then compared to the field values. This process was repeated many times, with small revisions made to one or more of the driver parameters each time. The driver parameter values that resulted in the best fit of the simulation data to the field data were retained for further use in the FlagSim simulation runs. The vehicle parameters were not varied from their initial settings. The vehicle and driver parameters are accessed through the ‘Advanced Vehicle/Driver Parameters’ screen in FlagSim (see Users Guide in Appendix C). These parameters and their settings are described in the remainder of this section.

Vehicle Parameters

Vehicle Dimensions (length, width, height)

The three truck classifications discussed in the previous chapter were generally matched to the standard FHWA classifications as follows:

- Small Truck—Class 5 and 6
- Medium Truck—Class 8
- Large Truck—Class 9, 11, and 12

The dimensions of the three truck types were set accordingly. The passenger car dimensions were based on common sedan-type vehicle—specifically a Honda Civic. The selected dimensions are shown in Table 4.

Maximum Acceleration

Maximum acceleration is not an input to FlagSim. FlagSim now uses a full vehicle dynamics modeling approach to determine the maximum acceleration of a vehicle. This model takes into account the vehicle’s physical (such as frontal area, drag coefficient, and weight) and drivetrain (such as engine output and transmission gearing) characteristics to determine the tractive effort available to accelerate the vehicle at every time step during the simulation. This approach also allows roadway grade to be accounted for, as this affects the grade resistance in the acceleration calculations. This approach for modeling maximum acceleration is described in more detail in the FlagSim Users Guide (see Appendix C).

Vehicle Weight

For another FDOT research project (BDK77-977-15), weigh-in-motion (WIM) data were obtained for numerous locations across the state for a recent 3.5 year period. Of the 24 WIM data collection locations, three of these stations were located on two-lane highways. The data from these three sites were used to establish weight values for the three truck types. The passenger car weight was based on the vehicle manufacturer’s data specification sheet. The selected weights are shown in Table 4.

Drag Coefficient

The drag coefficient values were set according to guidance in Mannering and Washburn (2012) (see Chapter 2).

Maximum Torque and Power

The maximum engine torque and power were set according to the values established through FDOT Project BDK77-977-15. These values are shown in Table 5.

Transmission Gear Ratios

The transmission gear ratios were set according to the values established through FDOT Project BDK77-977-15. The reader is referred to that project report for the specific values.

Maximum Deceleration

Typically achievable maximum deceleration rates as shown in Table 5 were used. However, since these deceleration rates usually only occur in emergency braking situations, they rarely are utilized in a FlagSim simulation.

Table 4. Vehicle Type Physical Characteristics

Vehicle Type	Length (ft)	Width (ft)	Height (ft)	Weight (lb)	Drag Coeff.
Passenger car	14.6	5.7	4.5	3060	0.33
Small truck	30	7	10	17000	0.55
Medium truck	45	8	10	36000	0.66
Large truck	68.5	9	10	53000	0.66

Table 5. Vehicle Type Drivetrain Characteristics

Vehicle Type	Max Torque (ft-lb)	Max Power (hp)	Max Decel (ft/s²)
Passenger car	139	197	-19
Small truck	660	300	-15
Medium truck	1650	485	-15
Large truck	1650	485	-15

Driver Parameters

Desired Acceleration

The desired acceleration rates were set as 3.8 ft/s², 2.5 ft/s², 2.0 ft/s², and 2.0 ft/s² for passenger cars, small trucks, medium trucks, and large trucks, respectively. These values were consistent with in-vehicle GPS data from other studies and observations from the field videos.

Desired Deceleration

Values of 10 and 11 ft/s² have been identified as appropriate for non-emergency braking situations (Mannering and Washburn, 2012). A value of 11 ft/s² was used for passenger cars. Since truck drivers are usually a little less tolerant of having to decelerate, slightly lower values were used—9 ft/s², 8 ft/s², and 7 ft/s² for small, medium, and large trucks, respectively.

Desired Speed %

The base desired speed value is a function of factors such as posted speed limit, construction activity, effective lane width, and direction of closed lane. This desired speed % input specifies the percentage difference from the base desired speed value that a driver will desire to travel when not constrained by other vehicles. To identify these values, the average speeds through work zone of the different vehicles types were calculated. Values were calculated for all vehicles traveling through the work zone, just the vehicles not considered to be in a following mode (using a headway threshold of 6 seconds), and just the lead vehicle of each platoon of vehicles traveling through the work zone. After examination of all the values, it was felt that the values based on just the lead vehicles of platoons were the most reliable. From these measurements, values of 7.5%, 0%, -3%, and -5% were set for passenger cars, small trucks, medium trucks, and large trucks, respectively. In other words, passenger car drivers will travel 7.5% above the base desired speed value, on average, while large truck drivers will travel 5% below the base desired speed value, on average.

Desired Headway

The desired following headway values were set as 1.5 s, 2.25 s, 2.75 s, and 3.0 s for passenger cars, small trucks, medium trucks, and large trucks, respectively.

Stop Gap

This input specifies the distance between the rear bumper of a lead vehicle and the front bumper of a trail vehicle, while at a stop (i.e., in a queue waiting to enter the work zone). The stop gap values were set as 12 ft, 16 ft, 20 ft, and 22 ft for passenger cars, small trucks, medium trucks, and large trucks, respectively.

Other Input Values

Other inputs necessary to run the simulations for the calibration, as well as all subsequent simulations are as follows.

Flag Control Settings

- Flagging method: As discussed in Chapter 3, the ‘time gap out’ flagging method was employed in FlagSim. Based on the field results of gap out times, it was decided to use a mean gap out time of 30 seconds (with a standard deviation of 5 seconds) for ‘rural’ conditions, which were considered to be sites with lane closures of one mile or greater and posted speed limits greater than 40 mi/h, and a mean gap out time of 25 seconds (with a standard deviation of 5 seconds) for all other conditions.
- Startup lost time: As for the gap out times, two different sets of times were used for rural and non-rural conditions. For rural conditions, a mean startup lost time of 15 seconds (with a standard deviation of 10 seconds) was used, and for all other conditions a mean startup lost time of 10 seconds (with a standard deviation of 5 seconds) was used.
- Minimum green time: This value was set to 5 seconds. This variable is essentially a non-factor when the time gap out flagging method is used.
- Maximum green time: This value was set to 300 seconds. Most field phases were considerably shorter than this, but a few phases reached as high as 290 seconds.

Vehicle Distribution

While a variety of total truck percentages were run as part of the overall set of simulation runs, the relative percentages of small, medium, and large trucks were varied only at two levels. Based on the field data, the small, medium, and large truck percentage splits used were 20, 35,

and 45, respectively, for rural conditions. For non-rural conditions, the small, medium, and large truck percentage splits used were 45, 20, and 35, respectively.

Approach Roadway Length

The approach roadway length was set to 1.5 miles, which was sufficient to accommodate the queuing for nearly all simulation scenarios. Any simulation runs that resulted in a queue length equal to the approach roadway length (FlagSim will only report queue lengths up to the length of the approach roadway length) were removed from the data set.

Approach Roadway Posted Speed

The approach roadway posted speed was set to the same value as the work zone posted speed.

Work Zone Travel Delay Threshold Speed

The work zone travel delay threshold speed is set to the work zone posted speed. Vehicles traveling less than this speed in the work zone accumulate travel delay.

Queue Delay Threshold Speed

The queue delay threshold speed is set to 10 mi/h. Vehicles traveling less than this speed on the approach roadway accumulate queue delay.

Simulation Duration

A 5-minute warm-up period and a 60-minute simulation period were used for each simulation run.

Results

The calibration results between FlagSim and the field data for average work zone travel speed were based on a total of 1012 individual phases that covered a wide range of inputs. A linear regression analysis of the two sets of values produced an adjusted R^2 value of 0.732.

The calibration results between FlagSim and the field data for average saturation headway were based on a total of 845 individual phases that covered a wide range of inputs. A linear regression analysis of the two sets of values produced an adjusted R^2 value of 0.852.

Again, any driver parameter values different from the values given above resulted in lower R-squared values. Overall, this level of calibration between the field data and FlagSim is quite reasonable given the considerable variability in the field conditions.

Simulation-Based Models

With the appropriate values set for the various driver parameters and other input variables through the calibration effort, the final models to be used in the analysis procedure were then developed. These models consisted of work zone travel speed, saturation headway, queue delay, and queue length.

Work Zone Speed Model

The work zone speed model was based on results for over 17,000 one-hour simulation runs that covered a wide range of inputs. A regression analysis of all the simulation results yielded the model formulation shown in Eq. 10.

$$\begin{aligned} WorkZoneSpd_i = & 2.7481 - 0.1246 \times \%HV_i - 11.5697 \times LW_Narrow \\ & - 7.3768 \times LW_Medium + 0.0577 \times \%HV_i \times LW_NarrowMedium \\ & - 2.1289 \times ConstAct_MedHigh - 0.6907 \times TravelDirClosedLane \\ & - 0.0004 \times (\text{Min}(WZLen} \times GradeProp_i), 300) + 0.7492 \times PostedSpd \end{aligned} \quad [10]$$

where

$WorkZoneSpd_i$ = average travel speed of vehicles through the work zone for direction i (mi/h)

$\%HV_i$ = percentage of heavy vehicles in the traffic stream for direction i

LW_Narrow = 1 if the effective lane width is narrow, 0 otherwise

LW_Medium = 1 if the effective lane width is medium, 0 otherwise

$LW_NarrowMedium$ = 1 if the effective lane width is narrow or medium, 0 otherwise

$ConstAct_MedHigh$ = 1 if the level of construction activity in the work zone is medium or high, 0 otherwise

$TravelDirClosedLane$ = 1 if vehicles are traveling in the direction of the closed lane (i.e., they perform a lane shift when entering and exiting work zone), 0 otherwise
 $WZLen$ = length of the work zone (ft)

$GradeProp_i$ = grade proportion (i.e., %grade/100) in direction i (downhill grades should be entered as zero)

$PostedSpd$ = the posted speed limit through the work zone (mi/h)

This model is generally consistent with the field data based model, with a few small differences. The field model included a term for the number of vehicles entering the work zone during a phase, although this variable was only marginally significant. Given the controlled entry of vehicles into the work zone, the traffic volume level by itself has much less effect on average travel speed like it does under less controlled traffic flow environments. Furthermore, significant reductions in average travel speed are usually not observed for low to moderate flow rates (of passenger cars only), which is usually the norm for work zone situations. The number of trucks in the traffic stream has a much more significant effect on the work zone average travel speed than the overall traffic demand level. While the number of trucks can be implemented through an interaction term of demand and percent heavy vehicles, the use of the percent heavy vehicles variable individually provides nearly as good of a model fit as the interaction term, and since this model is applied at the simulation period level as opposed to the phase level, the application of this model using just an overall average of heavy vehicle percentage is more straightforward.

The simulation model includes a term for the combination of grade proportion and length of grade. This term is statistically significant in the model, but it has a very small impact on the overall average speed. While steep and/or long grades can have a large effect on truck speeds, average speeds through the work zone are typically only in the 30-40 mi/h range, even for a passenger car only stream. Trucks are usually able to maintain speeds in this range even on

moderately steep and/or long grades. Length of grade multiplied by grade proportion is limited to a maximum value of 300, which corresponds approximately to the point at which trucks will reach their crawl speed. The effect of grade was not observed from the field data because all of the study sites had level or very nearly level terrain.

The other difference from the field model is that the narrow and medium effective lane width variables have been combined into one term. All of the model terms are significant at the 99% or better confidence level. The adjusted R^2 value of the model is 0.960.

Saturation Headway Model

The saturation headway model was based on over 109,000 individual phases that covered a wide range of inputs. A regression analysis of all the simulation results yielded the model formulation shown in Eq. 11.

$$\bar{h}_{sat_i} = 3.0875 + 0.0180 \times \%ST_i + 0.0276 \times \%MT_i + 0.0379 \times \%LT_i + 0.2812 \times GradeProp - 0.0095 \times AvgWZspeed \quad [11]$$

where

\bar{h}_{sat_i} = average saturation headway for direction i (s/veh)

$\%ST_i$ = percentage of small trucks in the traffic stream for direction i

$\%MT_i$ = percentage of medium trucks in the traffic stream for direction i

$\%LT_i$ = percentage of large trucks in the traffic stream for direction i

$GradeProp_i$ = grade proportion (i.e., %grade/100) in direction i (downhill grades should be entered as zero)

$AvgWZspeed$ = average work zone travel speed for direction i , as calculated from Eq. 10 or using field-measured speeds (mi/h)

This model is generally consistent with the field data based model, with the difference that two additional terms are included, one for the $GradeProp$ variable and one for the $AvgWZspeed$ variable. Since the grades at the field sites were generally level, it was not possible to include this variable in the field model. Since FlagSim can now account for the effect of grade on

vehicle acceleration, grade was included as a variable in the experimental design, and as expected its effect was found to be statistically significant. Also, given that the field sites had a narrow range of posted speeds (50-60 mi/h), it was not surprising that average work zone travel speed was not found to be significant in the field data based model. With the wider range of work zone posted speeds run in the experimental design for the simulation based models, average work zone travel speed was found to be significant. The coefficient sign is also as expected—higher speeds through the work zone will reduce the saturation headway. All of the model terms are significant at the 99% or better confidence level. The adjusted R^2 value of the model is 0.792.

Total Queue Delay and Maximum Queue Length Models

The queue delay and queue length models were based on a very large set of simulation scenarios. The variables and ranges of input values used to develop the set of simulation input scenarios are identified in Table 6.

Table 6. Experimental Design for Simulation-Based Models

Variable	Range of Input Values
Length (mi)	0.25-2
Posted Speed (mi/h)	35-55
Grade (%)	0-6
Total Volume (veh/h)	200-1000
D Factor	0.5-0.7
HV %	0-20
Effective Lane Width	Narrow, Medium, Wide
Construction Activity	Low, Medium, High
Lane Closure Direction	Direction 1, Direction 2

Six replications were run for each input scenario. After removing simulation runs that resulted in over-capacity conditions, a total of 7541 simulation runs were used for the development of the queuing models. For the development of queue delay and queue length models in this project, scenarios that yielded volume-to-capacity ratios of 1.2 or greater were

removed from the analysis data set. Generally, for over-capacity conditions, simple deterministic queuing equations can be applied to estimate queue delay and queue length.

A regression analysis of all the simulation results yielded the total queue delay model formulation shown in Eq. 12.

$$\begin{aligned} TotalQDelay_i = & -0.56844 \times (g_i / C) (\%) + 0.42799 \times (v / s)_i (\%) + 0.00591 \times C \\ & + 0.09670 \times g_i - 0.00064 \times HV_i \times g_i \end{aligned} \quad [12]$$

where

$TotalQDelay_i$ = total queue delay for a 1-hr time period for direction i (veh-hr)
 (g_i / C) = average effective green time to cycle length ratio for direction i (expressed as a percentage)
 $(v/s)_i$ = volume to saturation flow rate ratio for direction i (expressed as a percentage)
 C = average cycle length (sec)
 HV_i = percentage of heavy vehicles in the traffic stream for direction i
 g_i = average green time for direction i

All of the model terms are significant at the 99% or better confidence level. The adjusted R^2 value of the model is 0.790. A regression analysis of all the simulation results yielded the maximum queue length model formulation shown in Eq. 13.

$$\begin{aligned} MaxQLength_i = & -1.49485 \times (g_i / C) (\%) + 0.65045 \times (v / s)_i (\%) + 0.01432 \times C \\ & + 0.35359 \times g_i - 0.00138 \times HV_i \times g_i \end{aligned} \quad [13]$$

where

$MaxQLength_i$ = average maximum queue length per cycle for direction i (veh/cycle)
Other terms are as defined previously

All of the model terms are significant at the 99% or better confidence level. The adjusted R^2 value of the model is 0.738. These two models have the same formulation, but with differing coefficient values, as expected. It should be noted that the use of queue delay in this study represents an intermediate measure of delay. The value of queue delay will fall between the

measure of stop delay (where delay is only accumulated when vehicle velocity equals zero) and the measure of control delay (where delay is accumulated for a vehicle any time its velocity is less than what the average running speed would be without the control).

CHAPTER 5

ANALYSIS PROCEDURE OVERVIEW

This chapter provides a step-by-step overview of the analysis procedure that is implemented into the spreadsheet tool.

Step 1: Enter input values

The analyst needs to enter values for the following inputs:

- Traffic demand for each direction
- Percentage of small trucks, medium trucks, and large trucks for each direction
- Roadway grade for each direction
- Length of work zone
- Field measured or estimated work zone travel speed
- If work zone travel speed is field measured
 - Work zone travel speed by direction
- If work zone travel speed is estimated
 - Work zone posted speed
 - Effective lane width
 - Level of construction activity
 - Travel direction with lane closure
- Startup lost time (or can use default value)
- Green time (or can use calculated minimum value)

Step 2: Calculate the work zone average travel speed

This step is skipped if the analyst enters field-measured average work zone travel speeds.

$$\begin{aligned} \text{WorkZoneSpd}_i = & 2.7481 - 0.1246 \times \%HV_i - 11.5697 \times LW_Narrow \\ & - 7.3768 \times LW_Medium + 0.0577 \times \%HV_i \times LW_NarrowMedium \\ & - 2.1289 \times ConstAct_MedHigh - 0.6907 \times TravelDirClosedLane \\ & - 0.0004 \times (\text{Min}(WZLen} \times GradeProp_i), 300) + 0.7492 \times PostedSpd \end{aligned} \quad [14]$$

where

WorkZoneSpd_i = average travel speed of vehicles through the work zone for direction i
(mi/h)

$\%HV_i$ = percentage of heavy vehicles in the traffic stream for direction i

LW_Narrow = 1 if the effective lane width is narrow, 0 otherwise

LW_Medium = 1 if the effective lane width is medium, 0 otherwise

$LW_NarrowMedium$ = 1 if the effective lane width is narrow or medium, 0 otherwise

ConstAct_MedHigh = 1 if the level of construction activity in the work zone is medium or high, 0 otherwise

TravelDirClosedLane = 1 if vehicles are traveling in the direction of the closed lane (i.e., they perform a lane shift when entering and exiting work zone), 0 otherwise

WZLen = length of the work zone (ft)

GradeProp_i = grade proportion (i.e., %grade/100) in direction *i* (downhill grades should be entered as zero)

PostedSpd = the posted speed limit through the work zone (mi/h)

Step 3: Calculate average saturation headway

$$\bar{h}_{sat_i} = 3.0875 + 0.0180 \times \%ST_i + 0.0276 \times \%MT_i + 0.0379 \times \%LT_i + 0.2812 \times GradeProp - 0.0095 \times AvgWZspeed \quad [15]$$

where

\bar{h}_{sat_i} = average saturation headway for direction *i* (s/veh)

$\%ST_i$ = percentage of small trucks in the traffic stream for direction *i*

$\%MT_i$ = percentage of medium trucks in the traffic stream for direction *i*

$\%LT_i$ = percentage of large trucks in the traffic stream for direction *i*

GradeProp_i = grade proportion (i.e., %grade/100) in direction *i* (downhill grades should be entered as zero)

AvgWZspeed = average work zone travel speed for direction *i*, as calculated from Eq. 10 or using field-measured speeds (mi/h)

Step 4: Calculate saturation flow rate

$$s_i \text{ (veh/h)} = \frac{3600 \text{ (s/h)}}{\bar{h}_{sat_i} \text{ (s/veh)}} \quad [16]$$

Step 5: Calculate cycle length

$$PT_i = \frac{wzlen}{speed_i} + g_i + SLT_i \quad [17]$$

where

PT_i = phase time direction *i* (s)

wzlen = length of the work zone (ft)

speed_i = average work zone travel speed, as calculated from Eq. 14 or using field-measured speed, for direction *i* (ft/s)

g_i = green time for direction *i* (s)

SLT = startup lost time—elapsed time between last vehicle to exit work zone and time when flag person turns paddle/sign to “Slow” for other direction

$$C = PT_1 + PT_2 \quad [18]$$

where

$$C = \text{cycle length (sec)}$$

Initially, the green time used in Eq. 17 will use a maximum green time (determine by the analyst) in order to determine whether the work zone will operate below or above capacity, as discussed in the next step. If it is determined the work zone will operate under capacity, then the calculation for phase time will use either the analyst-entered green time or a calculated minimum green time, as determined from Eqs. 20 and 21.

It should be noted that to be entirely accurate, the value for the $speed_i$ variable used to calculate the phase time for direction i should be the speed of the last vehicle to enter the work zone in direction i . The use of the average work zone travel speed from Eq. 14 will create some error, but this error is minimal.

Step 6: Calculate capacity

Capacity can be calculated with the standard equation used for signalized intersection analysis (TRB, 2010), as shown in Eq. 19.

$$c_i = s_i \times g_i / C \quad [19]$$

where

c_i = capacity of the work zone in direction i (veh/h)

s_i = saturation flow rate for direction i (veh/h)

(g_i / C) = effective green time to cycle length ratio for direction i

To determine if the work zone will operate under capacity (i.e., conditions do not result in continually building queue lengths) for the given configuration, it is suggested to calculate Eq.

17 using the maximum green time (default is 300 seconds). The resulting capacity from Eq. 19 can then be compared to the input volume (by direction) to determine if none, either, or both directions are under or over capacity. If one or both directions are over capacity, an alternative work zone configuration should be considered; otherwise, delays and queue lengths will quickly become intolerable to motorists. Generally, for over-capacity conditions, simple deterministic queuing equations can be applied to estimate queue delays and queue lengths.

If the work zone is under capacity, the standard formula for calculating the minimum cycle length can be applied (TRB, 2010), shown in Eq. 20.

$$C_{min} = \frac{L \times X_c}{X_c - \left[\left(\frac{v}{s} \right)_1 + \left(\frac{v}{s} \right)_2 \right]} \quad [20]$$

where

C_{min} = minimum necessary cycle length (sec)

L = total lost time for cycle (sec)

X_c = critical v/c ratio for the work zone

$(v/s)_i$ = flow ratio for direction i

Note again that the total lost time includes the startup and clearance lost times. Here it assumed the critical v/c ratio, X_c , is 1.0. Eq. 21 (TRB, 2010) can be applied to proportion the green times to the two directions of travel.

$$g_i = \left(\frac{v}{s} \right)_i \left(\frac{C}{X_i} \right) \quad [21]$$

where

g_i = effective green time for phase (direction) i

$(v/s)_i$ = flow ratio for direction i

C = cycle length in seconds

X_i = v/c ratio for direction i (again, assumed to be 1.0)

It should be noted that the use of minimum cycle length, and corresponding green times, calculated from equations 20 and 21 do not necessarily lead to minimum delay values. These values just ensure that all the vehicles queued during the red period for a direction are served during the subsequent green period. It was beyond the scope of this project to develop optimal timing strategies, that is, timing guidelines that would minimize the value of specific performance measures, such as vehicle delay. Thus, for an under-capacity situation, the calculation procedure implemented in the spreadsheet tool uses equations 20 and 21 to determine the minimum cycle length and minimum green times to apply for the queue delay and queue length estimation models.

Step 7: Calculate total queue delay

$$\begin{aligned} TotalQDelay_i = & -0.56844 \times (g_i / C)(\%) + 0.42799 \times (v/s)_i(\%) + 0.00591 \times C \\ & + 0.09670 \times g_i - 0.00064 \times HV_i \times g_i \end{aligned} \quad [22]$$

where

- $TotalQDelay_i$ = total queue delay for a 1-hr time period for direction i (veh-hr)
- (g_i / C) = effective green time to cycle length ratio for direction i (expressed as a percentage)
- $(v/s)_i$ = volume to saturation flow rate ratio for direction i (expressed as a percentage)
- C = cycle length (sec)
- HV_i = percentage of heavy vehicles in the traffic stream for direction i
- g_i = green time for direction i

Step 8: Calculate maximum queue length

$$\begin{aligned} MaxQLength_i = & -1.49485 \times (g_i / C)(\%) + 0.65045 \times (v/s)_i(\%) + 0.01432 \times C \\ & + 0.35359 \times g_i - 0.00138 \times HV_i \times g_i \end{aligned} \quad [23]$$

where

- $MaxQLength_i$ = average maximum queue length per cycle for direction i (veh/cycle)
- Other terms are as defined previously

CHAPTER 6 RTF TASK

Introduction

The FDOT Plans Preparation Manual contains a chapter (Chapter 10) titled "Work Zone Traffic Control" that discusses a lane closure analysis procedure to calculate the restricted capacity for roadway segments with lane closures. The calculated capacity is compared with the estimated hourly traffic demand to determine the time of day/night that the lane(s) can be closed. The procedure employs a remaining traffic factor (RTF), which denotes the percentage of travelers choosing not to divert, to estimate the hourly traffic demand through the work zone. The estimation of RTF plays a critical role in the lane closure analysis. However, no guidance has been provided on obtaining the value of the RTF in the current manual.

Phase 1 of the project titled "Impact of Lane Closures on Roadway Capacity, Part C: Modeling Diversion Propensity at Work Zones" investigates drivers' diversion behaviors at work zones and estimates the RTF within the framework of discrete choice modeling. A binary Logit model was calibrated based on the route choice data obtained through a stated preference (SP) survey, considering 11 potential attributes that may contribute to drivers' diversion decisions. The model calibration procedure identifies three major factors influencing the diversion behavior, namely travel time, work zone location, and weather condition. No statistical evidence was found to support the hypothesis that the remaining eight factors are important to drivers' diversion decision at work zones. Table 7 summarizes the coefficient specification of the final calibrated model obtained from the Phase 1 study.

Table 7. Final RTF Model Specification

Explanatory Variables	Original Route		Alternative Route	
	Param.	t stat	Param.	t stat
Constant	-0.5013	-2.0800	--	--
Travel time	-0.1416	-10.1580	-0.1416	-10.1580
Location	0.7220	2.8440	--	--
Weather conditions	0.3959	1.5840	--	--
Number of cases		436		
Log likelihood at convergence		-201.3115		
LL for no-coefficient model		-302.2122		
Rho ²		0.3339		
Adjusted Rho ²		0.3277		

The negative sign associated with the travel time coefficient indicates that travelers prefer routes with shorter travel time, given other factors being equal. The positive sign associated with the location coefficient implies that travelers tend to stay on the original route in rural areas. This behavior can be explained by the fact that fewer alternative routes are generally available in rural areas than in urban ones. Furthermore, it could be more difficult for travelers to obtain updated travel information in rural areas. The sign of the weather coefficient is also positive, and it can be interpreted that travelers are more likely to divert when encountering bad weather. Intuitively, travel time reliability in work zone decreases in bad weather conditions and safety becomes one of the prominent concerns.

The Phase 1 study also proposes two estimation procedures to apply the calibrated binary Logit model to estimate the RTF, namely open- and closed-loop procedures. The former directly applies the model without considering the feedback of remaining and diverted flows on travel times while the latter applies the notion of traffic equilibrium and attempts to maintain the consistency between travel times and flows on different routes. As traffic equilibrium may not be

achieved in a short time, the open-loop procedure may be more appropriate for short-term work zones while the closed-loop procedure may be closer to actual diversion rates at long-term work zones. Therefore, the calibrated model from Phase 1 not only provides us more insights on the diversion behavior in work zone but also serves as the basis for developing analytic tools for work zone analysis.

That being said, the model calibration in Phase 1 was solely based on the SP survey data. It is widely known that respondents in SP surveys tend to over-predict their own responses. As a result, the calibrated model may overestimate the diversion rate and subsequently underestimate the RTF. One indication of that is the sign of the constant associated with the original route is negative (-0.5013) in Table 7. This implies that even when the travel times are equal, drivers are still inclined to divert, which may not be necessarily consistent with actual behaviors observed at work zones. Indeed, Hensher et al. (2005) pointed out that SP data often provide good estimates about the preference trade-offs that decision makers make but will not, unless by chance, reflect the true aggregate shares observed in the real world.

Methodology

The objective of this study is to further refine the choice model obtained in Phase 1 using field observed traffic data. One commonly adopted approach in the literature is to combine the actual choices made by individual travelers (i.e., revealed preference (RP) data) and SP survey data to address the validity issue of SP data and improve the accuracy of parameter estimates, see, e.g., Ben-Akiva et al. (1994) and Hensher et al. (2005). However, the integration of RP and SP data is only made possible when both data sources are available. Considering the time and budget limitations faced by this study, there are not enough resources to conduct another survey to collect RP data of individual travelers. Therefore, the data collection task in Phase 2 only records aggregate choice data instead of disaggregate route choices made by travelers.

To fully explore the limited data collected, the model refinement task in this phase focuses on calibrating the alternative-specific constants of the choice model estimated in Phase 1. By calibrating the constant term of the discrete choice model using the aggregate choice data collected in this phase, the inflated diversion rate can be adjusted to reproduce the actual diversion rate observed in the field. Meanwhile, the preference structure of the estimated choice model is also retained (Hensher et al., 2005).

Data Collection

It is difficult to exactly measure the number of vehicles diverting to alternative routes in a work zone construction site. In this study, tube detectors were strategically deployed in the road network surrounding a work zone. Traffic counts before and during the work zone construction were collected, and the difference between them was used to approximate the actual diversion rate in the field. The locations of the vehicle detectors were intended to cover major potential detours as well as the work zone site. Our research team initially identified three work zones located in both rural and urban areas. However, only one work zone site produced relatively reliable traffic counts and was adopted for the model recalibration in this study. It is also worth mentioning that limited useful data greatly restrict data analysis options available to us, but they justify the simplified model recalibration methodology proposed in the previous section.

The remaining parts of this section describe the work zone site and data collection work. The work zone is located on SR-20 near Hawthorne in Alachua County. Figure 24 illustrates the locations of the work zone site and loop detectors deployed. The work zone construction site is located just east of detector 1 shown in this figure. Detector 1 is intended to count traffic through the work zone site, while detectors 2 to 4 are used to capture traffic volumes on potential detour routes.

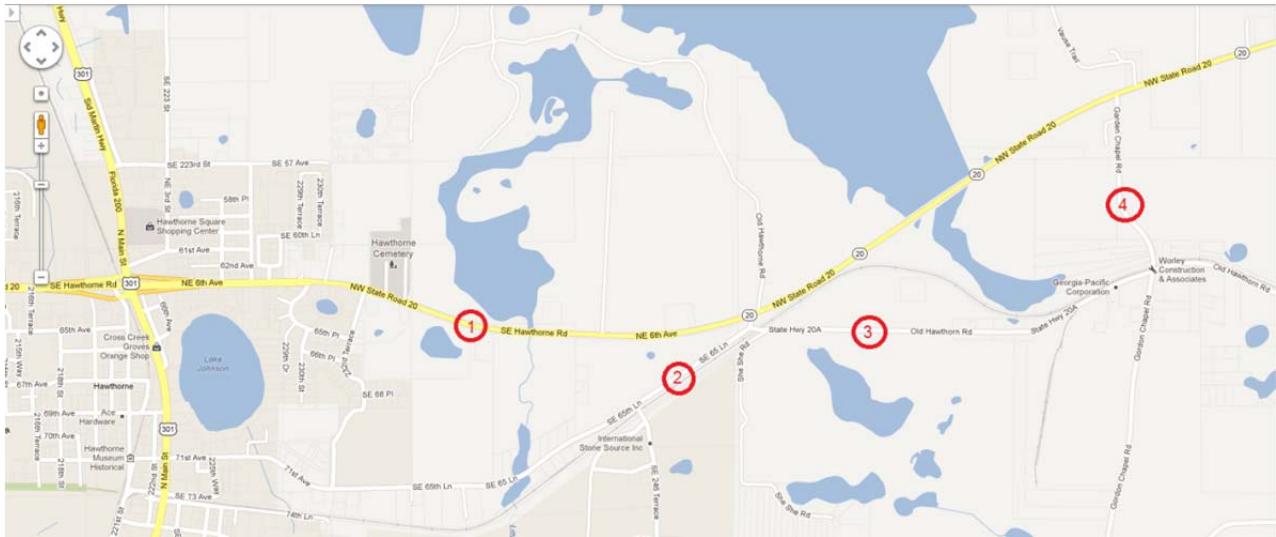


Figure 24. SR-20 work zone site

Traffic counts for both before- and during-construction periods were collected for three consecutive days in December 2012 and February 2013, respectively. Weather conditions during both periods were normal. Westbound traffic counts were collected and are shown in Table 8.

Table 8. Before and During Construction Traffic Counts (Westbound)

Date	Before Construction (veh/day)				During Construction (veh/day)			
	Dec-18	Dec-19	Dec-20	Average	Feb-19	Feb-20	Feb-21	Average
Detector 1	3410	3568	3576	3518	3136	3292	3406	3278
Detector 2	270	286	264	273	339	259	274	291
Detector 3	33	42	33	36	66	53	50	56
Detector 4	445	440	415	433	396	374	393	388

It is estimated that roughly 240 vehicles (6.8%) diverted during the work zone construction time assuming the total travel demand remains the same before and during construction. Table 8 also shows that more traffic passed through detectors 2 and 3 during the construction time as expected. For detector 4, slightly fewer vehicles actually used this segment during the construction time, which indicates that travelers may have already diverted to detours upstream of this segment, which is not accounted for by the deployed detectors. Traffic counts of different days have been averaged to reduce the influence of daily demand variation, however, the impact

of seasonal demand variation cannot be eliminated since the before- and during-construction traffic counts were collected two months apart.

Travel delays due to work zone construction directly influence travelers' diversion decisions. A flag person on each end of the work zone controlled the construction site. Only vehicles from one direction were allowed to enter the work zone site at a time while vehicles from the other direction have to wait in queue. Therefore, the primary source of travel delay experienced by travelers is the queuing delay before vehicles actually enter the work zone site. In this study, data obtained from video were used to estimate the queuing delay. Queuing delays for 518 vehicles were extracted from video obtained at the construction site on February 21. Table 9 shows the average queuing delays experienced by travelers.

Table 9. Average Queuing Delay (Westbound)

Length of Lane Closure (miles)	Posted Speed in Work Zone (mi/h)	Average Queuing Delay (s/veh)
0.904	55	206.52

Data Analysis

The utility functions of original (O) and alternative (A) routes obtained in Phase 1 are as follows:

$$U_O = -0.5013 - 0.1416TT_O + 0.7220L_O + 0.3959W_O + \varepsilon_O \quad [24]$$

$$U_A = -0.1416TT_A + \varepsilon_A \quad [25]$$

where

TT = travel time

L is a binary variable indicating the location of the work zone ($L = 1$ for rural work zone and $L = 0$ otherwise)

W is a weather condition binary variable ($W = 1$ for normal weather conditions and $W = 0$ for bad weather conditions).

Based on the binary Logit model, the diversion rate can be calculated using the following equation:

$$P(A) = \frac{e^{U_A}}{e^{U_A} + e^{U_O}} = \frac{1}{1 + e^{(U_O - U_A)}} \quad [26]$$

If the above equation is adopted in estimating the diversion rate for the work zone on SR-20, the estimated diversion rate is 24.90%. It is evident that the observed diversion rate (6.8%) is much lower than the estimated one, which coincides with the literature that models based on SP data tend to over-predict users' responses. Following the methodology discussed previously, the constant coefficient associated with the original route, β_O , is adjusted to solve the overestimation problem. Essentially, β_O is treated as an unknown variable instead of a known constant and the diversion rate, $P(A)$, is set to equal to 6.8%. The equation to calculate the diversion rate is used to solve for an adjusted β_O , and $\beta_O = 1.013$. Therefore, the new utility function for the original route can be recalibrated as:

$$U_O = 1.1013 - 0.1416TT_O + 0.7220L_O + 0.3959W_O + \varepsilon_O \quad [27]$$

and the utility function for the alternative route remains unchanged. The sign of β_O changed from negative in Phase 1 to positive. The newly recalibrated model implies that travelers have a general preference towards the original route and are not willing to divert to alternative routes, all things being equal.

Summary

This task aimed to refine the RTF model proposed in Phase 1 using field observed diversion data. The binary Logit model developed in Phase 1 was calibrated based on SP survey data, and SP data tend to overestimate the diversion rate in work zones. The aggregate traffic data collected in a work zone on SR-20 confirm this phenomenon. A simplistic methodology is adopted primarily due to limitations in data availability and quality. The constant coefficient

associated with the original route is adjusted to fix the overestimation problem while retaining the preference structure of the estimated route choice model. The recalibrated model was incorporated into the RTF modeling framework proposed in Phase 1 by updating the route choice model.

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APPENDIX A
DATA COLLECTED FROM FIELD SITES

Table A-1. Accepted and Rejected Gap Data for Determining Critical Gap at Site 1

Gap Interval (sec)	Midpoint of Gap Interval (t) (sec)	Number of Gaps Accepted Greater than t	Number of Gaps Rejected Less than t
0 - 4.9	2.5	380	0
5 - 9.9	7.5	173	0
10 - 14.9	12.5	83	0
15 - 19.9	17.5	53	2
20 - 24.9	22.5	36	5
25 - 29.9	27.5	27	13
30 - 34.9	32.5	18	23
35 - 39.9	37.5	10	29
40 - 44.9	42.5	9	36
45 - 49.9	47.5	9	48
50 - 54.9	52.5	8	56
55 - 59.9	57.5	6	63
>= 60	300	4	164

Table A-2. Accepted and Rejected Gap Data for Determining Critical Gap at Site 2

Gap Interval (sec)	Midpoint of Gap Interval (t) (sec)	Number of Gaps Accepted Greater than t	Number of Gaps Rejected Less than t
0 - 4.9	2.5	507	0
5 - 9.9	7.5	203	0
10 - 14.9	12.5	85	0
15 - 19.9	17.5	57	1
20 - 24.9	22.5	34	2
25 - 29.9	27.5	20	6
30 - 34.9	32.5	13	15
35 - 39.9	37.5	9	20
40 - 44.9	42.5	6	29
45 - 49.9	47.5	3	41
50 - 54.9	52.5	2	57
55 - 59.9	57.5	2	67
>= 60	300	2	207

Table A-3. Accepted and Rejected Gap Data for Determining Critical Gap at Site 3

Gap Interval (sec)	Midpoint of Gap Interval (t) (sec)	Number of Gaps Accepted Greater than t	Number of Gaps Rejected Less than t
0 - 4.9	2.5	1259	0
5 - 9.9	7.5	354	0
10 - 14.9	12.5	180	2
15 - 19.9	17.5	101	8
20 - 24.9	22.5	56	19
25 - 29.9	27.5	24	40
30 - 34.9	32.5	10	57
35 - 39.9	37.5	3	79
40 - 44.9	42.5	2	100
45 - 49.9	47.5	0	121
50 - 54.9	52.5	0	140
55 - 59.9	57.5	0	146
≥ 60	300	0	210

	A	B	C	D	E	F	G	H	I
1	EB Traffic	Phase 1	Phase 2	Phase 3	Phase 4	Phase 5	Phase 6	Phase 7	Phase 8
2	Time Last EB Veh from Previous Phase Enters WZ	Not Recorded	9:41:13 AM	9:46:10 AM	9:50:16 AM	9:55:13 AM	11:36:44 AM	11:41:52 AM	11:46:28 AM
3	Time 1st EB Veh Arrives at WZ	Not Recorded	9:42:17 AM	9:47:01 AM	9:51:05 AM	9:56:15 AM	11:37:33 AM	11:42:24 AM	11:47:03 AM
4	Period with No Queue at WZ (sec)	Not Recorded	64	51	49	62	49	32	35
5	Queue Delay of 1st Queued Veh (sec)	Not Recorded	212	131	217	146	174	193	239
6	Time Last WB Veh Exits WZ	9:40:40 AM	9:45:44 AM	9:48:59 AM	9:54:35 AM	9:58:33 AM	11:40:22 AM	11:45:34 AM	11:50:50 AM
7	Number of Vehs In Queue	5	8	5	6	5	10	16	12
8	Distance between 1st Queued Veh and Flag (ft)	6	8	15	5	20	3	2	2
9	Time Flag Changes to Slow	9:40:41 AM	9:45:46 AM	9:49:05 AM	9:54:38 AM	9:58:35 AM	11:40:23 AM	11:45:32 AM	11:51:00 AM
10	Time Flag Changes to Stop	9:41:35 AM	9:47:00 AM	9:50:25 AM	9:55:18 AM	9:59:29 AM	11:41:56 AM	11:46:33 AM	11:52:26 AM
11	Green Time (sec)	54	74	80	40	54	93	61	86
12	Total Lost Time (sec)	11	5	13	7	8	5	5	12
13	Number of PC that Entered WZ	5	6	11	7	9	16	15	17
14	Number of ST that Entered WZ	0	2	0	0	1	1	1	0
15	Number of MT that Entered WZ	0	0	0	0	0	0	1	0
16	Number of LT that Entered WZ	1	0	0	1	0	1	1	1
17	Number of CV that Entered WZ	0	0	0	0	0	0	0	0
18	Number of Vehs that Entered WZ	6	8	11	8	10	18	18	18
19	Number of Entering Vehs thatExited WZ	6	8	11	8	10	18	18	17
20	Time between 8th Veh in Queue (or Last Queued Veh) and 1st Veh Entry Time (sec)	19	21	13	14	11	23	20	28
21	Saturation Headway (sec/veh)	4.750	3.000	3.250	2.800	2.750	3.286	2.857	4.000
22	Avg Work Zone Travel Time (min)	1.600	1.279	1.461	1.356	1.238	1.307	1.420	1.409
23	Std Dev Work Zone Travel Time (min)	0.054	0.049	0.177	0.079	0.024	0.115	0.063	0.083
24	Avg Speed in Work Zone (mi/h)	33.750	42.215	36.971	39.816	43.607	41.303	38.018	38.330
25	1st Veh Entry Time	9:40:51 AM	9:45:49 AM	9:49:12 AM	9:54:42 AM	9:58:41 AM	11:40:27 AM	11:45:37 AM	11:51:02 AM
26	1st Veh Type	PC	PC	PC	PC	PC	PC	PC	PC
27	1st Veh Description	white car	black pick up truck	gold car	dark SUV	Chevy tahoe	black SUV	silver car	dark gray SUV
28	1st Veh Exit Time	9:42:32 AM	9:47:05 AM	9:50:51 AM	9:56:02 AM	9:59:54 AM	11:41:51 AM	11:47:07 AM	11:52:19 AM
29	1st Veh WZ Travel Time (min)	1.68	1.27	1.65	1.33	1.22	1.40	1.50	1.28
30	2nd Veh Entry Time	9:40:55 AM	9:45:54 AM	9:49:15 AM	9:54:46 AM	9:58:43 AM	11:40:30 AM	11:45:39 AM	11:51:05 AM
31	2nd Veh Type	LT	PC	PC	PC	PC	PC	PC	PC

Figure A-1: Example of Excel spreadsheet for video data from stationary cameras

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S
1	Video File Name	Site #	Date	Travel Direction	Phase #	Vehicle #	Start Video Time	End Video Time	Avg. Travel Time in WZ for Phase (min)	Avg. Speed in WZ for Phase (mi/h)	Number of Vehicles that Entered WZ	Percent Heavy Vehicles that Entered WZ	Percent Construction Vehicles that did not Exit WZ	Level of Construction Activity in WZ	Level of Construction Vehicle Presence in WZ	Effective Lane Width	Posted Speed in WZ (mi/h)	Travel Direction of Closed Lane	Is traveling in Direction of Closed Lane (0 = false, 1 = true)
2	LC1	1	10/25/11	Northbound	N/A	hey enter	N/A	N/A	-99.000	-99.00	-99	-99.00	-99.00	2	2	2	55	Northbound	1
3	LC2	1	10/25/11	Southbound	N/A	hicle in c	N/A	N/A	-99.000	-99.00	-99	-99.00	-99.00	2	2	2	55	Northbound	0
4	LC3	1	10/25/11	Northbound	N/A	queue fro	N/A	N/A	-99.000	-99.00	-99	-99.00	-99.00	2	2	2	55	Northbound	1
5	LC4	1	10/25/11	Southbound	1	et inside	N/A	N/A	2.853	36.81	9	33.33	11.11	2	2	2	55	Northbound	0
6	LC5	1	10/25/11	Northbound	8	9	N/A	N/A	-99.000	-99.00	16	25.00	-99.00	3	3	2	55	Northbound	1
7	LC6	1	10/25/11	Southbound	9	ne. Enter	N/A	N/A	3.163	33.19	8	62.50	25.00	3	3	2	55	Northbound	0
8	LC7&8	1	10/25/11	Northbound	11	15	N/A	N/A	3.126	33.59	15	20.00	6.67	3	2	2	55	Northbound	1
9	LC7&8	1	10/25/11	Southbound	11	7	N/A	N/A	2.883	36.42	9	11.11	0.00	3	2	2	55	Northbound	0
10	LC9	1	10/25/11	Northbound	12	11	N/A	N/A	3.003	34.96	11	18.18	9.09	3	2	2	55	Northbound	1
11	LC10	1	10/25/11	Southbound	18	4	N/A	N/A	3.102	33.85	11	45.45	18.18	3	3	2	55	Northbound	0
12	LC11-12-13	1	10/25/11	Northbound	19	11	N/A	N/A	3.439	30.53	14	35.71	0.00	3	3	2	55	Northbound	1
13	LC11-12-13	1	10/25/11	Southbound	19	17	N/A	N/A	3.013	34.85	18	22.22	5.56	3	3	2	55	Northbound	0
14	LC11-12-13	1	10/25/11	Northbound	20	12	N/A	N/A	3.079	34.10	12	25.00	0.00	3	3	2	55	Northbound	1
15	LC14	1	10/25/11	Southbound	N/A	N/A	N/A	N/A	-99.000	-99.00	-99	-99.00	-99.00	3	2	2	55	Northbound	0
16	LC15	1	10/27/11	Southbound	2	1	N/A	N/A	3.040	38.43	8	12.50	0.00	2	2	2	60	Northbound	0
17	LC16	1	10/27/11	Northbound	3	12	N/A	N/A	3.257	35.87	14	14.29	14.29	2	1	2	60	Northbound	1
18	LC17	1	10/27/11	Southbound	4	2	N/A	N/A	2.926	39.92	7	28.57	0.00	2	2	2	60	Northbound	0
19	LC18	1	10/27/11	Northbound	5	14	N/A	N/A	3.368	34.69	22	22.73	4.55	3	2	2	60	Northbound	1
20	LC19	1	10/27/11	Southbound	8	5	N/A	N/A	2.900	40.28	10	30.00	0.00	2	2	2	60	Northbound	0
21	LC20	1	10/27/11	Northbound	9	18	N/A	N/A	3.511	33.28	18	27.78	16.67	2	2	2	60	Northbound	1
22	LC21	1	10/27/11	Southbound	10	4	N/A	N/A	2.829	41.30	7	28.57	0.00	2	2	2	60	Northbound	0
23	LC22	1	10/27/11	Northbound	12	15	N/A	N/A	3.374	34.62	18	33.33	11.11	2	3	2	60	Northbound	1
24	LC23	1	10/27/11	Southbound	15	8	N/A	N/A	2.940	39.73	15	13.33	0.00	2	3	2	60	Northbound	0
25	LC24	1	10/27/11	Southbound	21	5	N/A	N/A	3.567	32.75	15	26.67	0.00	3	2	2	60	Northbound	0
26	LC25	1	10/27/11	Northbound	23	1	N/A	N/A	3.116	37.49	18	11.11	0.00	3	2	2	60	Northbound	1
27	LC26	1	10/27/11	Southbound	24	12	N/A	N/A	3.628	32.20	13	23.08	0.00	3	2	2	60	Northbound	0
28	LC27	1	10/27/11	Northbound	25	10	N/A	N/A	3.570	32.73	13	38.46	15.38	3	2	2	60	Northbound	1

Figure A-2: Example of Excel spreadsheet for video data from instrumented Honda Pilot

APPENDIX B
PICTURES OF VEHICLE TYPES BY CATEGORY



A



B



C

D

Figure B-1. Small trucks. A) Panel truck. B) Garbage truck. C) Two-axle single-unit dump truck. D) Small delivery truck. E) Passenger cars with trailers



E

Figure B-1. Continued



A



B



C



D



E

Figure B-2. Medium trucks. A) Three-axle single-unit dump truck. B) Concrete mixer. C) Passenger car with trailer using fifth wheel. D) Delivery truck. E) Single-unit cargo truck.



A



B

Figure B-3. Large trucks. A) Tractor plus trailer. B) Tractor plus flatbed. C) Buses.



C

Figure B-3. Continued

APPENDIX C
FLAGSIM USERS GUIDE

FlagSim User Guide

**Simulation Program for Two-Lane Roadways
with a Lane Closure under Flagging Control**

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January 2014

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Introduction to FlagSim

FlagSim is a Windows-based computer simulation program developed at the University of Florida Transportation Institute for the purpose of research and analysis of two-lane, two-way work zones under flagging or signal control (as illustrated in Fig. 1). This program utilizes a stochastic, microscopic modeling approach. It explicitly models the movement of every vehicle through the specified lengths of roadway, at a 0.1-second simulation time resolution.

It is not meant or designed to be used for other roadway/work zone configurations, and is designed only for operations utilizing flagging or signal control, without a pilot car. This user guide explains the inputs, how to run the simulation, and the outputs.

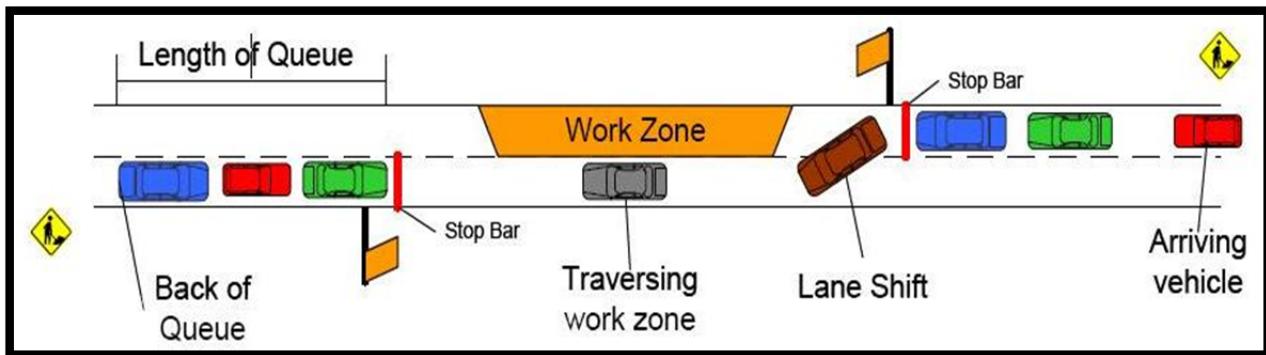


Figure 1. Work zone configuration to which FlagSim applies

Menu Items

File

Open

To open an existing file, select “Open” or press Ctrl+O on the keyboard.

Save/Save As

To save progress on a current file, select “Save” to save to an existing file or press Ctrl+S on the keyboard. Choose “Save As” in order to save the file under a different location or to a different name. *Note that only the input data are saved to this file.* The results are created in another file, as explained later.

Exit

To exit the FlagSim program, select “Exit” or click the “X” in the top right corner of the program window.

View

Inputs

To display the “Inputs” tab; enter all appropriate numerical inputs here.

Results

To display the summarized output file produced by FlagSim.

Help

Users Guide

This selection opens this document. This can also be accomplished by pressing Ctrl+F1 on the keyboard.

About

This selection opens the program information window.

Main Inputs Screen

This screen (see Fig. 2) facilitates the setting of the values for the roadway variables, traffic variables, results calculation variables, and flagging control variables. Information on the screen should generally be entered from left to right.

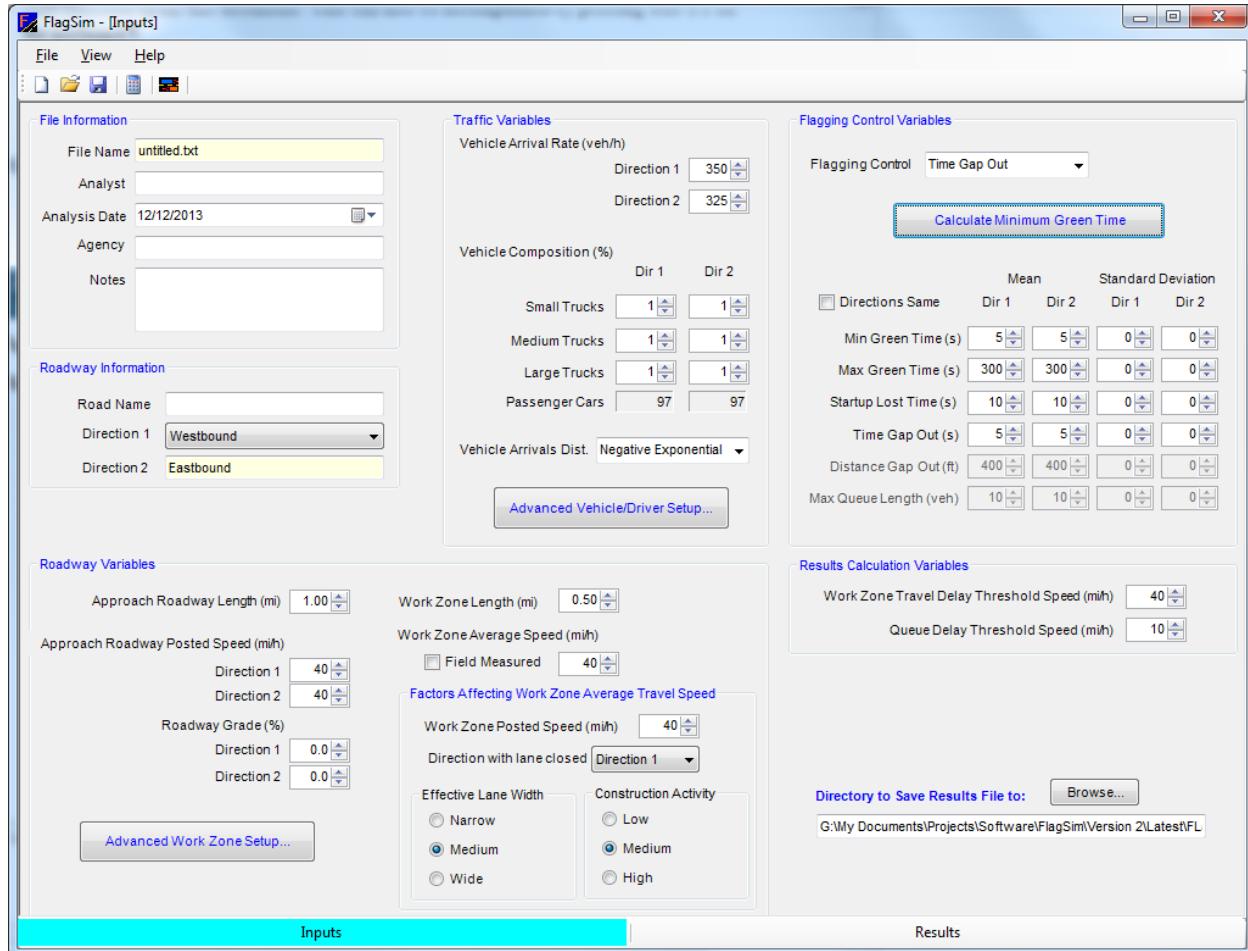


Figure 2. Inputs screen.

File Information

File Name

Displays the name of the file for this project after it has been saved to disk. This field is not user-editable.

Analyst

Field for entering the name of the analyst.

Analysis Date

Field for entering the date of analysis. Defaults to current date.

Agency

Field for entering the name of the agency for which the analyst works.

Notes

Field for entering any additional information.

Roadway Information

Road Name

Field for entering the name of the roadway being analyzed.

Direction 1

The chosen direction of travel to assign to direction 1.

Direction 2

The chosen direction of travel to assign to direction 2.

Roadway Variables

Approach Roadway Length

This input specifies the length of roadway preceding the lane closure area (i.e., work zone). This is the length of roadway where vehicles approach the work zone, and subsequently accommodate storage of queued vehicles waiting to enter the work zone. The minimum and maximum input values are 0.1 miles and 5 miles, respectively. To obtain accurate queue delay and queue length estimates, the specified approach roadway length should be longer than the longest expected maximum back of queue.

Approach Roadway Posted Speed

This input specifies the legal speed limit (in units of mi/h) that vehicles can travel on the section of roadway before and after the work zone area. The minimum and maximum input values are 25 and 70, respectively.

Roadway Grade

This input specifies the incline of the roadway, in percent. Note that for downhill grades, a value of zero should be entered.

Work Zone Length

This input specifies the length of the lane closure. The units are in miles; the minimum and maximum values are 0.1 and 10, respectively.

Field-Measured Work Zone Average Travel Speed

If an existing work zone site is being analyzed, and average travel speeds through the work zone have been measured, this checkbox should be checked. If field-measured speeds are not available, the average work zone travel speed will be estimated with the following four input variables. The minimum and maximum input values are 5 and 70, respectively.

Work Zone Posted Speed

This input assigns the legal speed limit (in units of mi/h) that vehicles can travel while traversing the work zone. The minimum and maximum input values are 25 and 70, respectively.

Travel Direction with Lane Closed

This input specifies the travel direction that must shift lanes when entering and exiting the work zone area.

Effective Lane Width

Narrow lane widths are considered to apply to lanes that have no, or a very narrow, shoulder and cones placed inside the lane. Medium lane widths are considered to apply to lanes that have a small shoulder and cones placed outside the lane or on the centerline. Medium lane widths also apply to lanes that have a relatively wide shoulder and cones placed inside the lane. Wide lane widths are considered to apply to lanes with a relatively wide shoulder and cones placed outside the lane or on the centerline. Wide lane widths also apply to lanes that have a narrow shoulder but cones placed outside the lane.

Construction Activity

Low construction activity is considered to apply for activities such as sodding, shoulder work, or any other activity that requires few construction vehicles or equipment to operate close to the open travel lane. Medium construction activity is considered to apply for activities such as milling or resurfacing or any other activity that requires several construction vehicles or pieces of equipment to operate close to the open travel lane. High construction activity is considered to apply for activities such as both milling and resurfacing taking place at the same time or any other activity that requires a large number of construction vehicles or equipment to operate close to the open travel lane.

Advanced Work Zone Setup (Feature Forthcoming)

This feature will allow the user to adjust settings pertaining to the configuration of the work zone and approach roadways.

Traffic Variables

This section of inputs allows the user to enter specific traffic flow parameters pertinent to the roadway being simulated.

Vehicle Arrival Rate

The total number of vehicles entering the network during the analysis hour (per direction, 1 and 2). Note that a “vehicle” includes both passenger cars and trucks. The minimum and maximum input values are 10 and 2000 veh/h, respectively.

Vehicle Composition (%)

FlagSim has the capability to model passenger cars and three different sized trucks. The percentage of small, medium, and large trucks present in the traffic stream can be specified. The percentage of passenger cars is calculated.

Percent Small Trucks

This input specifies the percentage of small-sized trucks in the traffic stream.

Percent Medium Trucks

This input specifies the percentage of medium-sized trucks in the traffic stream,

Percent Large Trucks

This input specifies the percentage of large-sized trucks in the traffic stream.

Percent Passenger Cars

The percentage of passenger cars is determined implicitly from the percentage of heavy vehicles (HV). Note that the passenger cars category includes SUVs, pickup trucks, minivans, etc.

Note: The length of each vehicle type, as well as its performance capabilities (acceleration and deceleration) can be modified in the advanced vehicle/driver parameters screen.

Vehicle Arrivals Distribution

This input (a drop down list box) specifies the vehicle arrival headway distribution. The two headway options are:

- Negative Exponential: Arrivals are assumed to be random (i.e., according to a Poisson distribution).
- Uniform: The headway between consecutive vehicle arrivals is a constant value.

The default setting is ‘negative exponential’. Thus, the vehicle arrival headway times are generated according to Eq. 1.

$$h = \ln(r) \times -\lambda \quad [1]$$

where

h = vehicle headway, in seconds

r = random number generated from a uniform distribution

λ = average arrival rate, in veh/s

\ln = natural logarithm

Car-Following Model

The car-following model is the mathematical foundation for the movement of a vehicle following another vehicle. The queue discharge aspect of traffic flow in the work zone area is a critical element to the validity of the simulation results. Therefore, the car-following model has

to be particularly suitable for modeling the queue discharge phenomenon. After review of various models, the Modified-Pitt car-following model (Cohen, 2002) was selected for implementation. The Modified-Pitt car-following model was demonstrated by Cohen (2002) and Washburn and Cruz-Casas (2007) to work well for queue discharge modeling situations. For more discussion on queue discharge models, refer to Washburn and Cruz-Casas (2007).

The Modified-Pitt car-following equation calculates the acceleration value for a trailing vehicle based on intuitive parameters such as the speed and acceleration of the lead vehicle, the speed of the trailing vehicle, the relative position of the lead and trail vehicles, as well as a desired headway. This equation also incorporates a sensitivity factor, K , which will be discussed later in more detail. This equation allows for relatively easy calibration. Car-following models are generally based on a ‘driving rule’, such as a desired following distance or following headway. The Modified-Pitt model is based on the rule of a desired following headway. The main form of the model is as follows.

$$a_f(t+T) = \frac{K \left\{ s_l(t+R) - s_f(t+R) - L_l - h v_f(t+R) + [v_f(t+R) - v_l(t+R)]T - \frac{1}{2} a_l(t+T)T^2 \right\}}{T(h + \frac{1}{2T})}$$

where

$a_f(t+T)$ = acceleration of follower vehicle at time $t+T$, in ft/s²

$a_l(t+R)$ = acceleration of lead vehicle at time $t+R$, in ft/s²

$s_l(t+R)$ = position of lead vehicle at time $t+R$ as measured from upstream, in feet

$s_f(t+R)$ = position of follower vehicle at time $t+R$ as measured from upstream, in feet

$v_f(t+R)$ = speed of follower vehicle at time $t+R$, in ft/s

$v_l(t+R)$ = speed of lead vehicle at time $t+R$, in ft/s

L_l = length of lead vehicle plus a buffer based on jam density, in ft

h = time headway parameter (refers to headway between rear bumper plus a buffer of lead vehicle to front bumper of follower), in seconds

T = simulation time-scan interval, in seconds

t = current simulation time step, in seconds

R = perception-reaction time, in seconds

K = sensitivity parameter (unitless)

For more information on the Modified-Pitt car-following model, see references 1-3.

Pitt Damping (K) Factor

The Pitt damping factor (K) is a sensitivity parameter used to adjust the acceleration calculated by the Pitt car-following model. This factor is analogous to a spring constant used to describe how tightly or loosely a coupled system (a platoon of vehicles in this case)

operates. This factor essentially adjusts how quickly or slowly acceleration changes, for one or more vehicles, propagate through the platoon.

The sensitivity parameter, K , has two separate values in the car-following model—one for the queue arrival and discharge and for the travel through the work zone. Cohen stated that a larger K value should be used in interrupted flow conditions (a more tightly coupled system) due to over-damping effects (Cohen, 2002a). This assumption was tested in the car-following model and yielded the best results. Vehicles had a smoother interaction in the work zone (uninterrupted flow, a more loosely coupled system) with $K = 0.75$ and for the queue arrival and queue discharge processes performed well with $K = 1.1$. The definition of the queue arrival area was 300 feet upstream of the last vehicle in queue, and the definition of the queue discharge area was 300 feet downstream of the entering work zone stop bar (see Figure 3).

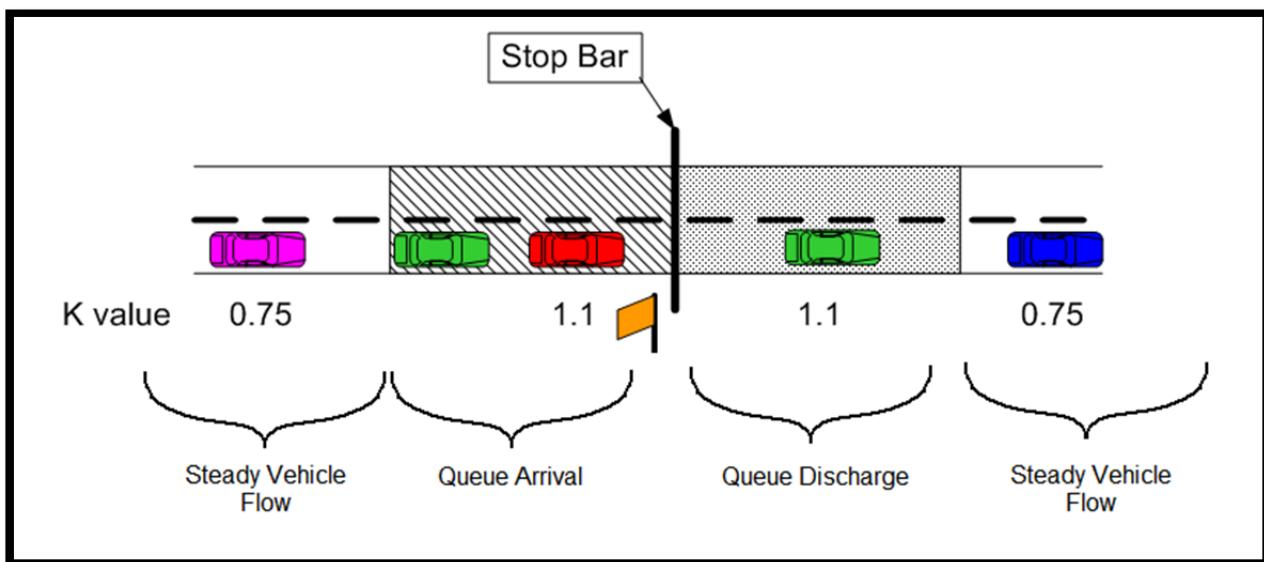


Figure 3. Modified-Pitt K-values

Advanced Vehicle/Driver Parameter Values Screen

Clicking on the “Advanced Vehicle/Driver Setup...” button will open the “Vehicle and Driver Parameter Values” screen (see Fig. 4). This screen allows the user to specify the parameter values for the drivers and vehicles that enter and travel through the simulated network. Note that the default values for these parameters have been carefully chosen based on previous studies and field data collection. Unless the analyst has more specific data for a particular work zone location, it is not recommended that these values be changed. The values of these parameters can significantly affect the simulation results. Note that parameters that use a mean and standard deviation input are based on a normal distribution. Thus, approximately 68% of the parameter values will fall within \pm one standard deviation.

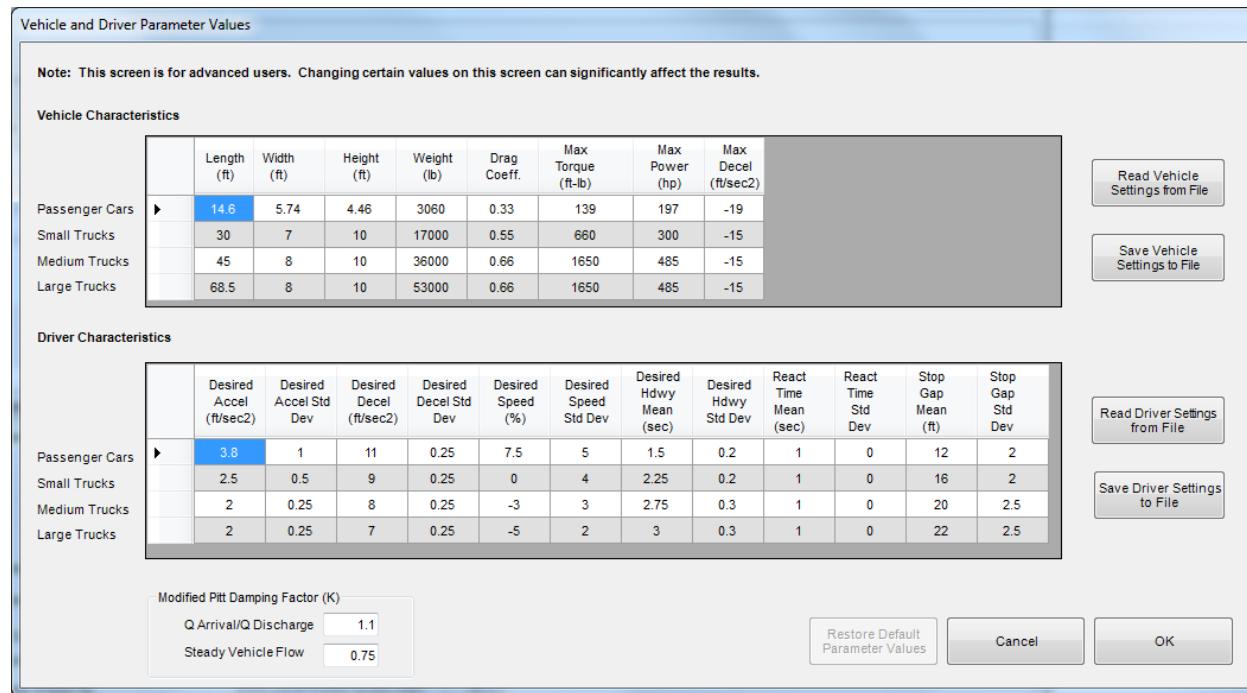


Figure 4. Vehicle and Driver Parameter Values screen.

Vehicle Characteristics

Being a microscopic simulation program, FlagSim generates, moves, and tracks individual vehicles through the specified network. The following properties can be specified for each of the four vehicle types available in FlagSim.

Vehicle Length

This input specifies the length of each type of vehicle, in units of feet.

Vehicle Width

This input specifies the width of each type of vehicle, in units of feet.

Vehicle Height

This input specifies the height of each type of vehicle, in units of feet.

Vehicle Weight

This input specifies the weight of each type of vehicle, in units of pounds.

Drag Coefficient

This input specifies the drag coefficient of each type of vehicle. This value is unitless.

Maximum Torque

This input specifies the maximum torque of the engine for each type of vehicle, in units of ft-lb.

Maximum Power

This input specifies maximum power of the engine for each type of vehicle, in units of hp.

Maximum Deceleration

This input specifies the maximum deceleration (i.e., braking) rate for each type of vehicle, in units of ft/s².

Driver Characteristics

For each individual vehicle generated during the simulation, a unique driver is attached to the vehicle. A number of characteristics are associated with each driver. Furthermore, to allow for variance from one driver to another, values of each of the characteristics are drawn from a Normal distribution, as specified by mean and standard deviation values. Thus, the property values were set according to Eq. 2.

$$\text{Value} = s \times r_{\text{norm}} + \bar{x} \quad [2]$$

where

Value = vehicle parameter value, such as desired acceleration

s = standard deviation input by the user

r_{norm} = random normal number generated by the random normal function

̄x = mean value of the property inputted by the user

Desired Acceleration (mean and standard deviation)

This input specifies the desired acceleration rate for a driver, in units of ft/s². This value will be applied when a vehicle is not in a car-following mode and is traveling less than its desired speed.

Desired Deceleration (mean and standard deviation)

This input specifies the desired deceleration rate for a driver, in units of ft/s². This deceleration rate is applied for normal braking situations, such as stopping when joining the queue at the approach to the work zone. Note that this value should be less than the maximum deceleration rate, which is used only in emergency braking situations.

Desired Speed % (mean and standard deviation)

This input specifies the percentage above (for positive values) or below (for negative values) the base desired speed that a particular driver will travel. For example, passenger car drivers will travel 7.5% above the base desired speed, on average, while large truck drivers will travel 5% below the base desired speed, on average (for the default values shown). The base desired speed value is a function of factors such as posted speed limit, construction activity, effective lane width, and direction of closed lane.

Headway (mean and standard deviation)

This input specifies the length of the vehicle headway (time interval between consecutive vehicles) value used in the Modified-Pitt car-following model (the h parameter).

Reaction Time (mean and standard deviation)

This input specifies the driver reaction time used in the Modified-Pitt car-following model (the R parameter).

Stop Gap (mean and standard deviation)

This input specifies the distance, in units of feet, between the rear bumper of a lead vehicle and the front bumper of a trail vehicle, while at a stop (i.e., in a queue waiting to enter the work zone). This value combined with the vehicle length value comprises the L parameter used in the Modified-Pitt car-following model.

Note that maximum acceleration is not an input to FlagSim. This value is determined explicitly by FlagSim for every vehicle at every simulation time step. More information about the maximum acceleration modeling approach utilized in FlagSim can be found in Appendix A.

The ‘Modified-Pitt Damping Factor’ inputs pertain to the car-following model employed in FlagSim. These inputs are discussed in more detail in the previous section.

It is not recommended that any of the above values be changed unless the analyst has specific data for a site contrary to these values.

Results Calculations Variables

Time delay accumulates when drivers are forced to travel under the specified speed limit or their desired free flow speed. The following two parameters allow the user to specify speeds that are considered “time-delay” to motorists – whether in a queue or traveling through the work zone at a speed lower than the posted speed limit.

Work Zone Travel Delay Threshold Speed

This input specifies the speed threshold for which delay for vehicles traveling through the work zone is accumulated. The average speed is calculated for every vehicle traveling through the work zone. If this average speed is below the speed threshold, it will have travel time delay calculated for it. Minimum and maximum input values are 5 mi/h and 70 mi/h, respectively.

Queue Delay Threshold Speed

This input specifies the speed threshold for which delay for vehicles approaching the work zone is accumulated. For example, if the threshold speed is 10 mi/h, for every time step (i.e., 0.1 seconds during the simulation) that a vehicle’s speed is below this speed, it accumulates queue delay. Note that a queue threshold speed of 0 mi/h would be

considered to be just stop delay. A higher value will also account for the delay accumulated while moving up in a queue (at slow speed) and some of the time decelerating to join the back of queue or re-accelerating from a queue to enter the work zone. Generally, the threshold speed accounts for the all the delays tallied from a queue listed previously. Minimum and maximum input values are 0 mi/h and 15 mi/h, respectively.

Flagging Control Variables

The “Flagging Control” variables section of the inputs window allows the user to first specify how the traffic volumes using the work zone will be controlled. Then, the user can specify the values of the applicable parameters for the chosen right-of-way allocation method.

Flagging Control

Four flagging control methods are available for use in FlagSim:

- Fixed Time
- Distance Gap Out
- Time Gap Out
- Maximum Queue Length

Fixed Time

The “Fixed Time” flagging control method assigns a fixed amount of green time to each direction, as specified in the “Max Green Time” input. Minimum and maximum values for mean max green time are 5 seconds and 300 seconds, respectively. The standard deviation for this input can also be adjusted by the user to allow for randomness in the actual green times applied by the flag person. A non-zero standard deviation would more realistic for human flaggers. Maximum and minimum standard deviation values are 0 seconds and 10 seconds, respectively.

	Mean		Standard Deviation	
	Dir 1	Dir 2	Dir 1	Dir 2
<input type="checkbox"/> Directions Same	5	5	0	0
Min Green Time (s)	5	5	0	0
Max Green Time (s)	300	300	0	0
Startup Lost Time (s)	10	10	0	0
Time Gap Out (s)	0	0	10	10
Distance Gap Out (ft)	400	400	0	0
Max Queue Length (veh)	10	10	0	0

Time Gap Out

The “Time Gap Out” flagging method keeps green time assigned to a given direction until the time elapsed between the last vehicle to enter the work zone and the next approaching vehicle exceeds the specified gap-out time. The minimum and maximum mean gap-out times are 0 seconds and 50 seconds, respectively. Minimum and maximum standard deviations are 0 seconds and 10 seconds, respectively.

Minimum and maximum green times are also applicable in this control mode, and take priority over the gap-out time. These minimum and maximum values are 5 seconds and 300 seconds, respectively. Note that the minimum green time can be automatically computed based upon the method given in reference 1. To have the minimum green time calculated, simply click on the “Calculate Minimum Green Time” button.

Flagging Control Variables

Flagging Control Time Gap Out

Calculate Minimum Green Time

	Mean		Standard Deviation	
<input type="checkbox"/> Directions Same	Dir 1	Dir 2	Dir 1	Dir 2
Min Green Time (s)	5	5	0	0
Max Green Time (s)	300	300	0	0
Startup Lost Time (s)	10	10	0	0
Time Gap Out (s)	0	0	10	10
Distance Gap Out (ft)	400	400	0	0
Max Queue Length (veh)	10	10	0	0

Distance Gap Out

The “Distance Gap Out” flagging method keeps green time assigned to a given direction until the distance between the last vehicle to enter the work zone and the next approaching vehicle exceeds the specified gap-out distance. The minimum and maximum mean gap-out distances are 20 feet and 1200 feet, respectively. A non-zero standard deviation can be applied to the mean distance gap out. Although a clear gap out zone can be marked by an orange cone or striped line across the road, the flag person may have a difficult time accurately depicting whether or not a vehicle has entered the gap out zone. Hence, a non-zero standard deviation would better simulate such flagging conditions. Minimum and maximum standard deviations are 0 ft and 50 ft, respectively.

Minimum and maximum green times are also applicable in this control mode, and take priority over the gap-out distance. These minimum and maximum values are 5 seconds and 300 seconds, respectively. Note that the minimum green time can be automatically computed based upon the method given in reference 1. To have the minimum green time calculated, simply click on the “Calculate Minimum Green Time” button.

Flagging Control Variables

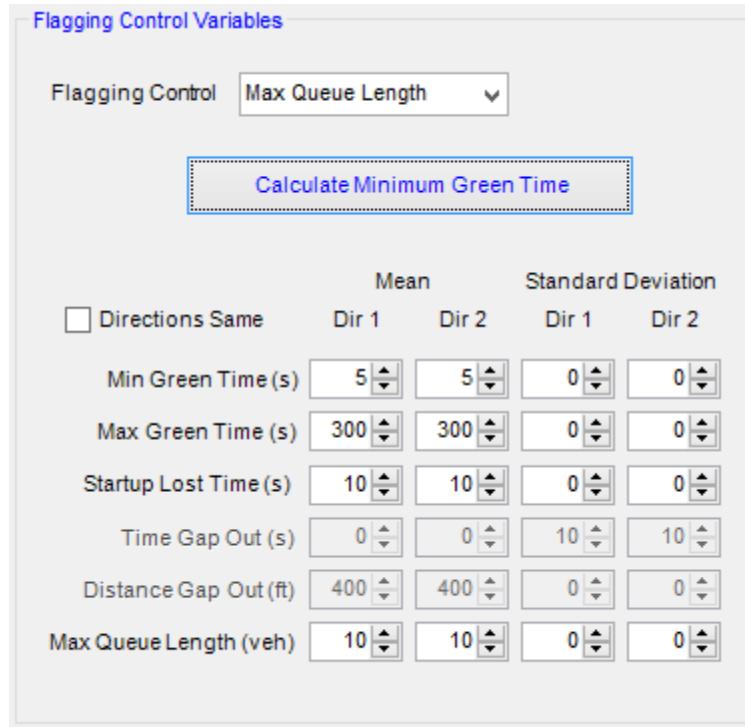
Flagging Control Distance Gap Out

Calculate Minimum Green Time

	Mean	Standard Deviation	
<input type="checkbox"/> Directions Same	Dir 1	Dir 2	Dir 1
Min Green Time (s)	5	5	0
Max Green Time (s)	300	300	0
Startup Lost Time (s)	10	10	0
Time Gap Out (s)	0	0	10
Distance Gap Out (ft)	400	400	0
Max Queue Length (veh)	10	10	0

Max Queue Length

The “Max Queue Length” flagging control method keeps green time assigned to a given direction until the opposing direction’s queue size reaches a specified value. The minimum and maximum values are 1 vehicle and 200 vehicles, respectively. The user can also specify a non-zero standard deviation, which would account for a human flagger under or over-estimating the queue length for the direction awaiting service. Minimum and maximum standard deviations are 0 vehicles and 10 vehicles, respectively.



Minimum and maximum green times are also applicable in this control mode, and take priority over the max queue length. These minimum and maximum values are 5 seconds and 300 seconds, respectively. Note that the minimum green time can be automatically computed based upon the method given in reference 1. To have the minimum green time calculated, simply click on the “Calculate Minimum Green Time” button.

Other Inputs

Startup Lost Time

Mean

This input specifies the average time, in seconds, that elapses between when the last vehicle in one direction exits the work zone and when the first queued vehicle in the other direction enters the work zone. The default value is 10 seconds. Minimum and maximum values for both directions are 1 second and 20 seconds, respectively.

Standard Deviation

The standard deviation for the startup lost time can also be specified in order to account for natural phase-to-phase randomness in this value. The randomness occurs from a difference in both the time it takes the flag person to turn the paddle to “Slow” after the last vehicle exits the work zone and the time it takes the first queued vehicle to startup and enter the work zone once the flag person turns the paddle to “Slow.” It should be noted that the position of the flag person and the beginning of work zone are assumed to

be at the same location, which is also where the first vehicle in queue stops in FlagSim. In the field, however, it is more typical that the first vehicle in queue stops 2-3 car lengths upstream of the flag person/work zone entry point. Thus, in FlagSim, the entry of the first vehicle in queue into the work zone and the changing of the flag paddle to “Slow” happen at the same time. In the field, the first vehicle usually enters the work zone a couple of seconds after the flag person turns the paddle to “Slow”. Thus, it is important that any field-measured lost times include the additional 2-3 seconds that it usually takes the first vehicle in queue to reach the work zone entry point after the flag paddle is turned “Slow”.

Directions Same Checkbox

Checking this box disables the inputs for direction 2 and applies the input values for direction 1 to both directions.

Flagging Control Variables

Flagging Control Time Gap Out

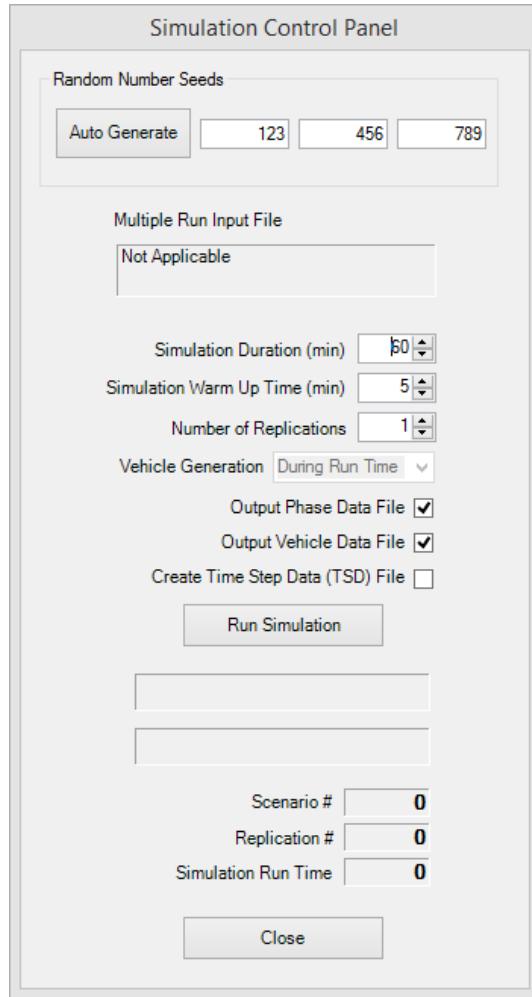
Directions Same

	Mean	Standard Deviation		
Dir 1	Dir 2	Dir 1	Dir 2	
Min Green Time (s)	5	5	0	0
Max Green Time (s)	300	300	0	0
Startup Lost Time (s)	10	10	0	0
Time Gap Out (s)	5	5	0	0
Distance Gap Out (ft)	400	400	0	0
Max Queue Length (veh)	10	10	0	0

Calculate Minimum Green Time

Simulation Control Panel

The simulation control panel is accessed from the toolbar (the calculator icon). It contains the parameters that control the running of the simulation.



Simulation Duration

This input specifies the time duration of the simulation, in minutes. The available time duration options are specified in increments of 5 minutes. The minimum and maximum warm-up times are 5 minutes and 60 minutes, respectively. The default simulation time is 60 minutes.

Simulation Warm Up Time

This input specifies the warm-up time. This time allows the network to be loaded with vehicles and reach an equilibrium state of operations. The simulation results reported by FlagSim do not include the operations during the warm-up time. Minimum and maximum warm-up times are 2 minutes and 15 minutes, respectively.

Number of Replications

The input specifies the number of times a given set of input conditions will be simulated. The random number seeds will be changed with each subsequent run.

Vehicle Generation

This feature is currently disabled.

Output Data Files

The output data files are generated for the simulation if the user checks the corresponding boxes. These files are written to the folder where FlagSim is installed, and are in a comma-separated values (CSV) format. Thus, they can easily be opened in the Microsoft Excel program. The data file for direction 1 is designated with a “1”, while the data file for direction 2 is designated with a “2”. Note that times reported in these files are in units of tenths of seconds.

Phase Data File

This output file summarizes data results for each phase (i.e., start of green to end of green). This file gives information such fields as the beginning and ending vehicle per phase; the time (in tenths of a second) at the start and end of green; the queue (number of vehicles lined up waiting to enter the work zone) at the onset of each green phase, the time when the maximum queue occurs, the maximum back of queue (the distance, in feet, from the stop bar to the rear bumper of the last car in the queue for a given phase); the amount of time spent delayed in the queue, and the average work zone speed. Note that the work zone speed is given in units of miles per hour. These parameters are specified for each direction (1 and 2). Separate CSV files are generated for each direction: “PhaseData_Dir_1 or PhaseData_Dir_2.”

Phase #	Begin Veh	End Vehicle	Start Green	End Green	Green Time	Q at Green Begin	Max Queue	Time of Max Q	Max Back of Q	Queue Delay	AvgWZSpeed	
1	1	2	0	952	0	0	0	0	0	0	0	
2	2	17	2198	2566	0	10	0	0	0	0	0	
3	3	25	3918	4134	216	6	6	3819	156	412.7467	35.19	
4	4	47	5613	6126	513	17	17	5538	446	688.9783	38.58	
5	5	71	7749	8328	579	18	19	7780	629	722.9632	36.795	
6	6	84	9775	10127	352	10	11	9783	315	786.5395	36.249	
7	7	105	11727	12208	481	17	19	11779	557	710.2848	38.033	
8	8	128	13765	14308	543	17	17	13518	495	763.2314	36.957	
9	9	147	16003	16441	438	11	13	16020	356	403.4268	36.708	
10	10	174	17960	18705	745	20	20	17838	722	782.2813	34.324	
11	11	197	20198	20755	557	20	21	20212	588	891.1823	37.499	
12	12	210	22430	22740	310	13	13	22381	338	812.3314	36.911	
13	211	237	24517	25183	666	21	21	24505	609	941.7245	36.462	
14	238	250	26683	27003	320	11	11	26614	296	813.8904	37.236	
15	251	261	28623	28929	306	11	11	28571	332	700.9207	35.849	
16	262	284	30600	31177	577	12	14	30678	445	607.5563	35.74	
17	285	302	32880	33307	427	14	15	32896	441	846.4069	37.956	
18	303	318	34825	35251	426	10	11	34828	370	539.0911	35.989	
19	319	348	36889	37595	706	19	21	36928	623	726.4072	38.377	
20												
21												
22												

Vehicle Data File

This output file records key measures for each vehicle that enters the system during a simulation. The vehicle #, type, and system entry/exit time are tallied for each vehicle. Additionally, the time step when each vehicle enters and exits the work zone is recorded. The length of time for which each vehicle is in the work zone as well as the average speeds within the work zone are computed. Time data are also recorded for each queue. Note that the units for work zone speed is feet per second. The corresponding average queue delay is computed (as shown in column k). Separate CSV files are generated for each direction: “VehicleData_Dir_1 or VehicleData_Dir_2.”

Vehicle#	Veh Type	Enter System Time	Exit System Time	Enter WZ Time	Exit WZ Time	Time in WZ	Avg WZ Speed	Queue Entry Time	Queue Exit Time	Queue Delay
1	Car		18	2394	934	1392	0	0	0	0
2	Car		39	2412	952	1410	0	0	0	0
3	Car		235	3610	2198	2690	0	0	1048	2231 1182.438
4	Car		283	3631	2247	2713	0	0	1072	2249 1176.364
5	Car		355	3649	2275	2731	0	0	1089	2262 1172.333
6	Car		435	3796	2301	2789	0	0	1362	2277 914.3254
7	Car		453	3813	2330	2807	0	0	1378	2299 920.0858
8	Car		835	3832	2355	2828	0	0	1630	2315 684.0502
9	Car		881	3850	2379	2847	0	0	1647	2329 680.9779
10	Car		899	3868	2402	2865	0	0	1666	2343 675.9536
11	Car		1101	3886	2423	2883	0	0	1893	2357 462.9999
12	Car		1119	3904	2445	2902	0	0	1910	2371 459.9314
13	Car		1389	3927	2469	2940	0	0	2254	2386 131.0137
14	Car		1552	4005	2508	2978	0	0	0	0
15	Car		1575	4023	2526	2996	0	0	0	0
16	Car		1744	4040	2544	3014	0	0	0	0
17	Car		1842	4060	2566	3036	0	0	0	0
18	Car		2034	5507	3918	4483	565	46.72566	3003	3968 964.2803
19	Car		2270	5528	3976	4505	529	49.90548	3165	3984 818.1917
20	Car		2570	5546	4007	4523	516	51.16279	3449	3998 548.1403
21	Car		2791	5564	4034	4542	508	51.96851	3579	4012 432.2122
22	Car		2925	5583	4060	4562	502	52.58964	3706	4026 319.1405
23	Car		2980	5602	4084	4581	497	53.11871	3819	4040 220.0998
24	Car		3103	5631	4108	4602	494	53.4413	0	0 0
25	Car		3187	5651	4134	4623	489	53.98773	0	0 0
26	Car		3347	7072	5613	6107	494	53.4413	4220	5638 1417.547

Time Step Data (TSD) File

Since FlagSim is a microscopic simulation program, detailed vehicle trajectory data (i.e., acceleration, velocity, position, etc. values) are generated at each time step. These data can be saved to a file if the user so desires, in which case one TSD file per travel direction is created.

Run Simulation

Clicking this button will start the simulation. A message specifying the progress of the simulation will appear in the text box directly below the “Run Simulation” button. While the simulation is running, the “Simulation in progress...,” message should appear, and after the simulation is finished running, “The simulation is complete” message should appear.

Simulation Run Time

This records the amount of time for a single simulation to complete. Once the simulation has completed, the timer will display the final value.

Simulation Run

This specifies the current simulation run being executed.

Close

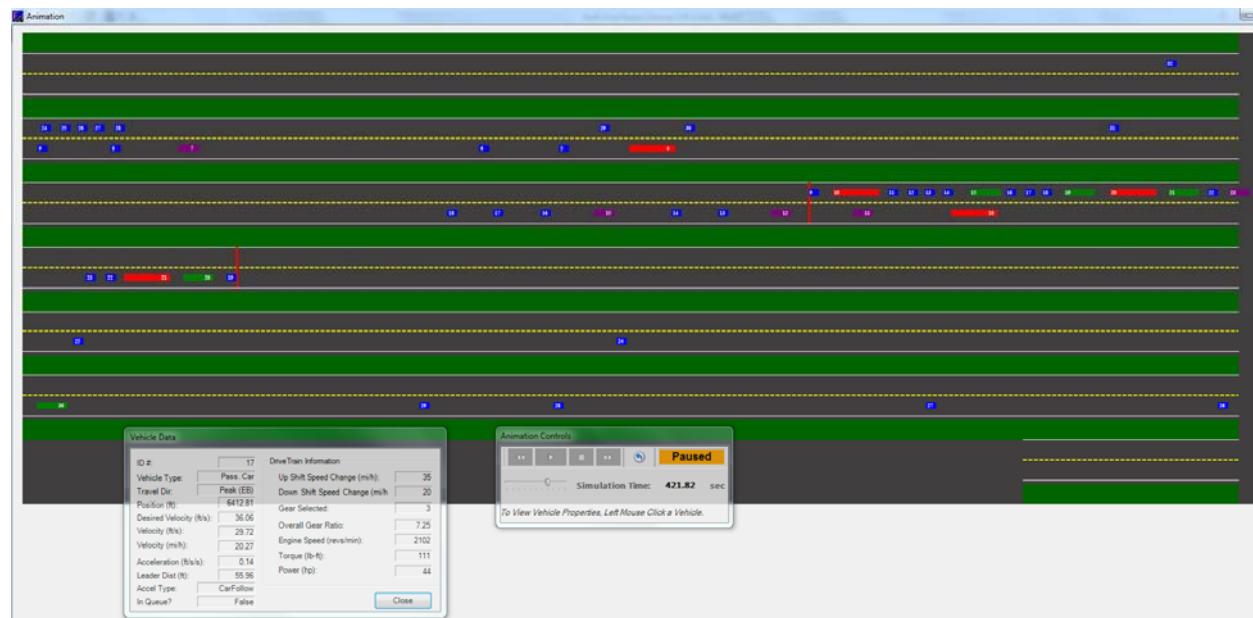
Clicking this button will close the Simulation Control Panel.

Animation Screen

FlagSim incorporates a 2-D post-processor animation viewer, shown in the figure below. The animation allows the user to view the computations previously performed. Viewing the animation gives the user an opportunity to review the simulation scenario visually. Items that can be easily checked are vehicle generation, car-following interaction, and the flagging operations.

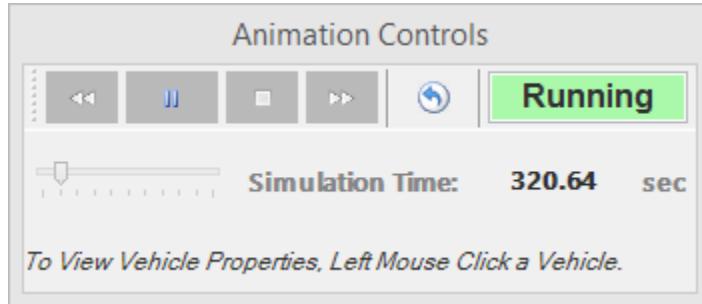
Click on the right-most button on the toolbar. This displays the work zone simulation animation. The work zone stop bars (also assumed to be the flagger position) are identified with green, yellow, and red vertical bars (i.e., running perpendicular to the roadway). The color of the stop bar indicates which direction will have or has the right-of-way. Yellow indicates the start-up lost time for a given phase.

Passenger cars are shown in blue, small trucks in purple, medium trucks in green, and large trucks in red. Since the animation can cover a significant length of roadway, the display of the roadway is presented in a stacked fashion to utilize the full screen area and avoid a lot horizontal scrolling. Thus, a vehicle that disappears off the edge of the screen on one side will reappear on the other side of the screen (except for vehicles exiting the system), one level higher or lower, depending on the direction of vehicle movement. This also allows most of the roadway network to be observed in its entirety for many roadway configurations.



Run Control

Once the animation screen is loaded, an “Animation Controls” dialog will also appear (see figure below). This dialog allows the user to control the animation—play, pause, stop and speed control. These features are described further below.



Animation Speed

This feature allows the user to adjust the rate at which the simulation animation occurs. The rate can be adjusted by dragging the arrow indicator left or right, by clicking individual hash marks on the meter for a desired rate, or by pressing the right and left arrow buttons. The allowable values range from 0-10 times normal speed. 0x stops the simulation, while 1x runs the simulation at the equivalent of real-time speed.

Simulation Playback

The playback console allows the user to play, stop, and pause the simulation animation by clicking the respective buttons. The playback status appears directly below the buttons. The time scale may also be adjusted by clicking the right and left double arrows, which speed up or slow down the animation playback rate.

Reset Animation

This will stop the animation at the current time step without restarting the animation from the beginning. To resume, simply press play.

Simulation Time

This timer keeps track of the simulation time, in seconds. Pausing or stopping the animation stops the simulation time counter. Adjusting the playback speed of the animation also adjusts the speed of the time counter.

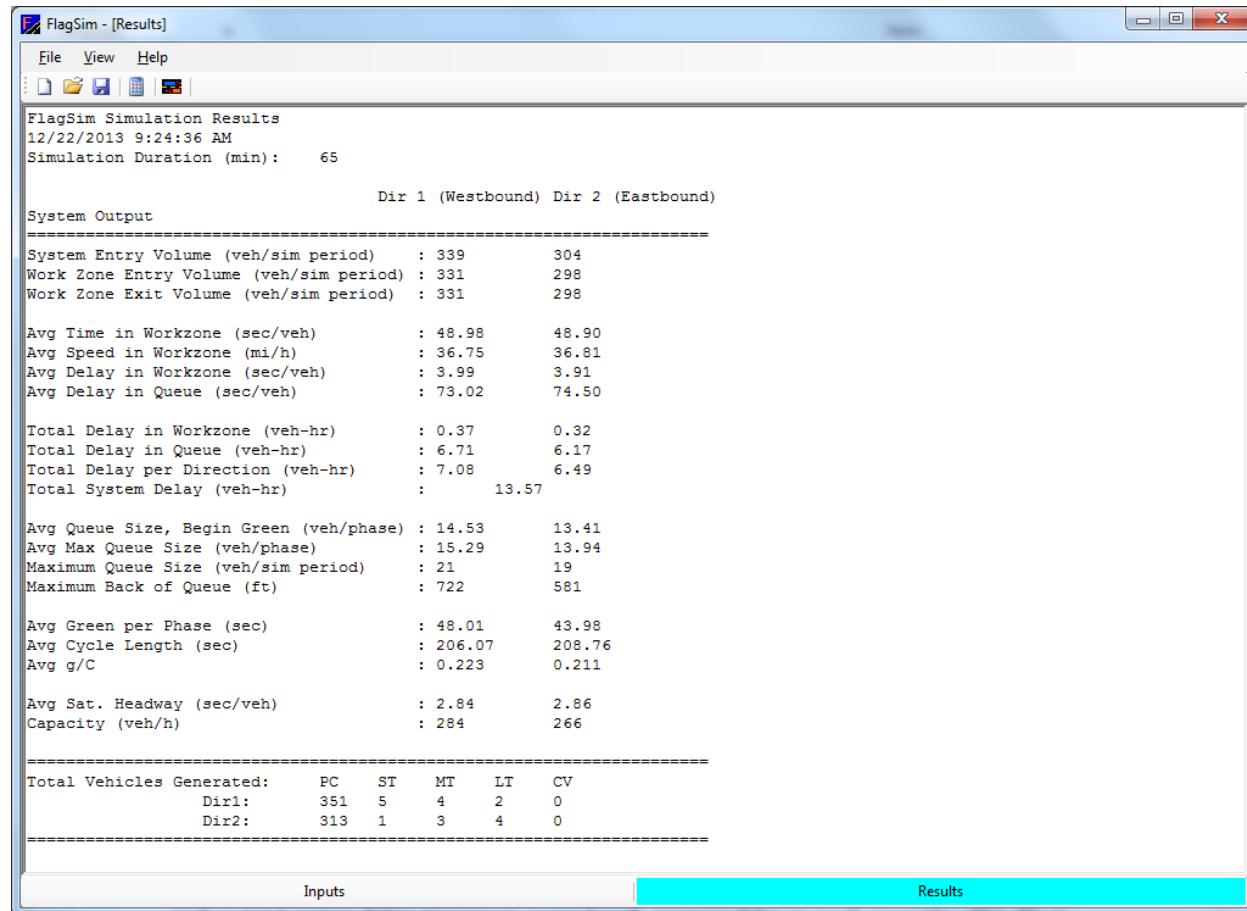
Vehicle Tracker

In order to view specific properties for vehicles present in the animation, press the left mouse button while the cursor is positioned above a vehicle (it typically helps to pause the animation before selecting a vehicle). A semi-transparent screen will appear that contains the data shown in the figure below, for every simulation time step (0.1 s). Any measures that do not apply will show “N.A.” (i.e., not applicable). This might apply, for example, for the leader distance measure for a vehicle not following another vehicle.

Vehicle Data	
ID #:	17
Vehicle Type:	Pass. Car
Travel Dir:	Peak (EB)
Position (ft):	4036.98
Desired Velocity (ft/s):	71.95
Velocity (ft/s):	71.20
Velocity (mi/h):	48.54
Acceleration (ft/s/s):	0.00
Leader Dist (ft):	676.55
Accel Type:	NoCarFollow
In Queue?	False
Drive Train Information	
Up Shift Speed Change (mi/h):	55
Down Shift Speed Change (mi/h):	40
Gear Selected:	5
Overall Gear Ratio:	4.39
Engine Speed (revs/min):	3049
Torque (lb-ft):	119
Power (hp):	69
<input type="button" value="Close"/>	

Results Screen

Once a simulation run is complete, the overall results for the simulation period can be accessed by clicking on the tab in the lower right corner of the screen.



The screenshot shows the 'FlagSim - [Results]' window. The menu bar includes File, View, Help, and icons for Print, Save, and Exit. The main area displays 'FlagSim Simulation Results' from 12/22/2013 at 9:24:36 AM, with a simulation duration of 65 minutes. The output is split into two columns: 'Dir 1 (Westbound)' and 'Dir 2 (Eastbound)'. The 'System Output' section contains various performance metrics such as entry volume, average speed, and total delay. The 'Inputs' tab is visible at the bottom left, and the 'Results' tab is highlighted in blue at the bottom right.

```

FlagSim Simulation Results
12/22/2013 9:24:36 AM
Simulation Duration (min): 65

Dir 1 (Westbound) Dir 2 (Eastbound)
System Output
-----
System Entry Volume (veh/sim period) : 339      304
Work Zone Entry Volume (veh/sim period) : 331      298
Work Zone Exit Volume (veh/sim period) : 331      298

Avg Time in Workzone (sec/veh)       : 48.98     48.90
Avg Speed in Workzone (mi/n)        : 36.75     36.81
Avg Delay in Workzone (sec/veh)      : 3.99      3.91
Avg Delay in Queue (sec/veh)         : 73.02     74.50

Total Delay in Workzone (veh-hr)     : 0.37      0.32
Total Delay in Queue (veh-hr)        : 6.71      6.17
Total Delay per Direction (veh-hr)   : 7.08      6.49
Total System Delay (veh-hr)          :           13.57

Avg Queue Size, Begin Green (veh/phase) : 14.53    13.41
Avg Max Queue Size (veh/phase)          : 15.29    13.94
Maximum Queue Size (veh/sim period)    : 21       19
Maximum Back of Queue (ft)             : 722      581

Avg Green per Phase (sec)            : 48.01     43.98
Avg Cycle Length (sec)              : 206.07    208.76
Avg g/C                            : 0.223     0.211

Avg Sat. Headway (sec/veh)          : 2.84      2.86
Capacity (veh/h)                   : 284       266

-----
Total Vehicles Generated: PC ST MT LT CV
Dir1: 351 5 4 2 0
Dir2: 313 1 3 4 0
-----
```

This window provides a summary of the key performance measures for the work zone operation, such as total system delay, maximum queue length, average delay in work zone, etc. This file is written to the same folder that contains the FlagSim program. It can be loaded into any text editing program for further formatting and/or printing.

Output Parameters and Equations

This section describes each of the measures provided in the results file. The equations used to calculate each of the output values, as appropriate, are also described.

System Entry Volume — number of vehicles entering the system for the simulation time period. Note that the system entry volume can be *smaller* than the work zone entry volume. This happens if a vehicle enters the system before the end of the warm-up period but enters the work zone after the warm-up period ends (excludes warm-up period).

Work Zone Entry Volume — number of vehicles entering the work zone for the simulation time period (excludes warm-up period).

Work Zone Exit Volume — number of vehicles exiting the work zone for the simulation time period. Note that the work zone exit volume can be *smaller* than the work zone entry volume. This happens if the simulation time period expires while some vehicles are still present in the work zone (excludes warm-up period).

Average Time in Work Zone — average travel time through the work zone for all vehicles traveling inside the work zone area. It is calculated according to the following equation.

$$\bar{tt}_{wz_k} = \frac{1}{n_{veh_k}} \sum_{i=x}^y tt_{wz_i_k}$$

\bar{tt}_{wz_k} = average travel time through the work zone for vehicles traveling in direction k , in seconds

$tt_{wz_i_k}$ = travel time through work zone for vehicle i in direction k , in seconds
= time vehicle i exits work zone – time vehicle i enters work zone

x = the first vehicle to enter the work zone in direction k after the simulation warm-up period has ended

y = the last vehicle to exit the work zone in direction k after the simulation warm-up period has ended

i = vehicle number

k = travel direction (1 or 2)

n_{veh_k} = total number of vehicles to traverse the work zone in direction k after the simulation warm-up period has ended in direction

Average Speed in Work Zone — average speed of all vehicles traveling inside the work zone area. It is calculated according to the following equation.

$$\bar{v}_{wz_k} = \frac{1}{n_{veh_k}} \sum_{i=x}^y \frac{WZlength}{tt_{wz_i_k}/3600}$$

\bar{v}_{wz_k} = average vehicle speed in the work zone for direction k , in mi/h

$WZlength$ = work zone length, in miles

Average Delay in Work Zone — average travel time delay experienced by all vehicles while within the work zone.

$$\bar{d}_{wz_k} = \frac{1}{n_{veh_k}} \sum_{i=x}^y d_{wz_i_k}$$

\bar{d}_{wz_k} = average work zone delay for vehicles traveling in direction k , in seconds

$d_{wz_i_k}$ = work zone delay for vehicle i traveling in direction k , in seconds
 $\equiv tt_{wz_i_k} - BaseWZTravTime$

$BaseWZTravTime$ = travel time through work zone if traveling at “Work Zone Travel Delay Threshold Speed” ($WZdelspd$) in seconds
 $= (WZlength/WZdelspd)/3600$

$WZdelspd$ = travel speed below which work zone travel delay accumulates (default is work zone posted speed), in mi/h

Average Delay in Queue — average travel time delay experienced by all vehicles while in queue. Queue delay for an individual vehicle is obtained by adding a second of delay for every second the vehicle is traveling at a speed below the “Queue Delay Threshold Speed.” The default “Queue Delay Threshold Speed” is 10 mi/h.

$$\bar{d}_{q_k} = \frac{1}{n_{veh_k}} \sum_{i=x}^y d_{q_i_k}$$

\bar{d}_{q_k} = average queue delay for vehicles traveling in direction k , in seconds

$d_{q_i_k}$ = queue delay for vehicle i traveling in direction k , in seconds

Total Delay in Work Zone — total travel time delay experienced by all vehicles while within the work zone.

$$d_{wz_tot_k} = \sum_{i=x}^y (d_{wz_i_k}/3600)$$

$d_{wz_tot_k}$ = total work zone delay for all vehicles traveling in direction k , in hours

Total Delay in Queue — total travel time delay experienced by all vehicles while in queue.

$$d_{q_tot_k} = \sum_{i=x}^y (d_{q_i_k}/3600)$$

$d_{q_tot_k}$ = total queue delay for all vehicles traveling in direction k , in hours

Total Delay per Direction — total travel time delay (sum of Total Delay in Work Zone and Total Delay in Queue) experienced by all vehicles for a given direction for the simulation time period.

$$d_{tot_k} = d_{wz_tot_k} + d_{q_tot_k}$$

d_{tot_k} = total delay for all vehicles traveling in direction k , in hours

Total System Delay — total travel time delay (sum of Total Delay for both directions) experienced by all vehicles traversing the work zone during the simulation time period (excluding the warm-up time).

$$d_{tot} = d_{tot_1} + d_{tot_2}$$

d_{tot_k} = total delay for all vehicles that traverse the work zone, traveling in direction k , during the simulation time period (excluding the warm-up time), in hours

Average Queue Size at Beginning of Green — the average number of vehicles in queue per phase measured at the time when the flag indication turns to green.

$$\bar{Q}_{beg_k} = \frac{1}{n_{phase_k}} \sum_{j=a}^b Q_{beg_j_k}$$

\bar{Q}_{beg_k} = average queue size per phase at the beginning of green period for direction k , in vehicles

$Q_{beg_j_k}$ = queue size at the beginning of green period for phase j in direction k , in vehicles

a = the first phase to occur in direction k after the simulation warm-up period has ended

b = the last phase to occur in direction k after the simulation warm-up period has ended

j = phase number

n_{phase_k} = total number of phases that occur for direction k after the simulation warm-up period has ended

Average Maximum Queue Size — the average number of vehicles in queue per phase measured at the time when the queue is largest. It should be noted that the queue size used for each phase is the absolute maximum queue, which accounts for vehicles arriving on green at the back of the initial queue at the start of green.

$$\bar{Q}_{max_k} = \frac{1}{n_{phase_k}} \sum_{j=a}^b Q_{max_j_k}$$

\bar{Q}_{max_k} = average maximum queue size per phase for direction k , in vehicles

$Q_{max_j_k}$ = maximum queue size for phase j in direction k , in vehicles

Maximum Queue Size — the maximum number of vehicles in queue during the entire simulation period; that is, across all phases.

$$Q_{max_k} = \max_{a \leq j \leq b} Q_{max_j_k}$$

Q_{max_k} = maximum queue size across all phases for direction k , in vehicles

Maximum Back of Queue — the distance corresponding to the maximum queue size, Q_{max_k} . This distance is calculated by taking the difference between the position of the stop bar for direction k and the position of the back bumper of the last vehicle in queue. This value is reported in feet.

Average Green per Phase — the average green period per phase where the green period is the elapsed time between when the flag indication turns to green and when it turns back to red. It should be noted that if the green period of the last phase to occur after the warm-up period has ended, phase b , does not terminate before the end of the simulation period this phase is not included in the calculation. In this case the phase prior to this phase is used as phase b .

$$\bar{g}_k = \frac{1}{n_{phase_k}} \sum_{j=a}^b g_{j_k}$$

\bar{g}_k = average green period per phase for direction k , in seconds

g_{j_k} = green period for phase j in direction k , in seconds

$$= t_{grnend_j_k} - t_{grnbeg_j_k}$$

$t_{grnend_j_k}$ = time flag indication turns to red to end phase j in direction k , in seconds after simulation began

$t_{grnbeg_j_k}$ = time flag indication turns to green to begin phase j in direction k , in seconds after simulation began

Average Cycle Length — the average cycle length, calculated simply as the sum of all cycle lengths divided by the number of cycles in the simulation period. Cycle length is measured as the time elapsed between the beginning of green for one phase and direction and the beginning of green for the next phase in the same direction.

$$\bar{C}_k = \frac{1}{n_{cycle}} \sum_{j=a}^{b-1} C_{j_k}$$

\bar{C}_k = average cycle length for direction k , in seconds

C_{j_k} = cycle length corresponding to phase j in direction k , in seconds

$$= t_{grnbeg,j+1_k} - t_{grnbeg,j_k}$$

n_{cycle} = total number of cycles that occur after the simulation warm-up period has ended

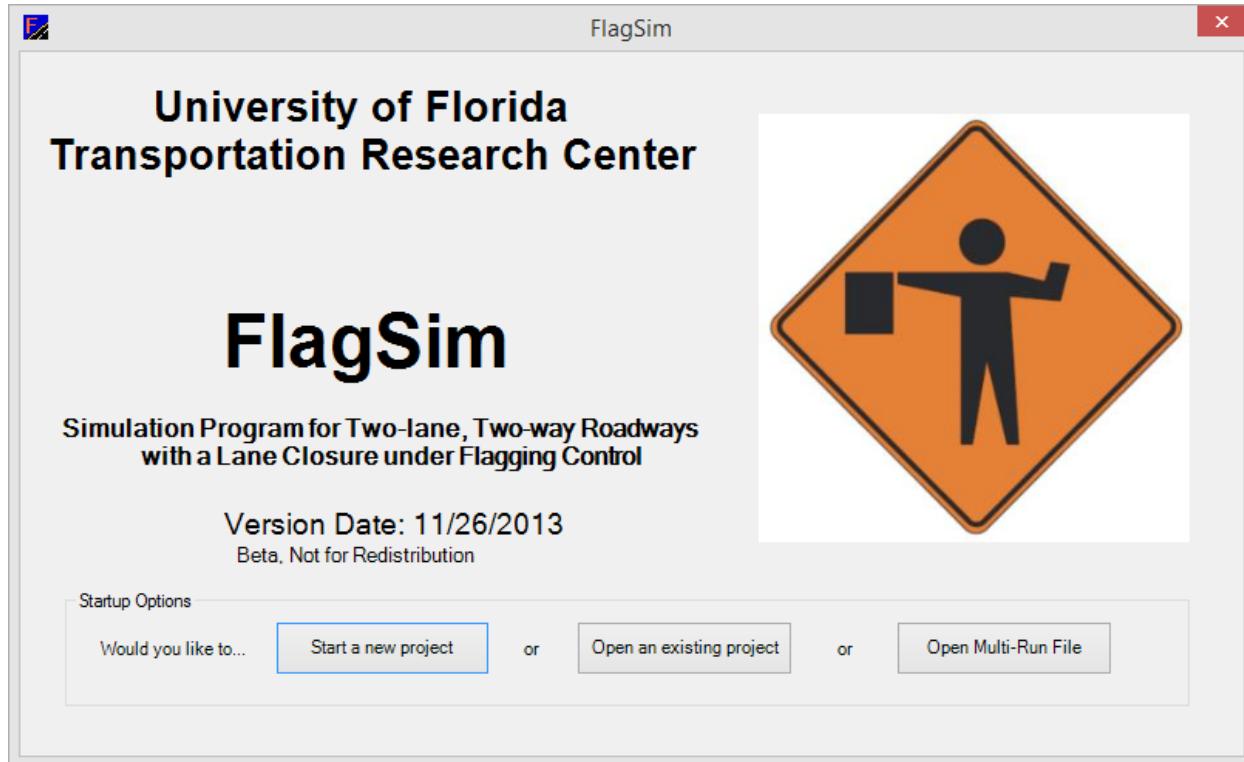
Average g/C — the average green period to cycle length ratio. It is calculated according to the following formula.

$$\overline{g/C_k} = \frac{1}{n_{cycle}} \sum_{j=a}^{b-1} \left(g_{j_k} / C_{j_k} \right)$$

$\overline{g/C_k}$ = average green period to cycle length ratio for direction k , unitless

Multi-Run Capability

To facilitate multiple runs for different scenarios (i.e., different sets of inputs), the user can choose to open a Multi-Run File from the FlagSim open dialog screen.



The multi-run file must be in a comma-separated values (i.e., “*.csv”) format and have the FlagSim inputs arranged in a specific way. The first row is used to label the FlagSim inputs, but is not read by the program. This simply provides the user with a reference as to which column corresponds to which FlagSim input. The second and subsequent rows are used to assign the FlagSim input values for the different scenarios. Each row is a separate scenario. Therefore, the inputs in row 2 are for scenario 1, and the inputs in row 3 are for scenario 2, etc. This is done for as many scenarios as one wishes to run. The FlagSim inputs should be placed in the .csv file in the following order with the corresponding column letters (per Microsoft Excel’s column labeling scheme, other programs may vary).

- A. Scenario # — the scenario number corresponding to the row of inputs
- B. AppLength — approach roadway length, in miles
- C. WZLength — length of the work zone, in miles
- D. AppSpeed_Dir1 — approach roadway posted speed for direction 1, in mi/h
- E. AppSpeed_Dir2 — approach roadway posted speed for direction 2, in mi/h
- F. GradeProp_Dir1 — roadway grade for direction 1, expressed as a proportion

- G. GradeProp_Dir2 — roadway grade for direction 2, expressed as a proportion
- H. WZMeasSpeed — average speed (or other appropriate percentile speed, at discretion of analyst) through the work zone measured from the field (if speed was not measured, use value of 0), in mi/h
- I. WZPostSpeed — posted speed in the work zone area, in mi/h
- J. EstSpeed? — is the work zone speed estimated? (use value of “Yes” if using “WZPostSpeed” for simulation and “No” if using “WZMeasSpeed”)
- K. EffLaneWidth — effective lane width in work zone (use value of “Narrow” for narrow lane width, “Med” for medium lane width, and “Wide” for wide lane width)
- L. ConstAct — level of construction activity in work zone (use value of “Low” for no or low construction activity, “Med” for medium construction activity, and “High” for high construction activity)
- M. DirClose — specifies which travel direction has the closed lane (use value of “Dir1” if the lane for direction 1 is closed and value of “Dir2” if the lane for direction 2 is closed)
- N. WZDelaySpeed — speed threshold used to calculate travel time delay of vehicles in the work zone. Vehicles accumulate work zone delay when traveling at a speed below this threshold. Set “WZDelaySpeed” equal to “WZMeasSpeed” or “WZPostSpeed,” unless it is desirable to use a different speed. Value should be in mi/h.
- O. QueueDelaySpeed — speed threshold used to calculate travel time delay of vehicles in queue. Vehicles accumulate queue delay when traveling at a speed below this threshold. Set QueueDelaySpeed equal to 10, unless there is a reason to use a different speed. Value should be in mi/h.
- P. PctCar_Dir1 — percentage of passenger cars traveling in direction 1
- Q. PctST_Dir1 — percentage of small trucks traveling in direction 1
- R. PctMT_Dir1 — percentage of medium trucks traveling in direction 1
- S. PctLT_Dir1 — percentage of large trucks traveling in direction 1
- T. PctCar_Dir2 — percentage of passenger cars traveling in direction 2
- U. PctST_Dir2 — percentage of small trucks traveling in direction 2
- V. PctMT_Dir2 — percentage of medium trucks traveling in direction 2
- W. PctLT_Dir2 — percentage of large trucks traveling in direction 2
- X. Vol_Dir1 — vehicle arrival rate for direction 1, in veh/h
- Y. Vol_Dir2 — vehicle arrival rate for direction 2, in veh/h
- Z. Control — type of flagging control used at the work zone (use value of “FixedTime” for Fixed Time flagging control, “MaxQueue” for Max Queue Length flagging control, “GapOutDistance” for Distance Gap Out flagging control, and “GapOutTime” for Time Gap Out flagging control)
- AA. MinGreenMean_Dir1 — mean of minimum green time for direction 1, in sec
- AB. MinGreenMean_Dir2 — mean of minimum green time for direction 2, in sec
- AC. MinGreenStdev_Dir1 — standard deviation of minimum green time for direction 1, in sec

- AD. MinGreenStdev_Dir2 — standard deviation of minimum green time for direction 2, in sec
- AE. MaxGreenMean_Dir1 — mean of maximum green time for direction 1, in sec
- AF. MaxGreenMean_Dir2 — mean of maximum green time for direction 2, in sec
- AG. MaxGreenStdev_Dir1 — standard deviation of maximum green time for direction 1, in sec
- AH. MaxGreenStdev_Dir2 — standard deviation of maximum green time for direction 2, in sec
- AI. LostTimeMean_Dir1 — mean of startup lost time for direction 1, in sec
- AJ. LostTimeMean_Dir2 — mean of startup lost time for direction 2, in sec
- AK. LostTimeStdev_Dir1 — standard deviation of startup lost time for direction 1, in sec
- AL. LostTimeStdev_Dir2 — standard deviation of startup lost time for direction 2, in sec
- AM. ControlMean_Dir1 — mean of input used for flagging control for direction 1 (for “Max Queue Length” flagging control is mean of “Max Queue Length” in vehicles, for “Distance Gap Out” flagging control is mean of “Distance Gap Out” in feet, and for “Time Gap Out” flagging control is mean of “Time Gap Out” in seconds). If using “Fixed Time” flagging control leave this input blank (fixed time uses the maximum green time inputs).
- AN. ControlMean_Dir2 — mean of input used for flagging control for direction 2 (for “Max Queue Length” flagging control is mean of “Max Queue Length” in vehicles, for “Distance Gap Out” flagging control is mean of “Distance Gap Out” in feet, and for “Time Gap Out” flagging control is mean of “Time Gap Out” in seconds). If using “Fixed Time” flagging control leave this input blank (fixed time uses the maximum green time inputs).
- AO. ControlStdev_Dir1 — standard deviation of input used for flagging control for direction 1 (for “Max Queue Length” flagging control is standard deviation of “Max Queue Length” in vehicles, for “Distance Gap Out” flagging control is standard deviation of “Distance Gap Out” in feet, and for “Time Gap Out” flagging control is standard deviation of “Time Gap Out” in seconds). If using “Fixed Time” flagging control leave this input blank (fixed time uses the maximum green time inputs).
- AP. ControlStdev_Dir2 — standard deviation of input used for flagging control for direction 2 (for “Max Queue Length” flagging control is standard deviation of “Max Queue Length” in vehicles, for “Distance Gap Out” flagging control is standard deviation of “Distance Gap Out” in feet, and for “Time Gap Out” flagging control is standard deviation of “Time Gap Out” in seconds). If using “Fixed Time” flagging control leave this input blank (fixed time uses the maximum green time inputs).

References

1. Washburn, Scott S, Hiles, Thomas, and Heaslip, Kevin. *Impact of Lane Closures on Roadway Capacity: Development of a Two-Lane Work Zone Lane Closure Analysis Procedure (Part A)*. Final Report. Florida Department of Transportation. Tallahassee, FL. January 2008.
2. Cohen, Stephen, L. (2002). *Application of Car-Following Systems in Microscopic Time-Scan Simulation Models*. Journal of the Transportation Research Board, TRR 1802, 239-247.
3. Cohen, Stephen, L. (2002). *Application of Car-Following Systems to Queue Discharge Problem at Signalized Intersections*. Journal of the Transportation Research Board, TRR 1802, 205-213.

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APPENDIX A

Vehicle Dynamics Approach to Truck Acceleration Modeling in FlagSim: Example Calculation

The approach used to model vehicle acceleration in FlagSim is based on the vehicle performance theory and equations given in *Principles of Highway Engineering and Traffic Analysis* (Mannering and Washburn, 2012). An overview of this approach is given here.

The approach at its most basic level determines acceleration through the fundamental equation relating tractive force to resistance forces, as follows.

$$F = ma + R_a + R_{rl} + R_g \quad [\text{A-1}]$$

The tractive force, F , referred to here as available tractive effort, is taken as the lesser of maximum tractive effort and engine-generated tractive effort. Maximum tractive effort is a function of several of the vehicle's physical characteristics (such as wheelbase, center of gravity, and weight) and the roadway coefficient of road adhesion. Maximum tractive effort represents the amount of longitudinal force that can be accommodated by the tire-pavement interface. Engine-generated tractive effort is a function of engine torque, transmission and differential gearing, and drive wheel radius. For vehicles with low power-to-weight ratios, such as commercial trucks, maximum tractive effort is very rarely the governing condition. Thus, the acceleration calculations for trucks in FlagSim are based on engine-generated tractive effort.

The major resistance forces are aerodynamic (R_a), rolling (R_{rl}), and grade (R_g). The equation for determining aerodynamic resistance is

$$R_a = \frac{\rho}{2} C_D A_f V^2 \quad [\text{A-2}]$$

where

- R_a = aerodynamic resistance in lb,
- ρ = air density in slugs/ft³,
- C_D = coefficient of drag (unitless),
- A_f = frontal area of the vehicle (projected area of the vehicle in the direction of travel) in ft², and
- V = speed of the vehicle in ft/s.

The coefficient of rolling resistance for road vehicles operating on paved surfaces is approximated as

$$f_{rl} = 0.01 \left(1 + \frac{V}{147} \right) \quad [\text{A-3}]$$

where

$$f_{rl} = \text{coefficient of rolling resistance (unitless), and}$$

$$V = \text{vehicle speed in ft/s.}$$

The rolling resistance, in lb, is simply the coefficient of rolling resistance multiplied by $W \cos \theta_g$, the vehicle weight acting normal to the roadway surface. For most highway applications θ_g is very small, so it can be assumed that $\cos \theta_g = 1$, giving the equation for rolling resistance (R_{rl}) as

$$R_{rl} = f_{rl} W \quad [\text{A-4}]$$

Grade resistance is simply the gravitational force (the component parallel to the roadway) acting on the vehicle. The expression for grade resistance (R_g) is

$$R_g = W \sin \theta_g \quad [\text{A-5}]$$

As in the development of the rolling resistance formula, highway grades are usually very small, so $\sin \theta_g \cong \tan \theta_g$. Thus, grade resistance is calculated as

$$R_g \cong W \tan \theta_g = WG \quad [\text{A-6}]$$

where

$$G = \text{grade, defined as the vertical rise per some specified horizontal distance in ft/ft.}$$

Grades are generally specified as percentages for ease of understanding. Thus a roadway that rises 5 ft vertically per 100 ft horizontally ($G = 0.05$ and $\theta_g = 2.86^\circ$) is said to have a 5% grade.

The relationship between vehicle speed and engine speed is

$$V = \frac{2\pi r n_e (1-i)}{\varepsilon_0} \quad [\text{A-7}]$$

where

$$V = \text{vehicle speed in ft/s,}$$

$$n_e = \text{engine speed in crankshaft revolutions per second,}$$

$$i = \text{slippage of the drive axle, and}$$

$$\varepsilon_0 = \text{overall gear reduction ratio}$$

The overall gear reduction ratio is a function of the differential gear ratio and the transmission gear ratio, which is a function of the selected transmission gear for the running speed. This equation can be rearranged to solve for engine speed given the current vehicle speed (if vehicle speed is zero, engine speed is a function of throttle input).

With the calculated engine speed, the torque being produced by the engine can be determined from the torque-engine speed relationship. For example, assuming an engine speed of 2000 revolutions/min with the torque-engine speed relationship (Paccar PX-7 Engine) shown in Figure 5 (Ref. 3), the resulting torque is 660 ft-lb. In addition, Figure 6 shows the torque-engine speed relationship for a Paccar MX-13 engine (Ref. 4).

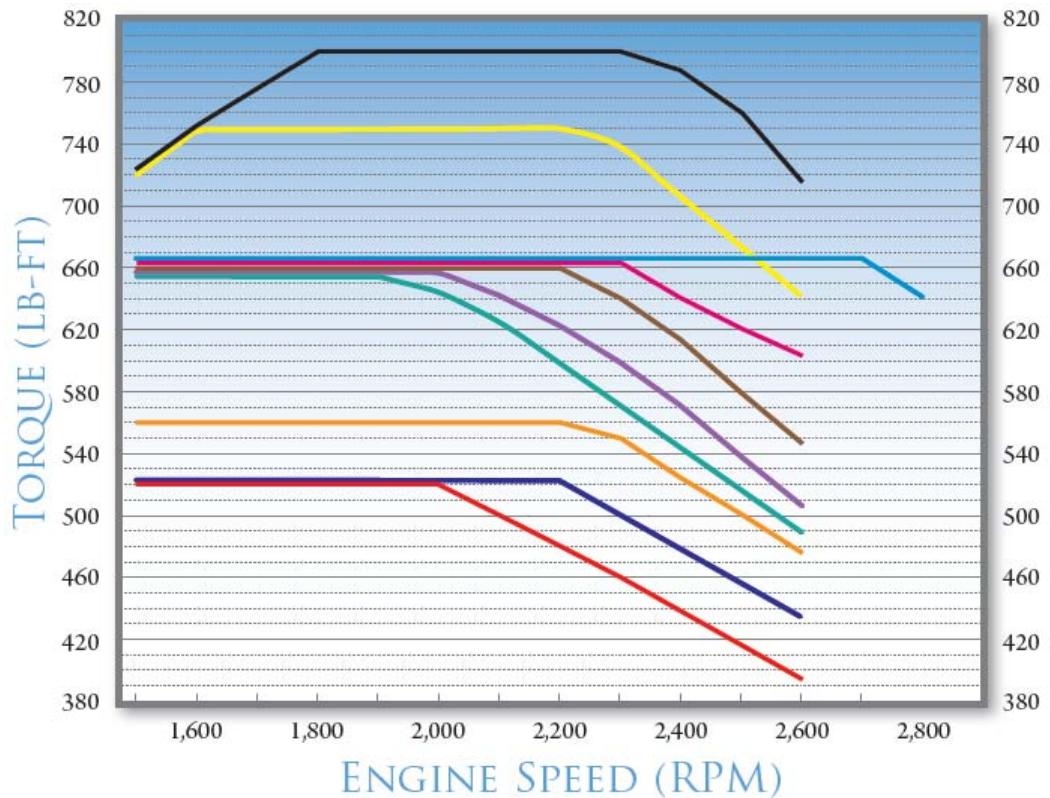


Figure 5. Torque-engine speed curve for a Paccar PX-7 engine

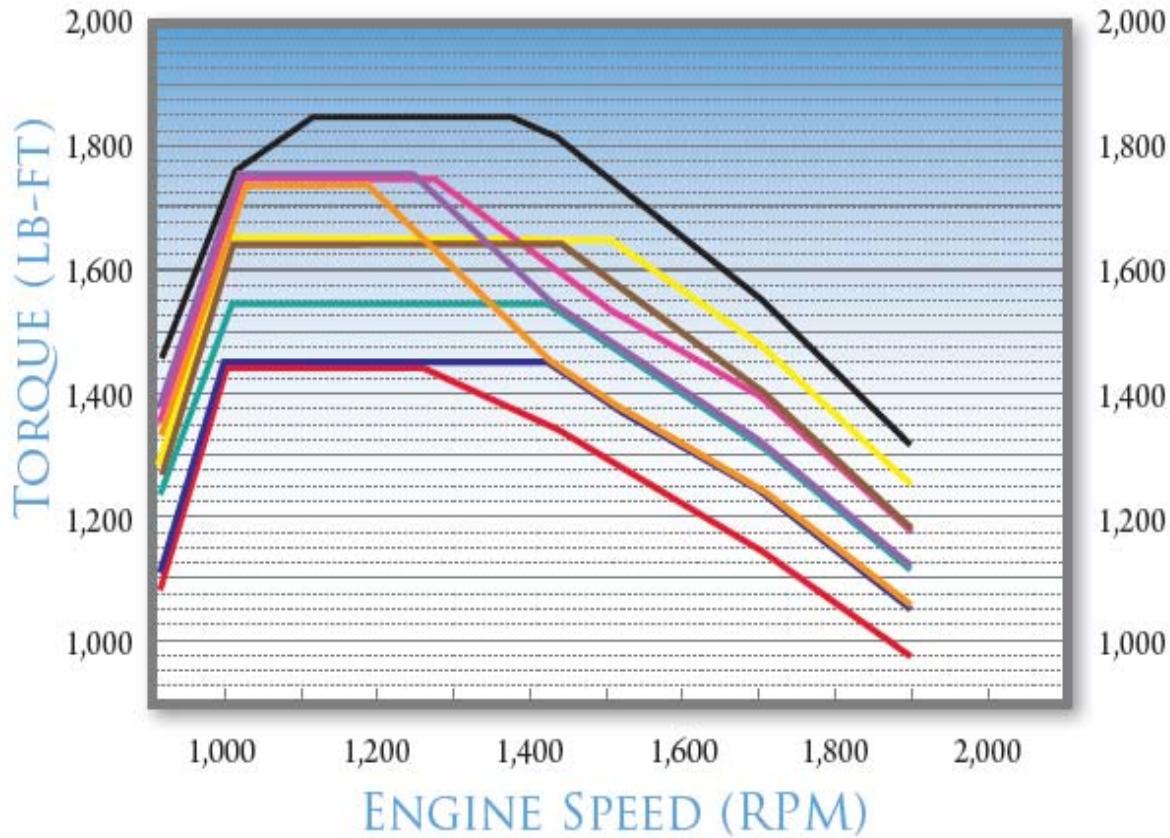


Figure 6. Torque-engine speed curve for a Paccar MX-13 engine

Power is the rate of engine work, expressed in horsepower (hp), and is related to the engine's torque by the following equation:

$$hp_e = \frac{2\pi M_e n_e}{550} \quad [A-8]$$

where

hp_e = engine-generated horsepower (1 horsepower equals 550 ft-lb/s),

M_e = engine torque in ft-lb, and

n_e = engine speed in crankshaft revolutions per second.

The engine-generated tractive effort reaching the drive wheels is given as

$$F_e = \frac{M_e \epsilon_0 \eta_d}{r} \quad [A-9]$$

where

F_e = engine-generated tractive effort reaching the drive wheels in lb,
 M_e = engine torque in ft-lb,
 ε_0 = overall gear reduction ratio,
 η_d = mechanical efficiency of the drivetrain, and
 r = radius of the drive wheels in ft.

Note that since torque and horsepower are directly related, if only a power-engine speed relationship is available, this can be converted to a torque-engine speed relationship through equation A-8.

For determining vehicle acceleration, equation A-1 is rearranged and an additional term, γ_m , to account for the inertia of the vehicle's rotating parts that must be overcome during acceleration, is included.

$$a = \frac{F - \sum R}{\gamma_m m} \quad [\text{A-10}]$$

γ_m , referred to as the mass factor, is approximated as

$$\gamma_m = 1.04 + 0.0025 \varepsilon_0^2 \quad [\text{A-11}]$$

More detail on this approach can be found in reference 1. An example application of this approach follows.

References

1. Mannerling, Fred L. and Washburn, Scott S. *Principles of Highway Engineering and Traffic Analysis*, 5th Edition (U.S. Customary Units). John Wiley and Sons, Hoboken, NJ, March 2012. 336 pages.
2. Washburn, Scott S. and Ozkul, Seckin. *Heavy Vehicle Effects on Florida Freeways and Multilane Highways*. Florida Department of Transportation. Tallahassee, FL. October 2013. 146 pages.
3. <http://www.peterbilt.com/resources/Engine%20Spec%20Sheets/2013%20PX7%20Spec%20Sheet%20121212.pdf> – Last accessed on August 8, 2013.
4. <http://www.peterbilt.com/resources/Engine%20Spec%20Sheets/2013%20MX%20Spec%20Sheet%20121212.pdf> – Last accessed on August 8, 2013.

Example Calculation

Inputs

$$W := 53000 \quad \text{height} := 10 \quad \text{width} := 8$$

$$A_f := \text{height} \cdot \text{width} = 80$$

$$C_D := 0.66 \quad r := 1.66$$

$$i := 0.05 \quad \eta_d := 0.80 \quad \text{DiffGearRatio} := 3.50$$

$$\rho := 0.002378 \quad \text{sea level value}$$

$$G := .05 \quad g := 32.2$$

$$V := 50 \cdot \frac{5280}{3600} \quad V = 73.333 \quad \text{ft/s} \quad \text{Current velocity}$$

Calculate Resistance Forces

Aerodynamic resistance

$$R_a := \frac{\rho \cdot C_D \cdot A_f \cdot V^2}{2} \quad R_a = 337.613$$

Rolling resistance

$$f_{rl} := 0.01 \cdot \left(1 + \frac{V}{147} \right) \quad f_{rl} = 0.015$$

$$R_{rl} := f_{rl} \cdot W \quad R_{rl} = 794.399$$

Grade Resistance

$$R_g := W \cdot G \quad R_g = 2650.0$$

Sum of resistance forces

$$R_{tot} := R_a + R_{rl} + R_g \quad R_{tot} = 3782.0$$

Calculate Engine-Generated Tractive Effort

Overall Gear Reduction Ratio

Gear := 8 for speeds between 43 mi/h and 55 mi/h Current transmission gear

TransGearRatio := 1.35 Current transmission gear ratio

$\varepsilon_0 := \text{DiffGearRatio} \cdot \text{TransGearRatio} = 4.725$

Engine Speed

$$n_e := \frac{V \cdot \varepsilon_0}{2 \cdot \pi \cdot r \cdot (1 - i)} \quad n_e = 34.97 \frac{\text{rev}}{\text{s}} \quad \text{RPM} := n_e \cdot 60 = 2098.2 \frac{\text{rev}}{\text{min}}$$

Note: If vehicle is stopped, engine speed at startup is a function of throttle input

Determine torque from torque-engine speed relationship

For the section of the torque-engine speed curve that covers this RPM value, torque is given by the following equation

$$M_e := -1.0741 \cdot \text{RPM} + 3455.6 \quad M_e = 1201.9 \quad \text{ft-lb}$$

$$F_e := \frac{M_e \cdot \varepsilon_0 \cdot \eta_d}{r} \quad F_e = 2737.0 \quad \text{lb}$$

Calculate Maximum Acceleration

$$\gamma_m := 1.04 + 0.0025 \cdot \varepsilon_0^2 \quad \gamma_m = 1.096 \quad \text{acceleration mass factor}$$

$$a := \frac{F_e - R_{\text{tot}}}{\gamma_m \cdot \left(\frac{W}{g} \right)} \quad a = -0.579 \quad \frac{\text{ft}}{\text{sec}^2}$$

For the given conditions, the truck will decelerate. For these same conditions, but with a level grade, the truck would have a maximum acceleration of 0.890 ft/s².