FlagSim User Guide

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

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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.

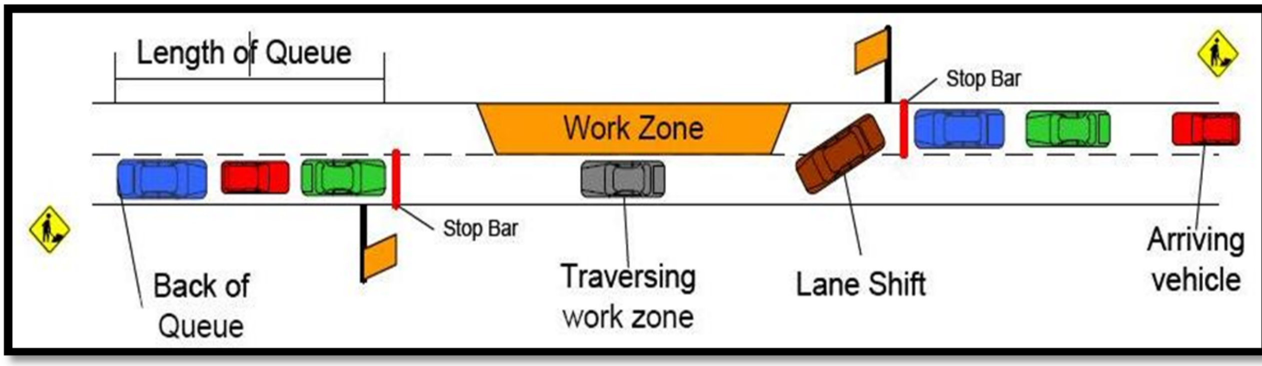


Figure 1. Work zone configuration to which FlagSim applies

Menu Items

File

<u>Open</u>

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

<u>Save/Save As</u>

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.

<u>Exit</u>

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.

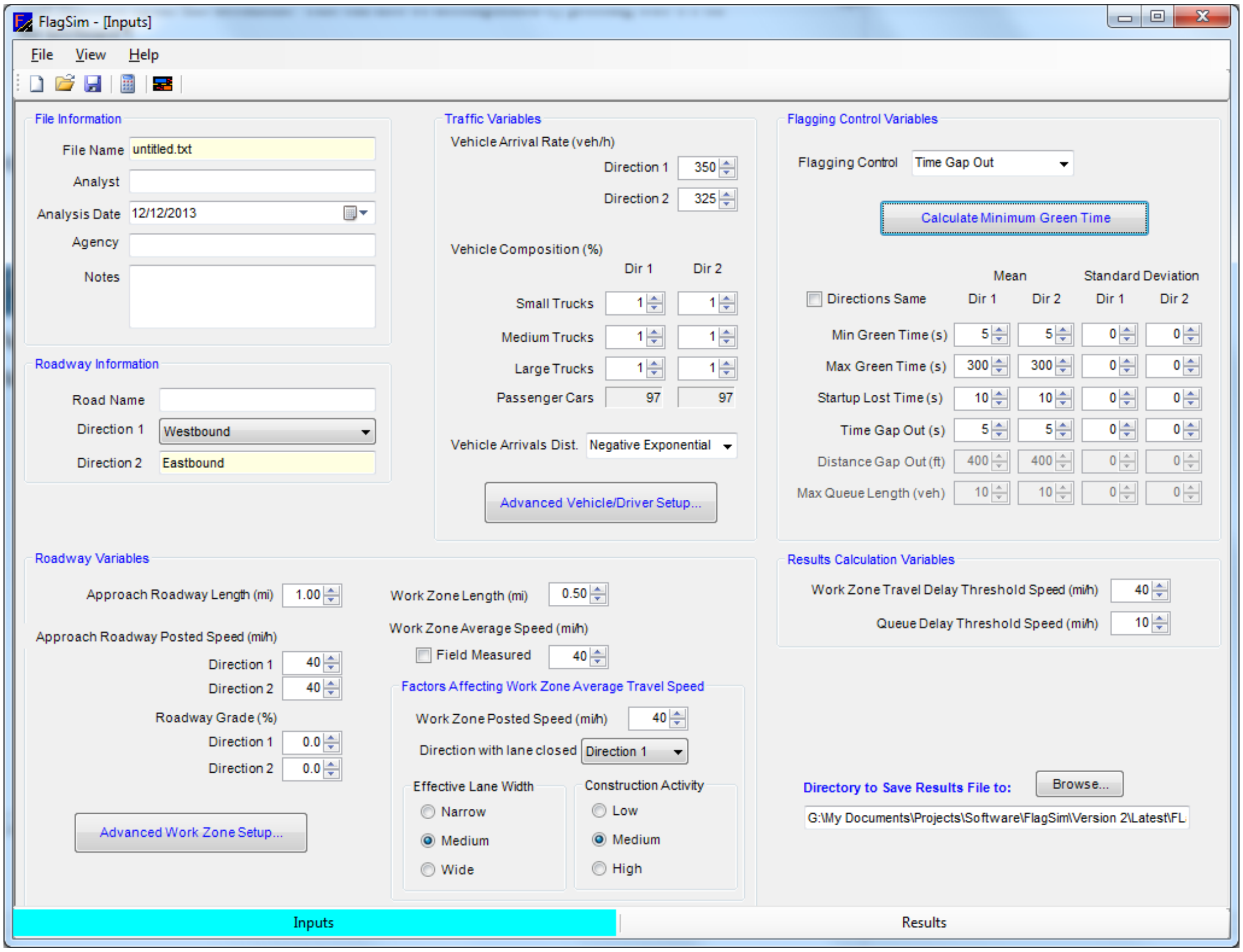


Figure 2. Inputs screen.

File Information

<u>File Name</u>

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

<u>Analyst</u>

Field for entering the name of the analyst.

<u>Analysis Date</u>

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

<u>Agency</u>

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

<u>Notes</u>

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.

<u>Percent Small Trucks</u>

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

<u>Percent Medium Trucks</u>

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

<u>Percent Large Trucks</u>

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

<u>Percent Passenger Cars</u>

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.

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

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.

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

where

$a_f(t+\mathrm{T})$ = acceleration of follower vehicle at time $t+T$, in ft/s^2
$a_l(t+R)$ = acceleration of lead vehicle at time $t+R$, in ft/s^2
$s_l(t+R)$ = 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.

<u>Pitt Damping (*K*) Factor</u>

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).

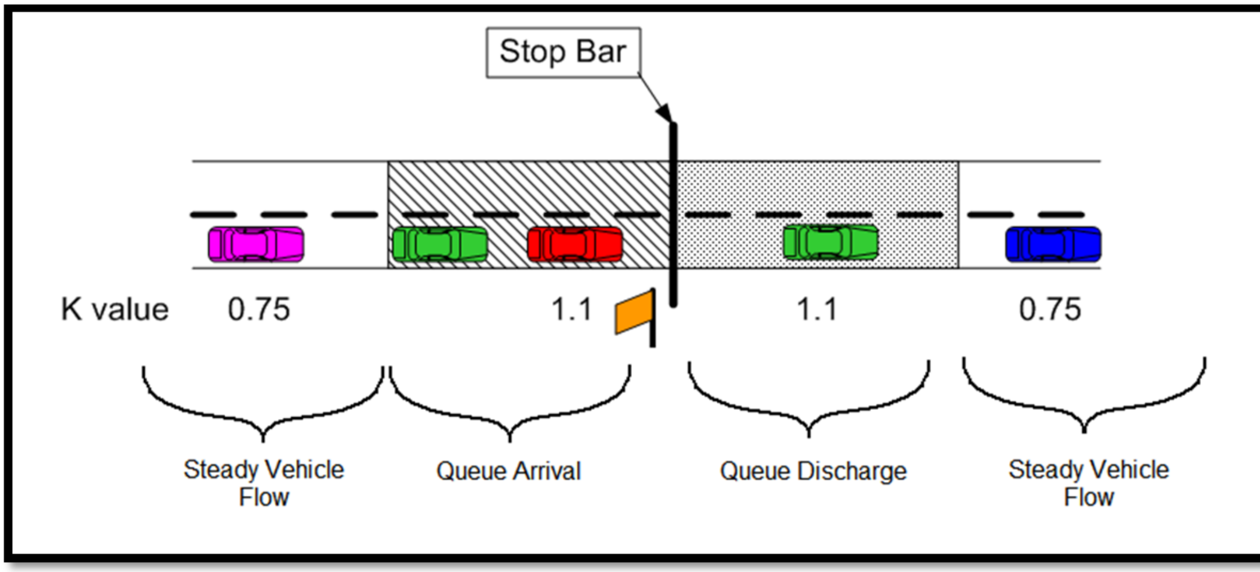


Figure 3. Modified-Pitt K-values

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 +/− one standard deviation.

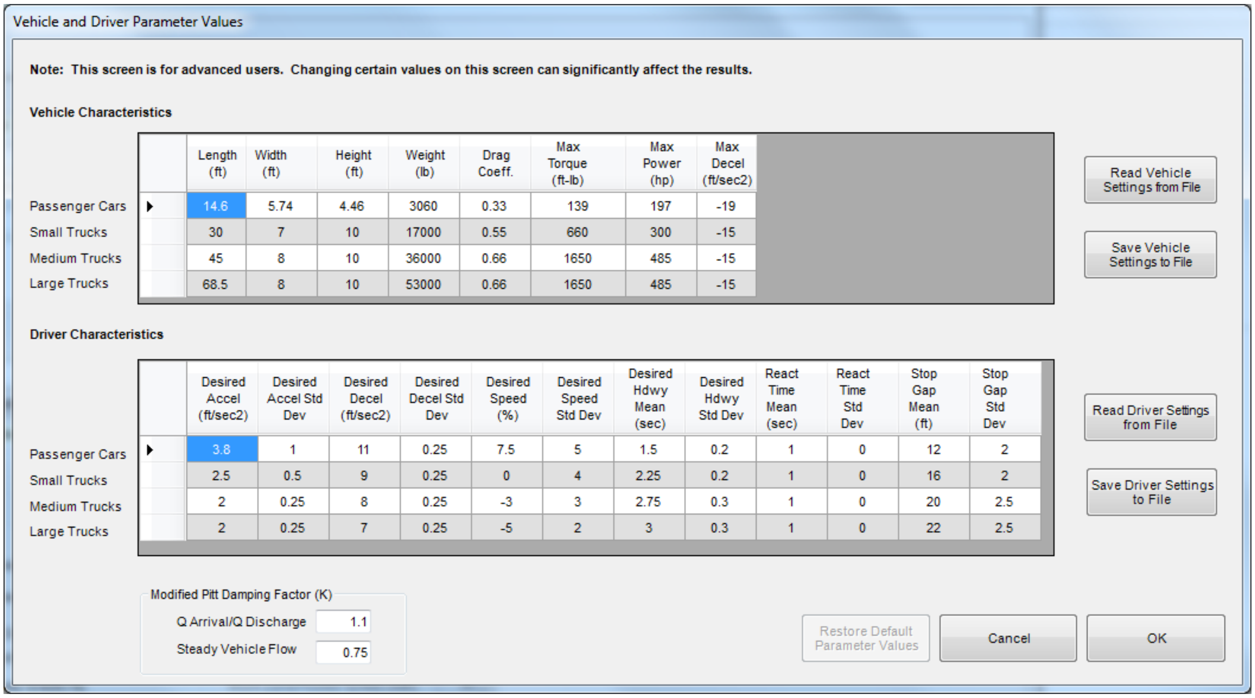


Figure 4. Vehicle and Driver Parameter Values screen.

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 length 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/s^2.

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.

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

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
$\bar{x}$ = 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/s^2. 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/s^2. 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.

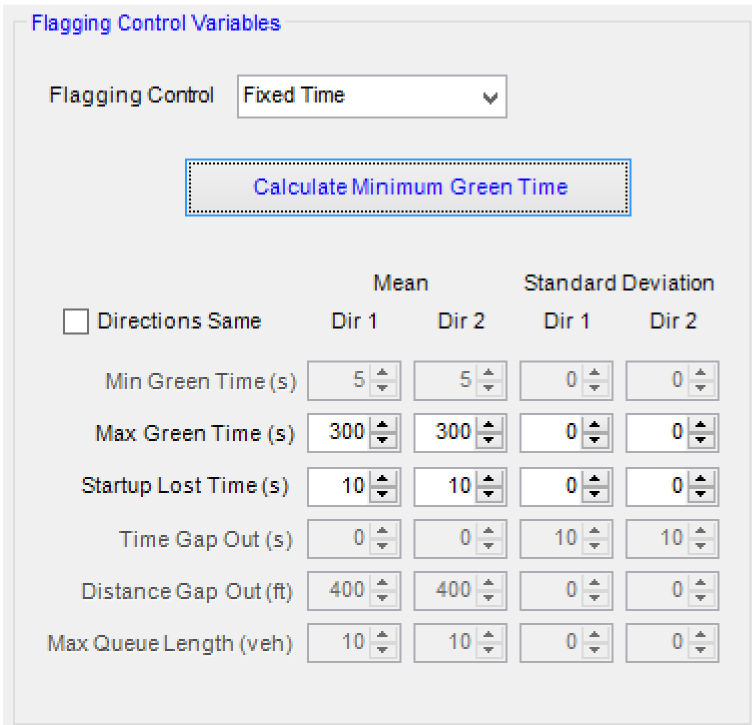
Flagging Control

Four flagging control methods are available for use in FlagSim:

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

Fixed Time

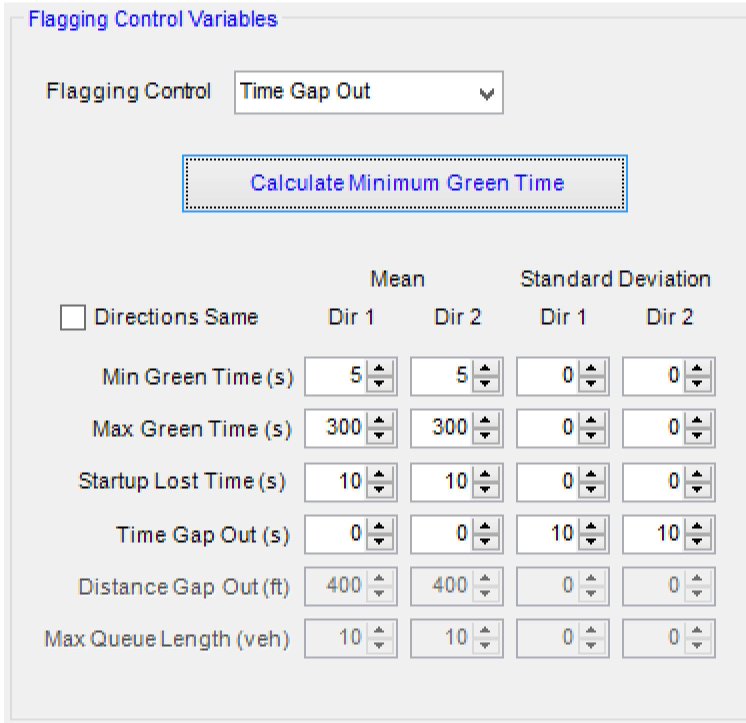
The “Fixed Time” flagging control method assigns a fixed amount of green time to each direction, as specified in the “Max Green Time” input. Minimum and maximum values for mean max green time are 5 seconds and 300 seconds, respectively. The standard deviation for this input can also be adjusted by the 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.



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.

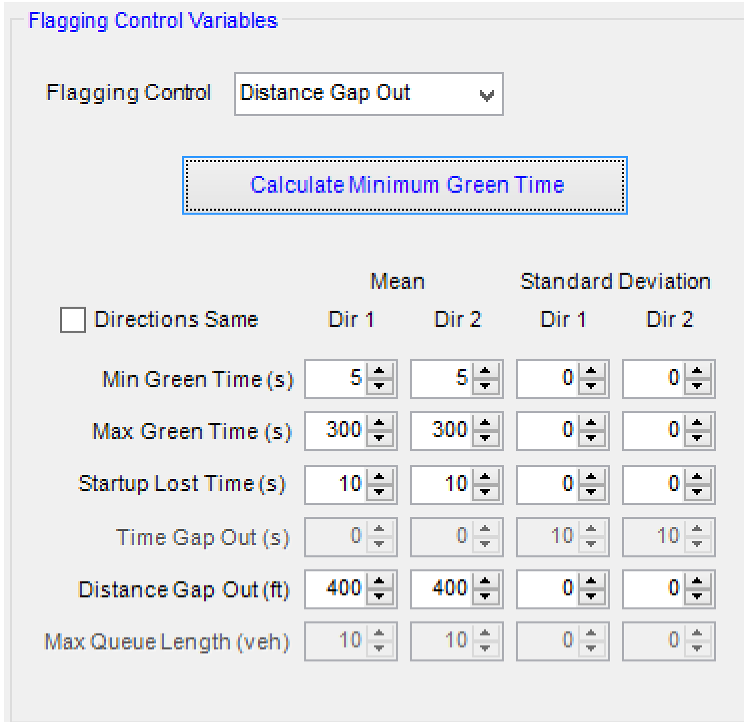
Minimum and maximum green times are also applicable in this control mode, and take priority over the gap-out time. These minimum and maximum values are 5 seconds and 300 seconds, respectively. Note that the minimum green time can be automatically computed based upon the method given in reference 1. To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



Distance Gap Out

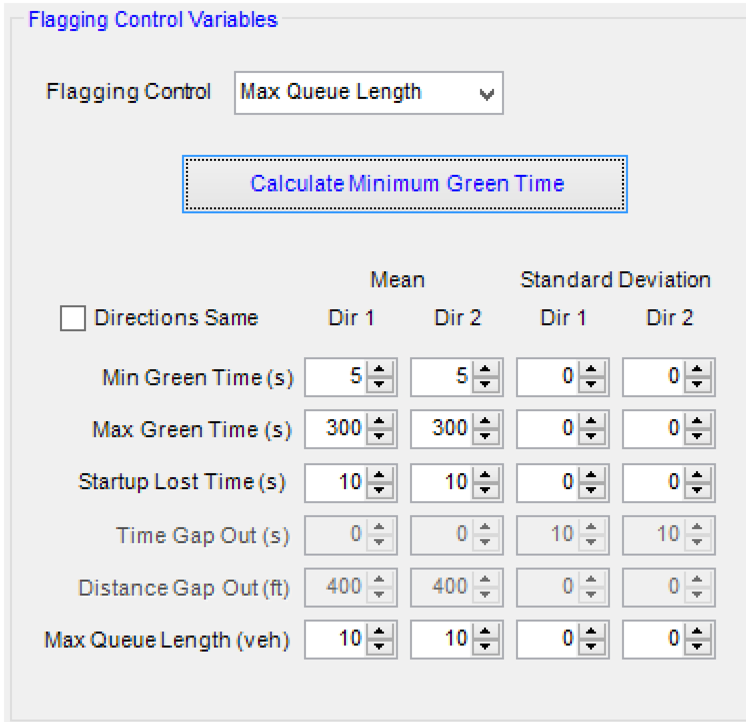
The "Distance Gap Out" flagging method keeps green time assigned to a given direction until the distance between the last vehicle to enter the work zone and the next approaching vehicle exceeds the specified gap-out distance. The minimum and maximum mean gap-out distances are 20 feet and 1200 feet, respectively. 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.



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.

<u>Other Inputs</u>

Startup Lost Time

<u>Mean</u>

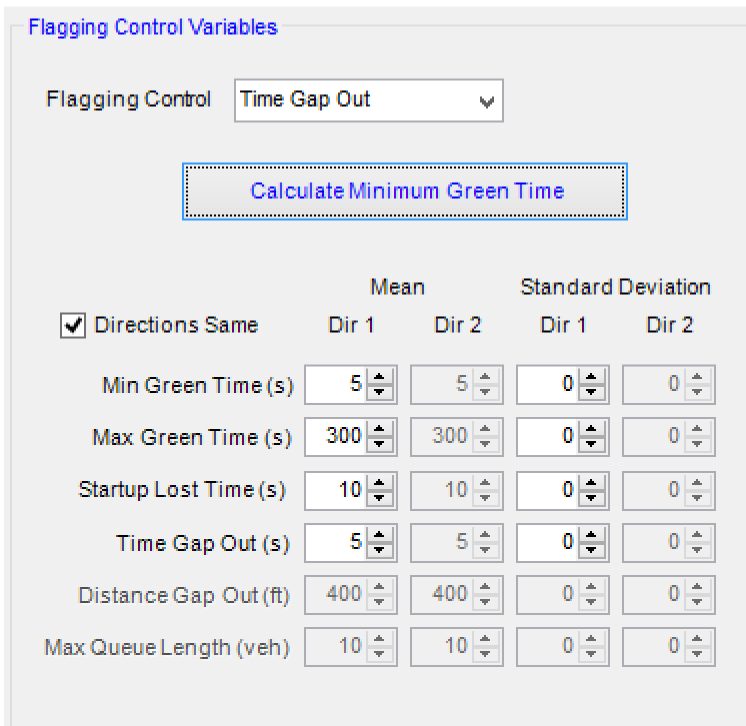
This input specifies the average time, in seconds, that elapses between when the last vehicle in one direction exits the work zone and when the first queued vehicle in the other direction enters the work zone. The default value is 10 seconds. Minimum and maximum values for both directions are 1 second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

<u>Standard Deviation</u>

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".

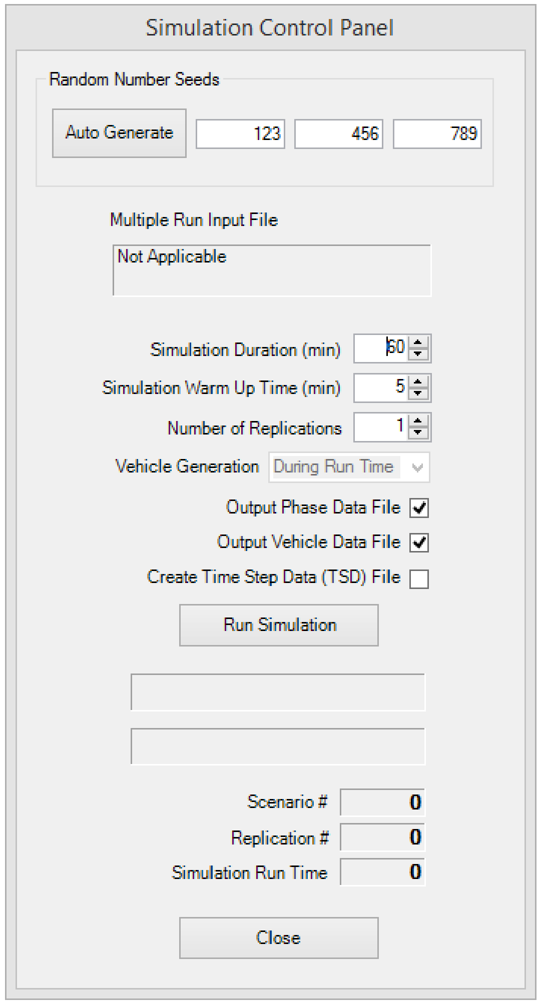
Directions Same Checkbox

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



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

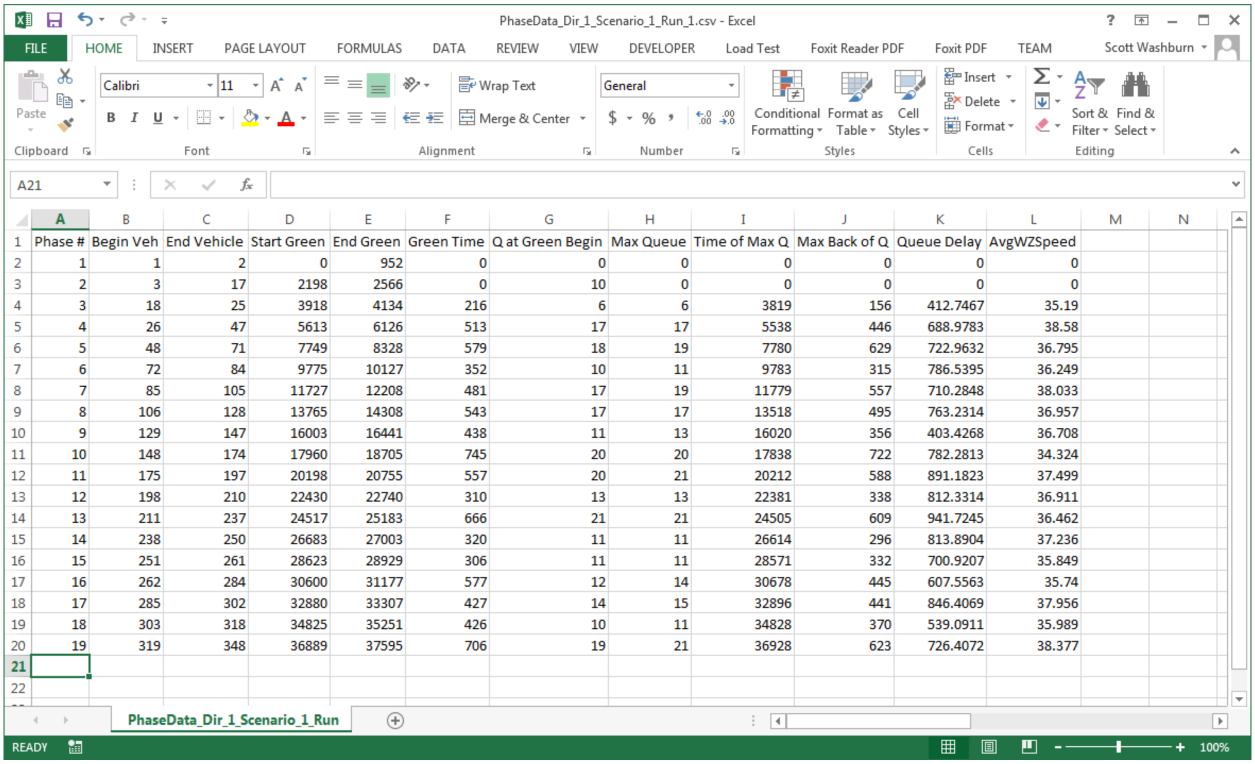
This feature is currently disabled.

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

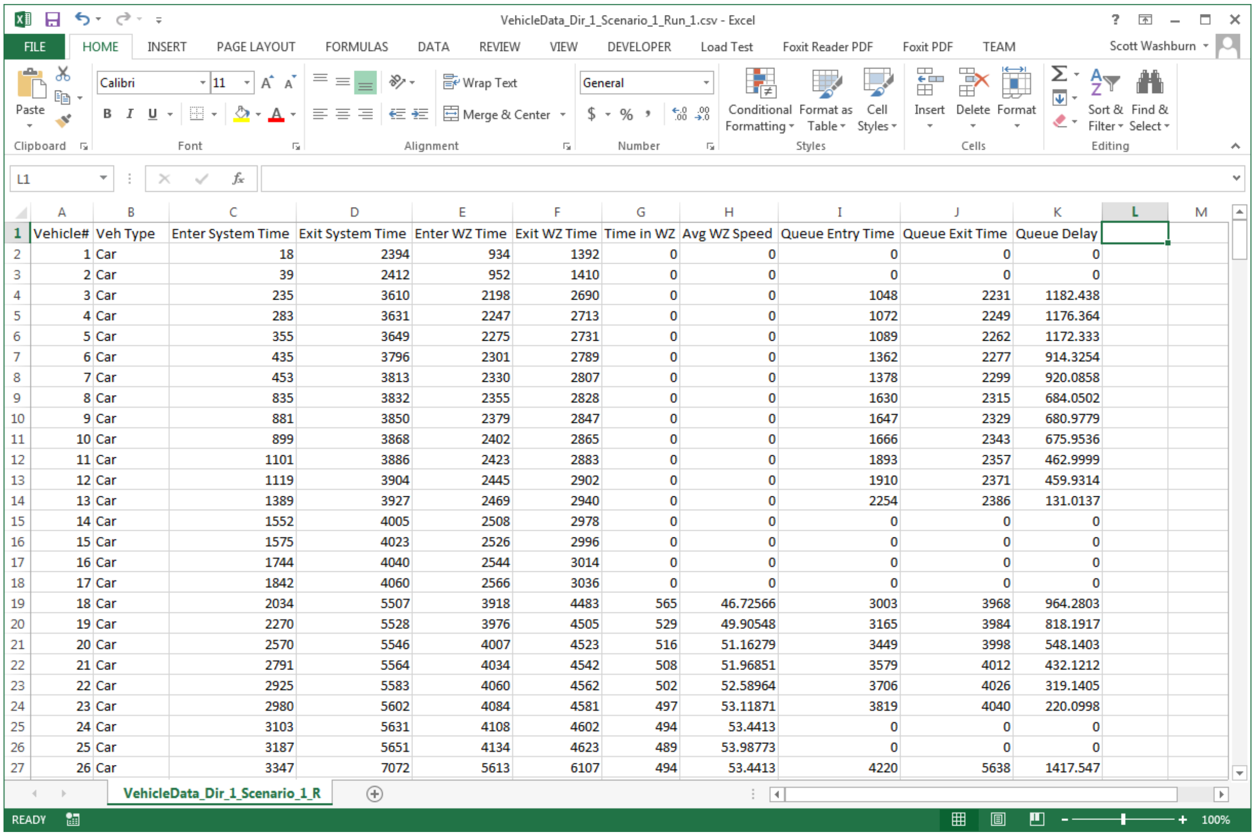
This output file summarizes data results for each phase (i.e., start of green to end of green). This file gives information such fields as the beginning and ending vehicle per phase; the time (in tenths of a second) at the start and end of green; the queue (number of vehicles lined up waiting to enter 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	3	17	2198	2566	0	10	0	0	0	0	0
3	18	25	3918	4134	216	6	6	3819	156	412.7467	35.19
4	26	47	5613	6126	513	17	17	5538	446	688.9783	38.58
5	48	71	7749	8328	579	18	19	7780	629	722.9632	36.795
6	72	84	9775	10127	352	10	11	9783	315	786.5395	36.249
7	85	105	11727	12208	481	17	19	11779	557	710.2848	38.033
8	106	128	13765	14308	543	17	17	13518	495	763.2314	36.957
9	129	147	16003	16441	438	11	13	16020	356	403.4268	36.708
10	148	174	17960	18705	745	20	20	17838	722	782.2813	34.324
11	175	197	20198	20755	557	20	21	20212	588	891.1823	37.499
12	198	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

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	0
2	Car	39	2412	952	1410	0	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	0
15	Car	1575	4023	2526	2996	0	0	0	0	0
16	Car	1744	4040	2544	3014	0	0	0	0	0
17	Car	1842	4060	2566	3036	0	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	432.1212
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.

<u>Run Simulation</u>

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.

<u>Simulation Run Time</u>

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

<u>Simulation Run #</u>

This specifies the current simulation run being executed.

<u>Close</u>

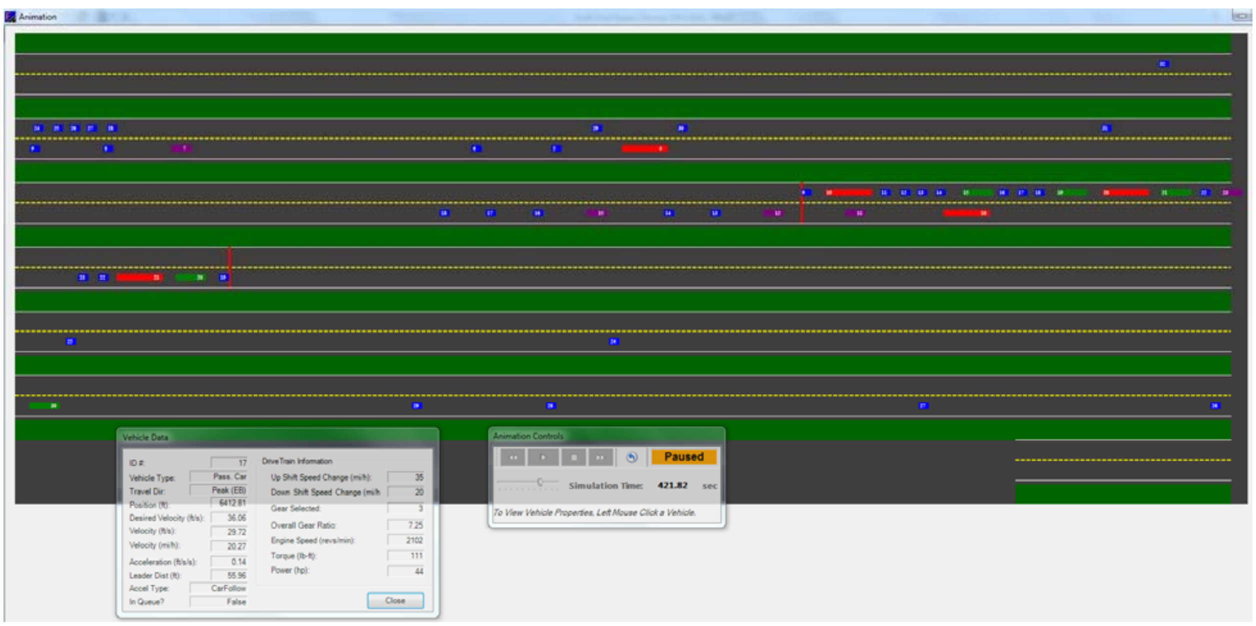
Clicking this button will close the Simulation Control Panel.

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.

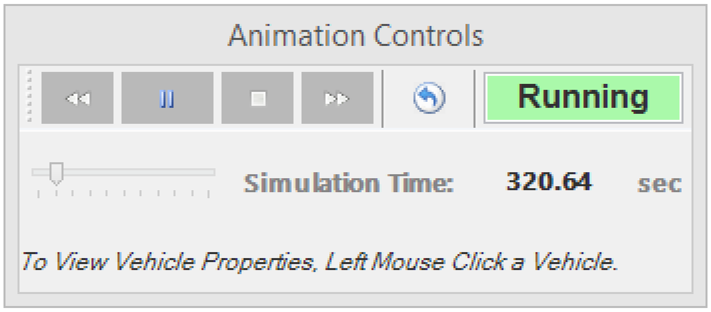
Click on the right-most button on the toolbar. This displays the work zone simulation animation. The work zone stop bars (also assumed to be the flagger position) are identified with green, yellow, and red vertical bars (i.e., running perpendicular to the roadway). The color of the stop bar indicates 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

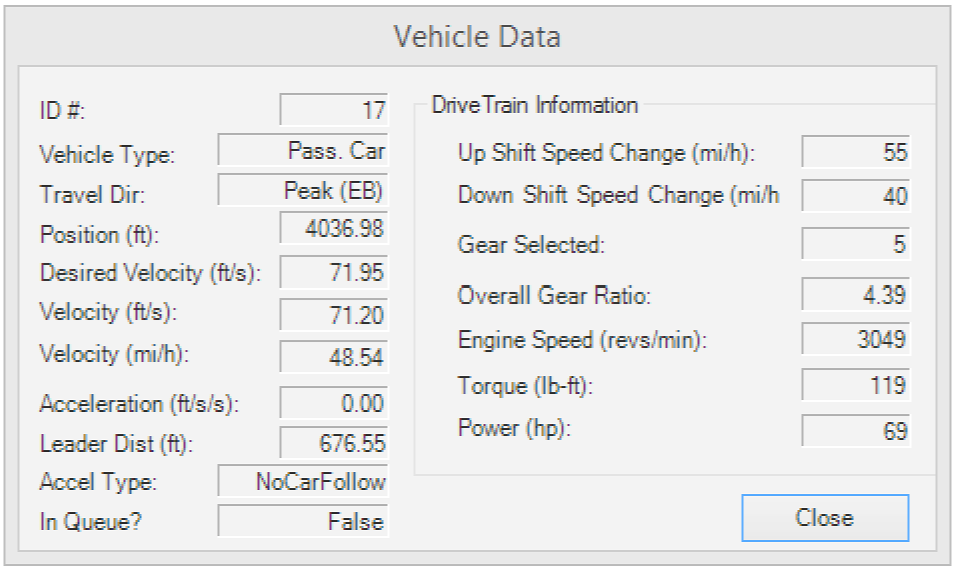
This will stop the animation at the current time step without restarting the animation from the beginning. To resume, simply press play.

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.

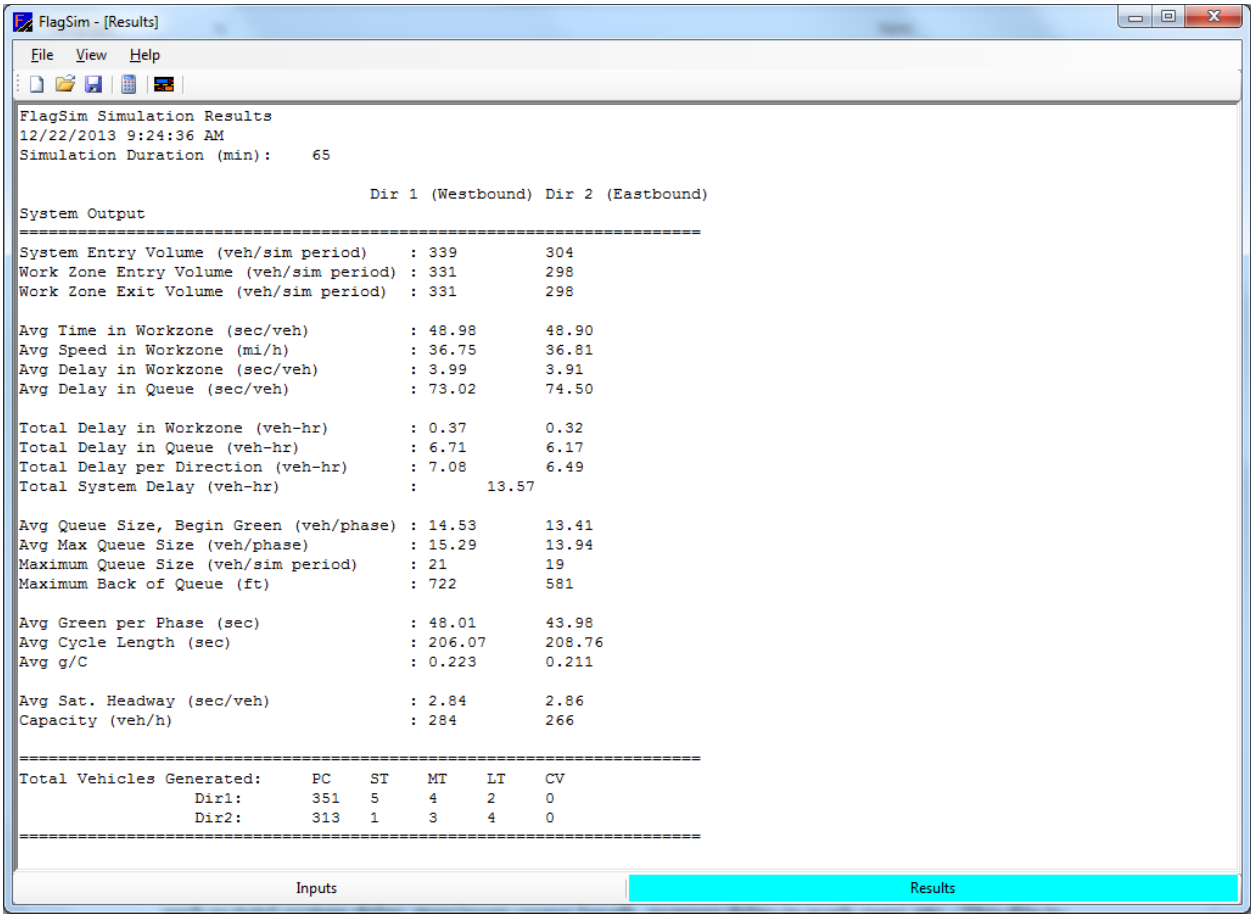
Vehicle Tracker

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.



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.




```
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/h)            : 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.

<u>System Entry Volume</u> — 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.

$$\overline{tt}_{wz\_k} = \frac{1}{n_{veh\_k}} \sum_{i=x}^{y} tt_{wz\_i\_k}$$

$\overline{tt}_{wz\_k}$ = 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
$= tt_{wz\_i\_k} - BaseWZTravTime$
$BaseWZTravTime$ = 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.

$$Q_{max\_k} = \max_{a \le j \le b} Q_{max\_j\_k}$$

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

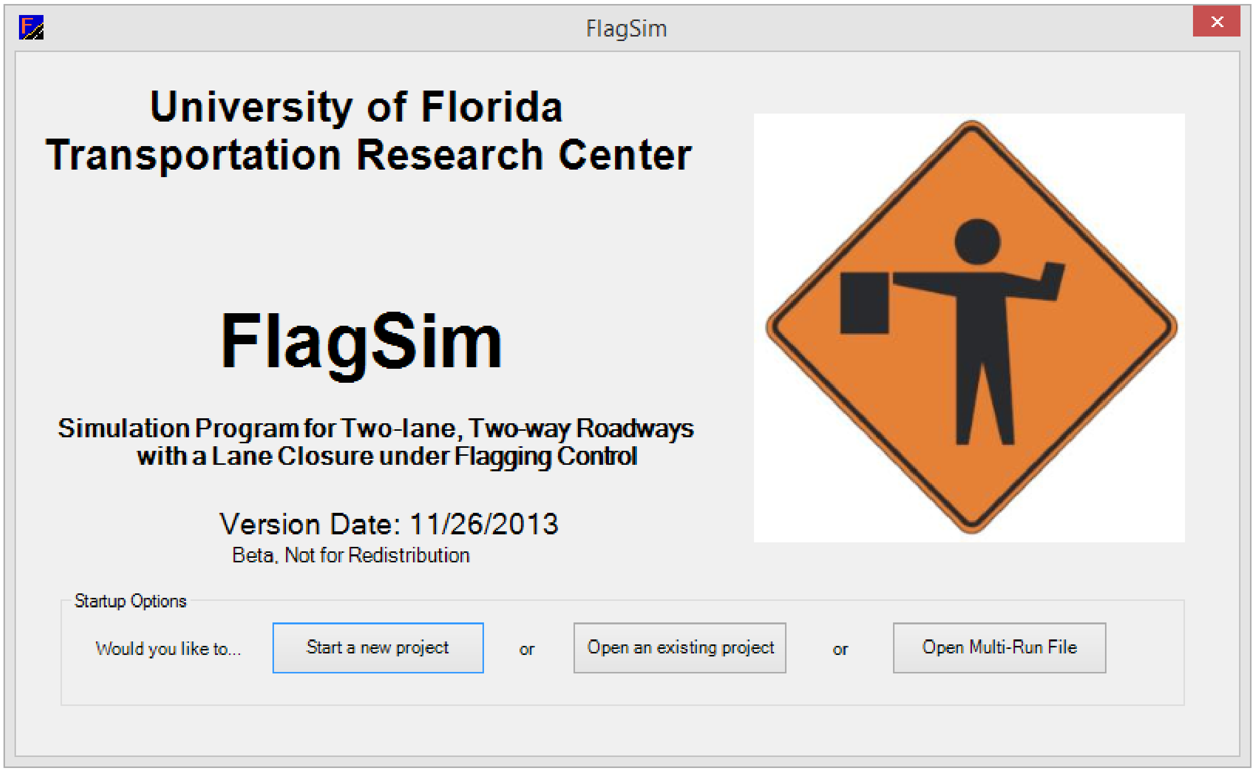
Average *g/C* — the average green period to cycle length ratio. It is calculated according to the following formula.

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

$\overline{{}^{g}/_{C}}_{k}$ = 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.

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

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

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

where

R_a = aerodynamic resistance in lb,
ρ = air density in slugs/ft^3,
C_D = coefficient of drag (unitless),
Af = frontal area of the vehicle (projected area of the vehicle in the direction of travel) in ft^2, and
V = speed of the vehicle in ft/s.

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

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

where

f_{rl} = coefficient of rolling resistance (unitless), and
V = 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

$$R_{rl} = f_{rl} W \qquad \textbf{[A-4]}$$

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

$$R_g = W \sin \theta_g \qquad \textbf{[A-5]}$$

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

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

where

G = 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 $\theta_g = 2.86°$) is said to have a 5% grade.

The relationship between vehicle speed and engine speed is

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

where

V = vehicle speed in ft/s,
n_e = engine speed in crankshaft revolutions per second,
i = slippage of the drive axle, and
ε_0 = 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).

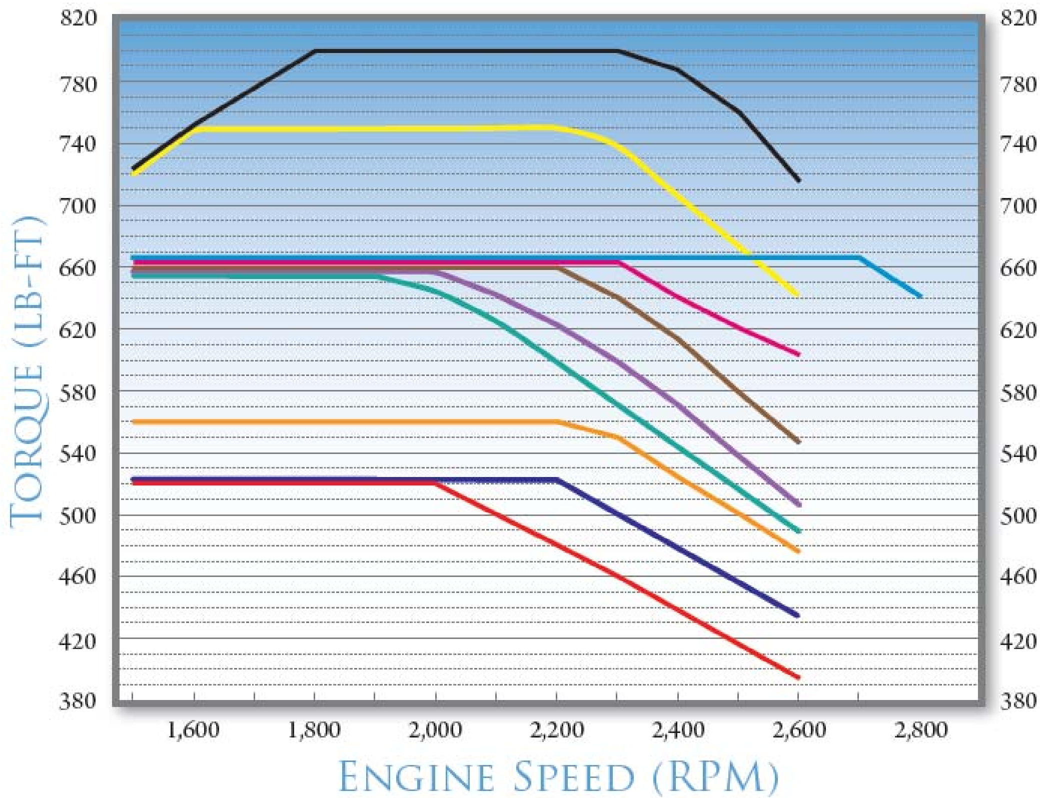

Figure 5. Torque-engine speed curve for a Paccar PX-7 engine

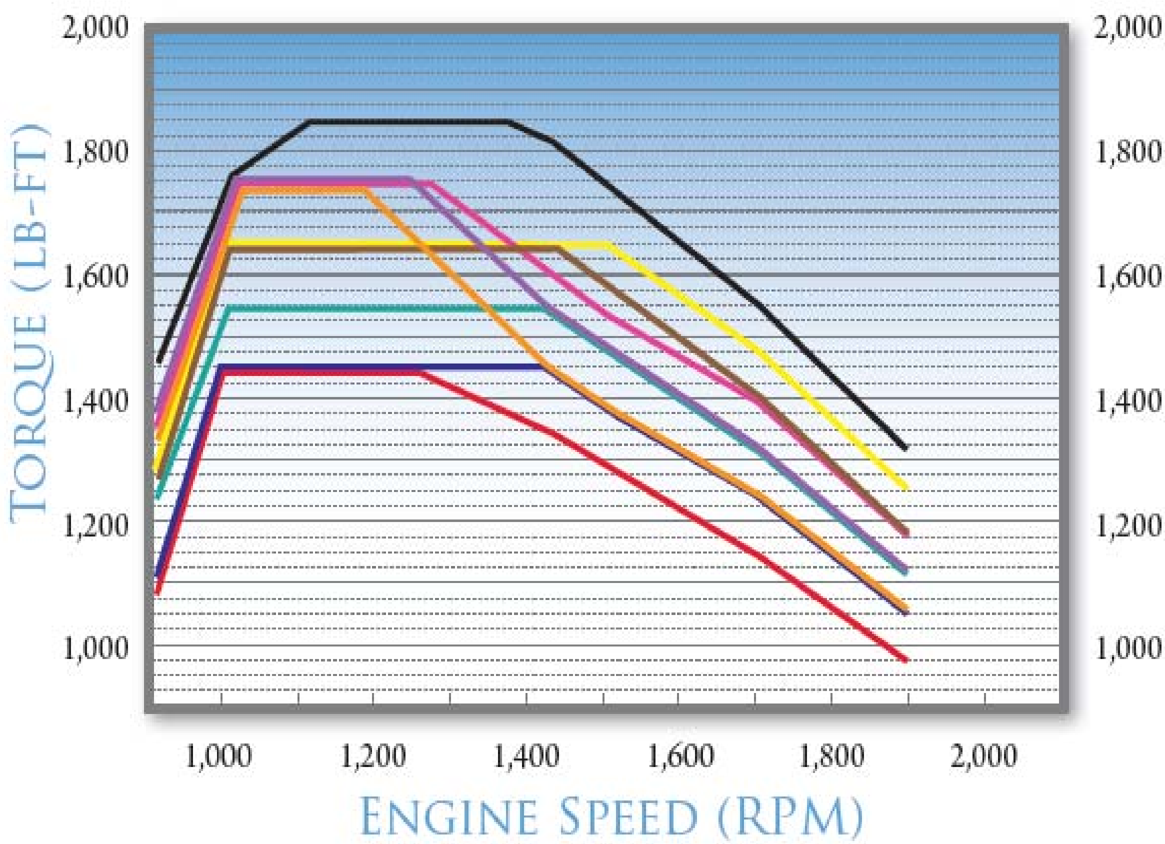

Figure 6. Torque-engine speed curve for a Paccar MX-13 engine

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

$$\mathrm{hp}_e = \frac{2\pi M_e n_e}{550} \quad \textbf{[A-8]}$$

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

$$F_e = \frac{M_e \varepsilon_0 \eta_d}{r} \quad \textbf{[A-9]}$$

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.

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

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

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

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

References

1. Mannering, 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

$W := 53000$ $\quad$ $height := 10$ $\quad$ $width := 8$

$A_f := height \cdot width = 80$

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

$i := 0.05$ $\quad$ $\eta_d := 0.80$ $\quad$ $DiffGearRatio := 3.50$

$\rho := 0.002378$ sea level value

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

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

Calculate Resistance Forces

Aerodynamic resistance

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

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

$\varepsilon_0 := DiffGearRatio \cdot TransGearRatio = 4.725$

Engine Speed

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

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

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

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

Calculate Maximum Acceleration

$$\gamma_m := 1.04 + 0.0025 \cdot \varepsilon_0^{\,2} \qquad \gamma_m = 1.096$$

acceleration mass factor

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

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/s^2.