Monte Carlo Simulation for Traffic Lights

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Introduction

Problem To Be Solved

Americans spend about 38 hours per year waiting at red lights and spend two billion dollars on gasoline while staying still. Signalized intersections are not as efficient as they could be. For example, during rush hour, traffic flow often gets extremely congested and drivers may have to sit through two or more cycles of traffic lights to pass through. Presently, most traffic signal lights are fixed and delay times do not depend on the amount of traffic. The few traffic signals that are actuated are based on limited data and patterns.

For current actuated signals (for e.g. in researcher's city of Plano) signal controls are based on utilizing multiple models, such as Webster's formula[5]. There is no one universal model that addresses all scenarios. Inputs for these models is determined by expensive traffic studies and real-life time intervals, and signals are optimized using hit and trial empirical methods since calculating delay time in live scenario is practically infeasible.

This project will use a Stochastic Monte Carlo simulation integrated within a Java program to bring accurate statistical analysis to predict the optimal traffic light delays, encouraging the most efficient traffic flow. An important advantage of the Monte Carlo simulation is that a huge number of trials can be run quickly, while in real life, the trials are limited by feasibility. The project will use traffic study data for three targeted signals provided generously by the City of Plano and validated independently by the researcher. The simulation will use these input parameters to run various scenarios varying independent parameters such as entry rates, green times/cycle times, red time and exit rates.

The results will be compared to the output from the theoretical models and with data from the traffic studies. If successful, this simulation will provide a single new and innovative tool for traffic planners to use multiple theoretical models, data from traffic studies and even real time actuated sensor data to simulate real world traffic flow and optimize traffic signal operation more quickly and efficiently.

Origin of the Idea

People often complain about elongated traffic delays. Driving is an integral part of people's daily lives and therefore should be as efficient as possible. People want to get to their destinations as quickly as they can and this project will find the fastest solution for everybody. This project will significantly improve the commute of anyone who is able to drive. Finding the best delay time ensures that no time is being wasted for anyone, saving gas and money.

Additionally, the researcher happens to live next to the busiest traffic signal in the whole city of Plano and was often frustrated at the delays encountered on a daily basis. Thus, the researcher wanted to understand why the delay was so lengthy and what could be done to help improve the situation.

Goal/ Rationale

Americans spend an incredibly long amount of time sitting at red lights. Traffic flow during rush hour tends to be extremely congested and efficiency can be improved. Therefore, the goal of this project is to minimize overall delay times for people waiting at a signalized intersection using a Monte Carlo simulation integrated into a computer program, to project delay times by changing several independent variables. The program will use data provided by a City of Plano traffic study to simulate an intersection. The program will then supply the average delay and standard deviation to show how different green light timings, entry rates, and red-light times can affect overall average delay for each vehicle. This single comprehensive simulation tool has the potential to model scenarios that could replace or supplement use of multiple models and traffic studies for analyzing and optimizing signal controls.

Background Information

Terms to Know

Signalized intersection: the intersection of two roads, one major and one minor, with light signals.

Queue length: the number of vehicles waiting at a light signal.

Phases: all the different traffic lights at an intersection. There are 8 phases at all intersections, for each direction and for left and straight. There are 4 different states a signal can be in because 2 phases take place at concurrently at any given time.

Cycle time: the amount of time in seconds it takes for all the directions at an intersection to go through all 8 phases (4 states).

Delay time: the amount of time in seconds a vehicle is waiting at a red light.

Saturation flow rate: the number of vehicles that would pass through a traffic light per hour of green light. The standard saturation flow rate is usually regarded as 1900 vehicles per hour per lane.

Unsaturated flow: The rate at which vehicles pass through a signal after the queue leaves (equal to the arrival rate when the light is green and the queue has cleared)

Degree of saturation: the ratio of the number of cars entering the signal to the capacity that a traffic light signal can support (expressed as a decimal or fraction)

Arrival flow rate/Entry rate: The rate that vehicles arrive at an intersection

Exit rate: the rate at which vehicles pass through the intersection (usually equal to the saturation flow rate).

Average delay: the average amount of time that vehicles wait at a red light, including vehicles that pass through without any delay.

Total Delay: The sum of all the delay that cars waiting at an intersection experience.

Effective green ratio: the ratio of the time where cars are passing through a green light at the saturation flow rate to the total cycle time.

Headway: distance/time between vehicles in a transit system

Uniform delay: delay based on an assumption of uniform arrivals and stable flow with no individual cycle failures

Random delay: delay in addition to uniform delay because flow is randomly distributed rather than uniform.

Overflow delay: additional delay that occurs when the volume of cars is greater than the capacity that a particular lane can serve.

Red time/Stop time: the time when all directions (north, south, east, west) are red because the green light is switching to another direction. Red time allows any remaining vehicles to clear the intersection.

Passage time: the amount of time that is required to pass between vehicles for an actuated signal to switch from green to red.

Maximum green time: at an actuated signal, the greatest amount of green time a direction is allowed to have if the passage time is never reached.

Minimum green time: at an actuated signal, the least amount of green time a direction is allowed to have so that every direction has at least some time for cars to pass through.

Max out: when an actuated signal reaches its maximum green time.

Gap out: when an actuated signal ends earlier than the maximum green time because the passage time is reached (most likely due to a lack of cars).

TRAFFIC SIGNALS

There are two main types of traffic signals - actuated and fixed. Fixed signals have the same cycle time all the time even as traffic demand varies throughout the day. At actuated signals, the cycle time can vary based on how many vehicles the sensors at the signal detect arriving. Typically, actuated signals have a predetermined minimum and maximum green light time, and if the passage time is reached, then the signal gaps out and switches to red. Actuated signals can significantly improve traffic flow. For example, in Tyler, Texas, Siemens Intelligent Traffic Systems implemented actuated signals, which reduced traffic delays by 22%. However, only about 3% of all traffic signals in the United States are actuated. According to the Plano Transportation and Traffic Department, almost all intersections in Plano are actuated.

Major and minor streets also play a large role in controlling cycle times. During a cycle, the major street will get more time because much more people will be passing through on that road rather than a minor street.

Traffic signals are controlled by a cabinet near the intersection. The cabinet contains detector amplifiers that receive a call of service from a detector at an actuated traffic signal, a controller that processes the call according to pre-programmed logic that has been set, and a load switch that sets the proper display based on output from the controller.

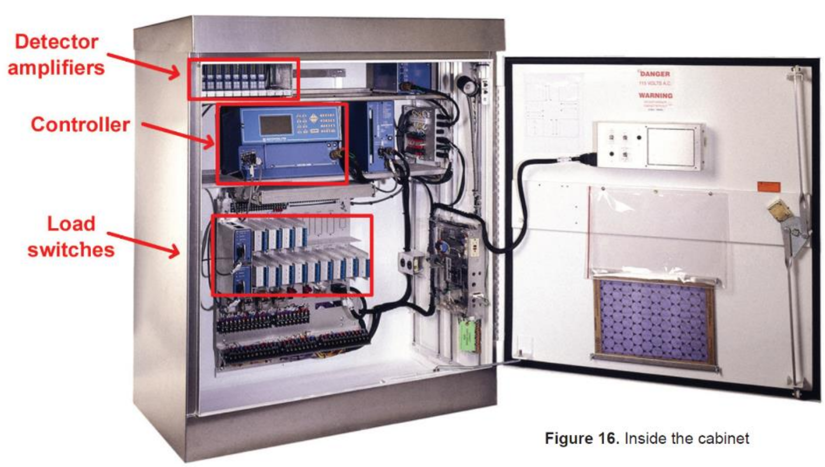
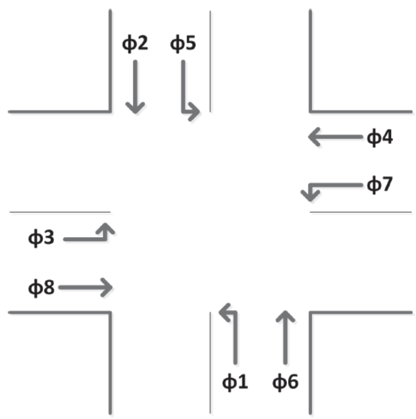


Figure 16. Inside the cabinet

One major reason cities aren't using intelligent traffic signal systems is because of price. Individual signals may cost up to $150,000 and the cost to overhaul a medium sized city could be tens of millions of dollars.

The National Electrical Manufacturers Association (NEMA) mandates that each traffic signal must have four stages. Phases 7 and 3 must correspond for the left turns, as well as phases 5 and 1. Similarly, phases 2 and 6 must correspond for the through movements, just like phases 4 and 8.



Review of Literature

Past Projects

Study on Monte Carlo Simulation of Intelligent Traffic Lights Based on Fuzzy Control Theory by Zeng Shengda, Wu Lurong, Jing Lin, and Wu Bizhi

One project that has been done on this topic is a combination of the Monte Carlo simulation, Fuzzy Control theory (a mathematical system that gives outputs based on numerical inputs that range continuously from 0 to 1 instead of a system that simply gives a true or false value for discrete values from 0 to 1), and the programming language MATLAB. A minimum and a maximum green time is set up so that delay time is not extremely high or low. First, some variables are set up for the Monte Carlo simulation. A domain of 3 to 54 seconds of passing queue length is used. Additionally, the project measures the number of vehicles that pass through a light in the last eight seconds of green light time. If the vehicle count is under 5, the green light time is reduced by 4 seconds for the next cycle. If the vehicle count is between 5 and 10, the green light time stays the same. If the vehicle count is over 10, the green light time increases by 4 seconds the next round. Next, the project displays graphs that show how values such as green light time will be translated to the fuzzy control system. Lastly, a Monte Carlo simulation was run with MATLAB on the domain of possible green lights and the most efficient time was evident when the data was displayed in a table.

What Cities are Doing to Combat Traffic Congestion

Cities all over the United States are working to increase the efficiency of traffic flow as congestion increases. For example, Atlanta has implemented the North Avenue SMART (Safety, Mobility, Automated Real time Traffic management), a 2.3 mile stretch of road which includes smart traffic signals, pedestrian and cycling streets, and a fast response to any accidents. Some cities are tracking pedestrian traffic to improve the timing of signals. Others, like Austin are starting to put into effect queue jumps. Queue jumps are effectively special light signals that give buses a 10 second head start before all other vehicles so that buses don't get caught in traffic congestion and more people are encouraged to use public transportation because it is now faster. New innovations are being experimented with and applied every day because traffic congestion is such a huge problem, and actuated light signals is a major factor that will contribute to more efficient traffic flow.

EXPERIMENTAL DESIGN AND RESEARCH PLAN

VARIABLES

The intersections of Park and Preston, Preston and Tennyson, and Parkwood and Tennyson will be simulated because they demonstrate differences in the amount of traffic at the intersection. Differences in the amount of traffic is useful in this project because it will show how relationships between variables will vary depending on the size of the intersection.

The program will test two cases:

Case 1: Varying entry rates and green light timings

Independent Variable	Control	Dependent Variable
The combined entry rate of all the directions will be multiplied by common factors of 0.1, 0.5, 0.7, 0.9, 1, 1.2, 1.4, and 1.6. All the green times of each of the directions will also be multiplied by 0.1, 0.5, 0.7, 0.9, 1, 1.2, 1.4, and 1.6. Each entry rate will be tested for each green time, representing how green time should be changed as the amount of traffic changes.	Red times Yellow times Exit rates Number of lanes	Average delay for each vehicle in each scenario

Case 2: Varying stop time and green light timings

Independent Variable	**Control**	**Dependent Variable**
Red time (time when all directions are red between switching of green lights) will be 0, 1, 2, 3, 4, and 5 seconds Green times of each direction will be multiplied by factors of 0.1, 0.5, 0.7, 0.9, 1, 1.2, 1.4, and 1.6. Each red time will be tested for each green time to represent how different red times change the delay for different cycle times.	Yellow times Entry rates - number of cars Exit rates Number of lanes	Average delay for each vehicle in each scenario

Materials

1. One car (for observing intersections - optional)
2. One video recorder (for observing intersections - optional)
3. One laptop for programming
4. Data for each direction for left and straight (red light time, yellow light time, green light time, number of lanes, entry rate, exit rate)

   Note: For this project, all the traffic data was supplied by the city of Plano.

Procedure

Calculate data for intersections of Park and Preston, Tennyson and Preston, and Parkwood and Tennyson.

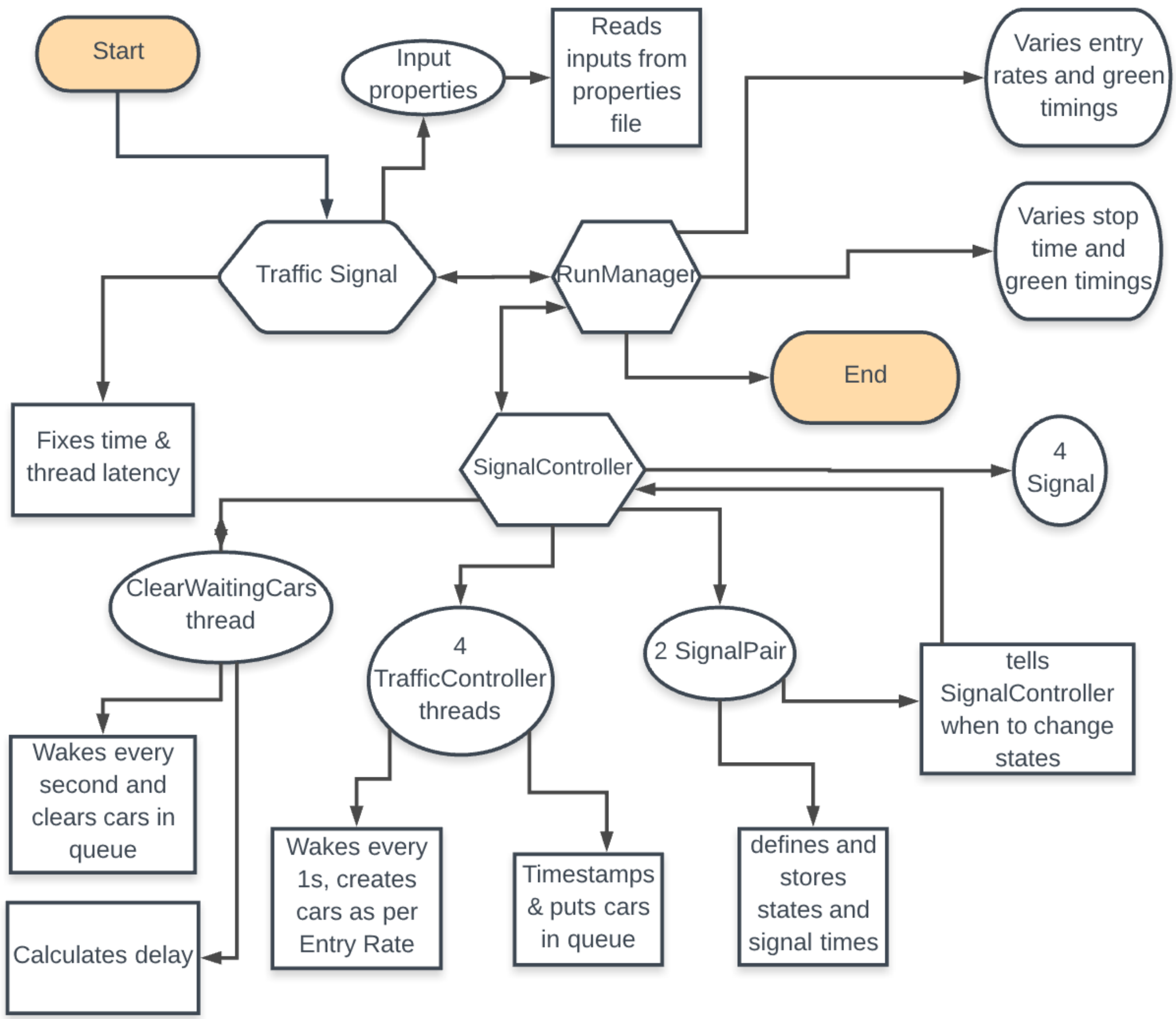
1. Entry Rate - number of cars that approach the intersection per second
2. Exit Rate - standard is 1900 vehicles/hour/lane
3. Green light time for each direction for left/straight
4. Yellow light time for each direction for left/straight
5. Red light time for each direction for left/straight
6. Number of lanes - lanes for left/straight for each direction

Write the program that simulates entry and exit cars through the signal using the attributes and data from the traffic study.

PROGRAM LOGIC

1. In the programmatic simulation one real world second will be modeled to be 5 milliseconds (MS) long. Any reference to times below will reference the real-world time intervals.
2. The class TrafficSignal reads inputs from a java properties file, fixes time and thread latency, and tells the program to sleep for 1 second after every traffic cycle is run.
3. TrafficSignal creates an instance of the class RunManager, which runs the different scenarios where green light times, entry rates, and stop times are varied. RunManager then starts a single run of a cycle and instantiates SignalController.
4. SignalController then creates 4 TrafficController threads, 2 SignalPairs, and 4 Signals. SignalController also instantiates the class ClearWaitingCars. This Class is the master controller of all signal operation and optimization.
5. The 4 TrafficController threads wake every second and create car objects according to the entry rates from the properties file. It timestamps the cars when they are created and puts them in a queue.
6. The 2 SignalPairs define and store signal states and timings so SignalController knows when to change the traffic light states and can simulate the traffic lights.
7. The Signal class, for which there are 4 signals (for each direction), store the attributes of each signal such as red, yellow, and green light time for left and straight.
8. ClearWaitingCars wakes every second and clears cars from the queue that the TrafficController threads created. It timestamps the car when they leave and then calculates how much delay the car object experienced.
9. After each cycle time is passed, the program sleeps, reinitializes, and starts running the next cycle. After 100 cycles have been run, the program terminates.

Program Logic Flow Chart



Entry Rates

Park and Preston									
Phases	Entry Rates (Cars / Hour)				Entry Rates (Cars / Second)				Exit
	Morning	Midday	Afternoon	Avg	Morning	Midday	Afternoon	Avg	# Lanes
NS	1,893	1,189	2,025	1,702	0.53	0.33	0.56	0.47	3
NL	320	345	325	330	0.09	0.10	0.09	0.09	2
SS	2,347	1,165	1,758	1,757	0.65	0.32	0.49	0.49	3
SL	215	274	387	292	0.06	0.08	0.11	0.08	2
ES	714	745	1,007	822	0.20	0.21	0.28	0.23	3
EL	142	392	378	304	0.04	0.11	0.11	0.08	2
WS	1,005	695	903	868	0.28	0.19	0.25	0.24	3
WL	297	450	277	341	0.08	0.13	0.08	0.09	2
Total	6,933	5,255	7,060	6,416	1.93	1.46	1.96	1.78	

Table 1. Entry Rates for Park and Preston – Created by the researcher on 1/4/19

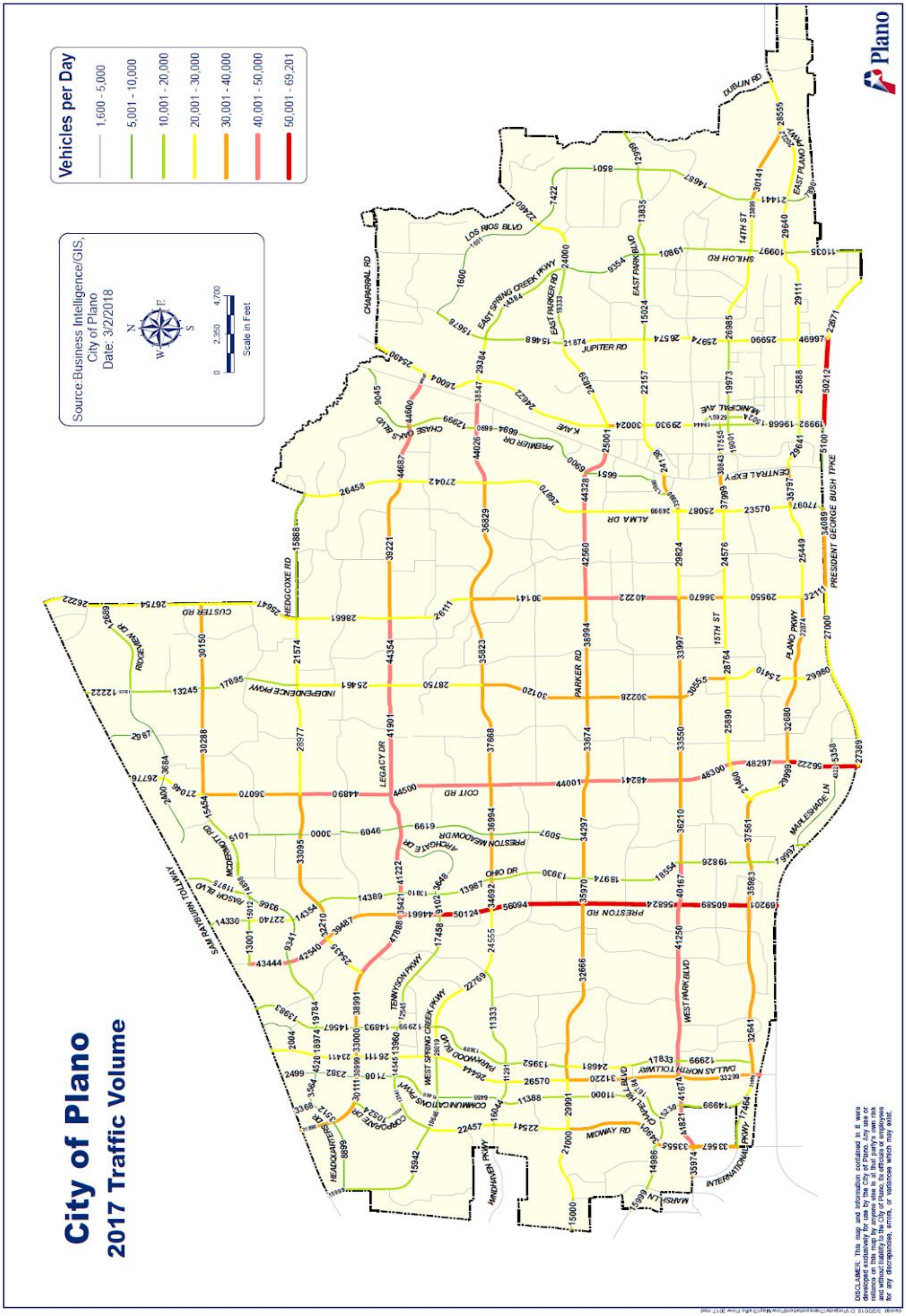
Preston and Tennyson									
Phases	Entry Rates (Cars every 1.5 Hour)				Entry Rates (Cars / Second)				Exit
	Morning	Midday	Afternoon	Avg	Morning	Midday	Afternoon	Avg	# Lanes
NS	2230	2682	2813	2,575	0.41	0.37	0.52	0.44	3
NL	517	442	151	370	0.10	0.06	0.03	0.06	2
SS	3264	2314	2716	2,765	0.60	0.32	0.50	0.48	3
SL	22	51	67	47	0.00	0.01	0.01	0.01	1
ES	73	249	879	400	0.01	0.03	0.16	0.07	2
EL	103	517	647	422	0.02	0.07	0.12	0.07	2
WS	594	236	122	317	0.11	0.03	0.02	0.06	2
WL	215	122	93	143	0.04	0.02	0.02	0.02	2
Total	7,018	6,613	7,488	7,040	1.30	0.92	1.39	1.20	

Table 2. Entry Rates for Preston and Tennyson – Created by the researcher on 1/4/19

Parkwood and Tennyson									
Phases	Entry Rates (Cars every 1.5 Hour)				Entry Rates (Cars / Second)				Exit
	Morning	Midday	Afternoon	Avg	Morning	Midday	Afternoon	Avg	# Lanes
NS	582	934	1309	942	0.11	0.13	0.24	0.16	3
NL	126	113	129	123	0.02	0.02	0.02	0.02	1
SS	1635	942	1109	1,229	0.30	0.13	0.21	0.21	3
SL*	315	266	210	264	0.058	0.04	0.04	0.05	1
ES	612	418	725	585	0.11	0.06	0.13	0.10	3
EL	192	293	563	349	0.04	0.04	0.10	0.06	2
WS	502	470	799	590	0.09	0.07	0.15	0.10	3
WL	63	111	262	145	0.01	0.02	0.05	0.03	1
Total	4,027	3,547	5,106	4,227	0.75	0.49	0.95	0.73	

Table 3. Entry Rates for Parkwood and Tennyson – Created by the researcher on 1/4/19

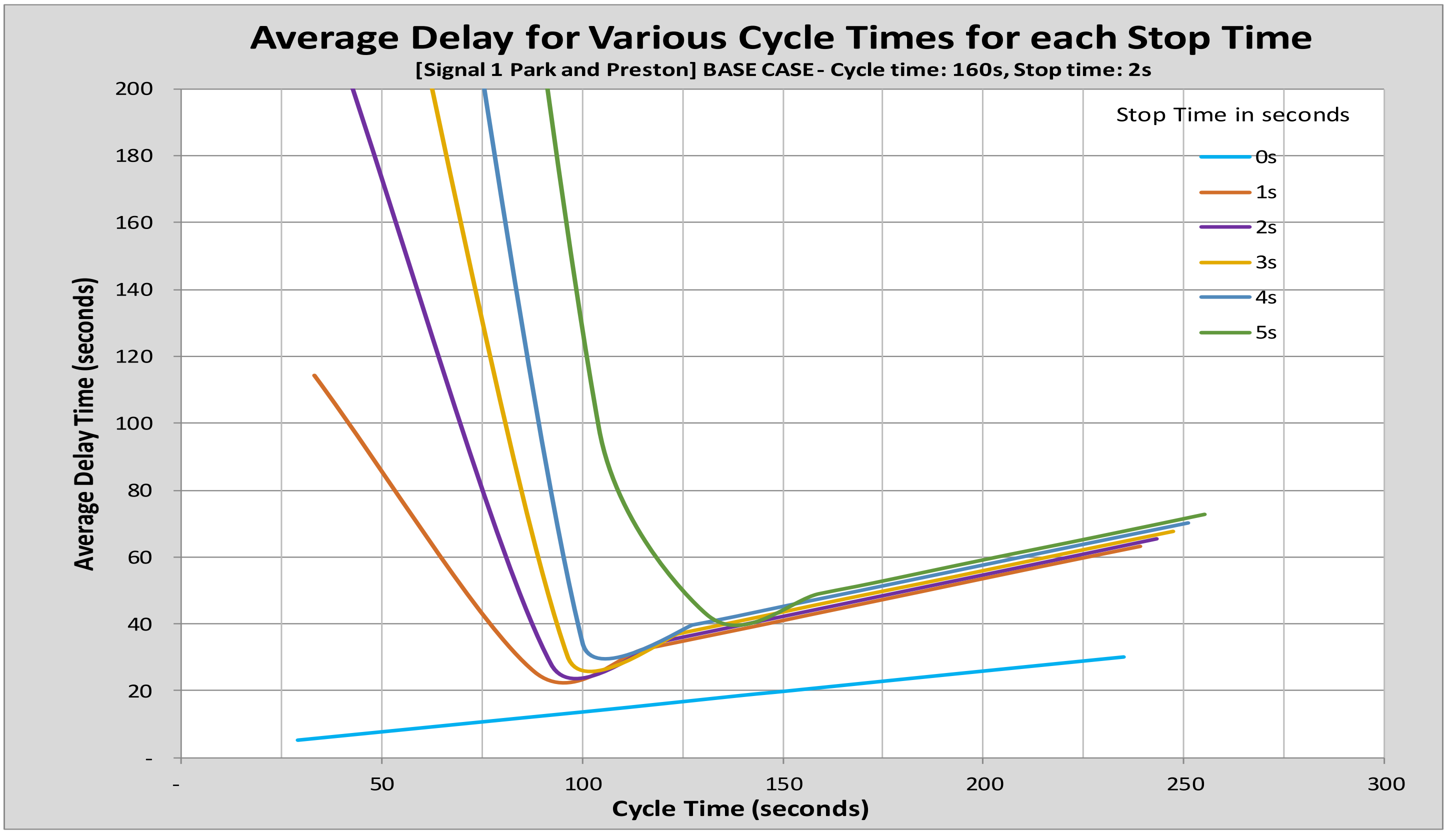
CITY OF PLANO TRAFFIC MAP



ACTUAL CODE

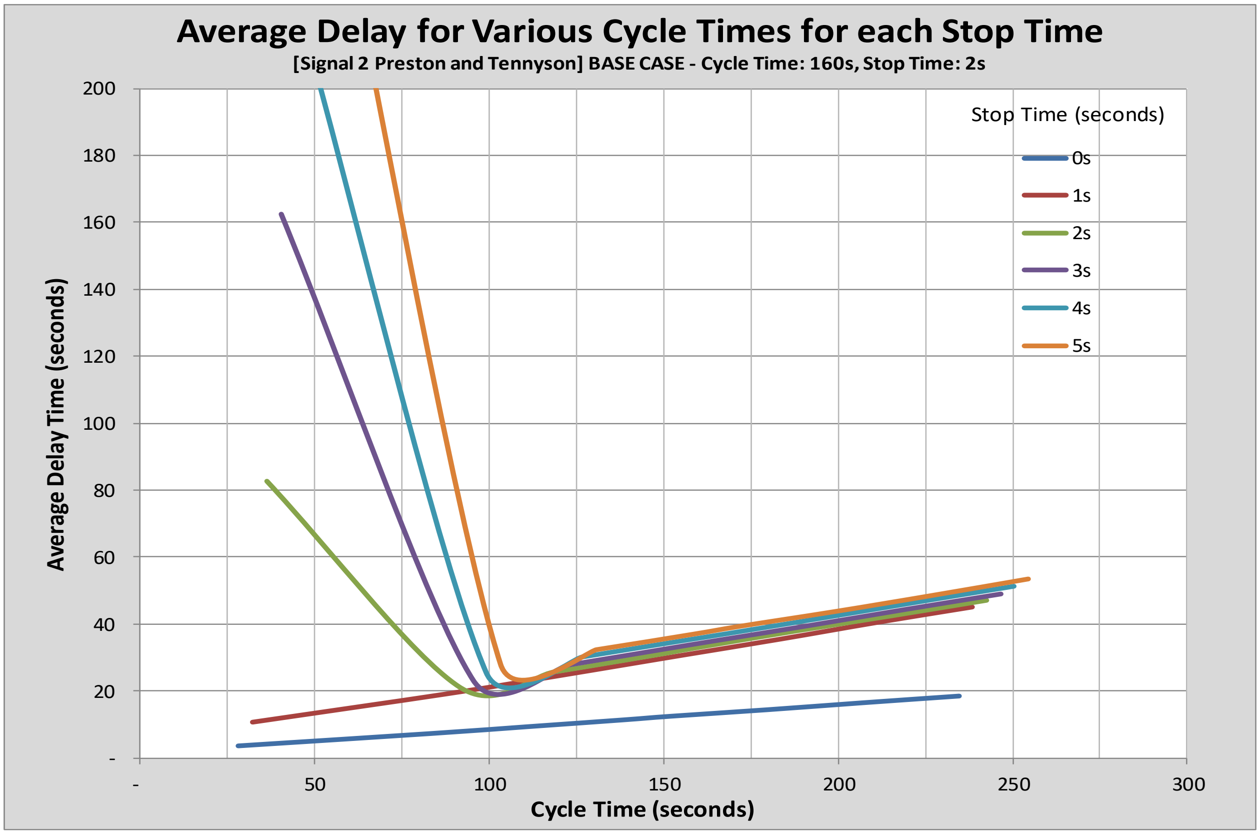
RESULTS

DELAY TIME VS CYCLE TIME

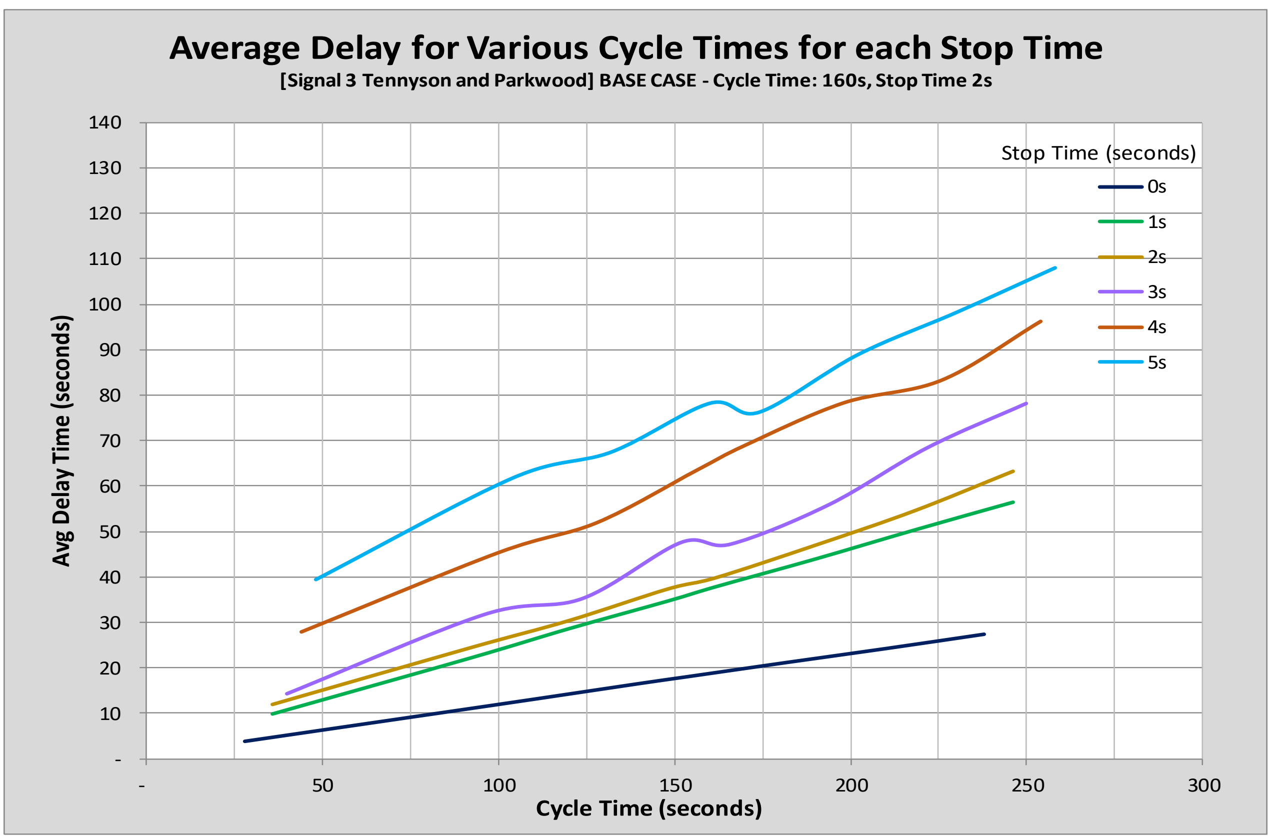


Graph 1. Average Delay vs Cycle Times – Created by the researcher on 1/4/19

Stop time is the time needed for vehicles that entered the intersection before the signal turned red to completely clear the intersection. City of Plano uses Stop Time that vary between 1.75s to 2.5s



Graph 2. Average Delay vs Cycle Times – Created by the researcher on 1/4/19

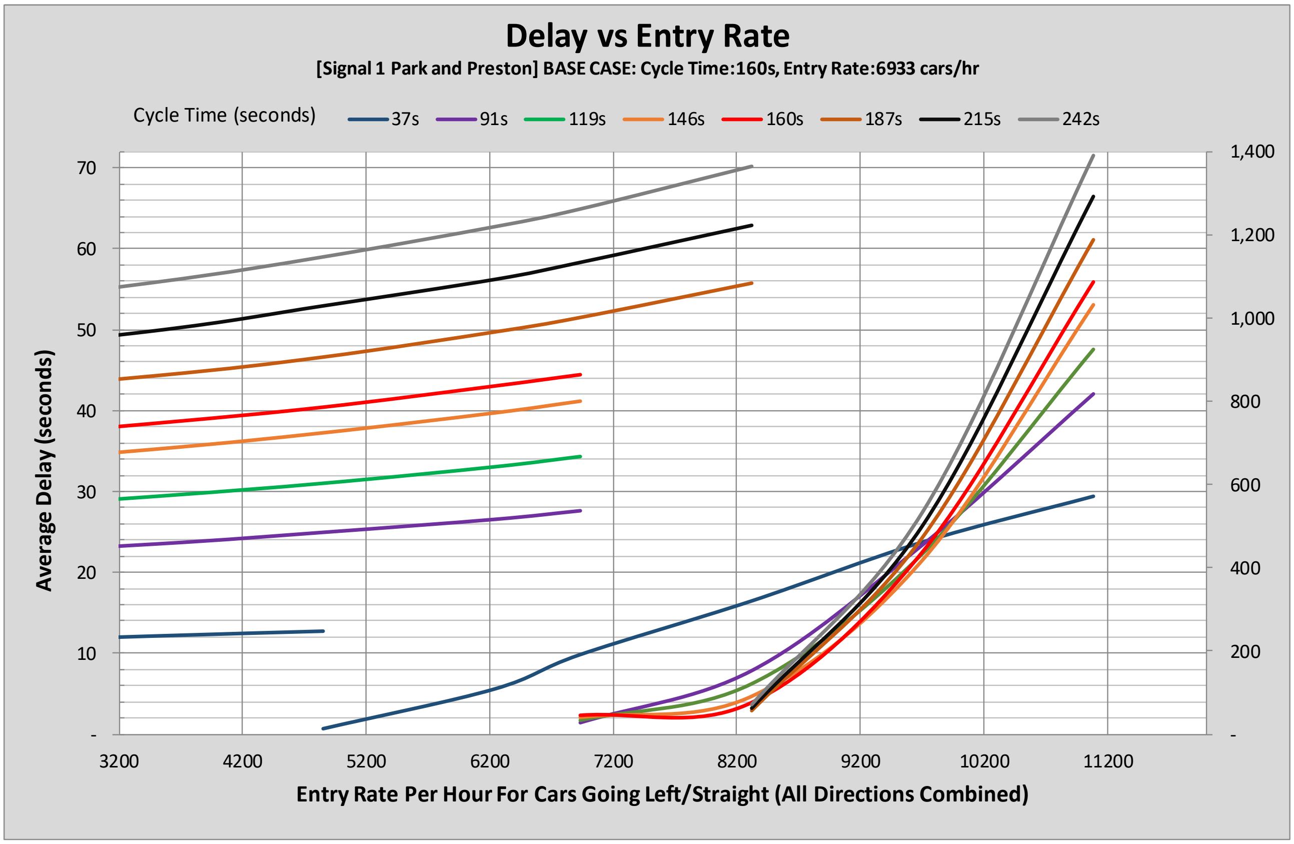


Graph 3. Average Delay vs Cycle Times – Created by the researcher on 1/4/19

			Preston and Tennyson			Park and Preston			Parkwood and Tennyson		
Run #	Stop Time	Green Rate Factor	Green Time (s)	Cycle Time (s)	Delay (s)	Green Time (s)	Cycle Time (s)	Delay (s)	Green Time (s)	Cycle Time (s)	Delay (s)
1	0.0	0.1	28	28	4	27	29	5	28	28	4
2	0.0	0.5	138	83	7	137	84	12	140	84	10
3	0.0	0.7	192	111	9	192	112	15	196	112	13
4	0.0	0.9	247	138	11	247	139	18	252	140	17
5	0.0	1.0	275	152	12	274	153	20	280	154	18
6	0.0	1.2	330	180	14	329	180	23	336	182	21
7	0.0	1.4	385	207	16	384	208	27	392	210	24
8	0.0	1.6	440	235	18	439	235	30	448	238	28
9	1.0	0.1	28	32	11	27	33	114	28	32	10
10	1.0	0.5	138	87	19	137	88	26	140	88	22
11	1.0	0.7	192	115	24	192	116	32	196	116	29
12	1.0	0.9	247	142	28	247	143	39	252	144	35
13	1.0	1.0	275	156	31	274	157	43	280	158	38
14	1.0	1.2	330	184	36	329	184	50	336	186	44
15	1.0	1.4	385	211	40	384	212	56	392	214	50
16	1.0	1.6	440	239	45	439	239	63	448	242	56
17	2.0	0.1	28	36	83	27	37	220	28	36	12
18	2.0	0.5	138	91	21	137	92	28	140	92	24
19	2.0	0.7	192	119	26	192	120	35	196	120	30
20	2.0	0.9	247	146	30	247	147	42	252	148	37
21	2.0	1.0	275	160	33	274	161	45	280	162	40
22	2.0	1.2	330	188	38	329	188	52	336	190	47
23	2.0	1.4	385	215	42	384	216	59	392	218	55
24	2.0	1.6	440	243	47	439	243	66	448	246	63
25	3.0	0.1	28	40	162	27	41	317	28	40	14
26	3.0	0.5	138	95	23	137	96	30	140	96	32
27	3.0	0.7	192	123	28	192	124	37	196	124	35
28	3.0	0.9	247	150	33	247	151	44	252	152	48
29	3.0	1.0	275	164	35	274	165	47	280	166	47
30	3.0	1.2	330	192	40	329	192	54	336	194	56
31	3.0	1.4	385	219	44	384	220	61	392	222	68
32	3.0	1.6	440	247	49	439	247	68	448	250	78
33	4.0	0.1	28	44	229	27	45	436	28	44	28
34	4.0	0.5	138	99	25	137	100	34	140	100	45
35	4.0	0.7	192	127	30	192	128	40	196	128	52
36	4.0	0.9	247	154	35	247	155	46	252	156	63
37	4.0	1.0	275	168	37	274	169	50	280	170	69
38	4.0	1.2	330	196	42	329	196	57	336	198	78
39	4.0	1.4	385	223	46	384	224	63	392	226	83
40	4.0	1.6	440	251	51	439	251	70	448	254	96
41	5.0	0.1	28	48	301	27	49	591	28	48	40
42	5.0	0.5	138	103	28	137	104	98	140	104	62
43	5.0	0.7	192	131	32	192	132	42	196	132	68
44	5.0	0.9	247	158	37	247	159	49	252	160	78
45	5.0	1.0	275	172	39	274	173	52	280	174	76
46	5.0	1.2	330	200	44	329	200	59	336	202	89
47	5.0	1.4	385	227	48	384	228	66	392	230	98
48	5.0	1.6	440	255	53	439	255	73	448	258	108

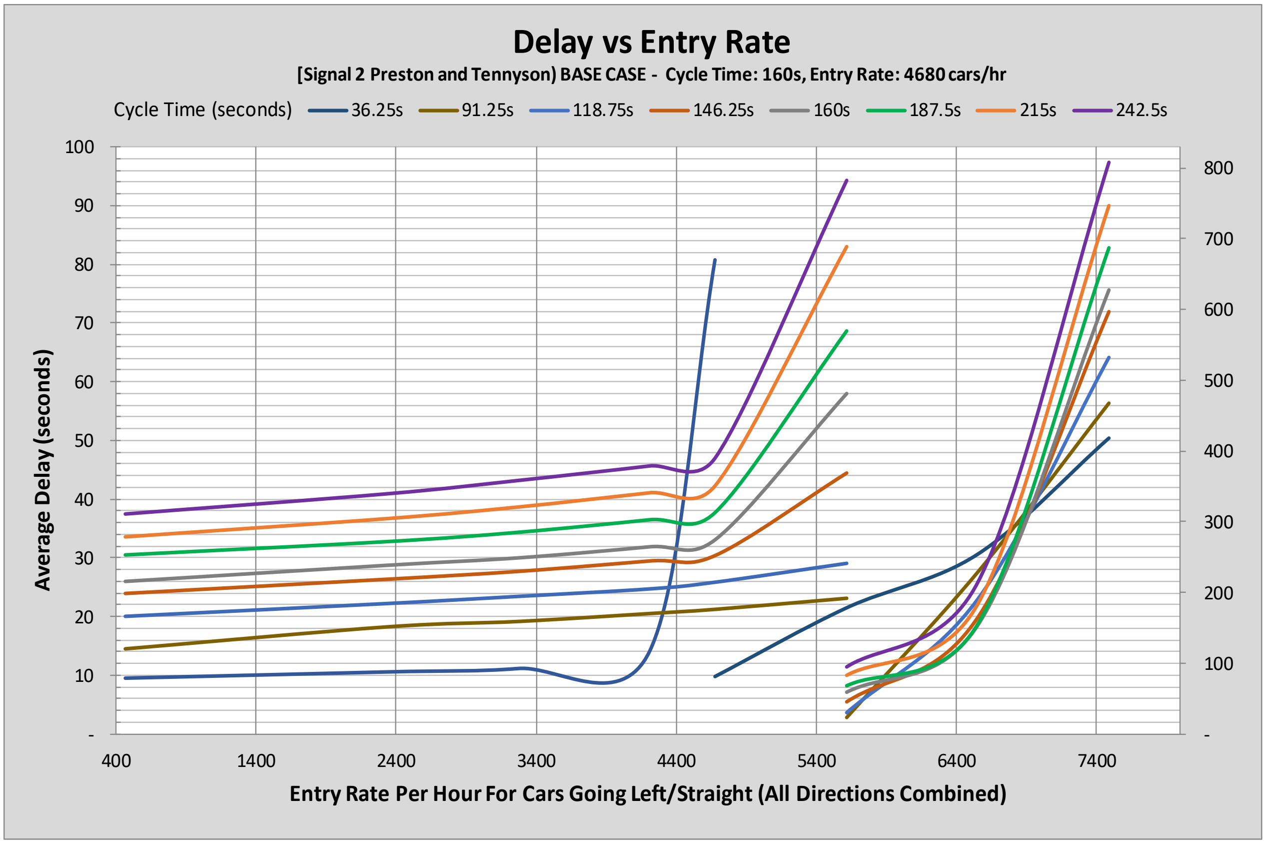
Table 4. Various stop times and green times raw data table – Created by the researcher on 12/30/19

DELAY VS ENTRY RATE

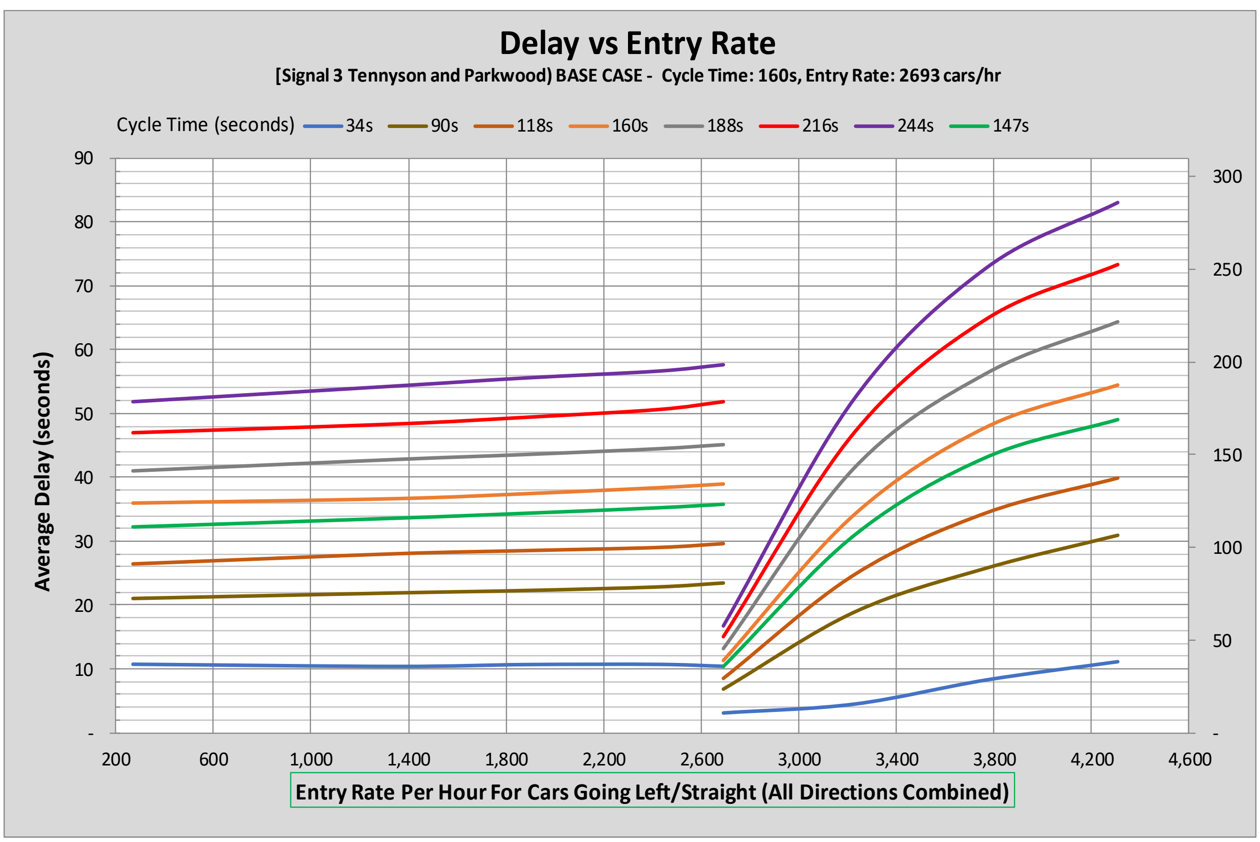


Graph 4. Delay vs Entry Rate – Created by the researcher on 1/4/19

The primary y axis refers to the average delay in seconds for a domain of 0 to 70. The secondary y axis refers to the average delay in seconds for a much larger domain, 0 to 1400. Two y axes were used because the average delay eventually becomes so high that it cannot be reflected on one axis, otherwise the smaller delays would be difficult to read.



Graph 5. Delay vs Entry Rate – Created by the researcher on 1/4/19

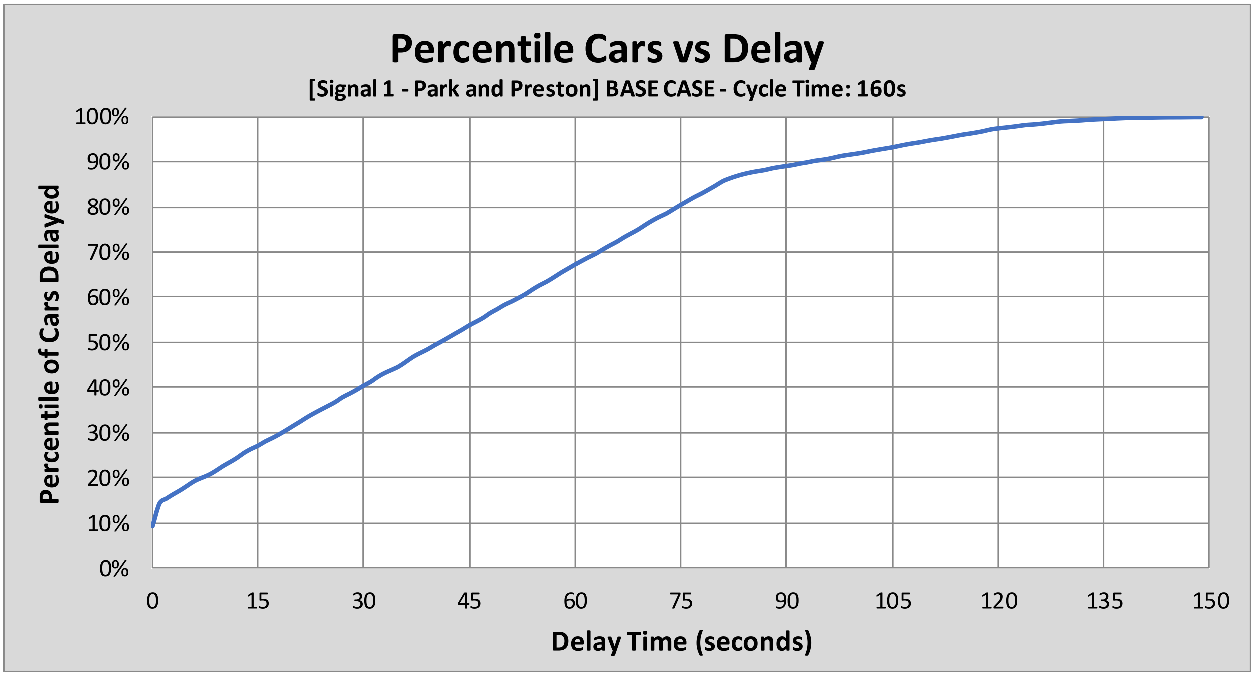


Graph 6. Delay vs Entry Rate – Created by the researcher on 1/4/19

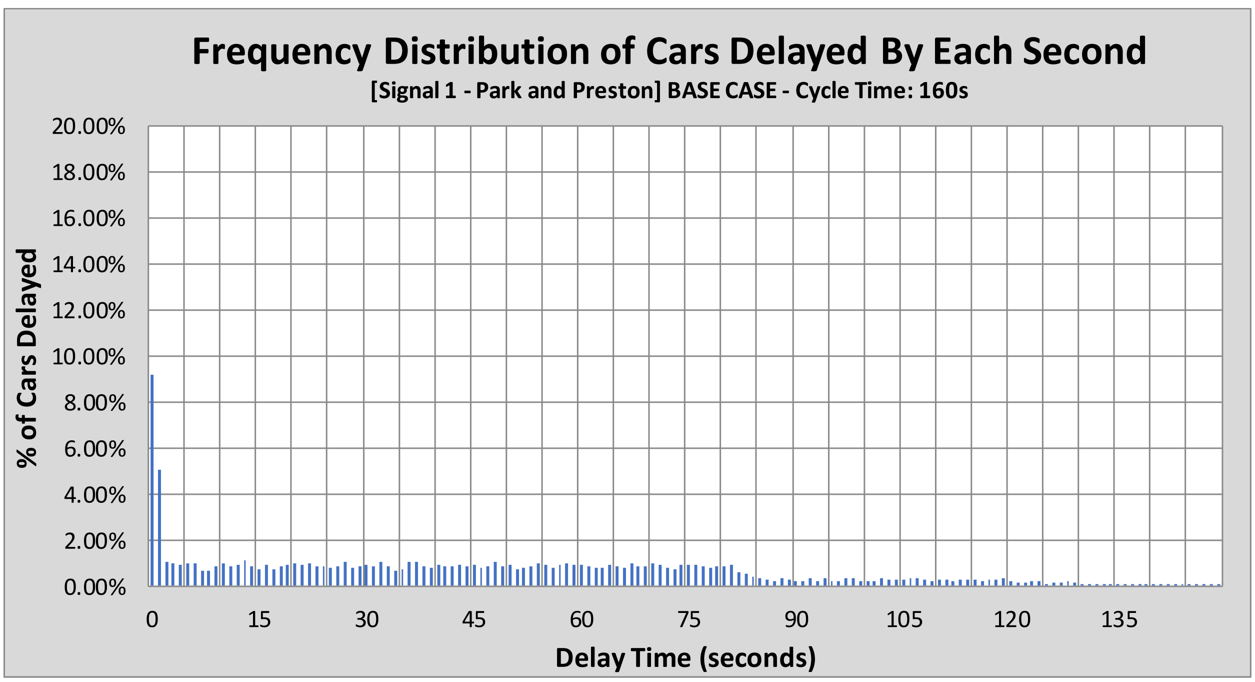
			Preston and Tennyson				Park and Preston				Parkwood and Tennyson			
Run #	Green Time Factor	Entry Rate Factor	Green Time (s)	Cycle Time (s)	Entry Rate (Cars/Hr)	Delay (s)	Green Time (s)	Cycle Time (s)	Entry Rate (Cars/Hr)	Delay (s)	Green Time (s)	Cycle Time (s)	Entry Rate (Cars/Hr)	Delay (s)
1	0.1	0.1	28	36	468	9	27	37	693	11	28	34	269	11
2	0.1	0.5	28	36	2,340	11	27	37	3,467	12	28	34	1,346	10
3	0.1	0.7	28	36	3,276	11	27	37	4,853	13	28	34	1,885	11
4	0.1	0.9	28	36	4,212	14	27	37	6,240	108	28	34	2,424	11
5	0.1	1.0	28	36	4,680	81	27	37	6,933	191	28	34	2,693	10
6	0.1	1.2	28	36	5,616	177	27	37	8,320	320	28	34	3,231	15
7	0.1	1.4	28	36	6,552	253	27	37	9,706	462	28	34	3,770	28
8	0.1	1.6	28	36	7,488	417	27	37	11,093	573	28	34	4,308	38
9	0.5	0.1	138	91	468	14	137	91	693	21	140	90	269	21
10	0.5	0.5	138	91	2,340	18	137	91	3,467	23	140	90	1,346	22
11	0.5	0.7	138	91	3,276	19	137	91	4,853	25	140	90	1,885	22
12	0.5	0.9	138	91	4,212	20	137	91	6,240	27	140	90	2,424	23
13	0.5	1.0	138	91	4,680	21	137	91	6,933	28	140	90	2,693	23
14	0.5	1.2	138	91	5,616	23	137	91	8,320	152	140	90	3,231	65
15	0.5	1.4	138	91	6,552	228	137	91	9,706	455	140	90	3,770	89
16	0.5	1.6	138	91	7,488	467	137	91	11,093	819	140	90	4,308	106
17	0.7	0.1	192	119	468	20	192	119	693	26	196	118	269	26
18	0.7	0.5	192	119	2,340	22	192	119	3,467	29	196	118	1,346	28
19	0.7	0.7	192	119	3,276	23	192	119	4,853	31	196	118	1,885	28
20	0.7	0.9	192	119	4,212	25	192	119	6,240	33	196	118	2,424	29
21	0.7	1.0	192	119	4,680	26	192	119	6,933	34	196	118	2,693	30
22	0.7	1.2	192	119	5,616	29	192	119	8,320	121	196	118	3,231	86
23	0.7	1.4	192	119	6,552	190	192	119	9,706	434	196	118	3,770	119
24	0.7	1.6	192	119	7,488	533	192	119	11,093	924	196	118	4,308	137
25	0.9	0.1	247	146	468	24	247	146	693	32	252	146	269	32
26	0.9	0.5	247	146	2,340	26	247	146	3,467	35	252	146	1,346	34
27	0.9	0.7	247	146	3,276	28	247	146	4,853	37	252	146	1,885	34
28	0.9	0.9	247	146	4,212	29	247	146	6,240	40	252	146	2,424	35
29	0.9	1.0	247	146	4,680	30	247	146	6,933	41	252	146	2,693	36
30	0.9	1.2	247	146	5,616	44	247	146	8,320	92	252	146	3,231	107
31	0.9	1.4	247	146	6,552	164	247	146	9,706	419	252	146	3,770	149
32	0.9	1.6	247	146	7,488	596	247	146	11,093	1,033	252	146	4,308	169
33	1.0	0.1	275	160	468	26	274	160	693	35	280	160	269	36
34	1.0	0.5	275	160	2,340	29	274	160	3,467	38	280	160	1,346	37
35	1.0	0.7	275	160	3,276	30	274	160	4,853	40	280	160	1,885	37
36	1.0	0.9	275	160	4,212	32	274	160	6,240	43	280	160	2,424	38
37	1.0	1.0	275	160	4,680	33	274	160	6,933	44	280	160	2,693	39
38	1.0	1.2	275	160	5,616	58	274	160	8,320	75	280	160	3,231	118
39	1.0	1.4	275	160	6,552	153	274	160	9,706	437	280	160	3,770	165
40	1.0	1.6	275	160	7,488	628	274	160	11,093	1,086	280	160	4,308	188
41	1.2	0.1	330	188	468	31	329	187	693	41	336	188	269	41
42	1.2	0.5	330	188	2,340	33	329	187	3,467	44	336	188	1,346	43
43	1.2	0.7	330	188	3,276	34	329	187	4,853	47	336	188	1,885	44
44	1.2	0.9	330	188	4,212	36	329	187	6,240	50	336	188	2,424	44
45	1.2	1.0	330	188	4,680	38	329	187	6,933	51	336	188	2,693	45
46	1.2	1.2	330	188	5,616	69	329	187	8,320	56	336	188	3,231	143
47	1.2	1.4	330	188	6,552	156	329	187	9,706	472	336	188	3,770	194
48	1.2	1.6	330	188	7,488	687	329	187	11,093	1,187	336	188	4,308	222
49	1.4	0.1	385	215	468	34	384	215	693	45	392	216	269	47
50	1.4	0.5	385	215	2,340	37	384	215	3,467	50	392	216	1,346	48
51	1.4	0.7	385	215	3,276	39	384	215	4,853	53	392	216	1,885	49
52	1.4	0.9	385	215	4,212	41	384	215	6,240	56	392	216	2,424	51
53	1.4	1.0	385	215	4,680	42	384	215	6,933	58	392	216	2,693	52
54	1.4	1.2	385	215	5,616	83	384	215	8,320	63	392	216	3,231	162
55	1.4	1.4	385	215	6,552	184	384	215	9,706	501	392	216	3,770	223
56	1.4	1.6	385	215	7,488	747	384	215	11,093	1,292	392	216	4,308	252
57	1.6	0.1	440	243	468	37	439	242	693	51	448	244	269	52
58	1.6	0.5	440	243	2,340	41	439	242	3,467	56	448	244	1,346	54
59	1.6	0.7	440	243	3,276	43	439	242	4,853	59	448	244	1,885	56
60	1.6	0.9	440	243	4,212	46	439	242	6,240	63	448	244	2,424	57
61	1.6	1.0	440	243	4,680	47	439	242	6,933	65	448	244	2,693	58
62	1.6	1.2	440	243	5,616	94	439	242	8,320	70	448	244	3,231	181
63	1.6	1.4	440	243	6,552	214	439	242	9,706	534	448	244	3,770	251
64	1.6	1.6	440	243	7,488	808	439	242	11,093	1,392	448	244	4,308	286

Table 5. Varying entry rates and green times raw data table – Created by the researcher on 12/30/19

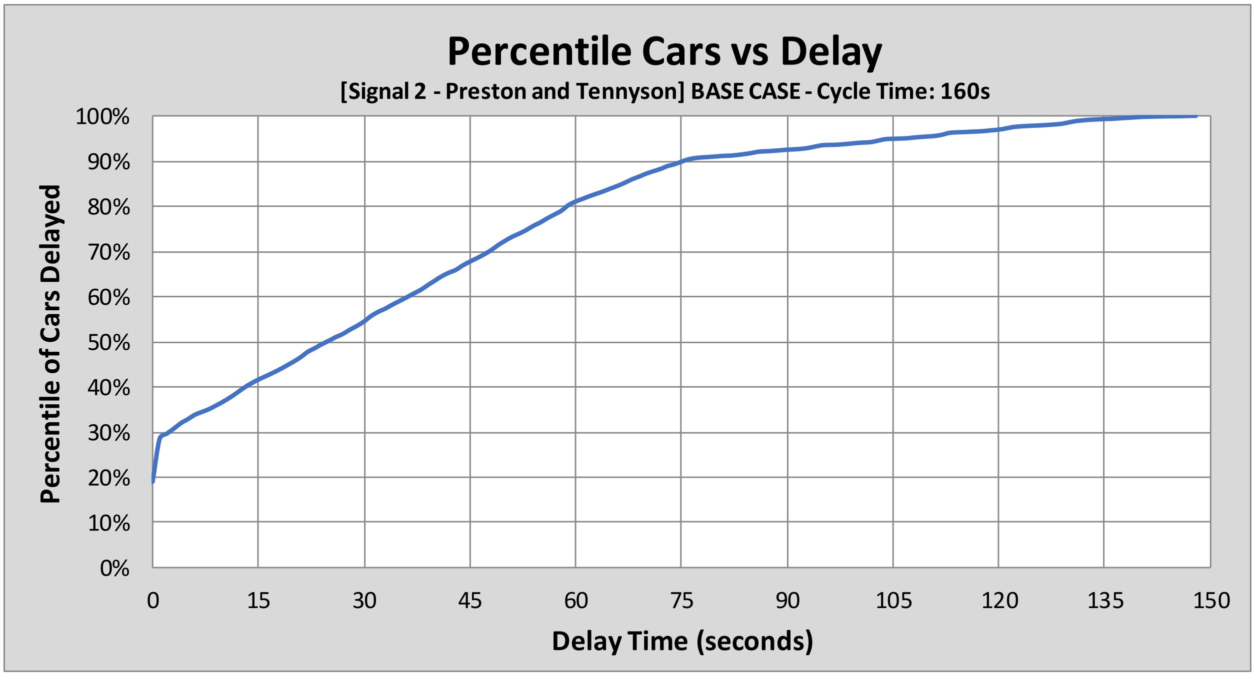
Histogram of Frequency Distribution



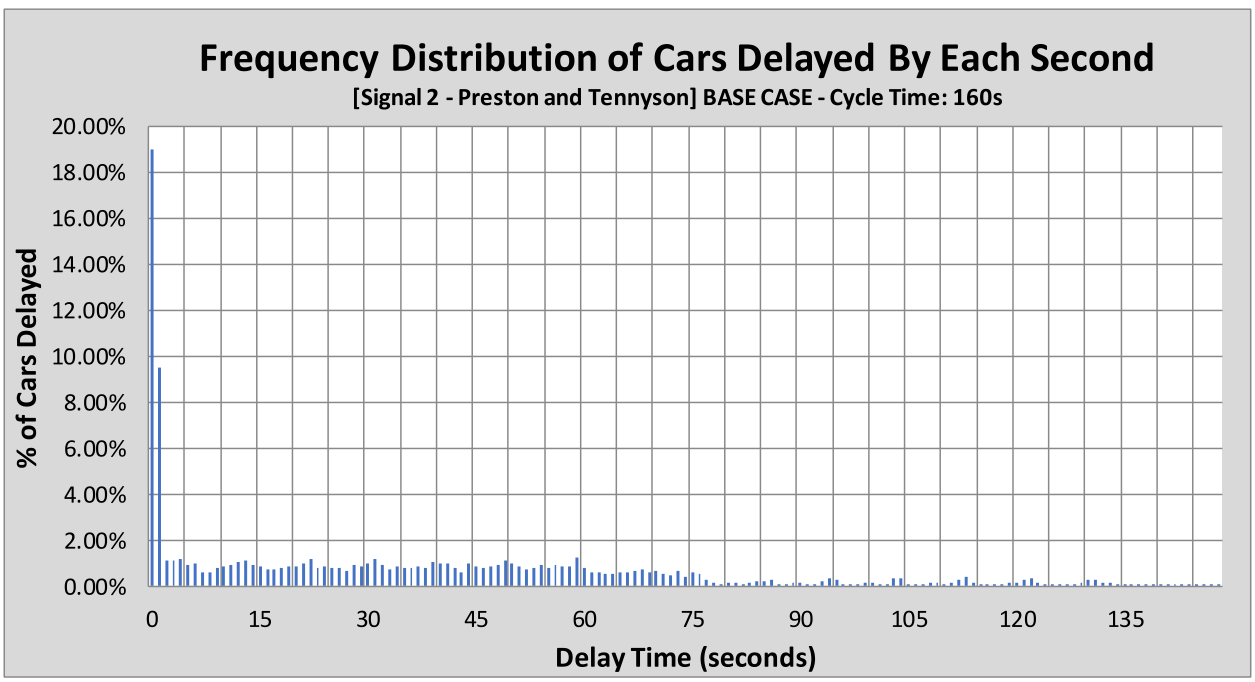
Graph 7. Percentile Cars vs Delay – Created by researcher on 1/4/19



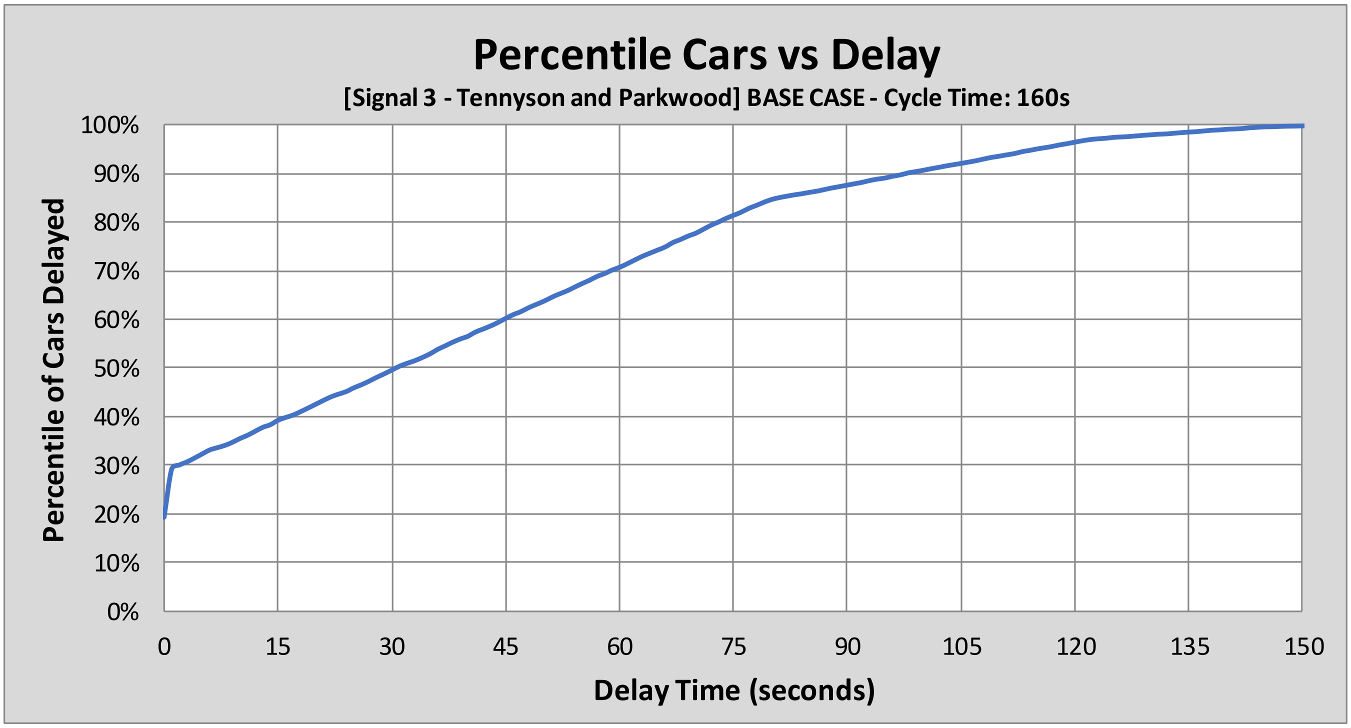
Graph 8. Frequency Distribution of Cars Delayed. Created by researcher on 1/4/19



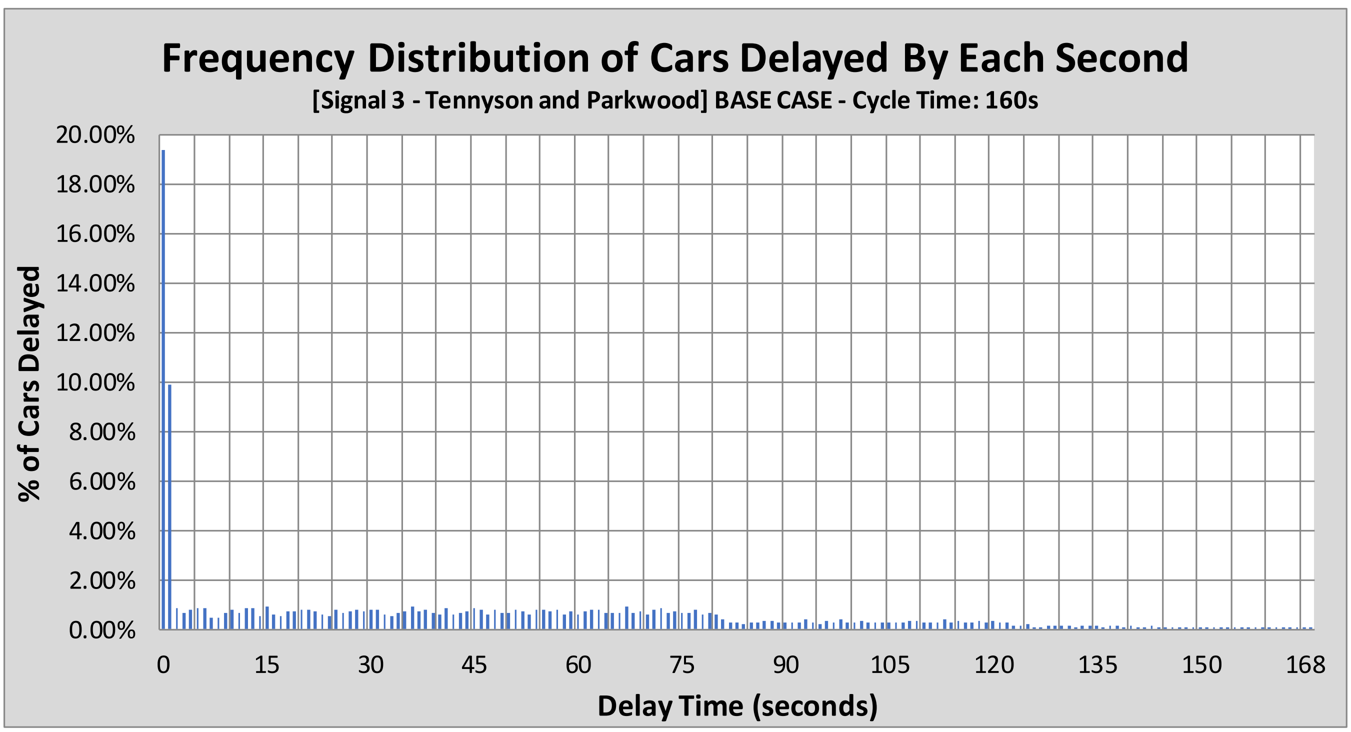
Graph 9. Percentile Cars vs Delay – Created by the researcher on 1/4/19



Graph 10. Frequency Distribution of Cars Delayed – Created by the researcher on 1/4/19



Graph 11. Percentile Cars vs Delay – Created by the researcher on 1/4/19



Graph 12. Frequency Distribution of Cars Delayed – Created by the researcher on 1/4/19

SIMULATION VERSUS WEBSTER'S FORMULA[5]

Park and Preston												
Phases	**Exit Rate Inputs**			**Exit Rate Calucation**			**Webster's Calculation**				**From Program**	
	GT (s)	YT (s)	Total (s)	Exit Rate C/Hr	Entry Rate C/Hr	# Lanes	Capacity C/Hr	Volume/ Capacity	Delay (s)	Signal Delay (s)	Delay (s)	Signal Delay
NS	72.7	4.3	77	5,700	1,893	3	2,743	0.69	32	37	33	38
NL	18.2	4.3	22.5	3,800	320	2	534	0.60	65		65	
SS	73.7	4.3	78	5,700	2,347	3	2,779	0.84	36	38	35	38
SL	19.2	4.3	23.5	3,800	215	2	558	0.39	62		61	
ES	28.8	4	32.8	5,700	714	3	1,169	0.61	58	60	58	60
EL	10.5	3	13.5	3,800	142	2	321	0.44	70		70	
WS	34.8	4	38.8	5,700	1,005	3	1,382	0.73	56	58	55	58
WL	16.5	3	19.5	3,800	297	2	463	0.64	67		65	
Total			**305.6**		**6,933**				**44**	**44**	**44**	**44**

Table 6. Simulation vs Webster's Formula for Park and Preston – Created by the researcher on 1/2/19

Tennyson and Preston												
Phases	**Exit Rate Inputs**			**Exit Rate Calucation**			**Webster's Calculation**				**From Program**	
	GT (s)	YT (s)	Total (s)	Exit Rate C/Hr	Entry Rate C/Hr	# Lanes	Capacity C/Hr	Volume/ Capacity	Delay (s)	Signal Delay (s)	Delay (s)	Signal Delay
NS	96	4.5	100.5	5,700	1,476	3	3,580	0.41	15	23	15	24
NL	26.5	3	29.5	3,800	345	2	701	0.49	59		59	
SS	80	4.5	84.5	5,700	2,160	3	3,010	0.72	29	29	28	29
SL	10.5	3	13.5	1,900	36	1	160	0.22	68		68	
ES	22.5	4	26.5	3,800	36	2	629	0.06	56	61	59	64
EL	15.5	3	18.5	3,800	72	2	439	0.16	64		67	
WS	15.5	4	19.5	3,800	396	2	463	0.86	69	70	68	70
WL	8.5	3	11.5	3,800	144	2	273	0.53	72		71	
Total			**304**		**4,665**				**32**	**32**	**33**	**33**

Table 7. Simulation vs Webster's Formula for Tennyson and Preston– Created by the researcher on 1/2/19

Parkwood and Tennyson													
Phases	**Exit Rate Inputs**			**Exit Rate Calucation**			**Webster's Calculation**				**From Program**	
	GT (s)	YT (s)	Total (s)	Exit Rate C/Hr	Entry Rate C/Hr	# Lanes	Capacity C/Hr	Volume/ Capacity	Delay (s)	Signal Delay (s)	Delay (s)	Signal Delay
NS	77	4	81	5,700	396	3	2,886	0.14	21	28	21	29
NL	15	3	18	1,900	72	1	214	0.34	65		68	
SS	77	4	81	5,700	1,080	3	2,886	0.37	24	32	24	31
SL*	15	3	18	1,900	207	1	214	0.97	71		70	
ES	35	4	39	5,700	396	3	1,389	0.29	49	54	49	55
EL	13	3	16	3,800	144	2	380	0.38	67		68	
WS	35	4	39	5,700	324	3	1,389	0.23	49	50	49	51
WL	13	3	16	1,900	36	1	190	0.19	66		66	
Total			**308**		**2,655**				**38**	**38**	**38**	**38**

Table 8. Simulation vs Webster’s Formula for Parkwood and Tennyson – Created by the researcher on 1/2/19

PHOTOS

Intersection of Park and Preston. Taken by the researcher on 11/28/18

Intersection of Tennyson and Preston. Taken by the researcher on 11/28/18

Intersection of Parkwood and Tennyson. Taken by the researcher on 11/28/18.

CONCLUSION

Besides optimizing a single signal, the City of Plano also needs to optimize traffic flow around the whole system of signals across the city so that traffic can flow smoothly across multiple signals on the most used and congested paths.

The city of Plano has previously determined that during peak hours, the optimal cycle time for all signals in the city is 160 seconds, and during off-peak hours, the optimal cycle time is 100s. As a result, even though the delay for one particular signal may be minimized by increasing or decreasing the cycle time from160s, it may not be optimal for the whole system of signals. That analysis is beyond the scope of this study.

DATA ANALYSIS

Delay vs Entry Rate

- Scenarios were run for the 3 chosen intersections with the base case representing morning peak hour entry rate and cycle time of 160s.
- It is observed from Graphs 4-6 and Table 4, that delay increases as entry rate increases, which makes intuitive sense. There is a parallel shift upwards in delay time as the cycle time increases.
- Typically, a signal would observe the highest entry rates at peak rush hours and the lowest entry rates during off-peak hours.
- Essentially, by knowing the entry rates (traffic density) during different times of the day (as provided in the Plano traffic study), using this graph can estimate how much delay (lost productivity) each driver is likely to experience at any given time of day.
- The delay time is also a function of the degree of saturation (cars entering vs cars that can be cleared). If the degree of saturation is less than one, cycle failure should be rare.

As the ratio approaches 1, the delay time increases. If the degree of saturation is greater than one, cycle failures are imminent and delays increase exponentially over time.

- Delay times for left turn lanes also appears to be higher. Both the number of lanes and green time, as well as entry rates, are lower than the straight direction. The city of Plano has tried to address this issue by adding more left turn lanes thereby increasing the exit rate.
- For Park and Preston, the peak hour delays are approximately 44s with an entry rate of 6,922 cars/hour, and 437s with an entry rate of 9,706 cars/hour for a 160s cycle time. For off-peak hours, a 91s cycle time corresponds with a delay of approximately 31s and an entry rate of 4,853 cars/hr.
- For Tennyson and Preston, the peak hour delays are approximately 33s for an entry rate of 4,680 cars/hour and 153s for an entry rate of 7,488 cars/hour for a 160s cycle time. For off-peak hours, a 91s cycle time corresponds with a delay of 20s and an entry rate of 4,112 cars/hour.
- For Parkwood and Tennyson, the peak hour delays are approximately 39s for an entry rate of 2,693 cars/hour and 165s for an entry rate of 3,770 cars/hour for a 160s cycle time. For off-peak hours, a 90s cycle time corresponds with a delay of 23s and an entry rate of 2,424 cars/hour.

Delay vs Cycle Time

- Scenarios were run for the 3 chosen intersections with the base case representing morning peak hour entry rate, cycle time of 160s and stop time of 2s.
- It is observed from Graphs 1-3 and Table 5, that generally delay increases as cycle time increases, and there is a parallel shift upwards in delay time as stop time increases.
- If stop time were zero, implying there was no switching cost or waiting time between changing signals, then delay times would theoretically tend to converge to zero as cycle times approach zero. This is represented in Graphs 1-3, for the scenario when stop time is 0s.

- However, in real life, after a signal turns red, there are cars in the intersection that need to clear and it takes a few seconds known as stop time or all red time (all signals are red). In Plano, the stop time varies from 1.75s to 2.5s and depends on the length of the intersection and the speed limit.
- When the stop time is more than 0, there are 4 states in a cycle where an all red happens and no new traffic is being exited from the intersection. For smaller cycle times, the total stop time across these 4 stages is a large enough fraction of the total cycle time such that it causes cycle failure.
- This behavior is demonstrated in Graphs 1-2 representing Signals 1-2, whereby for cycle times that are less than 100s, cycle failures are imminent and delay times are high. The system stabilizes when the cycle time is above 125s. This is consistent with Plano's choice to keep the cycle time of 160s for peak hour traffic in the stable range and keep the cycle time to 100s cycle time during off peak hour, preventing cycle failures.
- Graph 3 representing Signal 3 – Parkwood and Tennyson presents a slightly different behavior. The traffic volume or entry rate at this intersection is so low, that even low cycle times will not result in cycle failures. Consequentially, the ideal cycle time for this signal could be reduced considerably, but because of Plano's integrated approach to signal timings across the city, the peak and off-peak cycle times are maintained at 160s and 100s.

Histogram of Frequency Distribution

- Scenarios were run for the 3 chosen intersections with the base case representing morning peak hour entry rate and cycle time of 160s.
- From Graphs 7-10 and Signal 1-2 this behavior is clearly demonstrated. The average delay times for the 50th and 90th percentile cars are 41s and 77s for Signal 1, and 25s and 76s for Signal 2, respectively. The entry rate for Signal 1 is 6,693 cars/hour and 4,680 cars/hour for Signal 2.

- One interesting exception is observed for Signal 3. While the number of cars with zero wait is similar to Signal 2, the 50th and 90th percentile times are 31s and 98s respectively, which is surprisingly high considering the lower entry rate of 2,693.
- Essentially, the entry rate for Signal 3 is so low that less cars come in and exit during the green duration and more are trapped for longer during the red time. This signal would most benefit from a lower signal time and is exhibiting longer delays and adverse behavior because of the longer Cycle Time of 160s caused by macro system constraints.
- Additionally, the south-left turn for Signal 3 (see Table 8) is approaching a degree of saturation close to 1, which would increase delay for that turn and for the overall signal.

WEBSTER'S FORMULA ANALYSIS

The delay times calculated by the program were extremely similar to the standard formula for calculating average delay, Webster's Formula, with a margin error of 2%. For example, the program calculated the east direction's average delay time for the intersection of Park and Preston to be 60 seconds, including an average delay of 58 seconds for the east straight direction, and 70 seconds for the east left direction. Similarly, Webster's formula calculated the same numbers.

Webster's Formula[5] is known as

$$UD = \frac{C}{2}\frac{(1-\frac{g}{C})^2}{(1-\frac{g}{C}X)}$$

Where UD is uniform delay, C = cycle time, g = green time plus yellow time, and X is the volume/capacity ratio.

<u>Example Calculations and Comparison for Preston and Park signal going East</u>

<u>Straight Calculations</u>

Cycle Time = 160 seconds

Green + yellow time (for the east straight direction) = 32.8 seconds

Straight entry rate/volume = 0.1983333 cars/sec = 0.1983333*3600 cars/hour = 714 cars/hour

Straight exit rate = 3 lanes * 1900cars/hour saturation rate = 5700

Straight capacity: (g/C) * 5700 = (32.8/160) * 5700 = 1168.5 = 1169

$$\text{UD} = \frac{160(1-(\frac{32.8}{160}))^\wedge 2}{2(1-((\frac{32.8}{160})*(\frac{714}{1169})))} = \frac{80(1-0.205)^\wedge 2}{1-(0.205)(.611)} = \frac{80*.632025}{1-.125255} = \frac{50.562}{.874745} = 57.802 = \underline{58\text{ seconds}}$$

<u>Left Calculations:</u>

Cycle time =160 seconds

Green + yellow time (for the east left direction) = 13.5 seconds

Left entry rate/volume = 0.0394444 cars/sec = 0.0394444*3600 cars/hour = 142 cars/hour

Left exit rate = 2 lanes * 1900 saturation rate = 3800

Left capacity: (g/C) * 3800 = (13.5/160) * 3800 = 320.625 = 321

UD = $\frac{160(1-\left(\frac{13.5}{160}\right))\char`^2}{2(1-\left(\left(\frac{13.5}{160}\right)*\left(\frac{142}{321}\right)\right))} = \frac{80(1-0.084375)\char`^2}{1-(0.084375)(0.442)} = \frac{80(0.83837)}{1-0.0373} = \frac{67.07}{.9627}$ = 69.77 = <u>70 seconds</u>

As shown in these calculations, the simulation is very accurate even though it does not use Webster's formula, proving how empirical data and a huge number of random trials can bring a new, accurate method of minimizing traffic delays.

Conclusion

Traffic congestion is a growing problem in almost every city, which is why it is so important to increase the productivity of signalized intersections. Therefore, the goal of this project is to minimize delay times by simulating a traffic intersection using the Monte Carlo method, the concept of running a huge number of random trials in order to accurately predict results.

To simulate the Monte Carlo method for traffic lights, the researcher developed a detailed computer program that runs 100 of cycles of an intersection based on empirical traffic data supplied by the city of Plano, including red, green, and yellow light timings, and entry and exit rates for each of the directions for left and straight. The program tested two cases: varying stop time and cycle times, and varying entry rates and cycle times to find the average delay. An intersection was simulated for the crossings of Park and Preston, Preston and Tennyson, and Parkwood and Tennyson.

Recommendations

Based on the results of the simulation and the analysis limited to the 3 signals that were part of the study, recommendations are:

- Reduce the peak rate cycle time to 120s from 160s
- Reduce the cycle time for Parkwood and Tennyson (Signal 3) to half of the off-peak and peak cycle time for other signals (50s cycle time for off-peak and 60s cycle time for peak)

The researcher understands that while these recommendations are valid within the scope of this simulation, there might be additional constraints imposed by the citywide signals system that are beyond the scope of this study.

The simulation is successful and presents a new and innovative tool for traffic managers around the world. Specifically, the researcher was able to demonstrate that:

- Simulation results were consistent with those predicted by widely used Webster's theoretical models.
- Consistent with data from the City of Plano traffic study.
- Was able to identify specific areas of improvement for the 3 Signal Intersections that were part of the simulation.

Benefits

- This project brings statistical analysis to a field that has previously been based on empirical data. Cities usually spend thousands of dollars on traffic studies and have to use hit or miss trials to test the effectiveness of signals. On the other hand, this computer program brings a new aspect to minimizing delays by using simulation techniques that have never been applied to traffic lights before.
- Currently, theoretical models can only predict delay times for capacity ratios less than 0.85. Other techniques have to be used to project cycle failure rates and delays for capacity ratios greater than 0.85. This tool can be utilized to optimize and project off-peak and peak-hour delays and cycle failure rates for all capacity ratios. It also provides the ability to modify input parameters to simulate new scenarios.
- The results are representative of real-life problems. For example, if there is a huge event held in a city and many people plan to attend, traffic signal timings may need to be adapted to better serve the higher entry rates.
- As self-driving vehicles become developed universally, stop times can be reduced because the number of accidents will significantly be reduced and vehicles will need less clearance time. This program tests a number of stop times to test the effects on average delay. Second, traffic signal cycle times can be improved for every single traffic intersection in every city around the world, saving everyone a large amount gas and money.

- The project can be enhanced to produce a system where an entire city grid can be synced, meaning that a vehicle can follow an entire road throughout a city without having to stop at red lights.

ERROR ANALYSIS

- The program attempts to simulate real time operation of a traffic signal in computer time. For Java, the smallest time measurement unit is 1 nanosecond and ideally if 1 second in real time could be translated to 1 nanosecond in computer time, 30 years of signal operation could be simulated in one hour. 1 second was picked as the smallest measurable time in the real world and hence the smallest operational time for changing signal states. Essentially, multiple threads running in the program sleep and wake every 1 second equivalent of real time to perform signal operations.
- Unfortunately, running Java on windows 10, clock cycles and CPU frequencies also impose systems constraints. Specifically, the overhead from time measurement commands is about 1,000 nanoseconds and the overhead of putting a thread to sleep and wake is about 200,000 nanoseconds. Therefore, 5 milliseconds was chosen as the smallest practical computer time, representing 1 second of real time. To eliminate any effects of overhead at the beginning of the program, the command latencies and thread latencies were calculated and any future time calculations were adjusted with these overheads. By measuring the error and programming a fix for it, an entire day's worth of signal cycles can be simulated in under 10 minutes.
- The two different paths in a signal pair have to add up to the same time for a signal to work properly. If the two paths do not add up to the same time, the program takes the difference between the two path times, divided it by two, and adds each part to the left and straight direction of the shorter path time. This prevents any user input error and checks to see that the path times are equal.
- Since this the simulation accommodates random trial concepts, each simulation was run for 100 cycles to statistically minimize any variations from an individual run. An even higher number of cycles would further reduce any variances from individual runs.

Future Applications

- A simulation algorithm such as this could be accommodated with real time actuated sensor data to adjust signal time in response to real time traffic patterns.
- The results are representative of real-life problems. For example, if there is a huge event held in a city and many people plan to attend, traffic signal timings may need to be adapted to better serve the higher entry rates. The best signal timings can be obtained from running the computer program and finding the lowest delay time out of the various cycle times for the expected entry rate.
- Traffic signals are constantly being optimized due to growing congestion everywhere. Traffic signal cycle times can be improved for every single traffic intersection in every city around the world, saving everyone a large amount gas and money.
- The project can be enhanced to produce a system where an entire city grid can be synced, meaning that a vehicle can follow an entire road throughout a city without having to stop at red lights.
- Currently, scientists are attempting to decrease the stop time at signalized intersections by developing self-driving automated vehicles. Automated vehicles significantly reduce accidents, therefore lowering the necessary red time for clearance. When automated vehicles become widespread, stop time will have to be adjusted to improve traffic flow. Fortunately, this project provides results on the best cycle times for various stop times, helping traffic flow become more efficient after automated vehicles become universal.

Appendix - Data Supplied by City of Plano

Intersection Timings – Park and Preston

		AM				MD				PM		
	Green	**Yellow**	**Red**	**Total Splits**	**Green**	**Yellow**	**Red**	**Total Splits**	**Green**	**Yellow**	**Red**	**Total Splits**
Ph1	16.5	3	2.5	22	14.5	3	2.5	20	16.5	3	2.5	22
Ph2	28.8	4	1.2	34	23.8	4	1.2	29	37.8	4	1.2	43
Ph3	18.2	4.3	2.5	25	12.2	4.3	2.5	19	14.2	4.3	2.5	21
Ph4	73.7	4.3	1	79	26.7	4.3	1	32	68.7	4.3	1	74
Ph5	10.5	3	2.5	16	16.5	3	2.5	22	26.5	3	2.5	32
Ph6	34.8	4	1.2	40	21.8	4	1.2	27	27.8	4	1.2	33
Ph7	19.2	4.3	2.5	26	9.2	4.3	2.5	16	16.2	4.3	2.5	23
Ph8	72.7	4.3	1	78	29.7	4.3	1	35	66.7	4.3	1	72

Intersection Timings – Preston and Tennyson

		AM				MD				PM		
	Green	**Yellow**	**Red**	**Total Splits**	**Green**	**Yellow**	**Red**	**Total Splits**	**Green**	**Yellow**	**Red**	**Total Splits**
Ph1	15.5	3	2.5	21	12.5	3	2.5	18	11.5	3	2.5	17
Ph2	15.5	4	1.5	21	18.5	4	1.5	24	44.5	4	1.5	50
Ph3	26.5	3	2.5	32	20.5	3	2.5	26	15.5	3	2.5	21
Ph4	80	4.5	1.5	86	26	4.5	1.5	32	66	4.5	1.5	72
Ph5	8.5	3	2.5	14	12.5	3	2.5	18	36.5	3	2.5	42
Ph6	22.5	4	1.5	28	18.5	4	1.5	24	19.5	4	1.5	25
Ph7	10.5	3	2.5	16	20.5	3	2.5	26	10.5	3	2.5	16
Ph8	96	4.5	1.5	102	26	4.5	1.5	32	71	4.5	1.5	77

INTERSECTION TIMINGS – PARKWOOD AND TENNYSON

		AM				MD				PM		
	Green	**Yellow**	**Red**	**Total Splits**	**Green**	**Yellow**	**Red**	**Total Splits**	**Green**	**Yellow**	**Red**	**Total Splits**
Ph1	13	3	2	18	8	3	2	13	21	3	2	26
Ph2	35	4	1	40	25	4	1	30	39	4	1	44
Ph3	15	3	2	20	9	3	2	14	13	3	2	18
Ph4	77	4	1	82	38	4	1	43	67	4	1	72
Ph5	13	3	2	18	8	3	2	13	30	3	2	35
Ph6	35	4	1	40	25	4	1	30	30	4	1	35
Ph7	15	3	2	20	9	3	2	14	30	3	2	35
Ph8	77	4	1	82	38	4	1	43	50	4	1	55

PARK AND PRESTON – MORNING RUSH HOUR

CJ Hensch & Associates, Inc.

C. J. Hensch & Associates Inc.
5215 Sycamore Ave.

Pasadena, Texas, United States 77503
(281) 487-5417

Count Name: 3870 - Park Boulevard at Preston Road (Weekday)
Site Code: 3870
Start Date: 02/04/2015
Page No: 3

Turning Movement Peak Hour Data (7:30 AM)

Start Time	Preston Road Southbound						Park Boulevard Westbound					
	Left	Thru	Right	U-Turn	Peds	App. Total	Left	Thru	Right	U-Turn	Peds	App. Total
7:30 AM	54	636	59	0	0	749	80	223	72	0	0	375
7:45 AM	62	632	78	0	0	772	91	294	60	0	0	445
8:00 AM	57	514	58	0	0	629	59	261	65	0	0	385
8:15 AM	42	565	56	0	0	663	67	227	52	0	0	346
Total	215	2347	251	0	0	2813	297	1005	249	0	0	1551
Approach %	7.6	83.4	8.9	0.0	-	-	19.1	64.8	16.1	0.0	-	-
Total %	2.8	30.2	3.2	0.0	-	36.2	3.8	12.9	3.2	0.0	-	19.9
PHF	0.867	0.923	0.804	0.000	-	0.911	0.816	0.855	0.865	0.000	-	0.871
All Vehicles (no classification)	215	2347	251	0	-	2813	297	1005	249	0	-	1551
% All Vehicles (no classification)	100.0	100.0	100.0	-	-	100.0	100.0	100.0	100.0	-	-	100.0
Pedestrians	-	-	-	-	0	-	-	-	-	-	0	-
% Pedestrians	-	-	-	-	-	-	-	-	-	-	-	-

Start Time	Preston Road Northbound						Park Boulevard Eastbound						
	Left	Thru	Right	U-Turn	Peds	App. Total	Left	Thru	Right	U-Turn	Peds	App. Total	Int. Total
7:30 AM	53	476	31	0	0	560	37	144	41	0	0	222	1906
7:45 AM	85	472	29	0	0	586	39	198	57	0	0	294	2097
8:00 AM	102	457	41	0	0	600	38	198	53	0	0	289	1903
8:15 AM	80	488	30	1	0	599	28	174	63	0	0	265	1873
Total	320	1893	131	1	0	2345	142	714	214	0	0	1070	7779
Approach %	13.6	80.7	5.6	0.0	-	-	13.3	66.7	20.0	0.0	-	-	-
Total %	4.1	24.3	1.7	0.0	-	30.1	1.8	9.2	2.8	0.0	-	13.8	-
PHF	0.784	0.970	0.799	0.250	-	0.977	0.910	0.902	0.849	0.000	-	0.910	0.927
All Vehicles (no classification)	320	1893	131	1	-	2345	142	714	214	0	-	1070	7779
% All Vehicles (no classification)	100.0	100.0	100.0	100.0	-	100.0	100.0	100.0	100.0	-	-	100.0	100.0
Pedestrians	-	-	-	-	0	-	-	-	-	-	0	-	-
% Pedestrians	-	-	-	-	-	-	-	-	-	-	-	-	-

Park and Preston – Midday

C. J. Hensch & Associates Inc.
5215 Sycamore Ave.

Pasadena, Texas, United States 77503
(281) 487-5417

Count Name: 3870 - Park Boulevard at Preston Road (Weekday)
Site Code: 3870
Start Date: 02/04/2015
Page No: 5

Turning Movement Peak Hour Data (12:15 PM)

	Preston Road Southbound						Park Boulevard Westbound						Preston Road Northbound						Park Boulevard Eastbound						
Start Time	Left	Thru	Right	U-Turn	Peds	App. Total	Left	Thru	Right	U-Turn	Peds	App. Total	Left	Thru	Right	U-Turn	Peds	App. Total	Left	Thru	Right	U-Turn	Peds	App. Total	Int. Total
12:15 PM	72	328	49	0	0	449	108	173	64	0	0	345	82	314	73	1	0	470	100	224	67	0	0	391	1655
12:30 PM	73	289	45	0	3	407	108	187	78	0	2	373	98	332	78	5	0	513	104	160	52	0	0	316	1609
12:45 PM	60	277	49	1	0	387	119	174	66	0	0	359	75	262	74	1	0	412	92	183	46	1	0	322	1480
1:00 PM	69	271	62	0	1	402	115	161	70	0	0	346	90	281	77	0	0	448	96	178	63	0	0	337	1533
Total	274	1165	205	1	4	1645	450	695	278	0	2	1423	345	1189	302	7	0	1843	392	745	228	1	0	1366	6277
Approach %	16.7	70.8	12.5	0.1	-	-	31.6	48.8	19.5	0.0	-	-	18.7	64.5	16.4	0.4	-	-	28.7	54.5	16.7	0.1	-	-	-
Total %	4.4	18.6	3.3	0.0	-	26.2	7.2	11.1	4.4	0.0	-	22.7	5.5	18.9	4.8	0.1	-	29.4	6.2	11.9	3.6	0.0	-	21.8	-
PHF	0.938	0.888	0.827	0.250	-	0.916	0.945	0.929	0.891	0.000	-	0.954	0.880	0.895	0.968	0.350	-	0.898	0.942	0.831	0.851	0.250	-	0.873	0.948
All Vehicles (no classification)	274	1165	205	1	-	1645	450	695	278	0	-	1423	345	1189	302	7	-	1843	392	745	228	1	-	1366	6277
% All Vehicles (no classification)	100.0	100.0	100.0	100.0	-	100.0	100.0	100.0	100.0	-	-	100.0	100.0	100.0	100.0	100.0	-	100.0	100.0	100.0	100.0	100.0	-	100.0	100.0
Pedestrians	-	-	-	-	4	-	-	-	-	-	2	-	-	-	-	-	0	-	-	-	-	-	0	-	-
% Pedestrians	-	-	-	-	100.0	-	-	-	-	-	100.0	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Park and Preston – Afternoon Rush Hour

C. J. Hensch & Associates Inc.
5215 Sycamore Ave.

Pasadena, Texas, United States 77503
(281) 487-5417

Count Name: 3870 - Park Boulevard at Preston Road (Weekday)
Site Code: 3870
Start Date: 02/04/2015
Page No: 7

Turning Movement Peak Hour Data (5:00 PM)

	Preston Road Southbound						Park Boulevard Westbound						Preston Road Northbound						Park Boulevard Eastbound						
Start Time	Left	Thru	Right	U-Turn	Peds	App. Total	Left	Thru	Right	U-Turn	Peds	App. Total	Left	Thru	Right	U-Turn	Peds	App. Total	Left	Thru	Right	U-Turn	Peds	App. Total	Int. Total
5:00 PM	89	401	43	0	0	533	72	245	61	0	0	378	82	527	101	0	1	710	77	264	61	0	0	402	2023
5:15 PM	100	456	39	0	1	595	70	257	67	0	0	394	89	531	103	0	0	723	110	259	48	0	0	417	2129
5:30 PM	98	471	62	0	0	631	63	207	79	0	0	349	77	514	85	1	0	677	113	255	59	0	0	427	2084
5:45 PM	100	430	31	0	0	561	72	194	61	0	0	327	77	453	105	0	0	635	78	229	55	0	1	362	1885
Total	387	1758	175	0	1	2320	277	903	268	0	0	1448	325	2025	394	1	1	2745	378	1007	223	0	1	1608	8121
Approach %	16.7	75.8	7.5	0.0	-	-	19.1	62.4	18.5	0.0	-	-	11.8	73.8	14.4	0.0	-	-	23.5	62.6	13.9	0.0	-	-	-
Total %	4.8	21.6	2.2	0.0	-	28.6	3.4	11.1	3.3	0.0	-	17.8	4.0	24.9	4.9	0.0	-	33.8	4.7	12.4	2.7	0.0	-	19.8	-
PHF	0.968	0.933	0.706	0.000	-	0.919	0.962	0.878	0.848	0.000	-	0.919	0.913	0.953	0.938	0.250	-	0.949	0.836	0.954	0.914	0.000	-	0.941	0.954
All Vehicles (no classification)	387	1758	175	0	-	2320	277	903	268	0	-	1448	325	2025	394	1	-	2745	378	1007	223	0	-	1608	8121
% All Vehicles (no classification)	100.0	100.0	100.0	-	-	100.0	100.0	100.0	100.0	-	-	100.0	100.0	100.0	100.0	100.0	-	100.0	100.0	100.0	100.0	-	-	100.0	100.0
Pedestrians	-	-	-	-	1	-	-	-	-	-	0	-	-	-	-	-	1	-	-	-	-	-	1	-	-
% Pedestrians	-	-	-	-	100.0	-	-	-	-	-	-	-	-	-	-	-	100.0	-	-	-	-	-	100.0	-	-

Preston and Tennyson – Morning Rush Hour

COMBINED TURNING MOVEMENT COUNT

#132 PRESTON & TENNYSON - AM PEAK

LOCATION#:	132	QTD PROJ#:	2015146
NORTH / SOUTH:	PRESTON	DATE:	Thursday, April 09, 2015
EAST / WEST:	TENNYSON	VICINITY:	Plano, TX

DIRECTION:	NL	NT	NR	U	SL	ST	SR	U	EL	ET	ER	U	WL	WT	WR	U	TOTALS
LANES:	2	3	1	0	1	3	1	0	1	2	1	0	1	2	1	0	
7:00 AM	56	186	3	0	4	538	37	0	6	9	14	0	30	46	4	0	933
7:15 AM	79	334	5	0	3	476	34	0	21	9	14	0	34	47	6	0	1062
7:30 AM	82	420	4	0	3	603	79	0	18	16	28	0	40	103	18	0	1414
7:45 AM	112	459	10	0	4	593	124	0	21	10	22	1	36	130	10	0	1532
8:00 AM	83	421	14	0	4	539	111	0	16	14	18	0	40	130	15	0	1405
8:15 AM	105	410	14	0	4	515	94	0	21	15	17	0	35	138	19	0	1387

VOLUME STATS:	NL	NT	NR	U	SL	ST	SR	U	EL	ET	ER	U	WL	WT	WR	U	
TOTAL:	517	2230	50	0	22	3264	479	0	103	73	113	1	215	594	72	0	7733
P.H.V:	382	1710	42	0	15	2250	408	0	76	55	85	1	151	501	62	0	5738
P.H.F:	0.918				0.927				0.875				0.930				0.936

Preston and Tennyson - Midday

COMBINED TURNING MOVEMENT COUNT

#132 PRESTON & TENNYSON - MD PEAK

LOCATION#:	132	QTD PROJ#:	2015146
NORTH / SOUTH:	PRESTON	DATE:	Thursday, April 09, 2015
EAST / WEST:	TENNYSON	VICINITY:	Plano, TX

DIRECTION:	NL	NT	NR	U	SL	ST	SR	U	EL	ET	ER	U	WL	WT	WR	U	TOTALS
LANES:	2	3	1	0	1	3	1	0	1	2	1	0	1	2	1	0	
11:30 AM	29	293	5	0	6	332	28	0	63	27	78	0	15	14	2	0	892
11:45 AM	44	317	16	0	6	318	21	0	56	30	87	0	11	22	6	0	934
12:00 PM	34	309	8	0	11	254	17	0	111	45	86	0	22	23	2	0	922
12:15 PM	61	365	8	0	8	206	13	0	58	35	94	0	23	29	4	0	904
12:30 PM	63	340	18	0	11	295	62	0	60	39	81	1	11	23	6	0	1010
12:45 PM	74	394	13	0	3	308	65	0	56	25	53	0	13	42	10	0	1056
1:00 PM	76	337	19	0	4	298	53	0	61	23	66	0	13	41	6	0	997
1:15 PM	61	327	10	0	2	303	44	0	52	25	34	1	14	42	3	0	918

VOLUME STATS:	NL	NT	NR	U	SL	ST	SR	U	EL	ET	ER	U	WL	WT	WR	U	
TOTAL:	442	2682	97	0	51	2314	303	0	517	249	579	2	122	236	39	0	7633
P.H.V:	274	1398	60	0	20	1204	224	0	229	112	234	2	51	148	25	0	3981
P.H.F:	0.900				0.963				0.797				0.862				0.942

Preston and Tennyson – Afternoon Rush Hour

COMBINED TURNING MOVEMENT COUNT

#132 PRESTON & TENNYSON - PM PEAK

LOCATION#:	132	QTD PROJ#:	2015146
NORTH / SOUTH:	PRESTON	DATE:	Thursday, April 09, 2015
EAST / WEST:	TENNYSON	VICINITY:	Plano, TX

DIRECTION:	NL	NT	NR	U	SL	ST	SR	U	EL	ET	ER	U	WL	WT	WR	U	TOTALS
LANES:	2	3	1	0	1	3	1	0	1	2	1	0	1	2	1	0	
4:30 PM	22	478	26	0	6	451	21	0	87	83	106	0	20	16	5	0	1321
4:45 PM	31	491	25	0	5	441	26	0	91	86	92	0	18	22	7	0	1335
5:00 PM	28	499	21	0	15	468	29	0	118	191	146	0	12	18	7	0	1552
5:15 PM	23	419	26	0	14	466	26	0	122	186	130	0	12	22	11	0	1457
5:30 PM	28	432	33	0	16	495	17	0	120	167	128	0	15	20	10	0	1481
5:45 PM	19	494	24	0	11	395	22	0	109	166	110	0	16	24	16	0	1406

VOLUME STATS:	NL	NT	NR	U	SL	ST	SR	U	EL	ET	ER	U	WL	WT	WR	U	
TOTAL:	151	2813	155	0	67	2716	141	0	647	879	712	0	93	122	56	0	8552
P.H.V:	98	1844	104	0	56	1824	94	0	469	710	514	0	55	84	44	0	5896
P.H.F:	0.933				0.935				0.930				0.817				0.950

Parkwood and Tennyson – Morning Rush Hour

COMBINED TURNING MOVEMENT COUNT

#130 PARKWOOD & TENNYSON - AM PEAK

LOCATION#:	130	QTD PROJ#:	2015146
NORTH / SOUTH:	PARKWOOD	DATE:	Tuesday, June 02, 2015
EAST / WEST:	TENNYSON	VICINITY:	Plano, TX

DIRECTION:	NL	NT	NR	U	SL	ST	SR	U	EL	ET	ER	U	WL	WT	WR	U	TOTALS
LANES:	1	3	1	0	1	3	0	0	2	3	0	0	1	3	0	0	
7:00 AM	6	43	13	0	45	222	22	1	22	71	11	0	5	56	11	0	528
7:15 AM	14	82	26	0	61	293	46	4	25	87	13	0	8	51	16	0	726
7:30 AM	17	103	33	0	54	308	33	6	37	84	17	0	10	84	10	0	796
7:45 AM	24	140	49	0	58	256	60	4	39	147	8	0	13	115	14	0	927
8:00 AM	44	92	39	0	47	285	68	2	31	113	14	0	13	97	17	0	862
8:15 AM	21	122	41	0	64	271	53	2	38	110	12	0	14	99	20	0	867

VOLUME STATS:	NL	NT	NR	U	SL	ST	SR	U	EL	ET	ER	U	WL	WT	WR	U	
TOTAL:	126	582	201	0	329	1635	282	19	192	612	75	0	63	502	88	0	4706
P.H.V:	106	457	162	0	223	1120	214	14	145	454	51	0	50	395	61	0	3452
P.H.F:		0.851				0.977				0.838				0.891			0.931

Parkwood and Tennyson – Midday

COMBINED TURNING MOVEMENT COUNT

#130 PARKWOOD & TENNYSON - MD PEAK

LOCATION#:	130	QTD PROJ#:	2015146
NORTH / SOUTH:	PARKWOOD	DATE:	Tuesday, June 02, 2015
EAST / WEST:	TENNYSON	VICINITY:	Plano, TX

DIRECTION:	NL	NT	NR	U	SL	ST	SR	U	EL	ET	ER	U	WL	WT	WR	U	TOTALS
LANES:	1	3	1	0	1	3	0	0	2	3	0	0	1	3	0	0	
11:30 AM	10	82	5	0	15	98	15	1	37	41	17	0	22	54	36	0	433
11:45 AM	15	105	21	0	23	118	25	2	31	54	18	1	16	52	25	0	506
12:00 PM	23	199	37	0	25	97	23	1	45	53	12	0	18	66	43	0	642
12:15 PM	7	113	11	0	28	105	21	1	40	45	16	1	13	65	33	0	499
12:30 PM	14	104	16	0	45	136	39	2	43	59	7	1	11	67	38	0	582
12:45 PM	12	117	26	0	50	126	39	1	28	58	6	1	11	63	28	0	566
1:00 PM	16	99	8	0	36	132	29	2	41	59	7	0	8	49	27	0	513
1:15 PM	16	115	22	0	44	130	44	3	28	49	3	1	12	54	20	0	541

VOLUME STATS:	NL	NT	NR	U	SL	ST	SR	U	EL	ET	ER	U	WL	WT	WR	U	
TOTAL:	113	934	146	0	266	942	235	13	293	418	86	5	111	470	250	0	4282
P.H.V:	56	533	90	0	148	464	122	5	156	215	41	3	53	261	142	0	2289
P.H.F:		0.655				0.832				0.943				0.898			0.891

Parkwood and Tennyson – Afternoon Rush Hour

COMBINED TURNING MOVEMENT COUNT

#130 PARKWOOD & TENNYSON - PM PEAK

LOCATION#:	130	QTD PROJ#:	2015146
NORTH / SOUTH:	PARKWOOD	DATE:	Tuesday, June 02, 2015
EAST / WEST:	TENNYSON	VICINITY:	Plano, TX

DIRECTION:	NL	NT	NR	U	SL	ST	SR	U	EL	ET	ER	U	WL	WT	WR	U	TOTALS
LANES:	1	3	1	0	1	3	0	0	2	3	0	0	1	3	0	0	
4:30 PM	11	182	14	0	29	168	27	2	58	64	18	0	47	129	46	0	795
4:45 PM	12	200	14	0	26	182	34	4	91	94	27	0	26	110	54	0	874
5:00 PM	50	187	24	0	38	182	34	2	74	152	26	0	57	162	70	0	1058
5:15 PM	24	248	17	0	32	222	41	4	132	155	34	0	50	138	78	0	1175
5:30 PM	22	283	25	0	45	203	30	6	106	148	29	0	43	113	44	0	1097
5:45 PM	10	209	20	0	40	152	33	7	102	112	25	0	39	147	64	0	960

VOLUME STATS:	NL	NT	NR	U	SL	ST	SR	U	EL	ET	ER	U	WL	WT	WR	U	
TOTAL:	129	1309	114	0	210	1109	199	25	563	725	159	0	262	799	356	0	5959
P.H.V:	106	927	86	0	155	759	138	19	414	567	114	0	189	560	256	0	4290
P.H.F:		0.848				0.895				0.853				0.869			0.913

ANNOTATED BIBLIOGRAPHY

1. Actuated Traffic Controller Timing Processes. (n.d.). Retrieved October 4, 2018, from https://www.webpages.uidaho.edu/TrafficSignalSystems/traffic/instructor/ch4a.pdf

This source provides diagrams elaborating on the concept of passage time, minimum green time, and maximum green time from Chapter 1 in actuated signals.

2. City of Plano 2017 Traffic Volume. (n.d.). Retrieved September 26, 2018, from https://www.plano.gov/ArchiveCenter/ViewFile/Item/6258

This map of the roads of Plano displays the average vehicle volume per day for specific roads based on empirical data from a traffic study that Plano had done. The map shows the most occupied signals, as well as the least busy signals. This helped me choose what intersections to simulate, because I wanted to simulate a variety of sizes of intersections. As a result, the busiest signal I chose was Park and Preston, the medium sized signal was Tennyson and Preston, and the least busy intersection I chose was Parkwood and Tennyson.

3. Kenton, Will. “Monte Carlo Simulation.” *Investopedia*, Investopedia, 4 Aug. 2018, www.investopedia.com/terms/m/montecarlosimulation.asp.

A Monte Carlo simulation uses a large number of random trials in order to predict the probability of various outcomes that are otherwise difficult to anticipate due to the intervention of random variables, risk, and uncertainty. The Monte Carlo simulation can be applied in many fields, such as finance, sports, and technology.

4. Kroese, D. P., Brereton, T., Taimre, T., & Botev, Z. I. (2014). Why the Monte Carlo method is so important today. Wiley Interdisciplinary Reviews: Computational Statistics, 6(6), 386-392. doi:10.1002/wics.1314

Past Monte Carlo simulation applications

- Industrial Engineering and Operations Research - simulation of inventory processes, job scheduling, vehicle routing, queueing networks, and reliability systems.
- Physical processes and structures - the study of chemical kinetics by stochastic simulation, the simulation of photon transport through biological tissue, the development and analysis of new materials and structures such as organic LEDs or organic solar cells, and virtual materials design because physical development can be too expensive and/or time consuming.
- Random Graphs and Combinatorial Structures - statistical physics, probability theory, and computer science.
- Economics and Finance - pricing financial instruments, risk analysis, financial option pricing, stock market.
- Computational Statistics - impacts Bayesian and frequentist statistics.

Future Monte Carlo simulation applications

- Parallel computing - developing parallel processing algorithms.
- Non-asymptotic Error Analysis - as sample size grows to infinite, parameter becomes very big or very small.
- Adaptive Monte Carlo Algorithms - some simulations use their own random output to change their behavior, such as genetic algorithms.
- Improved Simulation of Spatial Processes - many spatial processes lack features such as independent increments and stationarity that makes simulation straight forward. Currently, it takes a very large sample size to produce independent results.
- Rare Events - do not always show up in a simulation run
- Quasi Monte Carlo - good for quasi-random number generators but there can be under/over sampling of the sample space.

5. Signalized Intersection Delay Models. (n.d.). Retrieved December 15, 2018, from https://nptel.ac.in/courses/105101008/downloads/cete_35.pdf

This paper defines the different types of delay - specifically uniform delay, random delay, and overflow delay. The paper gives the most widely used formulas for each of these types of delays, including the main one which was used in this project, Webster's Formula for uniform delay. Webster's Formula was used in this project to benchmark against the delays that the program outputted. Webster's Formula is:

$$UD = \frac{C}{2}\frac{(1-\frac{g}{C})^2}{(1-\frac{g}{C}X)}$$

6. MIT. (2017, May 19). Retrieved October 05, 2018, from ttps://www.youtube.com/watch?v=OgO1gpXSUzU

The Monte Carlo simulation was invented by Stanislaw Ulam, a Polish-American scientist, and was named after the Monte Carlo casino in Monaco. He was attempting to calculate the probability of winning at Solitaire. John von Neumann programmed the ENIAC computer to carry out the Monte Carlo simulation.

The simulation uses a random sample from a huge population. For example, using a Monte Carlo simulation to find out what the expected return of betting on roulette reveals that as the number of trials goes to infinite, the true probability goes to 0. As demonstrated, increasing the number of trials evens out the expected return, so the casino does not lose money.

The probability of an event does not change based on previous events if they are independent events. For example, if a coin is flipped 40 times and they are all heads, the chance that the next flip will be tails is still 50%. However, Francis Galton proposed the theory of Regression to the Mean in 1885, where he stated that after an extreme event happens, the next event will be less extreme. Referring to the roulette example again, if a roulette wheel is spun 10 times and it lands on 10 reds, it is likely that in the next 10 spins, there will be fewer than 10 reds, but the expected number is 5 (not 10 because of gambler's fallacy). Looking at the average of the first 20 spins, it will be closer to 50% red compared to the first 10 spins where the average was 100%, demonstrating how the probabilities even out.

A confidence interval is a range of values defined so that there is a specified probability that they value of the parameter is within it. A confidence interval is computed using empirical rules:

- 68% of data is within one standard deviation of the mean
- 95% of data is within 1.96 standard deviations of the mean (most commonly used)
- 99.7% of the data is within 3 standard deviations of the mean

When applied to roulette, the confidence interval decreases as the number of trials increases, showing how the data set usually evens out to 0. The empirical rule does not always work because of the assumptions that the high/low estimates are the same, and the error distribution is constant.

7. Modeling What We've Observed: Queuing Systems. (n.d.). Retrieved October 4, 2018, from https://www.webpages.uidaho.edu/TrafficSignalSystems/traffic/instructor/ch2a.pdf

This source provides graphs and diagram to better visualize and reinforce the relationships between arrival rate, departure rate, queue, and red and green lights. For example, one graph displays the concept that cars arrive at the intersection and the queue continuously increases while the light is red. When the light switches to green, the queue continuously decreases while the exit rate is equal to the saturation rate of 1900 vehicles per hour per lane. When the queue clears completely, the departure rate is equal to the arrival rate because vehicles can clear the signal without having to wait in

the queue. The PDF also establishes two models for finding the average delay, including Webster's Formula.

8. Morris, D. Z. (2015, August 20). Smart cars, meet smart signals. Retrieved September 26, 2018, from http://fortune.com/2015/08/20/smart-traffic-signals/

When implemented, actuated signals can significantly reduce average delay time for vehicles, as shown in Tyler, Texas, when average delay time was reduced by 22%. However, cities don't always invest in replacing the traffic lights because it can cost up to tens of millions of dollars to overhaul an entire city.

9. Shengda, Z., Lurong, W., Lin, J., & Bizhi, W. (2013, September 30). Study on Monte Carlo Simulation of Intelligent Traffic Lights Based on Fuzzy Control Theory. Retrieved September 26, 2018, from http://www.sensorsportal.com/HTML/DIGEST/september_2013/P_1349.pdf

10. Sotra, M. (2018, July 11). 7 Smart City Solutions to Reduce Traffic Congestion. Retrieved September 26, 2018, from https://www.geotab.com/blog/reduce-traffic-congestion/

11. The Simulation Environment: Learning to See a Traffic Signal System. (n.d.). Retrieved October 4, 2018, from https://www.webpages.uidaho.edu/TrafficSignalSystems/traffic/instructor/ch5a.pdf

This source classifies the various types of microsimulations and gives definitions for each. It categorizes the microsimulations into categories of computational or simulation, empirical or analytical, deterministic or stochastic, microscopic or macroscopic, event scan or time scan, and evaluation of optimization. The types that apply to this project include simulation, empirical, stochastic, macroscopic, time scan, and optimization. The source also tells what situations or which purposes that microsimulation models should be used for. Microsimulation models require a rich and detailed set of data but also give a complex set of data. There are 3 components of a microsimulation model, the inputs that describe the place/intersection of interest, the ways in which the users/vehicles interact with the system of facility, and the outputs that describe how the system is expected to perform.

12. The Traffic Signal Control System: Its Pieces and How They Fit Together. (n.d.). Retrieved October 4, 2018, from https://www.webpages.uidaho.edu/TrafficSignalSystems/traffic/instructor/ch1a.pdf

Actuated signals have detectors at the signals which detect incoming cars. When a car is detected, the passage time, or the required time that has to pass between cars for the signal to turn red, is reset. Actuated signals always have a predetermined minimum and maximum green time so cars have a chance to clear the intersection. When a signal does not detect a car and the passage time expires before the maximum green time, the light gaps out. This is most likely due to lack of cars or traffic. When a signal continuously detects cars and the passage time does not expire before the maximum green time is reached, the signal maxes out, due to a constant flow of many cars, likely during peak hour. The PDF display many graphs and visuals depicting the concept of passage time and detectors at actuated signals.

13. Timing Processes for the Intersection. (n.d.). Retrieved October 4, 2018, from https://www.webpages.uidaho.edu/TrafficSignalSystems/traffic/instructor/ch7a.pdf

This source examines the effect of cycle time on average delay. Using graphs to illustrate the difference in cycle times demonstrates that as the cycle time decreases, average delay decreases. However, there is a trade off - the stop time for each cycle times has to remain constant to allow cars to go through. Therefore, the effective green ratio, or the ratio of the length of green time compared to the total cycle time, is decreased when the cycle time is decreased, so less vehicles can clear the intersection. The solution to this problem is finding the best balance between cycle time and effective green ratio.

14. Timing Processes on One Approach. (n.d.). Retrieved October 4, 2018, from https://www.webpages.uidaho.edu/TrafficSignalSystems/traffic/instructor/ch6a.pdf

This PDF defines the saturation rate as 1900 cars per hour of green light time per lane. It uses this to calculate headway, the time/distance between vehicles. The document then establishes a relationship between flow rate and headway as the light goes through a traffic light cycle.

15. Traffic Signal Equipment. (n.d.). Retrieved September 26, 2018, from https://www.plano.gov/DocumentCenter/View/298/Traffic-Signal-Equipment?bidId=

According to the City of Plano, modern signal cost about $150,000 to implement. There are 3 parts to every signal:

- The Controller operates and selects the timings of the different phases.
- Signal indications control when the signal turns red, yellow, or green.
- Vehicle detectors detect vehicles and tell actuated signals whether to extend green time or not.

16. University of Idaho. (n.d.). Instructor Resources. Retrieved September 26, 2018, from https://www.webpages.uidaho.edu/TrafficSignalSystems/traffic/instructor/

17. Whose Turn is it? Phasing, Rings, and Barriers. (n.d.). Retrieved October 4, 2018, from https://www.webpages.uidaho.edu/TrafficSignalSystems/traffic/instructor/ch3a.pdf

This document establishes the different phases, first by using a phasing diagram, and then modeling an example conflict matrix to demonstrate which phases can be run simultaneously.