CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

In chapter four, after the DT3P has been simulated using the customized simulation tool (created using MATLAB) of which the functionality has been validated using a well-known simulator called “Sidra Intersections”, the results are shown in this chapter as an approval that the DT3P can practically perform better than the other existing traffic light controllers. It has been verified through the simulation results that the protocol has provided a more effectual method for controlling traffic lights at intersections. The purpose of this chapter is to test the effectiveness of adding a wider range of parameters when making traffic light phase decisions on its accuracy, efficiency, and stability.

4.1.1 Goals of the Research

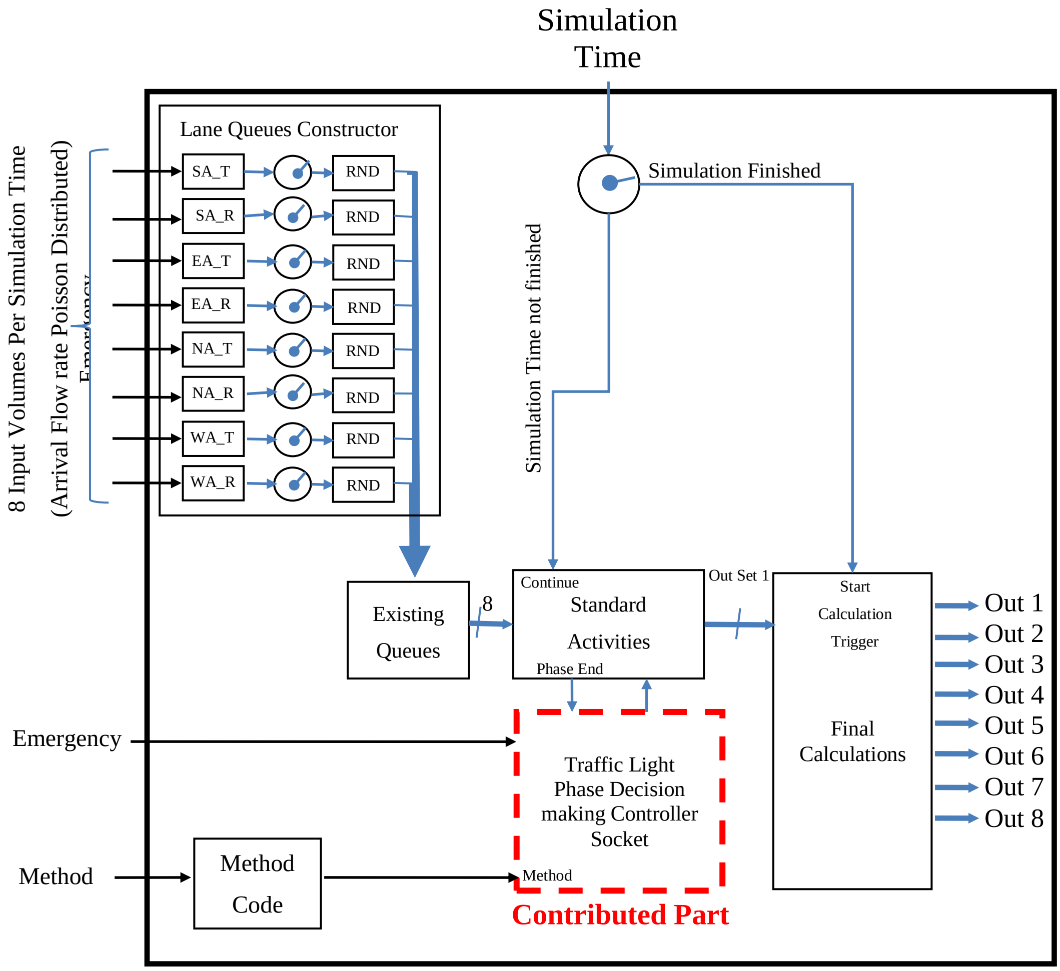
As stated in chapter 1, there are two main research aims: studying the currently exist traffic light control techniques and see how efficient they are in terms of stability and accuracy, then developing a new system to overcome their downsides, adopting the traffic light models from Sidra Intersections simulator and reproduce them with Matlab M files and finally use it to compare the newly developed system with the existing ones. Before this chapter, the proposed system algorithms, simulation tool creation, and evaluation procedures have been illustrated in detail after describing the messaging system used to collect the road status data.

4.1.2 Chapter Layout

In this chapter, the evaluation procedures, described in chapter 3, will be used to evaluate the system performance and compare it with other existing works. The next sections will explain a little more details about the simulator design and its validation then list down and discuss the results that came about from running a total of six case studies. Finally, the developed approach performance will be compared with the existing ones.

4.2 Simulation Tool Design

The experiments in this thesis have been performed using the authors' customized Traffic Light simulation tool created with MATLAB. Figure 4.1 shows the design of the simulation tool. The simulator receives a set of inputs that represents the case study setup at the beginning of the simulation process, then run the procedure repeatedly (according to the calculated number of replications) producing a set of outputs (Out Set 1) for each time it runs and a final set of outputs at the end of the simulation (Final Outputs). The queues will be built by the lanes queues constructor and dealt with through the standard traffic light activities (phase transition time, vehicles movement startup time, amber time, etc.). The main contribution added by this simulation tool is the ability to customize the traffic light controlling method and test it in addition to the five different controllers (pre-timed, fully-actuated, NM1, NM2, and DT3P) which were programmed for the purpose of comparing with.



Out Set 1:	Final Outputs:
8 lanes Maximum Queue Length	Out 1: Maximum Queue Length
8 lanes Average Queue Length	Out 2: Average Queue Length
8 lanes Maximum Waiting Time	Out 3: Maximum Waiting Time
8 lanes Average Waiting Time	Out 4: Average Waiting Time
8 lanes Total No. of Vehicles Arrived	Out 5: Total No. of Vehicles Arrived
8 lanes Total No. of Vehicles Passed	Out 6: Total No. of Vehicles Passed
8 lanes Total No. of Phase Changes	Out 7: Total No. of Phase Changes
8 lanes Total No. of times Vehicles stopped at Red traffic light	Out 8: Total No. of times Vehicles stopped at Red traffic light

Figure 4.1: Customized Simulation Tool Architecture

The Simulation tool has been made to run as a four leg intersection traffic light system, as shown in Figure 4.2. Considering the turn-left lane as slip lane, it would be ignored in the results, leaving eight lanes to deal with.

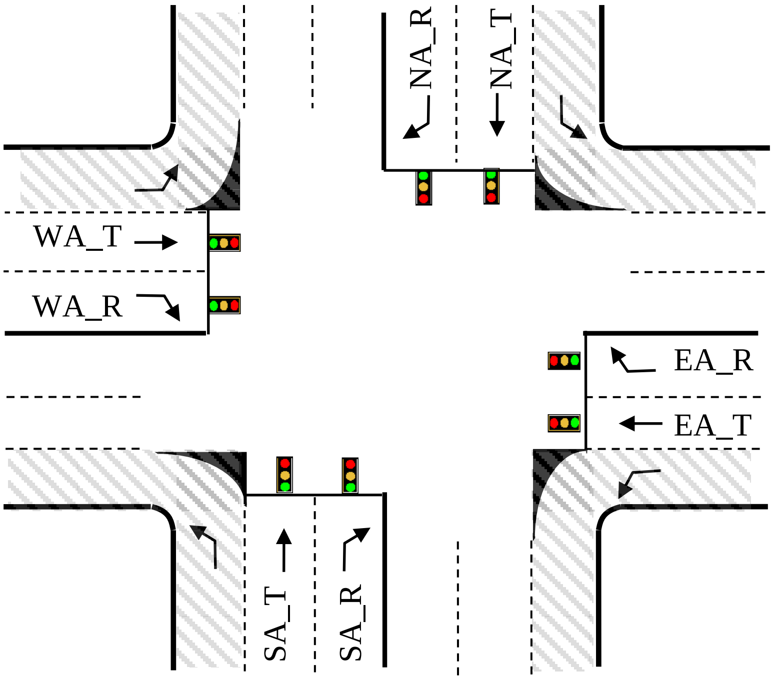


Figure 4.2: Standard Four Leg Intersection

Each of the four approaches had three lanes. It was assumed that each lane led to one direction only (No shared lanes). The lanes leading to the left side of the approach did not need a traffic light; it was called a slip lane so it was ignored within the traffic light controller. The middle lane was the through lane. Whilst, the right side lane leads to the right side only (No U-Turn).

The simulation tool's user is able to enter the simulation time (Sim_Time) and the Average input volume of the vehicles approaching each lane per the simulation time. In addition, the user had the ability to choose one traffic light controller amongst five choices. When the simulation started, the queue constructor of each lane received the average volume to arrive during the simulation time, according to which the vehicles arrival flow rate was decided. The queue constructor was actually a Poisson distributor.

Whilst the lane queues were being constructed, simultaneously, some standard traffic light activities were being implemented. The traffic light status at the intersection would be changed from being red, amber, or green, according to the Traffic Light Phase Decision Making Controller. According to the traffic light status changing, the lane queue lengths would be increased or decreased. Whilst the queue's status changed, it was being monitored to collect statistics about the maximum queue length of each lane and their maximum waiting time. Those were useful when the final calculation stage was executed.

A set of five controller methods had been programmed within the simulation tool to control the traffic light system at the intersection. The five controller methods were: the Fixed Preprogrammed controller (BM1), Fully Actuated Controller (BM2), Intelligent Fuzzy Controller (NM2), Fuzzy Controller (NM1), and Dynamic Traffic-Light Phase Plan Protocol (Present Work).

A whole experimental process flow has been illustrated in the Figure 4.3. Each case study setup was used five times (each time with one of the five methods) so that the performance of the methods could be compared with that specific case study. In addition, each time the simulation tool ran a case study it would keep repeating the same experiment (according to a calculated number of replications) till it reaches the level of confidence of 95%. The final results of the simulation tool represented as the results per the whole intersection. In addition, the simulation results per lane can be taken from the Simulation Matrix.

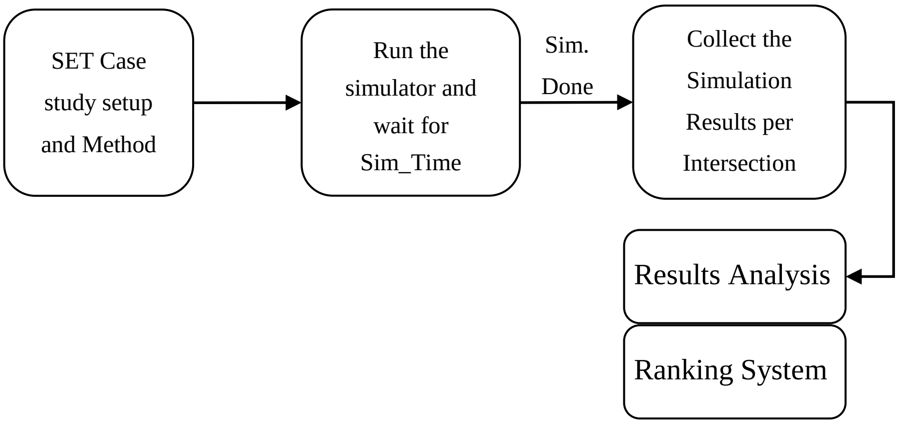


Figure 4.3: Experimental Process Flow

4.3 Customized Simulation Tool Validation

The Traffic Light Simulator Validation procedure described in section 3.3.3 was applied. Comparison results are shown in Table 4.1 and Figure 4.4. The Cycle time was exactly the same for both simulators. Whilst, the maximum queue lengths were almost the same with only tiny differences. Those differences appeared because in the customized simulation tool, some unnecessary geometrical factors (as the authors saw it) were ignored; whilst, they were considered by the Sidra Intersection simulator.

Table 4.1: Simulation Tool Validation Process Results

Case study	**Cycle Time (Sec)**		**Maximum Queue Length (Veh)**	
	Sidra Int. Sim.	**Customized Sim.**	**Sidra Int. Sim.**	**Customized Sim.**
VS-VS-VS-VS	132	132	16.6	13.6
S-S-S-S	132	132	28.2	18.7
M-M-M-M	132	132	207.1	217.3
L-L-L-L	132	132	395.7	367.62
VL-VL-VL-VL	132	132	483.8	495.29

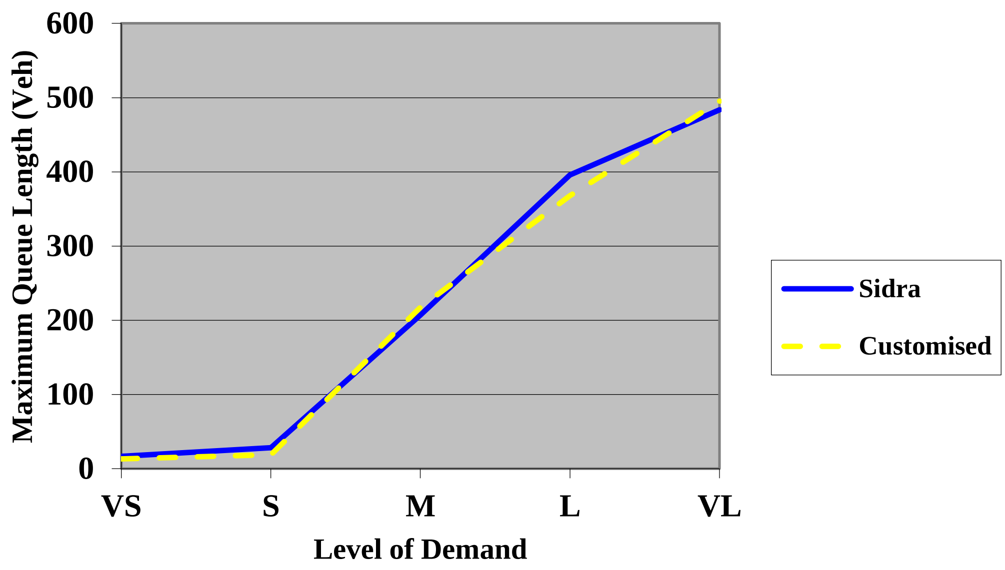


Figure 4.4: Customized Simulator Vs. Sidra Intersection Simulator Validation

4.4 Experiment Layout

As mentioned in Chapter 3, two patterns of experiments will be held; the first pattern consists of one single scenario and the second pattern consists of five other scenarios. In the first pattern experiment, four different levels of demand or arrival flow rates (Small, Medium, Large, and Very-Large) will be applied to the intersection's legs in one single experiment (Experiment-M). Then for the second pattern experiments, there are five individual experiments (Experiment-1 through Experiment-5). In the first two experiments, very-small and small vehicle arrival flow rates were applied, respectively, to all of the intersection's directions. It was expected that both the NM1 and NM2 methods would keep stable and perform fine compared to the benchmark methods, as the demand level was still within their detection range limits (25 – 30 vehicles per lane), but not as accurate as the DT3P in terms of calculating the amount of green time to be given.

In the third experiment, the medium arrival flow rate (750 vehicles per hour per direction) is applied where a slight instability might occur when using NM1 and NM2 methods. As the queues in this experiments starts to grow up more than 25 vehicles per queue which cannot be detected by roads data collecting systems proposed by NM1 and NM2.

In the fourth and fifth experiments, large and very-large vehicle arrival flow rates were applied, respectively, to all of the intersection's directions. It was expected to see a significant instability when using both the NM1 and NM2 methods as the demand levels on all of the intersection's legs were very high and out of their detection range.

The one hour experiments are planned to be repeated a number of times, according to the calculated number of replications of each scenario to ensure achieving the level of confidence of 95%. The calculated number of replications of each experiment is stated in that experiment's simulation parameters table.

4.5 Experiments and Results

Using the customized simulation tool, it was aimed to measure the accuracy of the developed decision making algorithm performance accuracy through Experiment-M by applying four different levels of demand to the intersection's legs whilst it was aimed to check other performance measures of the developed algorithm at five different levels of input. So in each of the last five experiments, the applied inputs on all of the intersection's legs were equal in order to check at which level each of the methods worked or failed. It was expected that DT3P would perform stable at all of the levels. In this section, the result data of all of the experiments have been shown as tables and figures. At the end of the section, the data will be compared and summarized.

4.5.1 Experiment-M - Four Legs Intersection with Four Different Arrival Rates

In this section, the first pattern experiment's setup will be shown. Then there will be a discussion of the results obtained after running the experiment on the customized traffic light simulation tool.

4.5.1.1 Experiment-M Setup

Table 4.2 shows the geometrical, initial, and case study parameters. In this experiment, each approach would receive a different level of demand compares to the other approaches as shown in Table 4.2. This experiment is required to be repeated for 297 times to achieve 95% level of confidence.

4.5.1.2 Experiment-M Results

Figure 4.5 represents the Output-to-Input response of the five traffic light controllers. The input to the controllers is the vehicles arrival rate or the level of demand rate (represented in black bar), while the output is the rate of the amount of green time given to each of the intersection lanes. As can be seen, DT3P's bars are very much following the level of demand rates. Both of NM1 and NM2 have responded to the arrival rates however were not accurate enough to beat DT3P which came with a total error up to 2.317% whilst NM1 and NM2 came with total errors of up to 31.484% and 28.095%. Both of BM1 and BM2 got the same error rate (50.847%) as they perform fixed timing.

From Table 4.3, it can be seen that both of NM1 and NM2 have lost their stability when they let at least one lane waiting for 3168.99 sec and 2930.75 sec respectively, which makes both unsuitable for such intersections. By looking to the performance measures of DT3P and the two benchmark methods, it can be seen that DT3P have succeeded to increase the intersection's throughput by approximately 15% compares to the benchmark methods. In addition, DT3P have reduced the maximum and the average queue length at the intersection by approximately up to 70% and 51% respectively. In term of average and maximum waiting time, DT3P have increased them which seems as a negative indicator however this is incompletely true. DT3P was programmed to expand the phase green time according to the queue lengths to decrease the total number of phase transitions (Moving from one state to another). In other words, DT3P converting some of the "must to waste time" to "Extra green time" within an hour of time, this is the main reason of having extra waiting time at the lanes. As an indication of the system's accuracy, the ratio of the green time wastage was reduced by DT3P by approximately 15.5% than the benchmark methods.

Table 4.2: Experiment-M Simulation Parameters

Geometrical Parameters	
Parameter	**Value / Choice**
Intersection type	4 leg intersection
Number of Directions in each leg	3
Slip lanes (Lane's index)	0,3,6,9
Initial Parameters	
Parameter	**Value / Choice**
Emergency Level	1 (No Emergency)
On-Duty flag	0
Next road availability	100%
Back road urgency	0
Vehicle Arrival distribution	Random (Poisson Distribution)
Initial Queue lengths for all on directions (veh.)	0,0,0, 0,90,90, 0,60,60, 0,30,30
Initial Green lights (Direction's index)	1 and 2
Amber Time (Sec.)	3
All Red Time (Sec.)	0
Direction-0's Vehicle Arrival flow rate	Slip Lane
Direction-1's Vehicle Arrival flow rate	1300 Veh./Hour/Direction
Direction-2's Vehicle Arrival flow rate	1300 Veh./Hour/Direction
Direction-3's Vehicle Arrival flow rate	Slip Lane
Direction-4's Vehicle Arrival flow rate	1125 Veh./Hour/Direction
Direction-5's Vehicle Arrival flow rate	1125 Veh./Hour/Direction
Direction-6's Vehicle Arrival flow rate	Slip Lane
Direction-7's Vehicle Arrival flow rate	750 Veh./Hour/Direction
Direction-8's Vehicle Arrival flow rate	750 Veh./Hour/Direction
Direction-9's Vehicle Arrival flow rate	Slip Lane
Direction-10's Vehicle Arrival flow rate	375 Veh./Hour/Direction
Direction-11's Vehicle Arrival flow rate	375 Veh./Hour/Direction
Level of Confidence aimed for	95%
Number of replications (Runs)	297

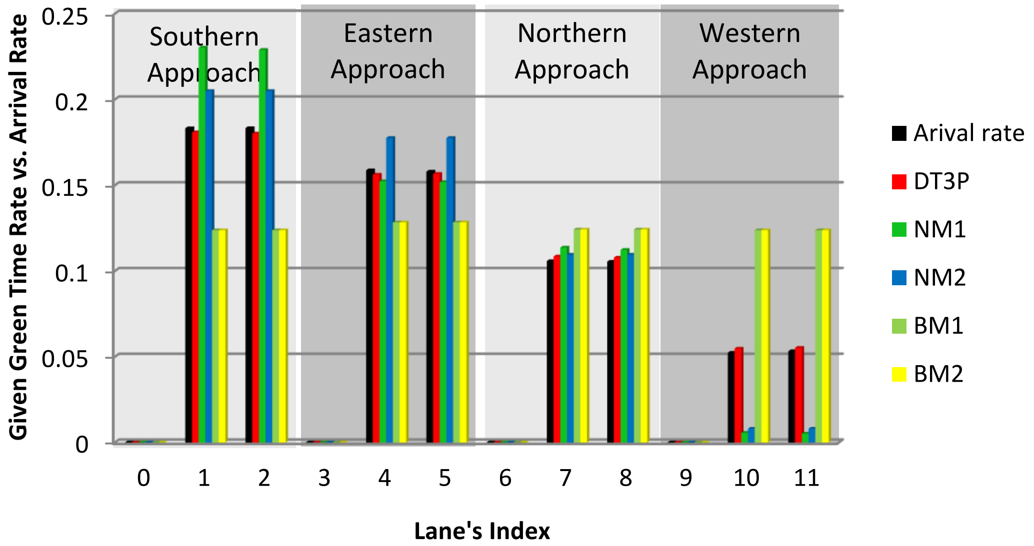


Figure 4.5: Experiment-M Output-to-Input Response

Table 4.3: Experiment-M Simulation Evaluation Measures

Parameters	BM1	BM2	NM1	NM2	DT3P
Passed/Arrival %	73.33195	73.48763	77.67128	87.09769	88.41551
Max. Q. L. (Veh)	547.35	544.22	346.12	330.3	152.18
Avg. Q. L. (Veh)	133.6936	132.1652	102.5935	80.9984	65.09566
Max. W.T. (Sec)	99	99	**3168.99**	**2930.75**	233.61
Avg. W.T. (Sec)	94.8457	94.86811	91.43073	217.1497	123.5001
Green Time Utilization Ratio	86.54137	86.4724	99.07581	93.09595	99.78928
Stability (1:Stable, 0:Not)	1	1	**0**	**0**	1

4.5.2 Experiment 1 - Four Legs Intersection with Very Small Volumes

In this section, the first experimental setup will be shown then there will be a discussion of the results obtained after running the experiment on the customized traffic light simulation tool.

4.5.2.1 Experiment-1 Setup

Table 4.4 shows the Geometrical, Initial, and case study parameters. In this experiment, all of the eight directions received around 250 vehicles during the one hour of simulation. This experiment is required to be repeated for 152 times to achieve 95% level of confidence.

4.5.2.2 Experiment-1 Results

The first result to be discussed is the relationship between the traffic light's given green-time, the number of vehicles that left the lane during the green time and the number of vehicles that arrived at each lane. The desired behavior of the system is to give enough green time to each lane according to its need. In other words, the shape of the two output variable curves must follow the input curve shape to achieve the best performances. Ideally, the shape of the three curves must be identical. In addition, the nearer the Number of Passed Vehicles' curve goes towards the Number of Arrived Vehicles' curve, the better the achieved performance.

Table 4.5 shows some results that were recorded when applying the case study that was set above to a Fixed Mode Traffic light controller. As can be seen, the given green time was independent and did not follow the input (Arrived Vehicles) because the amount of given green time for each phase was preset and did not change according to the input. Each time a green phase hit any two lanes the vehicles queuing at those lanes started moving out of the queue (being served). That was why the average number of passed vehicles was always converging towards the input value. In this case, 98.52% of the vehicles that had arrived at the intersection were released and the average number of vehicles leaving the traffic light (Output) did not depend on the average number of vehicles arriving at the road (input). That was because of the given green time's independency.

Table 4.4: First Experiment Simulation Parameters

Geometrical Parameters	
Parameter	**Value / Choice**
Intersection type	4 leg intersection
Number of Directions in each leg	3
Slip lanes (Lane's index)	0,3,6,9
Initial Parameters	
Parameter	**Value / Choice**
Emergency Level	1 (No Emergency)
On-Duty flag	0
Next road availability	100%
Back road urgency	0
Vehicle Arrival distribution	Random (Poisson Distribution)
Initial Queue lengths for all on directions (veh.)	0,0,0, 0,90,90, 0,60,60, 0,30,30
Initial Green lights (Direction's index)	1 and 2
Amber Time (Sec.)	3
All Red Time (Sec.)	0
Direction-0's Vehicle Arrival flow rate	Slip Lane
Direction-1's Vehicle Arrival flow rate	250 Veh./Hour/Direction
Direction-2's Vehicle Arrival flow rate	250 Veh./Hour/Direction
Direction-3's Vehicle Arrival flow rate	Slip Lane
Direction-4's Vehicle Arrival flow rate	250 Veh./Hour/Direction
Direction-5's Vehicle Arrival flow rate	250 Veh./Hour/Direction
Direction-6's Vehicle Arrival flow rate	Slip Lane
Direction-7's Vehicle Arrival flow rate	250 Veh./Hour/Direction
Direction-8's Vehicle Arrival flow rate	250 Veh./Hour/Direction
Direction-9's Vehicle Arrival flow rate	Slip Lane
Direction-10's Vehicle Arrival flow rate	250 Veh./Hour/Direction
Direction-11's Vehicle Arrival flow rate	250 Veh./Hour/Direction
Level of Confidence aimed for	95%
Number of replications (Runs)	152

Table 4.5: Vehicles Departure-to-Arrival Relationship and the Given Green Time When Applying Very-Small Volume to BM1 Controller

Parameters	Southern Road			Eastern Road			Northern Road			Western Road	
	Lane 1	Lane 2		Lane 4	Lane 5		Lane 7	Lane 8		Lane 10	Lane 11
Avg. No. of Arrived vehicles	251.62	248.75		252.55	248.45		251.07	248.84		251.24	249.21
Avg. No. of Passed Vehicles	251.39	248.5		245.13	241.16		246.13	244.08		248.78	246.85
Given Green Time (Sec)	840	840		813	813		810	810		810	810

Table 4.6 shows the results from applying the same case study that was set above to the BM2 controller. Again, the output did not follow the input because of the given green time curve independency. The percentage of the vehicles released from the queues was 98.52% which was not affected even after adding the actuation belt.

Table 4.6: Vehicles Departure-to-Arrival Relationship and the Given Green Time When Applying Very-Small Volume to BM2 Controller

Parameters	Southern Road			Eastern Road			Northern Road			Western Road	
	Lane 1	Lane 2		Lane 4	Lane 5		Lane 7	Lane 8		Lane 10	Lane 11
Avg. No. of Arrived vehicles	252.22	250.6		250.33	248.71		250.12	251.07		249.48	249.73
Avg. No. of Passed Vehicles	252.01	250.44		243.12	241.59		245.27	245.82		246.86	247.45
Given Green Time (Sec)	840	840		813	813		810	810		810	810

After applying the above case study to the system of NM1, it was found that the given green time had been utilized in a better way which let the total number of vehicles that passed the traffic light reaches nearer towards the total number of vehicles queuing. In addition, the intersection hourly capacity increased to 98.54%. See Table 4.7.

Table 4.7: Vehicles Departure-to-Arrival Relationship and the Given Green Time When Applying Very-Small Volume to NM1 Controller

Parameters	Southern Road			Eastern Road			Northern Road			Western Road	
	Lane 1	Lane 2		Lane 4	Lane 5		Lane 7	Lane 8		Lane 10	Lane 11
Avg. No. of Arrived vehicles	248.42	250.05		249.23	250.36		252.64	249.55		250.03	250.22
Avg. No. of Passed Vehicles	245.37	247.38		245.24	246.08		248.64	245.35		246.9	246.32
Given Green Time (Sec)	860.84	860.84		844.79	844.79		839.77	839.77		829.6	829.6

The same case study was applied again but to a different controller, NM2. As can be seen in Table 4.8, the controller distributed the green time in a way that let the number of passed vehicles (Output) follow the amount of vehicles arriving at the queue of each direction; although, the given green time was not utilized to let the intersection's hourly capacity exceed the 98.54% of the total hourly queues.

Table 4.8: Vehicles Departure-to-Arrival Relationship and the Given Green Time When Applying Very-Small Volume to NM2 Controller

Parameters	Southern Road			Eastern Road			Northern Road			Western Road	
	Lane 1	Lane 2		Lane 4	Lane 5		Lane 7	Lane 8		Lane 10	Lane 11
Avg. No. of Arrived vehicles	248.42	250.05		249.23	250.36		252.64	249.55		250.03	250.22
Avg. No. of Passed Vehicles	245.37	247.38		245.24	246.08		248.64	245.35		246.9	246.32
Given Green Time (Sec)	860.84	860.84		844.79	844.79		839.77	839.77		829.6	829.6

Finally, the same experiment was repeated whilst using the proposed DT3P controller and the results are shown in Table 4.9. The relation between the input and the given green time was not very clear in this experiment and that was because of the very small arrival rate that could not build long queues; those needed a long green time. Nevertheless, DT3P had managed to make the average number of Passed vehicles (output) follow the input, just like NM1 and NM2 but the total passed/arrived vehicle ratio reached an increase of 99.58%. This increment happened because of the DT3P's decision accuracy for the traffic light phase plan.

Table 4.9: Vehicles Departure-to-Arrival Relationship and the Given Green Time When Applying Very-Small Volume to DT3P Controller

Parameters	Southern Road			Eastern Road			Northern Road			Western Road	
	Lane 1	Lane 2		Lane 4	Lane 5		Lane 7	Lane 8		Lane 10	Lane 11
Avg. No. of Arrived vehicles	252.59	249.48		249.37	248.99		250.98	251.12		250.69	248.51
Avg. No. of Passed Vehicles	251.65	248.48		248.52	248.03		249.74	250.05		249.55	247.3
Given Green Time (Sec)	662.29	661.12		656.53	654.45		594.39	593.22		589.31	587.23

Table 4.10: The Five Methods' Achievements in Terms of Avg.Q.L., Avg.W.T., Max.Q.L., and Max.W.T When Very-Small Volume Applied.

Parameters	BM1	BM2	NM1	NM2	DT3P
Avg. Q.L. (Veh)	6.76	6.76	2.08	9.71	2.12
Avg. W.T. (Sec)	85.37	85.33	18.62	128.54	17.86
Max. W.T. (Sec)	99.26	99.37	99.72	189.99	73.64
Max. Q.L. (Veh)	13.33	13.26	7.38	16.91	6.50

The five methods' achievements in terms of the average queue length (Avg.Q.L.), average waiting time (Avg.W.T.), maximum waiting time (Max.W.T.) and maximum queue length (Max.Q.L.) are shown in Table 4.10. Making the right decisions would lead to utilizing more green time. That was why DT3P topped the green time utilization performance hierarchy. The second top method was NM1, whilst NM2 came at the bottom of the hierarchy. See Table 4.11.

Table 4.11: Given Green Time Utilization When Applying a Very-Small Level of Demand on an Intersection

Ctrlr	Southern Road			Eastern Road			Northern Road			Western Road	
	Lane 1	Lane 2		Lane 4	Lane 5		Lane 7	Lane 8		Lane 10	Lane 11
BM1	0.382786	0.380274		0.391993	0.386531		0.39137	0.388778		0.394148	0.393333
BM2	0.383952	0.38025		0.390025	0.387983		0.390037	0.389543		0.393074	0.394185
NM1	0.735648	0.733328		0.797486	0.798171		0.865491	0.864973		0.872532	0.875156
NM2	0.325752	0.325694		0.332307	0.334841		0.337188	0.334103		0.339513	0.340598
DT3P	0.821815	0.81368		0.822902	0.823149		0.922509	0.924092		0.924318	0.923199

After running the five methods whilst applying a very small arrival flow rate to each lane, it was shown that all of the five methods were stable and both the DT3P and NM1 utilized the given green time better than the two bench mark methods. DT3P have enhanced the green time utilization to 224.4% compares to the benchmark methods while NM1 have enhanced it to 210.4%.

4.5.3 Experiment 2 - Four legs intersection with Small Volumes

In this section, the setup of the second experiment will be shown. Then there will be a discussion of the results obtained after running the experiment on the customized traffic light simulator.

4.5.3.1 Experiment-2 Setup

Table 4.12 shows the Geometrical, Initial, and case study parameters. In this experiment, all of the eight directions received around 375 vehicles during the one hour of simulation. The number of replications required for this experiment is 190 Times to achieve 95% level of confidence.

4.5.3.2 Experiment-2 Results

The first result to be discussed is the relationship amongst the traffic light's given green-time, the number of vehicles that left the lane during the green time and the number of vehicles that arrived at each lane. The desired behavior of the system is to give enough green time to each lane according to its need. In other words, the value of the two output variables should converge towards the input value (number of vehicles that have arrived) to achieve the best performances. Ideally, the two values are identical.

Table 4.13 shows some results that were logged after applying the case study that was set above to the BM1 controller. As can be seen, the amount of given green time for each phase was preset and did not change according to the input. Each time a green phase hit any two lanes the vehicles queuing at those lanes started moving out of the queue (being served). In this case, 98.52% of the vehicles that had arrived at the intersection were released.

Table 4.12: Second Experiment Simulation Parameters

Geometrical Parameters	
Parameter	**Value / Choice**
Intersection type	4 leg intersection
Number of Directions in each leg	3
Slip lanes (Lane's index)	0,3,6,9
Initial Parameters	
Parameter	**Value / Choice**
Emergency Level	1 (No Emergency)
On-Duty flag	0
Next road availability	100%
Back road urgency	0
Vehicle Arrival distribution	Random (Poisson Distribution)
Initial Queue lengths for all on directions (veh.)	0,0,0, 0,90,90, 0,60,60, 0,30,30
Initial Green lights (Direction's index)	1 and 2
Amber Time (Sec.)	3
All Red Time (Sec.)	0
Direction-0's Vehicle Arrival flow rate	Slip Lane
Direction-1's Vehicle Arrival flow rate	375 Veh./Hour/Direction
Direction-2's Vehicle Arrival flow rate	375 Veh./Hour/Direction
Direction-3's Vehicle Arrival flow rate	Slip Lane
Direction-4's Vehicle Arrival flow rate	375 Veh./Hour/Direction
Direction-5's Vehicle Arrival flow rate	375 Veh./Hour/Direction
Direction-6's Vehicle Arrival flow rate	Slip Lane
Direction-7's Vehicle Arrival flow rate	375 Veh./Hour/Direction
Direction-8's Vehicle Arrival flow rate	375 Veh./Hour/Direction
Direction-9's Vehicle Arrival flow rate	Slip Lane
Direction-10's Vehicle Arrival flow rate	375 Veh./Hour/Direction
Direction-11's Vehicle Arrival flow rate	375 Veh./Hour/Direction
Level of Confidence aimed for	95%
Number of replications (Runs)	190

Table 4.13: Vehicles Departure-to-Arrival Relationship and the Given Green Time When Applying Small Volume to BM1 Controller

Parameters	Southern Road			Eastern Road			Northern Road			Western Road	
	Lane 1	Lane 2		Lane 4	Lane 5		Lane 7	Lane 8		Lane 10	Lane 11
Avg. No. of Arrived vehicles	375.02	374.23		374.83	374.11		377.57	375.43		373.29	373.73
Avg. No. of Passed Vehicles	374.78	373.95		363.62	363.73		370.13	368.14		369.26	370.11
Given Green Time (Sec)	840	840		813	813		810	810		810	810

Table 4.14 shows the results from applying the same case study that was set above to the BM2 controller. Again, the output values did not follow the inputs because of the given green time's independency. Whilst the percentage of the vehicles released from the arrival queues was 98.5%.

Table 4.14: Vehicles Departure-to-Arrival Relationship and the Given Green Time When Applying Small Volume to BM2 Controller

Parameters	Southern Road			Eastern Road			Northern Road			Western Road	
	Lane 1	Lane 2		Lane 4	Lane 5		Lane 7	Lane 8		Lane 10	Lane 11
Avg. No. of Arrived vehicles	374.66	373.82		374.84	372.82		374.58	375.03		376.32	373.96
Avg. No. of Passed Vehicles	374.27	373.54		363.72	361.91		367.23	367.46		372.36	370.41
Given Green Time (Sec)	840	840		813	813		810	810		810	810

After applying the above case study to the system of NM1, it was found that the given green time had been utilized in a better way; it let the number of passed vehicles follow the arrival rate, as shown in Table 4.15. That led to an increase in the intersection hourly capacity to peak at 99.36% for the arrival queues.

Table 4.15: Vehicles Departure-to-Arrival Relationship and the Given Green Time When Applying Small Volume to NM1 Controller

Parameters	Southern Road			Eastern Road			Northern Road			Western Road	
	Lane 1	Lane 2		Lane 4	Lane 5		Lane 7	Lane 8		Lane 10	Lane 11
Avg. No. of Arrived vehicles	371.83	375.85		375.93	374.45		374.86	376.26		378.05	371.77
Avg. No. of Passed Vehicles	369.58	373.3		373.92	372.12		372.63	373.57		375.43	369.22
Given Green Time (Sec)	741.19	743.32		711.66	706.88		683.56	685.69		680.11	675.33

The same case study was applied again but to a different controller that was illustrated in NM2. As can be seen in Table 4.16, the controller distributed the green time in a way that let the number of passed vehicles follow the arrival rate but the given green time was not utilized accurately enough to let the intersection hourly capacity exceed the 98.28% for the total arrival queues.

Table 4.16: Vehicles Departure-to-Arrival Relationship and the Given Green Time When Applying Small Volume to NM2 Controller

Parameters	Southern Road			Eastern Road			Northern Road			Western Road	
	Lane 1	Lane 2		Lane 4	Lane 5		Lane 7	Lane 8		Lane 10	Lane 11
Avg. No. of Arrived vehicles	377.1	373.74		376.01	374.98		371.86	375.09		377.67	374.95
Avg. No. of Passed Vehicles	370.95	367.54		369.86	368.96		365.67	368.38		370.13	368.29
Given Green Time (Sec)	858.39	858.39		848.13	848.13		834.87	834.87		833.61	833.61

Finally, the same experiment was repeated but controlled by the proposed DT3P controller and the results are shown in Table 4.17. The relation between the input and the given green time was not very clear in this experiment and that was because of the very small arrival rate that could not build long queues as those needed a long green time. Nevertheless, DT3P managed to make the number of passed vehicles follow the vehicle arrival rate just like NM1 and NM2. Nevertheless, the total passed/arrived vehicle ratio reached 99.42%, which was the highest amongst all of the other methods. The five methods' achievements in terms of the average queue length (Avg.Q.L.), average waiting time (Avg.W.T.), maximum waiting time (Max.W.T.) and maximum queue length (Max.Q.L.) are shown in Table 4.18.

Table 4.17: Vehicles Departure-to-Arrival Relationship and the Given Green Time When Applying Small Volume to DT3P Controller

Parameters	Southern Road			Eastern Road			Northern Road			Western Road	
	Lane 1	Lane 2		Lane 4	Lane 5		Lane 7	Lane 8		Lane 10	Lane 11
Avg. No. of Arrived vehicles	374.83	374.62		379.21	374.78		379.68	374.71		380.17	373.17
Avg. No. of Passed Vehicles	372.5	372.16		376.82	372.96		377.58	372.58		378.02	371.11
Given Green Time (Sec)	669.59	667.36		670.34	663.25		658.28	656.05		661.21	654.12

Table 4.18: The Five Methods' Achievements in Terms of Avg.Q.L., Avg.W.T., Max.Q.L., and Max.W.T when Small Volume Applied.

Parameters	BM1	BM2	NM1	NM2	DT3P
Avg. Q.L. (Veh)	10.11	10.14	4.39	14.57	3.87
Avg. W.T. (Sec)	89.94	89.99	33.68	133.38	27.14
Max. W.T. (Sec)	99.51	99.52	105.35	183.38	75.24
Max. Q.L. (Veh)	18.23	18.25	11.20	23.16	9.90

Making the right decisions will lead to the utilization of more green time. That was why DT3P topped the green time utilization performance hierarchy with 93.86% utilization. The second top method was NM1 with the 82.57% utilization, whilst NM2 came at the bottom of the hierarchy by achieving only 46.93% of the given green time utilization. See Table 4.19.

Table 4.19: Given Green Time Utilization When Applying a Small Level of Demand on an Intersection

Ctrlr.	Southern Road		Eastern Road		Northern Road		Western Road	
	Lane 1	Lane 2	Lane 4	Lane 5	Lane 7	Lane 8	Lane 10	Lane 11
BM1	0.5226786	0.5218214	0.5294096	0.530492	0.5363951	0.534284	0.5355062	0.5352716
BM2	0.5216071	0.5200119	0.5316974	0.5282042	0.5338519	0.5341852	0.5411605	0.5397407
NM1	0.7927252	0.7942205	0.8228649	0.8254018	0.8458511	0.8431507	0.8422608	0.8394563
NM2	0.4620394	0.4579503	0.4683362	0.4664379	0.472912	0.4737744	0.4777054	0.476038
DT3P	0.925656	0.9257372	0.9322732	0.9343234	0.9493681	0.94694	0.9482161	0.946814

After running the five methods whilst applying a small arrival flow rate to each direction, it has been shown that all of the 5 methods were stable at this level and both the DT3P and NM1 utilized the given green time more efficiently than the two bench mark methods. DT3P have enhanced the green time utilization to 177% compares to the benchmark methods while NM1 have enhanced it to 155.6%.

4.5.4 Experiment-3 Four legs intersection with Medium Volumes

In this section, the setup of the third experiment will be shown. Then there will be a discussion of the results obtained after running the experiment on the customized traffic light simulator.

4.5.4.1 Experiment-3 Setup

Table 4.20 shows the Geometrical, Initial, and case study parameters. In this experiment all of the eight directions received around 750 vehicles during the one hour of simulation. The number of replications required for this experiment is 254 Times to achieve 95% level of confidence.

4.5.4.2 Experiment-3 Results

The first result to be discussed is the relationship between the traffic light's given green-time, the number of vehicles that left the lane during the green time and the number of vehicles that arrived at each lane. The desired behavior of the system is to give enough green time to each lane according to its need. In other words, the two output variables must follow the input, in terms of increasing or decreasing, to achieve the best performances. Ideally, the number of vehicles that leaves a direction is identical to the number of vehicles that arrive at the queue. This means that the nearer the number of passed vehicles goes towards the number of vehicles that have arrived, the better the performance that is obtained.

Table 4.21 shows some results that were recorded when applying the case study that was set above to the BM1 controller. As can be seen, the given green time values were independent and did not follow the inputs because the time amounts were preset. Each time a green phase hit any two lanes the vehicles queuing at those lanes started moving out of the queue (being served). In this case, 70.16% of the vehicles that had arrived to the intersection were released.

Table 4.20: Third Experiment Simulation Parameters

Geometrical Parameters	
Parameter	**Value / Choice**
Intersection type	4 leg intersection
Number of Directions in each leg	3
Slip lanes (Lane's index)	0,3,6,9
Initial Parameters	
Parameter	**Value / Choice**
Emergency Level	1 (No Emergency)
On-Duty flag	0
Next road availability	100%
Back road urgency	0
Vehicle Arrival distribution	Random (Poisson Distribution)
Initial Queue lengths for all on directions (veh.)	0,0,0, 0,90,90, 0,60,60, 0,30,30
Initial Green lights (Direction's index)	1 and 2
Amber Time (Sec.)	3
All Red Time (Sec.)	0
Direction-0's Vehicle Arrival flow rate	Slip Lane
Direction-1's Vehicle Arrival flow rate	750 Veh./Hour/Direction
Direction-2's Vehicle Arrival flow rate	750 Veh./Hour/Direction
Direction-3's Vehicle Arrival flow rate	Slip Lane
Direction-4's Vehicle Arrival flow rate	750 Veh./Hour/Direction
Direction-5's Vehicle Arrival flow rate	750 Veh./Hour/Direction
Direction-6's Vehicle Arrival flow rate	Slip Lane
Direction-7's Vehicle Arrival flow rate	750 Veh./Hour/Direction
Direction-8's Vehicle Arrival flow rate	750 Veh./Hour/Direction
Direction-9's Vehicle Arrival flow rate	Slip Lane
Direction-10's Vehicle Arrival flow rate	750 Veh./Hour/Direction
Direction-11's Vehicle Arrival flow rate	750 Veh./Hour/Direction
Level of Confidence aimed for	95%
Number of replications (Runs)	254

Table 4.21: Vehicles Departure-to-Arrival Relationship and the Given Green Time When Applying Medium Volume to BM1 Controller

Parameters	Southern Road			Eastern Road			Northern Road			Western Road	
	Lane 1	**Lane 2**		**Lane 4**	**Lane 5**		**Lane 7**	**Lane 8**		**Lane 10**	**Lane 11**
Avg. No. of Arrived vehicles	748.33	751.64		749.32	751.29		747.95	749.74		752.77	748.71
Avg. No. of Passed Vehicles	520.12	519.64		533.71	533.32		538.28	538.54		512.91	512.87
Given Green Time (Sec)	840	840		813	813		810	810		810	810

Table 4.22 shows the results from applying the same case study that was set above to an Actuated Mode Traffic light controller. Again, the output values did not follow the input's because of the given green time presetting. Whilst the percentage of the vehicles that were released from the arrival queues was 70.18%.

Table 4.22: Vehicles Departure-to-Arrival Relationship and the Given Green Time When Applying Medium Volume to BM2 Controller

Parameters	Southern Road			Eastern Road			Northern Road			Western Road	
	Lane 1	**Lane 2**		**Lane 4**	**Lane 5**		**Lane 7**	**Lane 8**		**Lane 10**	**Lane 11**
Avg. No. of Arrived vehicles	749.93	751.54		753.37	744.05		751.24	747.94		749.94	748.59
Avg. No. of Passed Vehicles	519.86	519.75		533.29	533.13		538.02	538.36		512.87	512.91
Given Green Time (Sec)	840	840		813	813		810	810		810	810

After applying the above case study to the system of NM1, it was found that the given green time was utilized in a better way that let the number of passed vehicles converge nearer towards the number of vehicles that had arrived, as shown in Table 4.23. That led to the increase in the intersection's hourly capacity to peak at 92.13% of the arrived queues.

Table 4.23: Vehicles Departure-to-Arrival Relationship and the Given Green Time When Applying Medium Volume to NM1 Controller

Parameters	Southern Road			Eastern Road			Northern Road			Western Road	
	Lane 1	Lane 2		Lane 4	Lane 5		Lane 7	Lane 8		Lane 10	Lane 11
Avg. No. of Arrived vehicles	755.55	752.92		751.9	751.29		747.67	752.9		744.95	746.06
Avg. No. of Passed Vehicles	732.26	730.3		723.68	724.47		718.79	720.41		590.12	590.52
Given Green Time (Sec)	844.94	845.01		810.35	810.67		808.7	808.77		660.15	660.47

The same case study was applied again but to a different controller that has been illustrated in NM2. As can be seen in Table 4.24, the controller had distributed the green time in a way that let the number of passed vehicles follow the arrival rate, in terms of increment and decrement, but the given green time was not utilized sufficiently enough to let the intersection hourly capacity exceed the 97.2% of the total arrived vehicles.

Table 4.24: Vehicles Departure-to-Arrival Relationship and the Given Green Time When Applying Medium Volume to NM2 Controller

Parameters	Southern Road			Eastern Road			Northern Road			Western Road	
	Lane 1	Lane 2		Lane 4	Lane 5		Lane 7	Lane 8		Lane 10	Lane 11
Avg. No. of Arrived vehicles	751.87	752.26		749.23	748.65		751.58	749.36		753.59	751.1
Avg. No. of Passed Vehicles	735.39	736.02		730.59	729.84		732.82	731.15		722.81	720.93
Given Green Time (Sec)	874.95	874.95		852.48	852.48		841.26	841.26		806.36	806.36

Finally, the same experiment was repeated but controlled by the proposed DT3P controller and the results are shown in Table 4.25. DT3P managed to make the number of passed vehicles follow the input arrival rate just like NM1 and NM2 with an increment of 0.06% in the total passed/arrived vehicle ratio that reached 97.26%.

Table 4.25: Vehicles Departure-to-Arrival Relationship and the Given Green Time When Applying Medium Volume to DT3P Controller

Parameters	Southern Road			Eastern Road			Northern Road			Western Road	
	Lane 1	Lane 2		Lane 4	Lane 5		Lane 7	Lane 8		Lane 10	Lane 11
Avg. No. of Arrived vehicles	749.4	748.96		747.67	756.64		750.06	748.64		747.74	752.49
Avg. No. of Passed Vehicles	728.14	729.57		728.32	736.36		728.21	727.8		725.79	732.79
Given Green Time (Sec)	803.22	804.41		801.5	807.6		799.89	801.08		798.07	804.17

Table 4.26: The Five Methods' Achievements in Terms of Avg.Q.L., Avg.W.T., Max.Q.L., and Max.W.T when Medium Volume Applied.

Parameters	BM1	BM2	NM1	NM2	DT3P
Avg. Q.L. (Veh)	121.21	120.90	39.18	30.49	15.74
Avg. W.T. (Sec)	98.81	98.80	68.73	139.89	82.43
Max. W.T. (Sec)	100.05	100.13	263.01	226.44	134.02
Max. Q.L. (Veh)	215.40	214.99	135.56	32.84	24.97

The five methods' achievements in terms of the average queue length (Avg.Q.L.), average waiting time (Avg.W.T.), maximum waiting time (Max.W.T.) and maximum queue length (Max.Q.L.) are shown in Table 5.26. Making the right decisions will lead to the utilization of more green time. That was why DT3P topped the green time utilization performance hierarchy. The second top method was NM1, whilst NM2 came at the bottom of the hierarchy.

Table 4.27: Given Green Time Utilization When Applying A Medium Level of Demand on an Intersection

Ctrlr	Southern Road			Eastern Road			Northern Road			Western Road	
	Lane 1	Lane 2		Lane 4	Lane 5		Lane 7	Lane 8		Lane 10	Lane 11
BM1	0.9737738	0.9729881		0.9891759	0.9882042		0.9978889	0.9978025		0.9998765	0.9998519
BM2	0.9736905	0.974381		0.988278	0.9880812		0.9973457	0.9978889		0.9998889	0.9998889
NM1	0.9644945	0.9636099		0.9980502	0.997977		0.995907	0.9971562		0.9978035	0.9976532
NM2	0.8846105	0.8871821		0.9061679	0.9058981		0.9190381	0.9171005		0.9445905	0.9414529
DT3P	0.99441	0.994294		0.9984903	0.9988608		0.9987623	0.9981775		0.9984463	0.9986819

After running the five methods whilst applying the medium arrival flow rate to each lane, it has been shown that both of the bench mark methods and DT3P were stable; whilst, a slight instability had been noticed with both the NM1 and NM2. The best utilization of the given green time was achieved by DT3P, as shown in Table 4.27.

4.5.5 Experiment-4 Four legs intersection with Large Volumes

In this section, the setup of the fourth experiment will be shown. Then there will be a discussion of the results obtained after running the experiment on the customized traffic light simulator.

4.5.5.1 Experiment-4 Setup

Table 4.28 shows the Geometrical, Initial, and case study parameters. In this experiment, all of the eight directions received around 1125 vehicles during the one hour of simulation. The number of replications required for this experiment is 287 Times to achieve 95% level of confidence.

Table 4.28: Fourth Experiment Simulation Parameters

Geometrical Parameters	
Parameter	**Value / Choice**
Intersection type	4 leg intersection
Number of Directions in each leg	3
Slip lanes (Lane's index)	0,3,6,9
Initial Parameters	
Parameter	**Value / Choice**
Emergency Level	1 (No Emergency)
On-Duty flag	0
Next road availability	100%
Back road urgency	0
Vehicle Arrival distribution	Random (Poisson Distribution)
Initial Queue lengths for all on directions (veh.)	0,0,0, 0,90,90, 0,60,60, 0,30,30
Initial Green lights (Direction's index)	1 and 2
Amber Time (Sec.)	3
All Red Time (Sec.)	0
Direction-0's Vehicle Arrival flow rate	Slip Lane
Direction-1's Vehicle Arrival flow rate	1125 Veh./Hour/Direction
Direction-2's Vehicle Arrival flow rate	1125 Veh./Hour/Direction
Direction-3's Vehicle Arrival flow rate	Slip Lane
Direction-4's Vehicle Arrival flow rate	1125 Veh./Hour/Direction
Direction-5's Vehicle Arrival flow rate	1125 Veh./Hour/Direction
Direction-6's Vehicle Arrival flow rate	Slip Lane
Direction-7's Vehicle Arrival flow rate	1125 Veh./Hour/Direction
Direction-8's Vehicle Arrival flow rate	1125 Veh./Hour/Direction
Direction-9's Vehicle Arrival flow rate	Slip Lane
Direction-10's Vehicle Arrival flow rate	1125Veh./Hour/Direction
Direction-11's Vehicle Arrival flow rate	1125 Veh./Hour/Direction
Level of Confidence aimed for	95%
Number of replications (Runs)	287

4.5.5.2 Experiment-4 Results

The first result to be discussed is the relationship between the traffic light's given green-time, the number of vehicles that left the lane during the green time and the number of vehicles that arrived at each lane. The desired behavior of the system is to give enough green time to each lane according to its need. In other words, the two output variable values must increase or decrease as the input goes to achieve a better performance. The nearer the number of passed vehicles goes towards the number of arrived vehicles, the better the performance that is obtained.

Table 4.29 shows some results that were recorded when applying the case study that was set above to a Fixed Mode Traffic Light Controller. In this type of traffic control, the given green time was preset and did not change according to the input. In this case, 67.32% of the vehicles that had arrived to the intersection were released and the output pattern did not follow the input pattern because of the given green time's independency.

Table 4.29: Vehicles Departure-to-Arrival Relationship and the Given Green Time When Applying Large Volume to BM1 Controller

Parameters	Southern Road			Eastern Road			Northern Road			Western Road	
	Lane 1	Lane 2		Lane 4	Lane 5		Lane 7	Lane 8		Lane 10	Lane 11
Avg. No. of Arrived vehicles	1123.42	1118.16		1125.44	1124.09		1121.17	1128.2		1124.79	1123.47
Avg. No. of Passed Vehicles	765.92	765.84		748.53	748.68		755.19	754.88		755.88	755.99
Given Green Time (Sec)	840	840		813	813		810	810		810	810

Table 4.30 shows the results from applying the same case study that was set above to an Actuated Mode Traffic Light Controller. Again, the output was independent of the input because of the given green time's independency. The percentage of the vehicles released from the arrival queues was 67.14%.

Table 4.30: Vehicles Departure-to-Arrival Relationship and the Given Green Time When Applying Large Volume to BM2 Controller

Parameters	Southern Road		Eastern Road		Northern Road		Western Road	
	Lane 1	**Lane 2**	**Lane 4**	**Lane 5**	**Lane 7**	**Lane 8**	**Lane 10**	**Lane 11**
Avg. No. of Arrived vehicles	1123.58	1132.81	1130.62	1128.39	1125.76	1124.1	1124.94	1122.31
Avg. No. of Passed Vehicles	765.97	766.38	748.09	749.05	754.61	754.75	756	756
Given Green Time (Sec)	840	840	813	813	810	810	810	810

After applying the above case study to the system of NM1, it was found that the given green time was utilized in a better way that let the number of passed vehicles follow the arrival queue, as shown in Table 4.31. That led to an increase in the intersection's hourly capacity to peak at 61.88% of the arrived queues.

Table 4.31: Vehicles Departure-to-Arrival Relationship and the Given Green Time When Applying Large Volume to NM1 Controller

Parameters	Southern Road		Eastern Road		Northern Road		Western Road	
	Lane 1	**Lane 2**	**Lane 4**	**Lane 5**	**Lane 7**	**Lane 8**	**Lane 10**	**Lane 11**
Avg. No. of Arrived vehicles	1128.7	1124.47	1120.49	1119.7	1121.39	1128.89	1121.85	1135.37
Avg. No. of Passed Vehicles	1099.94	1096.38	955.46	960.65	679.08	675.78	48.43	53.66
Given Green Time (Sec)	1245.95	1242.41	1064.82	1070.65	757.08	753.54	54.11	59.94

The same case study was applied again but to a different controller that was illustrated in NM2. As can be seen in Table 4.32, the controller distributed the green time according to the vehicles' arrival pattern but it was not utilized sufficiently to let the intersection's hourly capacity exceed 69.26% of the total arrival queues.

Table 4.32: Vehicles Departure-to-Arrival Relationship and the Given Green Time When Applying Large Volume to NM2 Controller

Parameters	Southern Road			Eastern Road			Northern Road			Western Road	
	Lane 1	Lane 2		Lane 4	Lane 5		Lane 7	Lane 8		Lane 10	Lane 11
Avg. No. of Arrived vehicles	1123.52	1126.05		1130.17	1124.36		1122.04	1122.85		1124.63	1128.24
Avg. No. of Passed Vehicles	1104	1104.98		1095.7	1090.69		886.72	886.47		33.02	32.86
Given Green Time (Sec)	1225.49	1225.49		1175.61	1175.61		936.54	936.54		41.34	41.34

Finally, the same experiment was repeated but controlled by the proposed DT3P controller and the results are shown in Table 4.33. DT3P managed to make the number of passed vehicles converge nearer towards the number of arrived vehicles just like NM1 and NM2 but with a higher total passed/arrived vehicle ratio of 68.76%.

Table 4.33: Vehicles Departure-to-Arrival Relationship and the Given Green Time When Applying Large Volume to DT3P Controller

Parameters	Southern Road			Eastern Road			Northern Road			Western Road	
	Lane 1	Lane 2		Lane 4	Lane 5		Lane 7	Lane 8		Lane 10	Lane 11
Avg. No. of Arrived vehicles	1123.69	1121.84		1124.89	1120.67		1124.97	1126.77		1124.53	1126.76
Avg. No. of Passed Vehicles	770.86	769.77		774.21	772.75		775.52	774.3		774.35	772.92
Given Green Time (Sec)	824.59	823.3		825.73	824.22		827.37	826.08		824.96	823.45

The five methods' achievements in terms of the average queue length (Avg.Q.L.), average waiting time (Avg.W.T.), maximum waiting time (Max.W.T.) and maximum queue length (Max.Q.L.) are shown in Table 4.34. When looking at the Maximum queue length and the Average queue length, it becomes obvious that both the NM1 and NM2 lost their stability when a large level of demand appeared. The high values mean that there was at least one direction that had been left behind and did not get enough green time which led to that long queue. The same goes for the waiting time.

Table 4.34: The Five Methods' Achievements in Terms of Avg.Q.L., Avg.W.T., Max.Q.L., and Max.W.T When Large Volume Applied.

Parameters	BM1	BM2	NM1	NM2	DT3P
Avg. Q.L. (Veh)	196.21	198.73	788.85	798.75	185.49
Avg. W.T. (Sec)	98.90	98.89	2386.54	2511.09	107.25
Max. W.T. (Sec)	100.45	100.34	3182.06	3348.13	144.98
Max. Q.L. (Veh)	347.50	355.60	1051.80	1065.38	331.36

Making the right decisions will lead to the utilization of more green time. That was why DT3P topped the green time utilization performance hierarchy. The second top method was NM1, whilst NM2 came at the bottom of the hierarchy. See Table 4.35.

Table 4.35: Given Green Time Utilization When Applying a Large Level of Demand on an Intersection

Ctrlr	Southern Road		Eastern Road		Northern Road		Western Road	
	Lane 1	Lane 2	Lane 4	Lane 5	Lane 7	Lane 8	Lane 10	Lane 11
BM1	0.9705595	0.9706429	0.9894588	0.9898155	0.9992469	0.9988272	0.9998889	1
BM2	0.9706905	0.9710833	0.9890529	0.990492	0.9984815	0.9984321	1	1
NM1	0.9803042	0.9801032	0.9999812	1	0.9998679	0.9998806	0.9992608	0.9998332
NM2	0.9367845	0.9373965	0.974022	0.9701176	0.9910628	0.991223	0.8115627	0.801403
DT3P	0.9960223	0.9965505	0.9999394	0.9997695	0.9998791	0.9997942	0.9999515	0.9999514

After running the five methods whilst applying a large arrival flow rate to each lane, it has been shown that both of the bench mark methods and the DT3P kept stable at the large demand level whilst both the NM1 and NM2 went unstable. DT3P kept maintaining its top place in the utilization of the given green time.

4.5.6 Experiment-5 Four legs intersection with Very-Large Volumes

In this section, the setup of the fifth experiment will be shown. Then there will be discussed the results got after running the experiment on the customized traffic light simulator.

4.5.6.1 Experiment-5 Setup

Table 4.36 shows the Geometrical, Initial, and case study parameters. In this experiment, all of the eight directions received around 1300 vehicles during the one hour of simulation. The number of replications required for this experiment is 297 Times to achieve 95% level of confidence.

4.5.6.2 Experiment-5 Results

The first result to be discussed is the relationship between the traffic light's given green-time, the number of vehicles that left the lane during the green time and the number of vehicles that arrived at each lane. The desired behavior of the system is to give enough green time to each lane according to its need. In other words, the two output variable values must follow the vehicle arrival pattern to achieve better performances.

Table 4.37 shows some results recorded when applying the case study that was set above to a Fixed Mode Traffic Light Controller. In this controlling method, the given green time was preset and did not follow the input’s pattern. Each time a green phase hit any two lanes the vehicles queuing at those lanes started moving out of the queue (being served). In this case, 58.34% of the vehicles that arrived at the intersection were released and the output did not follow the vehicle arrival pattern because of the given green time’s independency.

Table 4.36: Fifth Experiment Simulation Parameters

Geometrical Parameters	
Parameter	**Value / Choice**
Intersection type	4 leg intersection
Number of Directions in each leg	3
Slip lanes (Lane's index)	0,3,6,9
Initial Parameters	
Parameter	**Value / Choice**
Emergency Level	1 (No Emergency)
On-Duty flag	0
Next road availability	100%
Back road urgency	0
Vehicle Arrival distribution	Random (Poisson Distribution)
Initial Queue lengths for all on directions (veh.)	0,0,0, 0,90,90, 0,60,60, 0,30,30
Initial Green lights (Direction's index)	1 and 2
Amber Time (Sec.)	3
All Red Time (Sec.)	0
Direction-0's Vehicle Arrival flow rate	Slip Lane
Direction-1's Vehicle Arrival flow rate	1300 Veh./Hour/Direction
Direction-2's Vehicle Arrival flow rate	1300 Veh./Hour/Direction
Direction-3's Vehicle Arrival flow rate	Slip Lane
Direction-4's Vehicle Arrival flow rate	1300 Veh./Hour/Direction
Direction-5's Vehicle Arrival flow rate	1300 Veh./Hour/Direction
Direction-6's Vehicle Arrival flow rate	Slip Lane
Direction-7's Vehicle Arrival flow rate	1300 Veh./Hour/Direction
Direction-8's Vehicle Arrival flow rate	1300 Veh./Hour/Direction
Direction-9's Vehicle Arrival flow rate	Slip Lane
Direction-10's Vehicle Arrival flow rate	1300 Veh./Hour/Direction
Direction-11's Vehicle Arrival flow rate	1300 Veh./Hour/Direction
Level of Confidence aimed for	95%
Number of replications (Runs)	297

Table 4.37: Vehicles Departure-to-Arrival Relationship and the Given Green Time When Applying Very-Large Volume to BM1 Controller

Parameters	Southern Road			Eastern Road			Northern Road			Western Road	
	Lane 1	Lane 2		Lane 4	Lane 5		Lane 7	Lane 8		Lane 10	Lane 11
Avg. No. of Arrived vehicles	1298.66	1295.92		1294.7	1299.38		1301.1	1302.2		1299.4	1299.8
Avg. No. of Passed Vehicles	768.14	768		751.12	751.49		755.8	755.57		756	756
Given Green Time (Sec)	840	840		813	813		810	810		810	810

Table 4.38 shows the results from applying the same case study that was set above to an Actuated Mode Traffic Light Controller. Again, the output did not follow the input pattern because of the given green time’s independency. Whilst the percentage of the vehicles released from the arrival queues was 58.34%.

Table 4.38: Vehicles Departure-to-Arrival Relationship and the Given Green Time When Applying Very-Large Volume to BM2 Controller

Parameters	Southern Road			Eastern Road			Northern Road			Western Road	
	Lane 1	Lane 2		Lane 4	Lane 5		Lane 7	Lane 8		Lane 10	Lane 11
Avg. No. of Arrived vehicles	1294.49	1306.25		1297.48	1300.48		1299.25	1296.47		1300.9	1294.67
Avg. No. of Passed Vehicles	767.1	768.06		751.43	751.18		755.94	755.63		756	756
Given Green Time (Sec)	840	840		813	813		810	810		810	810

After applying the above case study to the system of NM1, it was found that the intersection’s hourly capacity was 53.59%. Nevertheless, it is obvious in Table 4.39 that NM1 did not give the green time to Lane 10 and Lane 11 for a long period, which was a sign of control loss.

Table 4.39: Vehicles Departure-to-Arrival Relationship and the Given Green Time When Applying Very-Large Volume to NM1 Controller

Parameters	Southern Road			Eastern Road			Northern Road			Western Road	
	Lane 1	**Lane 2**		**Lane 4**	**Lane 5**		**Lane 7**	**Lane 8**		**Lane 10**	**Lane 11**
Avg. No. of Arrived vehicles	1301.72	1304.47		1305.88	1299.23		1304.51	1304.84		1296.24	1303
Avg. No. of Passed Vehicles	1272.13	1275.28		804.35	804.51		682.76	686.6		29.05	29.06
Given Green Time (Sec)	1435.57	1439.57		894.69	894.84		760.77	764.77		32.38	32.53

The same case study was applied again but to a different controller that was illustrated in NM2. As can be seen in Table 4.40, the controller distributed the green time in a way that let the passed/arrived vehicle ratio became 60.5%. Nevertheless, just like NM1, NM2 lost control at this very high level of demand when it did not give the green light to Lane 10 and Lane 11 for a long period.

Table 4.40: Vehicles Departure-to-Arrival Relationship and the Given Green Time When Applying Very-Large Volume to NM2 Controller

Parameters	Southern Road			Eastern Road			Northern Road			Western Road	
	Lane 1	**Lane 2**		**Lane 4**	**Lane 5**		**Lane 7**	**Lane 8**		**Lane 10**	**Lane 11**
Avg. No. of Arrived vehicles	1301.51	1299.53		1299.14	1297.26		1306.94	1304.39		1293.23	1301.96
Avg. No. of Passed Vehicles	1279.03	1276.85		1251	1251.07		601.12	600.78		17.1	16.94
Given Green Time (Sec)	1400.2	1400.2		1327.48	1327.48		633.98	633.98		22.77	22.77

Finally, the same experiment was repeated but controlled by the proposed DT3P controller and the results are shown in Table 4.41. DT3Pmanaged to make the number of passed vehicles follow the pattern of the arrival rate just like NM1 and NM2 but DT3P kept stable at this level of demand. DT3P was able to release 59.32% of the total number of the arrived vehicles.

Table 4.41: Vehicles Departure-to-Arrival Relationship and the Given Green Time When Applying Very-Large Volume to DT3P Controller

Parameters	Southern Road			Eastern Road			Northern Road			Western Road	
	Lane 1	Lane 2		Lane 4	Lane 5		Lane 7	Lane 8		Lane 10	Lane 11
Avg. No. of Arrived vehicles	1307.49	1297.98		1296.92	1297.41		1297.48	1302.77		1300.23	1294.27
Avg. No. of Passed Vehicles	772.6	772.26		773.19	769.57		772.72	772.37		768.39	764.58
Given Green Time (Sec)	827	826.7		825.65	821.86		824.79	824.49		820.27	816.48

The five methods' achievements in terms of the average queue length (Avg.Q.L.), average waiting time (Avg.W.T.), maximum waiting time (Max.W.T.) and maximum queue length (Max.Q.L.) are shown in Table 4.42. As expected, the queues in NM1 and NM2 got very long as they lost their stability in controlling the intersection at this very large level of demand. The same went for the waiting time.

Table 4.42: The Five Methods' Achievements in Terms of Avg.Q.L., Avg.W.T., Max.Q.L., and Max.W.T When Very-Large Volume Applied.

Parameters	BM1	BM2	NM1	NM2	DT3P
Avg. Q.L. (Veh)	282.45	282.85	932.955	941.265	273.37
Avg. W.T. (Sec)	98.93	98.93	2598	2660.4	105.16
Max. W.T. (Sec)	100.56	100.93	3464.00	3547.20	138.36
Max. Q.L. (Veh)	518.68	525.51	1243.94	1255.02	511.31

Making the right decisions will lead to the utilization of more green time. That was why DT3P topped the green time utilization performance hierarchy. The second top method was NM1, whilst NM2 came at the bottom of the hierarchy. See Table 4.43.

Table 4.43: Given Green Time Utilization When Applying a Very Large Level of Demand on an Intersection

Ctrlr	Southern Road			Eastern Road			Northern Road			Western Road	
	Lane 1	Lane 2		Lane 4	Lane 5		Lane 7	Lane 8		Lane 10	Lane 11
BM1	0.973	0.9721786		0.9933333	0.9938745		0.9997284	0.9995926		1	1
BM2	0.9715	0.972881		0.9937761	0.9935301		0.9999506	0.9995926		1	1
NM1	0.983874	0.9834187		0.9999553	1		0.9999737	1		0.9996912	0.9972333
NM2	0.9367845	0.9373965		0.974022	0.9701176		0.9910628	0.991223		0.8115627	0.801403
DT3P	0.9960223	0.9965505		0.9999394	0.9997695		0.9998791	0.9997942		0.9999515	0.9999514

After running the five methods whilst applying a very large arrival flow rate to each lane, it has been shown that both of the bench mark methods and the DT3P kept stable at the very large demand level whilst both the NM1 and NM2 went unstable. DT3P kept maintaining its top place in the utilization of the total given green time for the whole intersection when it scored (7.992 / 8).

4.6 Experimental Results Analysis

After running the simulation for the Experiment-M and verifying that the system is developed controller is working as desired with a high accurate response (approximately 98%), The experiments of the second pattern were run to evaluate the developed controller performance according to the evaluation measures, including the stability, at all five levels of demand. All of the resulting data and the analytical results for the last five experiments have been summarized and compiled into five tables (Table 4.44 – 4.48) to make them ready to be evaluated by the order-based ranking system that was described in Chapter 3.

Table 4.44: Experimental and Analytical Results for Experiment-1 (Very-Small Arrival Flow Rate)

Parameters	BM1	BM2	NM1	NM2	DT3P
Departure-Arrival Percentage	98.52%	98.52%	98.54%	98.54%	99.58%
Avg. Q. L. (Veh)	6.76	6.76	2.08	9.71	2.12
Avg. W.T. (Sec)	85.37	85.33	18.62	128.54	17.86
Max. W.T. (Sec)	99.26	99.37	99.72	189.99	73.64
Max. Q. L. (Veh)	13.33	13.26	7.38	16.91	6.5
G. G. Time Utilization	0.3886516	0.38863115	0.8178481	0.3337493	0.87195
Stability (1:Yes, 0: No)	1	1	1	1	1

Table 4.45: Experimental and Analytical Results for Experiment-2 (Small Arrival Flow Rate)

Parameters	BM1	BM2	NM1	NM2	DT3P
Departure-Arrival Percentage	98.52%	98.49%	99.36%	98.28%	99.42%
Avg. Q. L. (Veh)	10.11	10.14	4.39	14.57	3.87
Avg. W.T. (Sec)	89.94	89.99	33.68	133.38	27.14
Max. W.T. (Sec)	99.51	99.52	105.35	183.38	75.24
Max. Q. L. (Veh)	18.23	18.25	11.2	23.16	9.9
G. G. Time Utilization	0.530732	0.5313073	0.8257414	0.4693992	0.938666
Stability (1:Yes, 0: No)	1	1	1	1	1

Table 4.46: Experimental and Analytical Results for Experiment-3 (Medium Arrival Flow Rate)

Parameters	BM1	BM2	NM1	NM2	DT3P
Departure-Arrival Percentage	70.16%	70.18%	92.13%	97.20%	97.26%
Avg. Q. L. (Veh)	121.21	120.9	39.18	30.49	15.74
Avg. W.T. (Sec)	98.81	98.8	68.73	139.89	82.43
Max. W.T. (Sec)	100.05	100.13	263.01	226.44	134.02
Max. Q. L. (Veh)	215.4	214.99	135.56	32.84	24.97
G. G. Time Utilization	0.989945	0.9899303	0.9890814	0.91325509	0.997515
Stability (1:Yes, 0: No)	1	1	1	1	1

Table 4.47: Experimental and Analytical Results for the Experiment-4 (Large Arrival Flow Rate)

Parameters	BM1	BM2	NM1	NM2	DT3P
Departure-Arrival Percentage	67.32%	67.14%	61.88%	69.26%	68.76%
Avg. Q. L. (Veh)	196.21	198.73	788.85	798.75	185.49
Avg. W.T. (Sec)	98.9	98.89	2386.54	2511.09	107.25
Max. W.T. (Sec)	100.45	100.34	3182.06	3348.13	144.98
Max. Q. L. (Veh)	347.5	355.6	1051.8	1065.38	331.36
G. G. Time Utilization	0.989804	0.9897790	0.9949038	0.92669651	0.998982
Stability (1:Yes, 0: No)	1	1	0	0	1

Table 4.48: Experimental and Analytical Results for Experiment-5 (Very-Large Arrival Flow Rate)

Parameters	BM1	BM2	NM1	NM2	DT3P
Departure-Arrival Percentage	58.34%	58.34%	53.59%	60.50%	59.32%
Avg. Q. L. (Veh)	282.45	282.85	932.955	941.265	273.37
Avg. W.T. (Sec)	98.93	98.93	2598	2660.4	105.16
Max. W.T. (Sec)	100.56	100.93	3464	3547.2	138.36
Max. Q. L. (Veh)	518.68	525.51	1243.94	1255.02	511.31
G. G. Time Utilization	0.991463	0.9914038	0.9955182	0.92669651	0.999137
Stability (1:Yes, 0: No)	1	1	0	0	1

Starting from the Very-Small arrival rate, Table 4.44, till the Medium arrival flow rate, Table 4.46, it can be seen that both the NM1 and DT3P achieved better results than the bench mark methods in maintaining the Maximum Queue Length and the Maximum Waiting Time. DT3P continued to perform well through the fourth and fifth experiments, Table 4.47 and Table 4.48; whilst both the NM1 and NM2 methods totally lost their stability, this is why their performance at the Large and Very-Large demand levels must be neglected. From Figure 4.6 and Figure 4.7, it can be seen that DT3P reduced the Maximum and the Average Queue Length better than all of the other methods at all of the levels. It peaked at the medium level of demand, with the least effect on the Maximum waiting time as can be seen in Tables 4.44 through Table 4.48; unlike NM1 and NM2, which lost their control at the large and the very-large arrival flow rates.

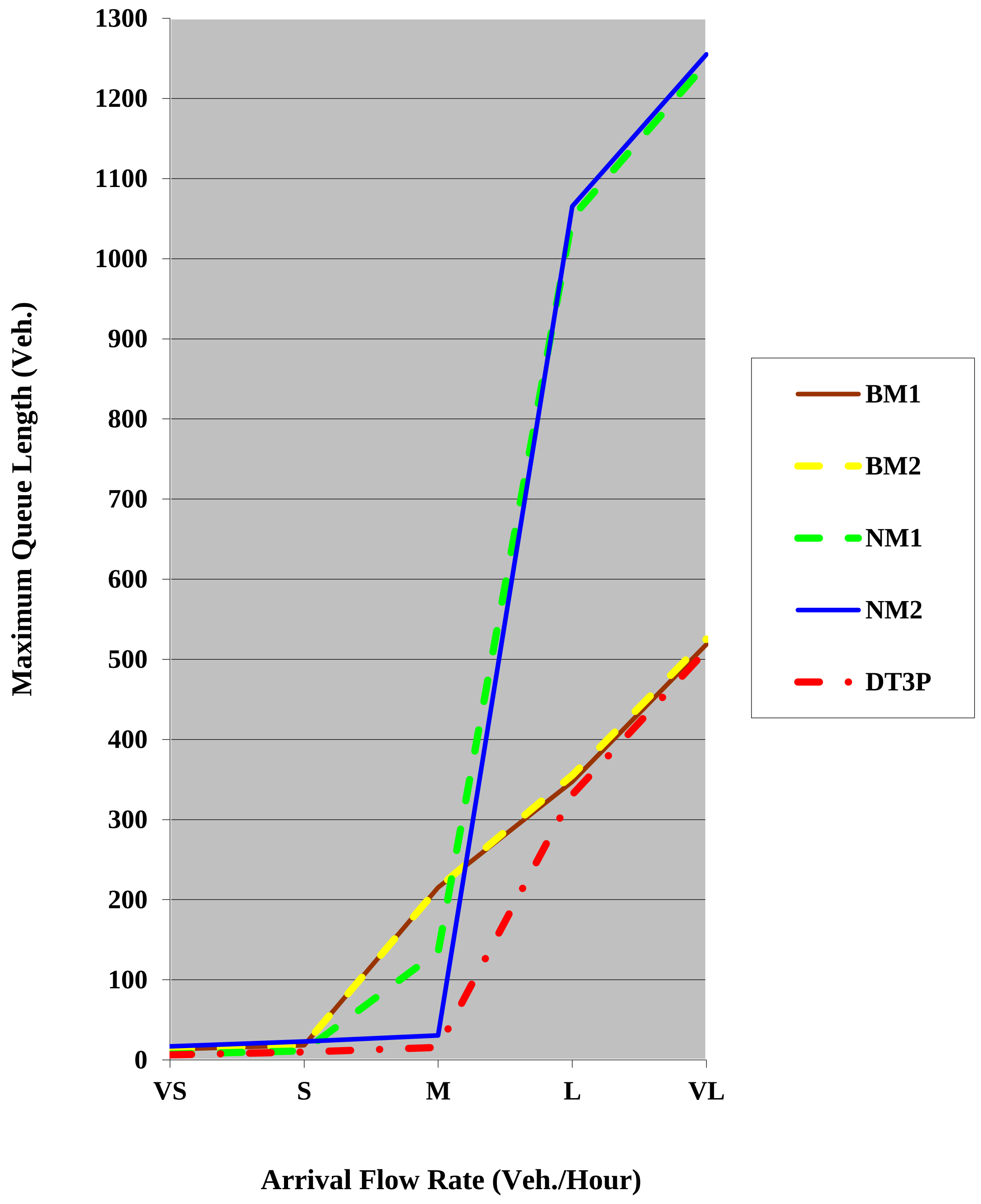


Figure 4.6: Maximum Queue Length for the Five Methods at Five Different Levels of the Vehicle Arrival Flow Rates

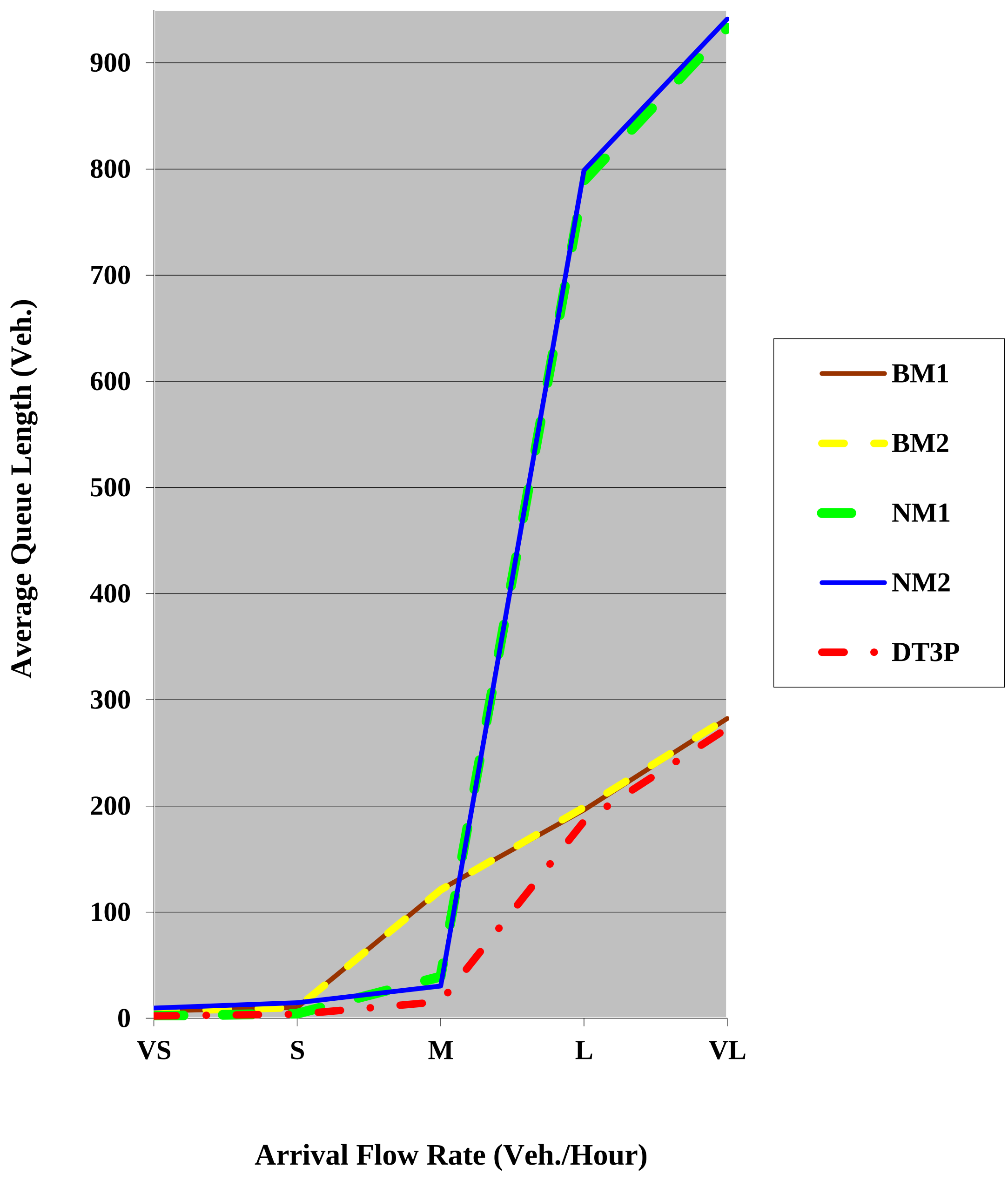


Figure4.7: Average Queue Length for the Five Methods at Five Different Levels of the Vehicle Arrival Flow Rates

Figure 4.8 shows the performance of all of the five methods in terms of the Average Waiting Time. It can be seen that DT3P has performed very well for the first three arrival flow rates when it managed to reduce them. Whilst, a slightly higher waiting time can be seen at the large and the very-large arrival flow rates. That slight extra waiting time appeared because when DT3P detected a direction’s situation reaching the saturation status; it would give a high amount of green time. This was to reduce the time being wasted when changing the traffic light phase. Giving long green lights to all of the directions would lead to a reduction in the number of phase changing, letting other directions wait for a longer time. The given green time utilization curves achieved by each of the five controllers are shown in Figure 4.9 where DT3P can be seen as the best performer compares to all other methods at all levels of demand.

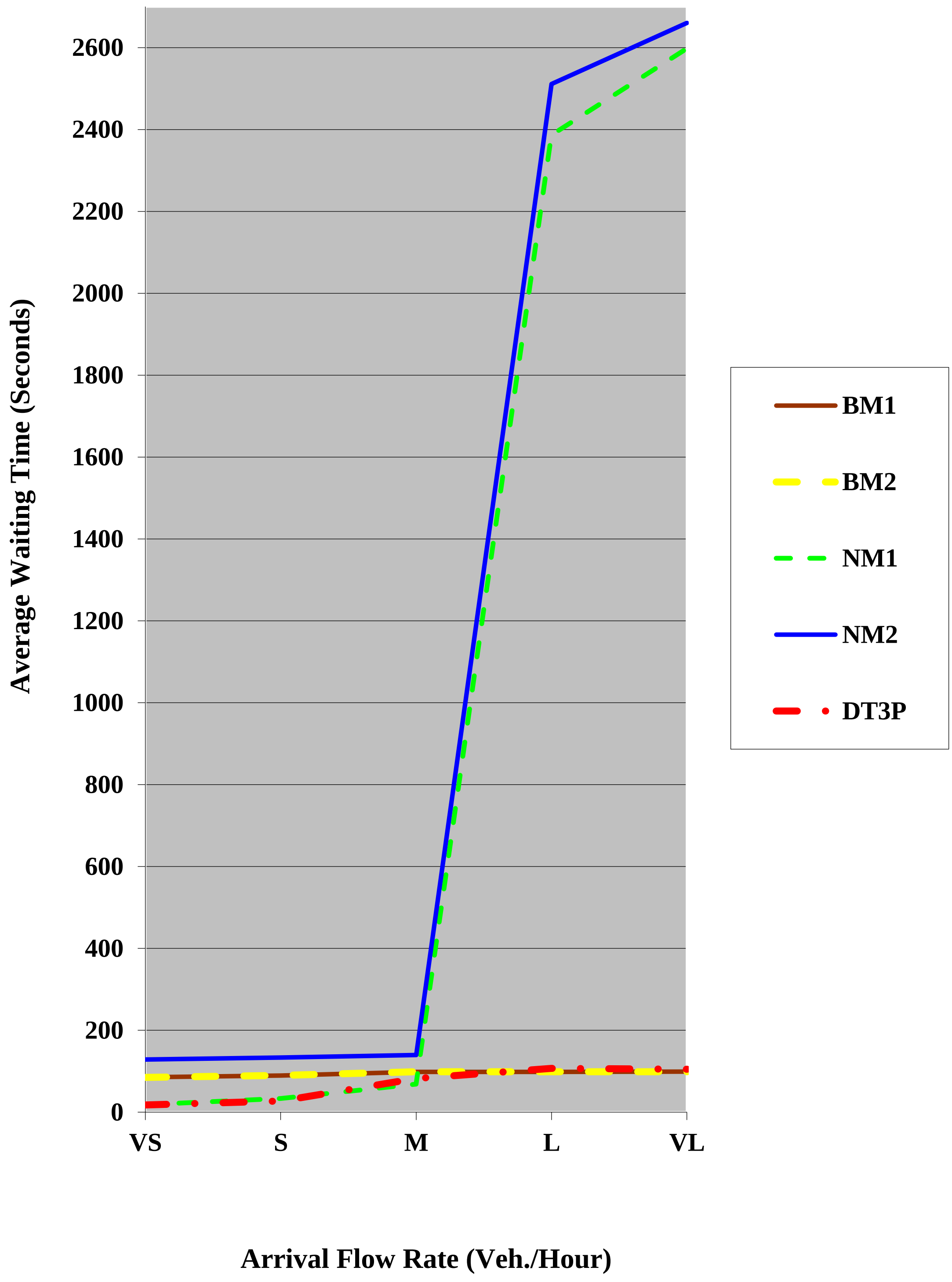


Figure 4.8: Average Waiting Time for the Five Methods at Five Different Levels of the Vehicle Arrival Flow Rates

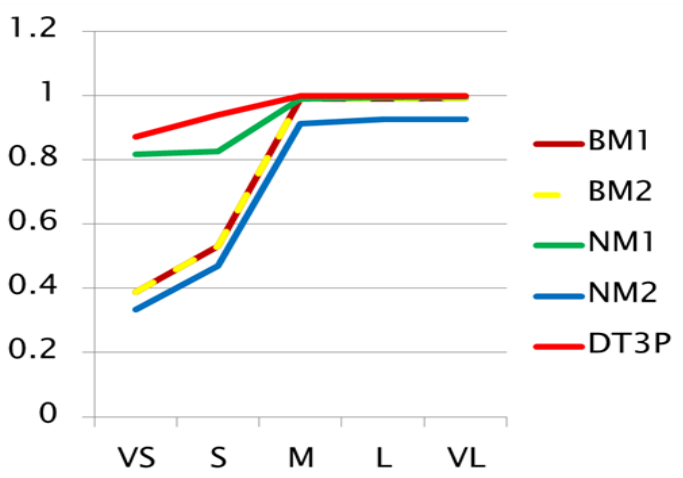


Figure 4.9: Given Green Time Utilization Achieved by the Five Controllers

After compiling the results into tables, it was the time to apply the order-based ranking system where each cell in the tables were replaced with a number that referred to the descending order of the cell contents compared to its row cells, as illustrated in chapter 3; Traffic Light Performance Ranking System section**.** At the bottom of each table, each method has a total score which reflects how efficient (as an overall reference) the method was compared to the others. See Tables 4.49 – 4.53. The total score would be calculated based on the seven evaluation factors:

1. Departure-to-Arrival Percentage (A) - (Range: 1 - 5)
2. Average Queue Length (B) - (Range: 1 - 5)
3. Average Waiting Time (C) - (Range: 1 - 5)
4. Maximum Waiting Time (D) - (Range: 1 - 5)
5. Maximum Queue Length (E) - (Range: 1 - 5)
6. Given Green Time Utilization (F) - (Range: 1 - 5)
7. Stability (G) - (Range: 0 - 1)

The next equation (4.1) used to calculate the total score for each method is:

$$Total\ Score = (A + B + C + D + E + F) * G \qquad (4.1)$$

Table 4.49: Experimental and Analytical Results for Experiment-1 after Applying the Ranking System (Very-Small Arrival Flow Rate)

Parameters	BM1	BM2	NM1	NM2	DT3P
Departure to Arrival Percentage	2	1	3	3	5
Avg. Q. L. (Veh)	3	2	5	1	4
Avg. W. T. (Sec)	2	3	4	1	5
Max. W. T. (Sec)	4	3	2	1	5
Max. Q. L. (Veh)	2	3	4	1	5
Given Green Time Utilization	3	2	4	1	5
Stability	1	1	1	1	1
Total Score	16	14	22	8	29

Table 4.50: Experimental and Analytical Results for Experiment-2 after Applying the Ranking System (Small Arrival Flow Rate)

Parameters	BM1	BM2	NM1	NM2	DT3P
Departure to Arrival Percentage	3	2	4	1	5
Avg. Q. L. (Veh)	3	2	4	1	5
Avg. W. T. (Sec)	3	2	4	1	5
Max. W. T. (Sec)	4	3	2	1	5
Max. Q. L. (Veh)	3	2	4	1	5
Given Green Time Utilization	1	2	4	1	5
Stability	1	1	1	1	1
Total Score	17	13	22	6	30

Table 4.51: Experimental and Analytical Results for Experiment-3 after Applying the Ranking System (Medium Arrival Flow Rate)

Parameters	BM1	BM2	NM1	NM2	DT3P
Departure to Arrival Percentage	1	2	3	4	5
Avg. Q. L. (Veh)	1	2	3	4	5
Avg. W. T. (Sec)	2	3	4	1	5
Max. W. T. (Sec)	5	4	1	2	3
Max. Q. L. (Veh)	1	2	3	4	5
Given Green Time Utilization	4	3	2	1	5
Stability	1	1	1	1	1
Total Score	14	16	16	16	28

Table 4.52: Experimental and Analytical Results for Experiment-4 after Applying the Ranking System (Large Arrival Flow Rate)

Parameters	BM1	BM2	NM1	NM2	DT3P
Departure to Arrival Percentage	3	2	1	5	4
Avg. Q. L. (Veh)	4	3	2	1	5
Avg. W. T. (Sec)	4	5	2	1	3
Max. W. T. (Sec)	4	5	2	1	3
Max. Q. L. (Veh)	4	3	2	1	5
Given Green Time Utilization	3	2	4	1	5
Stability	1	1	0	0	1
Total Score	22	20	0	0	25

Table 4.53: Experimental and Analytical Results for Experiment-5 after Applying the Ranking System (Very-Large Arrival Flow Rate)

Parameters	BM1	BM2	NM1	NM2	DT3P
Departure to Arrival Percentage	3	2	1	5	4
Avg. Q. L. (Veh)	4	3	2	1	5
Avg. W. T. (Sec)	5	4	2	1	3
Max. W. T. (Sec)	5	4	2	1	3
Max. Q. L. (Veh)	4	3	2	1	5
Given Green Time Utilization	3	2	4	1	5
Stability	1	1	0	0	1
Total Score	24	18	0	0	25

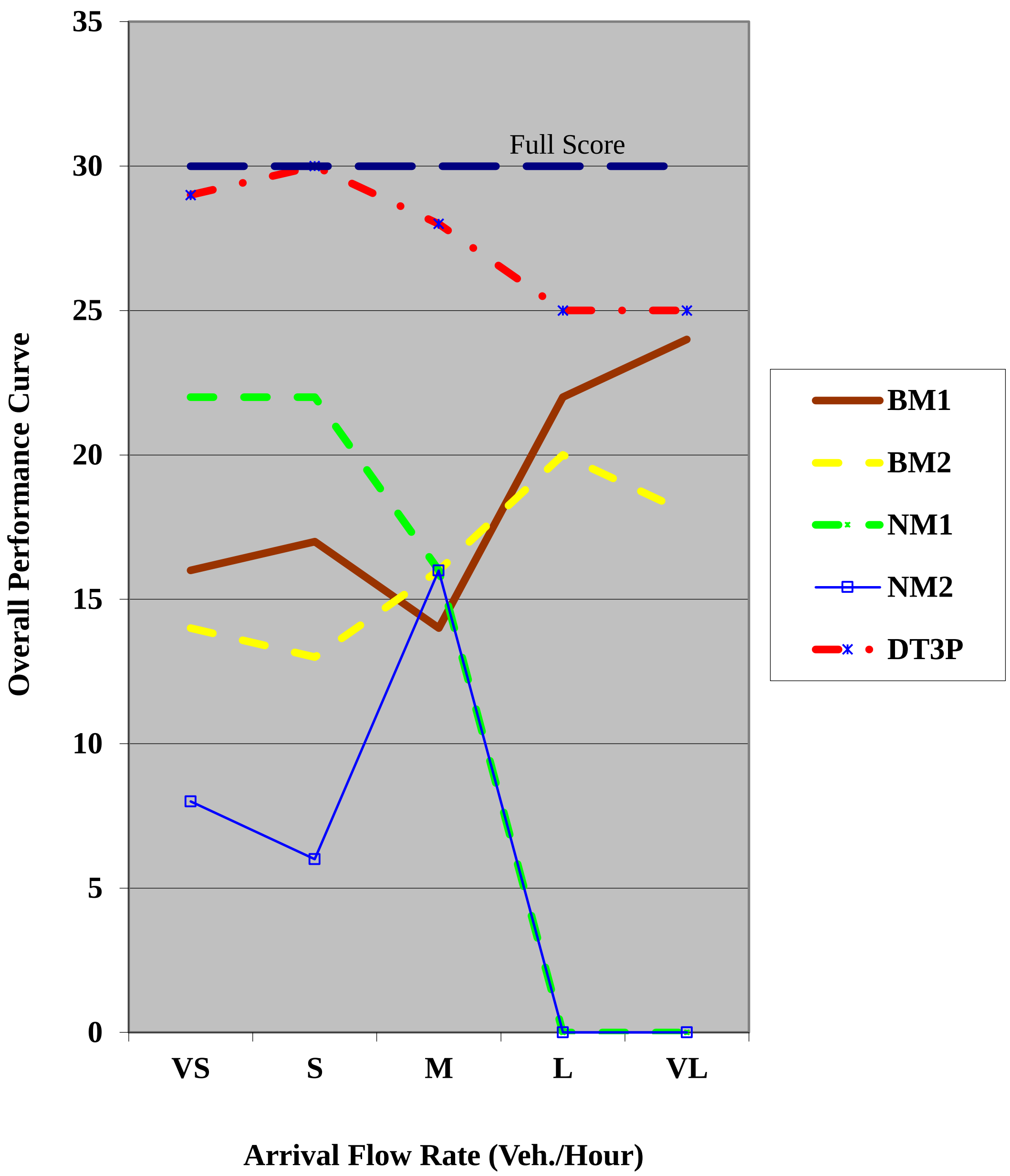


Figure 4.10: Overall Performance for the Five Methods at the Five Different Levels of Demand

In Figure 4.10, five curves can be seen; each acts as the overall performance of one traffic light controlling method. It is obvious that DT3P has the ability to perform the best at all of the levels of demand as DT3P did not lose its stability and performed more efficiently than the other methods. DT3P's efficiency and high stability relate back to the accurate decisions made by its algorithms. Whilst, the failure of NM1's and NM2's methods at the Large and the Very-Large levels of demand is quite obvious as they totally lost control over managing the traffic lights. As for NM1's method, it managed to stay stable and perform more efficiently than the bench mark methods at the first three levels of demand. Whilst NM2's method, kept stable for the first three levels of demand but its performance was quite poor except at the Medium level of demand where it performed better than the two bench mark methods. Although, NM1's method performed better than the bench mark methods at the first three levels of demand, but its decisions were not accurate enough to beat DT3P.

4.7 Summary

The developed system has been simulated using the customized simulation tool and its performance was compared with some of the existing solutions. The developed simulation tool has been used to achieve 95% of confidence. Using the simulation tool have shown significant enhancement in terms of maintaining output-to-Input response accuracy, stability, average queue length, maximum queue length, average waiting time, maximum waiting time, and time utilization.

In terms of accuracy, DT3P had responded to the arrival rate accurately with a minor error percentage reaches up to 2.317%. Although, both of NM1 and NM2 have responded to the levels of demand, however, they were not accurate enough to beat DT3P, as their error percentages were 31.484% and 28.095% respectively.

In addition, both of NM1 and NM2 have lost their stability at the large and the very large levels of demand experiments and in Experiment-M. This makes them ineligible to be used at the intersections with large, very large, and mixed levels of demand. Unlike NM1 and NM2, DT3P stability in controlling an intersection was seen at all the five levels of demand and the Mixed levels of demand. Additionally, DT3P have managed to reduce the maximum queue length and the maximum waiting time for the queue. At the same time, DT3P have increased the green time utilization at the intersection which led to increase the intersection's total capacity.