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Appendix I

The traffic scenario

The hypothetical traffic scenario in which the TPC was evaluated is given in the Table A-I 1. This scenario is related to the corridor shown in Fig. 4.19.

The *Discharge rate* is the average number of cars that can leave the queue in a unit time.

Table A-I 1. Traffic scenario for the TPC evaluation

Junction 1	Approach 1	Average Speed		40 km/h
		Vehicle injection rate		560 p.c.u./h
		Turning Movement 1 (Through Movement)	Probability	0.65
			Discharge rate	1800 p.c.u./h
		Turning Movement 2 (Left turn)	Probability	0.2
			Discharge rate	1500 p.c.u./h
		Turning Movement 3 (Right turn)	Probability	0.15
			Discharge rate	1500 p.c.u./h
	Approach 2	Average Speed		35 km/h
		Vehicle injection rate		450 p.c.u./h
		Turning Movement 1 (Through Movement)	Probability	0.2
			Discharge rate	1850 p.c.u./h
		Turning Movement 2 (Left turn)	Probability	0.5
			Discharge rate	1600 p.c.u./h
		Turning Movement 3 (Right turn)	Probability	0.3
			Discharge rate	1450 p.c.u./h

Table A-I 1. Continued...

	Approach 3	Average Speed		37 km/h
		Vehicle injection rate		230 p.c.u./h
		Turning Movement 1 (Through Movement)	Probability	0.1
			Discharge rate	1750 p.c.u./h
		Turning Movement 2 (Left turn)	Probability	0.3
			Discharge rate	1450 p.c.u./h
		Turning Movement 3 (Right turn)	Probability	0.55
			Discharge rate	1450 p.c.u./h
Junction 1	Approach 4	Average Speed		40 km/h
		Vehicle injection rate		175 p.c.u./h
		Turning Movement 1 (Through Movement)	Probability	0.5
			Discharge rate	1600 p.c.u./h
		Turning Movement 2 (Left turn)	Probability	0.25
			Discharge rate	1500 p.c.u./h
		Turning Movement 3 (Right turn)	Probability	0.1
			Discharge rate	1500 p.c.u./h
Junction 2	Approach 1	Average Speed		42 km/h
		Vehicle injection rate		90 p.c.u./h
		Turning Movement 1 (Through Movement)	Probability	0.5
			Discharge rate	1760 p.c.u./h
		Turning Movement 2 (Left turn)	Probability	0.3
			Discharge rate	1400 p.c.u./h
		Turning Movement 3 (Right turn)	Probability	0.2
			Discharge rate	1450 p.c.u./h
	Approach 2	Average Speed		35 km/h
		Vehicle injection rate		380 p.c.u./h
		Turning Movement 1 (Through Movement)	Probability	0.15
			Discharge rate	1850 p.c.u./h
		Turning Movement 2 (Left turn)	Probability	0.5
			Discharge rate	1650 p.c.u./h
		Turning Movement 3 (Right turn)	Probability	0.3
			Discharge rate	1500 p.c.u./h

Table A-I 1. Continued...

	Approach 3	Average Speed		34 km/h
		Vehicle injection rate		230 p.c.u./h
		Turning Movement 1 (Through Movement)	Probability	0.1
			Discharge rate	1700 p.c.u./h
		Turning Movement 2 (Left turn)	Probability	0.5
			Discharge rate	1360 p.c.u./h
		Turning Movement 3 (Right turn)	Probability	0.4
			Discharge rate	1400 p.c.u./h
Junction 2	Approach 4	Average Speed		42 km/h
		Vehicle injection rate		175 p.c.u./h
		Turning Movement 1 (Through Movement)	Probability	0.7
			Discharge rate	1790 p.c.u./h
		Turning Movement 2 (Left turn)	Probability	0.1
			Discharge rate	1650 p.c.u./h
		Turning Movement 3 (Right turn)	Probability	0.2
			Discharge rate	1600 p.c.u./h
Junction 3	Approach 1	Average Speed		50 km/h
		Vehicle injection rate		200 p.c.u./h
		Turning Movement 1 (Through Movement)	Probability	0.6
			Discharge rate	1700 p.c.u./h
		Turning Movement 2 (Right turn)	Probability	0.4
			Discharge rate	1750 p.c.u./h
	Approach 2	Average Speed		45 km/h
		Vehicle injection rate		380 p.c.u./h
		Turning Movement 1 (Through Movement)	Probability	0.8
			Discharge rate	1850 p.c.u./h
		Turning Movement 2 (Right turn)	Probability	0.3
			Discharge rate	1800 p.c.u./h
	Approach 3	Average Speed		35 km/h
		Vehicle injection rate		520 p.c.u./h
		Turning Movement 1 (Through Movement)	Probability	0.6
			Discharge rate	1750 p.c.u./h
		Turning Movement 2 (Right turn)	Probability	0.4
			Discharge rate	1700 p.c.u./h

Appendix II

TPC Progress Report

A sample progress report generated by the traffic signal calculator is shown in the Table A-II 1. This report is a text file formatted such that Microsoft Excel can open it in the same way the table shows. This is helpful for further analysis.

Table A-II 1. Progress report generated by the TPC

Genetic Algorithm based Traffic Signal Calculator Progress	
Population Size	30
Number of generations	40
Crossover probability	0.6
Mutation	0.1
Started from the beginning	
Simulator Time (sec.)	4800
Queue Lengths are Evaluated.	
Maximum queue remained after a green phase is Evaluated.	
Interrupted vehicle flow is not evaluated.	
Cycle times are not evaluated.	
Date	17-Mar-00
Start Time	13:36:54
Generation	Best PI
1	1.22719
2	1.22719
3	1.22719
4	1.22719
5	1.22719
6	1.22719
7	1.22719
8	2.07982
9	2.07982
10	2.07982

Table A-II 1. Continued...

11	2.07982
12	2.07982
13	2.07982
14	2.07982
15	2.07982
16	2.07982
17	2.07982
18	2.07982
19	2.07982
20	2.07982
21	2.07982
22	2.07982
23	2.07982
24	2.09357
25	2.09357
26	2.09357
27	2.09357
28	2.09357
29	2.09357
30	2.09357
31	2.09357
32	2.09357
33	2.09357
34	2.09357
35	2.09357
36	2.09357
37	2.09357
38	2.09357
39	2.09357
40	2.09357
Date	17-Mar-00
End Time	14:55:26

Table A-II 1. Continued...

Green Stage Times for the Cluster Map 1	
Junction 1	
Junction Offset (sec.)	19.5294
Approach ID	Green Duration (sec.)
1	26.2863
2	24.2039
3	13.7922
4	59.3725
Junction 2	
Junction Offset (sec.)	10.1176
Approach ID	Green Duration (sec.)
1	46.4157
2	30.6824
3	27.9059
4	60.5294
Junction 3	
Junction Offset (sec.)	13.8039
Approach ID	Green Duration (sec.)
1	56.1333
2	30.9137
3	23.0471

Appendix III

Results Generated By Traffic Simulator for Different Traffic Signal Plans

Best traffic plans calculated by the TPC are subjected to simulation session of one-hour. The results of these sessions are given here. These tables give information in sequence of Junction, Approach and Turning Movement.

In the table the *'Simulator period'* field gives the time duration the plan is simulated. Then the result sheet is divided into 2 columns. The first column gives the component name in the network, Cluster name, junction names, approach names and movement names and under each component their parameters. The second column gives the relevant value of each parameter.

Table A-III 1. Simulation results of the traffic plan calculated to minimize *L*.

Evaluation parameters at the end of the simulator session	
Simulator period 1h:00m:01s	
Map 1	
Junction 1	
Approach 1	
Number of vehicles came (passing at least one junction)	0
Number of vehicles passed without stopping	0
Maximum Queue	22
Maximum Queue at the end of green period	2
Turning 1	
Queue	10
Turning 2	
Queue	1
Turning 3	
Queue	0

Approach 2	
Number of vehicles came (passing at least one junction)	0
Number of vehicles passed without stopping	0
Maximum Queue	18
Maximum Queue at the end of green period	1
Turning 1	
Queue	0
Turning 2	
Queue	2
Turning 3	
Queue	3
Approach 3	
Number of vehicles came (passing at least one junction)	0
Number of vehicles passed without stopping	0
Maximum Queue	12
Maximum Queue at the end of green period	3
Turning 1	
Queue	0
Turning 2	
Queue	1
Turning 3	
Queue	1
Approach 4	
Number of vehicles came (passing at least one junction)	731
Number of vehicles passed without stopping	278
Maximum Queue	35
Maximum Queue at the end of green period	1
Turning 1	
Queue	10
Turning 2	
Queue	4
Turning 3	
Queue	0
Junction 2	
Approach 1	
Number of vehicles came (passing at least one junction)	732
Number of vehicles passed without stopping	171
Maximum Queue	35
Maximum Queue at the end of green period	12
Turning 1	
Queue	3
Turning 2	
Queue	2
Turning 3	
Queue	0

Approach 2	
Number of vehicles came (passing at least one junction)	0
Number of vehicles passed without stopping	0
Maximum Queue	17
Maximum Queue at the end of green period	6
Turning 1	
Queue	0
Turning 2	
Queue	8
Turning 3	
Queue	3
Approach 3	
Number of vehicles came (passing at least one junction)	0
Number of vehicles passed without stopping	0
Maximum Queue	7
Maximum Queue at the end of green period	0
Turning 1	
Queue	0
Turning 2	
Queue	1
Turning 3	
Queue	4
Approach 4	
Number of vehicles came (passing at least one junction)	580
Number of vehicles passed without stopping	203
Maximum Queue	23
Maximum Queue at the end of green period	1
Turning 1	
Queue	7
Turning 2	
Queue	0
Turning 3	
Queue	2
Junction 3	
Approach 1	
Number of vehicles came (passing at least one junction)	726
Number of vehicles passed without stopping	331
Maximum Queue	25
Maximum Queue at the end of green period	4
Turning 0	
Queue	4
Turning 1	
Queue	4

Approach 2	
Number of vehicles came (passing at least one junction)	0
Number of vehicles passed without stopping	0
Maximum Queue	8
Maximum Queue at the end of green period	0
Turning 0	
Queue	2
Turning 1	
Queue	0
Approach 3	
Number of vehicles came (passing at least one junction)	0
Number of vehicles passed without stopping	0
Maximum Queue	14
Maximum Queue at the end of green period	2
Turning 0	
Queue	3
Turning 1	
Queue	3

Table A-III 2. Simulation results of the traffic plan calculated to minimize L_R.

Evaluation parameters at the end of the simulator session	
Simulator period 1h:00m:06s	
Map 1	
Junction 1	
Approach 1	
Number of vehicles came (passing at least one junction)	0
Number of vehicles passed without stopping	0
Maximum Queue	18
Maximum Queue at the end of green period	0
Turning 1	
Queue	14
Turning 2	
Queue	2
Turning 3	
Queue	1

Approach 2	
Number of vehicles came (passing at least one junction)	0
Number of vehicles passed without stopping	0
Maximum Queue	17
Maximum Queue at the end of green period	1
Turning 1	
Queue	3
Turning 2	
Queue	3
Turning 3	
Queue	2
Approach 3	
Number of vehicles came (passing at least one junction)	0
Number of vehicles passed without stopping	0
Maximum Queue	22
Maximum Queue at the end of green period	2
Turning 1	
Queue	1
Turning 2	
Queue	2
Turning 3	
Queue	1
Approach 4	
Number of vehicles came (passing at least one junction)	705
Number of vehicles passed without stopping	340
Maximum Queue	33
Maximum Queue at the end of green period	1
Turning 1	
Queue	0
Turning 2	
Queue	0
Turning 3	
Queue	1
Junction 2	
Approach 1	
Number of vehicles came (passing at least one junction)	725
Number of vehicles passed without stopping	198
Maximum Queue	29
Maximum Queue at the end of green period	4
Turning 1	
Queue	11
Turning 2	
Queue	4
Turning 3	
Queue	10

Approach 2	
Number of vehicles came (passing at least one junction)	0
Number of vehicles passed without stopping	0
Maximum Queue	12
Maximum Queue at the end of green period	2
Turning 1	
Queue	0
Turning 2	
Queue	9
Turning 3	
Queue	1
Approach 3	
Number of vehicles came (passing at least one junction)	0
Number of vehicles passed without stopping	0
Maximum Queue	9
Maximum Queue at the end of green period	2
Turning 1	
Queue	0
Turning 2	
Queue	3
Turning 3	
Queue	1
Approach 4	
Number of vehicles came (passing at least one junction)	542
Number of vehicles passed without stopping	182
Maximum Queue	23
Maximum Queue at the end of green period	1
Turning 1	
Queue	0
Turning 2	
Queue	0
Turning 3	
Queue	0
Junction 3	
Approach 1	
Number of vehicles came (passing at least one junction)	675
Number of vehicles passed without stopping	332
Maximum Queue	40
Maximum Queue at the end of green period	7
Turning 0	
Queue	1
Turning 1	
Queue	2

Approach 2	
Number of vehicles came (passing at least one junction)	0
Number of vehicles passed without stopping	0
Maximum Queue	11
Maximum Queue at the end of green period	0
Turning 0	
Queue	6
Turning 1	
Queue	0
Approach 3	
Number of vehicles came (passing at least one junction)	0
Number of vehicles passed without stopping	0
Maximum Queue	20
Maximum Queue at the end of green period	0
Turning 0	
Queue	1
Turning 1	
Queue	5

Table A-III 3. Simulation results of the traffic plan calculated to minimize C_T.

Evaluation parameters at the end of the simulator session	
Simulator period 1h:00m:15s	
Map 1	
Junction 1	
Approach 1	
Number of vehicles came (passing at least one junction)	0
Number of vehicles passed without stopping	0
Maximum Queue	13
Maximum Queue at the end of green period	4
Turning 1	
Queue	5
Turning 2	
Queue	0
Turning 3	
Queue	0

Approach 2	
Number of vehicles came (passing at least one junction)	0
Number of vehicles passed without stopping	0
Maximum Queue	14
Maximum Queue at the end of green period	6
Turning 1	
Queue	0
Turning 2	
Queue	2
Turning 3	
Queue	0
Approach 3	
Number of vehicles came (passing at least one junction)	0
Number of vehicles passed without stopping	0
Maximum Queue	6
Maximum Queue at the end of green period	2
Turning 1	
Queue	0
Turning 2	
Queue	1
Turning 3	
Queue	1
Approach 4	
Number of vehicles came (passing at least one junction)	785
Number of vehicles passed without stopping	258
Maximum Queue	33
Maximum Queue at the end of green period	18
Turning 1	
Queue	21
Turning 2	
Queue	5
Turning 3	
Queue	4
Junction 2	
Approach 1	
Number of vehicles came (passing at least one junction)	683
Number of vehicles passed without stopping	149
Maximum Queue	35
Maximum Queue at the end of green period	21
Turning 1	
Queue	20
Turning 2	
Queue	0
Turning 3	
Queue	0

Approach 2	
Number of vehicles came (passing at least one junction)	0
Number of vehicles passed without stopping	0
Maximum Queue	17
Maximum Queue at the end of green period	9
Turning 1	
Queue	0
Turning 2	
Queue	6
Turning 3	
Queue	0
Approach 3	
Number of vehicles came (passing at least one junction)	0
Number of vehicles passed without stopping	0
Maximum Queue	8
Maximum Queue at the end of green period	4
Turning 1	
Queue	0
Turning 2	
Queue	1
Turning 3	
Queue	1
Approach 4	
Number of vehicles came (passing at least one junction)	563
Number of vehicles passed without stopping	185
Maximum Queue	17
Maximum Queue at the end of green period	2
Turning 1	
Queue	8
Turning 2	
Queue	0
Turning 3	
Queue	3
Junction 3	
Approach 1	
Number of vehicles came (passing at least one junction)	626
Number of vehicles passed without stopping	194
Maximum Queue	21
Maximum Queue at the end of green period	11
Turning 0	
Queue	0
Turning 1	
Queue	0

Approach 2	
Number of vehicles came (passing at least one junction)	0
Number of vehicles passed without stopping	0
Maximum Queue	6
Maximum Queue at the end of green period	1
Turning 0	
Queue	2
Turning 1	
Queue	2
Approach 3	
Number of vehicles came (passing at least one junction)	0
Number of vehicles passed without stopping	0
Maximum Queue	6
Maximum Queue at the end of green period	1
Turning 0	
Queue	1
Turning 1	
Queue	3

Table A-III 4. Simulation results of the traffic plan calculated to maximize P_p and to minimize L.

Evaluation parameters at the end of the simulator session	
Simulator period 0h:15m:28s	
Map 1	
Junction 1	
Approach 1	
Number of vehicles came (passing at least one junction)	0
Number of vehicles passed without stopping	0
Maximum Queue	26
Maximum Queue at the end of green period	0
Turning 1	
Queue	2
Turning 2	
Queue	0
Turning 3	
Queue	0

Approach 2	
Number of vehicles came (passing at least one junction)	0
Number of vehicles passed without stopping	0
Maximum Queue	20
Maximum Queue at the end of green period	0
Turning 1	
Queue	1
Turning 2	
Queue	11
Turning 3	
Queue	5
Approach 3	
Number of vehicles came (passing at least one junction)	0
Number of vehicles passed without stopping	0
Maximum Queue	12
Maximum Queue at the end of green period	0
Turning 1	
Queue	0
Turning 2	
Queue	4
Turning 3	
Queue	2
Approach 4	
Number of vehicles came (passing at least one junction)	165
Number of vehicles passed without stopping	79
Maximum Queue	41
Maximum Queue at the end of green period	10
Turning 1	
Queue	16
Turning 2	
Queue	2
Turning 3	
Queue	0
Junction 2	
Approach 1	
Number of vehicles came (passing at least one junction)	159
Number of vehicles passed without stopping	67
Maximum Queue	23
Maximum Queue at the end of green period	3
Turning 1	
Queue	0
Turning 2	
Queue	1
Turning 3	
Queue	0

Approach 2	
Number of vehicles came (passing at least one junction)	0
Number of vehicles passed without stopping	0
Maximum Queue	9
Maximum Queue at the end of green period	0
Turning 1	
Queue	1
Turning 2	
Queue	2
Turning 3	
Queue	1
Approach 3	
Number of vehicles came (passing at least one junction)	0
Number of vehicles passed without stopping	0
Maximum Queue	9
Maximum Queue at the end of green period	3
Turning 1	
Queue	0
Turning 2	
Queue	4
Turning 3	
Queue	0
Approach 4	
Number of vehicles came (passing at least one junction)	131
Number of vehicles passed without stopping	79
Maximum Queue	14
Maximum Queue at the end of green period	3
Turning 1	
Queue	9
Turning 2	
Queue	0
Turning 3	
Queue	0
Junction 3	
Approach 1	
Number of vehicles came (passing at least one junction)	164
Number of vehicles passed without stopping	134
Maximum Queue	7
Maximum Queue at the end of green period	0
Turning 0	
Queue	1
Turning 1	
Queue	0

Approach 2	
Number of vehicles came (passing at least one junction)	0
Number of vehicles passed without stopping	0
Maximum Queue	10
Maximum Queue at the end of green period	0
Turning 0	
Queue	5
Turning 1	
Queue	2
Approach 3	
Number of vehicles came (passing at least one junction)	0
Number of vehicles passed without stopping	0
Maximum Queue	21
Maximum Queue at the end of green period	7
Turning 0	
Queue	11
Turning 1	
Queue	2

Table A-III 5. Simulation results of the traffic plan calculated to maximize P_p together with minimizing both L and L_R.

Evaluation parameters at the end of the simulator session	
Simulator time 0h:15m:14s	
Map 1	
Junction 1	
Approach 1	
Number of vehicles came (passing at least one junction)	0
Number of vehicles passed without stopping	0
Maximum Queue	22
Maximum Queue at the end of green period	1
Turning 1	
Queue	6
Turning 2	
Queue	0
Turning 3	
Queue	0

Approach 2	
Number of vehicles came (passing at least one junction)	0
Number of vehicles passed without stopping	0
Maximum Queue	18
Maximum Queue at the end of green period	0
Turning 1	
Queue	0
Turning 2	
Queue	0
Turning 3	
Queue	0
Approach 3	
Number of vehicles came (passing at least one junction)	0
Number of vehicles passed without stopping	0
Maximum Queue	9
Maximum Queue at the end of green period	0
Turning 1	
Queue	0
Turning 2	
Queue	1
Turning 3	
Queue	8
Approach 4	
Number of vehicles came (passing at least one junction)	158
Number of vehicles passed without stopping	52
Maximum Queue	29
Maximum Queue at the end of green period	1
Turning 1	
Queue	11
Turning 2	
Queue	5
Turning 3	
Queue	1
Junction 2	
Approach 1	
Number of vehicles came (passing at least one junction)	165
Number of vehicles passed without stopping	56
Maximum Queue	35
Maximum Queue at the end of green period	2
Turning 1	
Queue	7
Turning 2	
Queue	4
Turning 3	
Queue	6

Approach 2	
Number of vehicles came (passing at least one junction)	0
Number of vehicles passed without stopping	0
Maximum Queue	14
Maximum Queue at the end of green period	0
Turning 1	
Queue	1
Turning 2	
Queue	1
Turning 3	
Queue	1
Approach 3	
Number of vehicles came (passing at least one junction)	0
Number of vehicles passed without stopping	0
Maximum Queue	15
Maximum Queue at the end of green period	4
Turning 1	
Queue	0
Turning 2	
Queue	7
Turning 3	
Queue	0
Approach 4	
Number of vehicles came (passing at least one junction)	136
Number of vehicles passed without stopping	6
Maximum Queue	35
Maximum Queue at the end of green period	1
Turning 1	
Queue	27
Turning 2	
Queue	0
Turning 3	
Queue	2
Junction 3	
Approach 1	
Number of vehicles came (passing at least one junction)	161
Number of vehicles passed without stopping	105
Maximum Queue	23
Maximum Queue at the end of green period	0
Turning 0	
Queue	3
Turning 1	
Queue	3

Approach 2	
Number of vehicles came (passing at least one junction)	0
Number of vehicles passed without stopping	0
Maximum Queue	15
Maximum Queue at the end of green period	0
Turning 0	
Queue	0
Turning 1	
Queue	0
Approach 3	
Number of vehicles came (passing at least one junction)	0
Number of vehicles passed without stopping	0
Maximum Queue	19
Maximum Queue at the end of green period	0
Turning 0	
Queue	9
Turning 1	
Queue	4

Table A-III 6. Simulation results of the traffic plan that calculated by continuing the earlier session of maximizing P_p, together with minimizing both L and L_R.

Evaluation parameters at the end of the simulator session	
Simulator time 0h:15m:13s	
Map 1	
Junction 1	
Approach 1	
Number of vehicles came (passing at least one junction)	0
Number of vehicles passed without stopping	0
Maximum Queue	22
Maximum Queue at the end of green period	1
Turning 1	
Queue	3
Turning 2	
Queue	2
Turning 3	
Queue	1

Approach 2	
Number of vehicles came (passing at least one junction)	0
Number of vehicles passed without stopping	0
Maximum Queue	18
Maximum Queue at the end of green period	0
Turning 1	
Queue	0
Turning 2	
Queue	1
Turning 3	
Queue	0
Approach 3	
Number of vehicles came (passing at least one junction)	0
Number of vehicles passed without stopping	0
Maximum Queue	10
Maximum Queue at the end of green period	0
Turning 1	
Queue	2
Turning 2	
Queue	3
Turning 3	
Queue	5
Approach 4	
Number of vehicles came (passing at least one junction)	156
Number of vehicles passed without stopping	23
Maximum Queue	35
Maximum Queue at the end of green period	0
Turning 1	
Queue	9
Turning 2	
Queue	4
Turning 3	
Queue	0
Junction 2	
Approach 1	
Number of vehicles came (passing at least one junction)	187
Number of vehicles passed without stopping	72
Maximum Queue	36
Maximum Queue at the end of green period	5
Turning 1	
Queue	10
Turning 2	
Queue	8
Turning 3	
Queue	2

Approach 2	
Number of vehicles came (passing at least one junction)	0
Number of vehicles passed without stopping	0
Maximum Queue	16
Maximum Queue at the end of green period	0
Turning 1	
Queue	0
Turning 2	
Queue	5
Turning 3	
Queue	1
Approach 3	
Number of vehicles came (passing at least one junction)	0
Number of vehicles passed without stopping	0
Maximum Queue	11
Maximum Queue at the end of green period	0
Turning 1	
Queue	0
Turning 2	
Queue	1
Turning 3	
Queue	1
Approach 4	
Number of vehicles came (passing at least one junction)	128
Number of vehicles passed without stopping	3
Maximum Queue	36
Maximum Queue at the end of green period	0
Turning 1	
Queue	15
Turning 2	
Queue	0
Turning 3	
Queue	0
Junction 3	
Approach 1	
Number of vehicles came (passing at least one junction)	157
Number of vehicles passed without stopping	104
Maximum Queue	21
Maximum Queue at the end of green period	0
Turning 0	
Queue	1
Turning 1	
Queue	0

Approach 2	
Number of vehicles came (passing at least one junction)	0
Number of vehicles passed without stopping	0
Maximum Queue	15
Maximum Queue at the end of green period	0
Turning 0	
Queue	6
Turning 1	
Queue	0
Approach 3	
Number of vehicles came (passing at least one junction)	0
Number of vehicles passed without stopping	0
Maximum Queue	19
Maximum Queue at the end of green period	0
Turning 0	
Queue	4
Turning 1	
Queue	8

Appendix IV

The Genetic Algorithm

When the degree of freedom is increased and their contribution to the function cannot be represented in a polynomial equation, the problem is known to be a Non Deterministic Polynomial time hard problem (NP hard). Solving such problem needs excessive amount of computational resources and time. The development of an algorithm to solve such a problem itself is a very difficult task. One such problem is traffic signal plan optimization for a synchronized network of TSCs.

Rather than employing a conventional mathematical algorithm, such problems can be solved with some evolutionary algorithm with less effort. Selection of a proper algorithm, which can be mapped to the problem properly and which has the capability of handling the degree of freedom required, is the key factor that governs the success of the effort. One such algorithm is the Genetic Algorithm (GA). This is formulated based on known biological theories on natural evolution.

A-IV.1. Natural Evolution

Charles Darwin suggested, in his controversial publication *The Origin of Species* that a species is continually developing. He noticed that in almost all organisms there is a huge potential for the production of offspring, but that only a small percentage survive to adulthood. Even within a population there is a great deal of variation. Analyzing these facts he suggested that ones, most fit to the struggle, survived. Therefore he leads to deduce that the natural selection of inheritable variations is the Evolution. Several other experiments done by other scientists strengthened the theory of natural selection and they have come to know that the one that governs the characteristics of a species is the gene, which is a part of a chromosome in the nucleus.

There are two major methods of producing offspring of species to maintain their population called asexual reproduction and sexual reproduction. Asexual evolution is confined to a limited number of animals and plants. In this method, the offspring bares the same properties as the earlier generation. But the offspring of a sexual reproduction does not carry the same properties. Instead they inherit certain properties form each. This is because certain genes come from the father while the others come from the mother. This process is known as *crossover*.

Occasionally, distinct differences within a species are found. This is because of the process called *mutation*. If a gene is mutated there will be a change in properties of the species. That change may be negligible if the property is governed by a series of genes. But if the gene governs a property in total, the change will be a dramatic one. Hence mutation is a powerful tool in nature to evolve differences in species.

A-IV.2. GA in Biology

This is characterized by the following phenomena, which are applicable to biological systems:

1. Gene
2. Chromosome
3. Individual
4. Population
5. Mating
6. Cross-over
7. Mutation
8. Evolution
9. Fitness
10. Dying

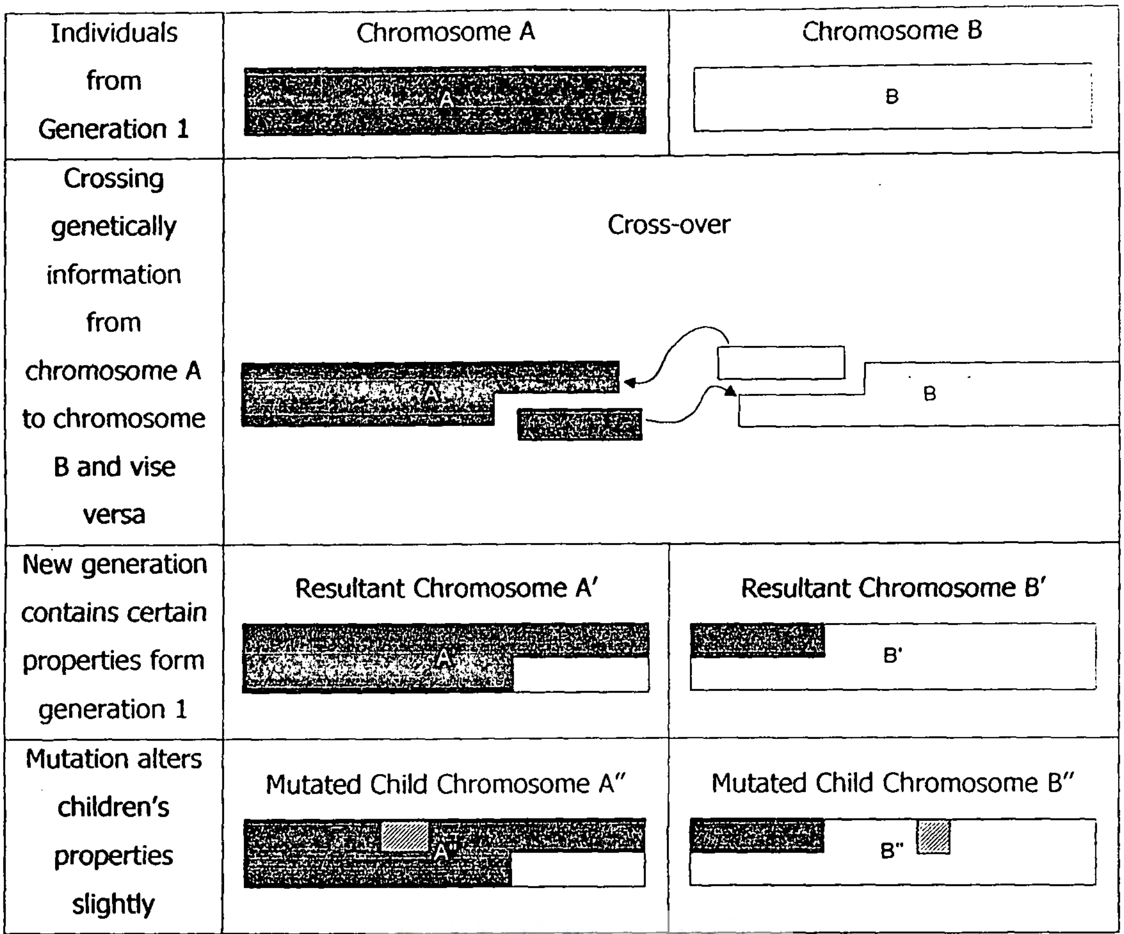


Fig. A-IV.1. Evolution of new chromosomes

An *individual* is a member of a community of a species. Each individual possesses a unique structure made up of *genes* that governs its properties. This structure is called a *chromosome*. A *population* is a set of individuals who are geographically in close proximity such that they can interact with each other easily. *Fitness* is the property that governs an individual's ability to survive in the given environment. This value is a complex function of the parameters such as the ability to find food, competition for food, resistivity of the individual to the climate and ability to survive from their predators. If an individual is not fit to the given environment it will *die*. Most fit individuals have a high probability of getting a chance to *mate*. In the process of mating, genes of two individuals *cross over* to make two kinds of new chromosomes which posses certain properties of the parents. In this process these two individuals gives birth to two new individuals, which might display different properties than their parents. Usually those two individuals do not inherit their parent's genetic information as it is. They tend to get their genes altered slightly. This is called *mutation*. Mutation assigns new properties to children and who may have greater degree survivability than their parents.

An individual, who gets the opportunity to mate, contributes to *evolve* a new generation. The process of forming two new chromosomes from parent chromosomes is described in Fig. A-IV.1. Two parent chromosomes split into two parts. They interchange parts of their chromosomes to form new chromosomes. Some genes may get mutated during the process of generating offspring.

A-IV.3. GA in Mathematics

Mathematicians have studied the biological GA and have come up with a powerful global search and optimization algorithm. This simply is referred to as GA [17].

The power of this algorithm is demonstrated in mathematical, engineering and economical problems successfully [17]. In this algorithm, a candidate solution to the subjected problem is encoded into a chromosome. The meanings of the gene and the chromosome vary according to the data type involved in the problem. For example, if the problem is an integer based one (e.g. to find the minimum integer solution to a parabolic equation) the gene may be a single bit of the integer and the chromosome may be the integer itself (Fig. A-IV.2.). If the problem is a character string based one, the gene may be a character and the chromosome is the character string (Fig. A-IV.3.).

0	1	1	0	1	0	0	1

Fig. A-IV.2. Chromosome to represent an integer

	O	p	t	i	m	u	m

Fig. A-IV.3. Chromosome to represent a character string

From the mathematical point of view, the algorithm is, usually, started with a random population of candidate solutions to the problem. Alternatively a candidate solution, which is know to be closer to the optimum solution, can be supplied to the algorithm. Each individual in the population is evaluated against its performance (fitness) given in terms of a score calculated by an *Objective Function (OF)*, which evaluates the applicability of the candidate solution to the problem. Lowest fit individuals die i.e. removed from the set of solutions being considered. Out of the remaining, individuals are selected for mating. The probability of getting a chance to mate is higher if the fitness is high.

Fig. A-IV.4 shows how two binary strings go through the evolution procedure. Mating produces a new set of individuals. These are evaluated separately to get fitness values. From this resulting generation, with or without the parent generation, most unfit individuals are killed to maintain the population size within a given limit.

Parent strings	Binary String A 0 1 1 0 1 0 0 1	Binary String B 1 1 0 0 0 1 1 1
Cross-over	0 1 1 0 1 | 0 0 1	1 1 0 | 0 0 1 1 1
	Child String A′ 0 1 1 0 1 1 1 0	Child String B′ 0 0 1 0 0 1 1 1
Mutation	Final Result after the Mutation A″ 0 1 1 1 1 1 1 0	Final Result after the Mutation B″ 0 0 1 0 0 0 1 1

Fig. A-IV.4. Evolution of an integer child generation

GA is not a sequential algorithm. It searches the solution space in parallel at several points (a 'population' of points). It does not find solutions at pre-determined locations. Instead it searches for a solution at randomly selected points from the solution space.

Therefore it does not get stuck at sub-optimal solutions such as local minima of a minimization problem. Instead, there is a very high probability of converging to a global solution. On the other hand the algorithm does not depend on mathematical concepts like integration and differentiation. This makes the algorithm simple and more understandable. Most of the time, the algorithm converges at a faster rate than any other conventional technique.

A-IV.3.1. Types of GAs

GAs are classified according to how populations are handled.

Non-overlapping GA (Simple GA)

This type of GA generates an entirely new population, rejecting everyone in the parent population. Each mate produces two members to the new population. The size of the population remains constant throughout the evolution process. Even though this algorithm is simple to implement, its rate of convergence is low. This is because some preferred genes, which are owned by parents, are lost in the next generation.

Overlapping GAs

In this algorithm, only a part of the population is replaced by the new generation. There are several possible strategies of selecting individuals from the parent population (and vise-versa) to be replaced by the fit individuals from the child population. Some of them are:

1. Worst fit

   Worst fit individuals from both the child and parent populations are removed to maintain the size of the population constant. This is the best replacement scheme.
2. Parent

   Children replaces the parents.
3. Random

   The individuals to be replaced are selected randomly.

Parallel GAs

These types of GAs emulate the natural barriers of mating such as geological islands, borders and distance. The GA is parallelised in a number of ways. For example several parallel populations can simultaneously be incorporated. Parallel GA can take the advantage of parallel computers or a set of computers connected over a high performance network. Brief introduction to three types of Parallel GAs is given below.

1. Global GAs

   Only a single population is considered in this algorithm. Each individual is a process. The genetic algorithm is another process, which manage individuals in Worker-Farmer parallel model (Fig. A-IV.5.). GA Farmer holds the entire population, initializes it, assigns fitness to each individual and selects individuals for mating. Individual workers handle operations, which are owned by each individual such as recombination, mutation and evaluation.

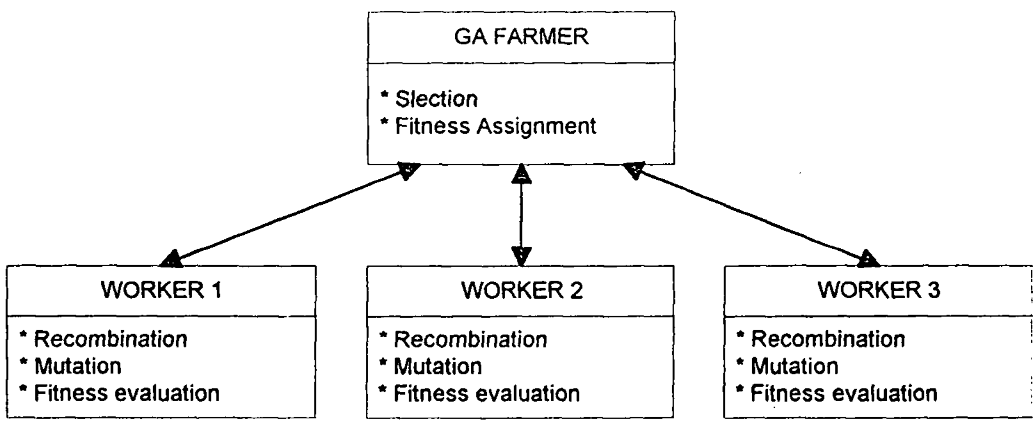


Fig.A-IV.5. Worker – Farmer model of the Global GA

2. Migration GAs

Natural evolution is not confined to a single population. Instead, several semi-isolated populations evolve independently keeping provisions for occasional inter-population migration of one or more individuals. A good example of this model is the evolution of the human being. There are several barriers imposed on human breeding such as racial differences, political boundaries geological boundaries and religious barriers. It is a common practice that some human beings break these barriers in their breeding.

Migration GAs handle several parallel such populations in separate processes Fig. 5.6. Occasionally, some of their individuals migrate to another population. Usually most fit members in one population get the opportunity of crossing the boundary.

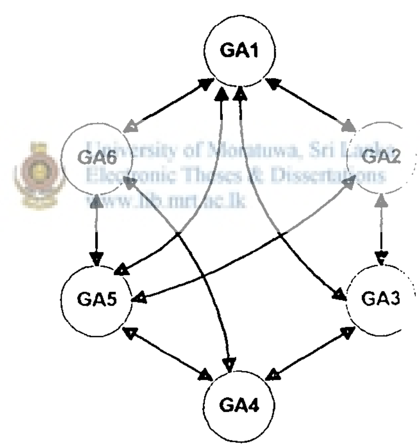
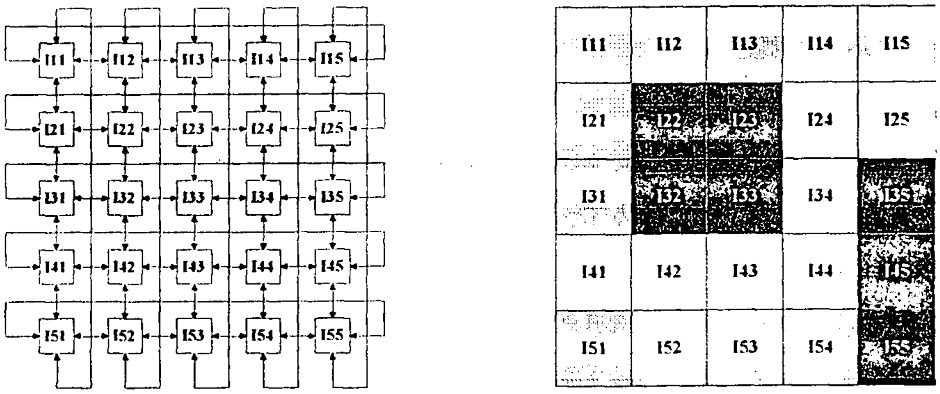


Fig. A-IV.6. Multiple generations of the Migration GA and their possible migration patterns

3. Diffusion GAs

In Migration GAs, the total population is broken into several discrete sub-populations. But in Diffusion GAs it is a single population, but each individual is assigned a geographical location to distribute them on the geo-plane, imposing a distance barrier for breeding. Only nearby individuals get the opportunity of mating. This restriction is implemented by restricting the communication between individuals, which are separate processes (Fig. A-IV.7.).



(a) Parallelised Individuals, their communication and localization

(b) Virtual Islands

Fig. A-IV.7.

A-IV.3.2. GA Parameters

After selecting the proper type of GA a number of parameters can be change its behavior. They are described below.

Starting method

This determines how the initial population is generated. There are two methods of initializing the population. In the first method, a random population is created. It is important to distribute this generation throughout the solution space. Alternatively, a specific solution can be supplied to the algorithm.

Terminating method

The simplest form of termination is the number of generations. Several other methods can be selected according to the requirement. For example convergence can be taken as the key to terminate the evolution.

Population size

This represents the number of individuals in the population.

Crossover method

The simplest form is the single point crossover as introduced in Section 3. There are several other methods such as Multipoint crossover, uniform crossover, intermediate recombination and linear recombination [17]. Any problem specific method can also be used.

Crossover probability

This determines the probability of an individual in the population getting an opportunity to mate. Higher the probability, the higher the number of individuals who will participate in forming the next generation.

Mutation method

The simplest form is the binary mutation in which values of selected bits are flipped. More complex methods too can be selected according to the data type of the problem.

Mutation probability

This determines how many individuals are subjected to mutation as a fraction of the population size.

A-IV.4. Application Areas of GA

Genetic Algorithms are used in a wide range of optimization problems. Mathematicians claim that the biggest advantage of using GA in such optimization is its likelihood of converging towards the global optimum value. A GA can tolerate noisy and discontinuous function evaluations, which are common characteristics of the real problems. The algorithm does not require formal initial estimation of a solution region or derivative information [17]. Followings are some examples.

Gas Turbine Blade Cooling Problem [17]

Modern gas turbine blades are cooled by passing cooler air through a series of passages in the blade. These passages must be designed carefully in order to get the maximum benefit without affecting the performance of the normal function. To ensure the soundness of the design, designers models these cooling systems on computers. The Rolls-Royce engineers have adapted a parameter tuning process in order to maintain the accuracy of the model. A GA based optimizer has been used to get the best set of parameters.

Job Shop Scheduling Problem [17]

This is the problem of allocating time, in the most efficient manner, for activities, which share a common pool of resources. This problem is one of the most difficult instances of NP Hard problems. The GA has been applied with good success to solve this optimization problem.

VLSI Routing Problem [17,18]

The GA has been used in solving interconnection design problems. The optimum layout of a VLSI must be designed under the constraints imposed by cross talk, electrical delay, area etc. The GA has provideds rather simple way of solving to this optimization problem.

Genetic Programming [19]

This is a an interesting use of GA. GA is used in programming. This is called Koza's method [19] after J.R. Koza who has applied this technique successfully. The algorithm is started with a random set of programs. The programmer defines the fitness.

Other than above specific applications there are applications in neural networks to optimize parameters like training rate and weights.