Reports of experiments

Hyperparameter tunning with Grid Search:

Parameter Grid and Trial Selection

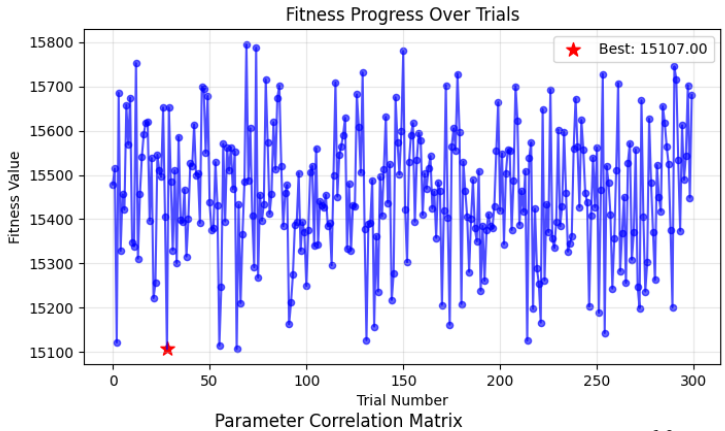
The parameter grid consisted of the following values:

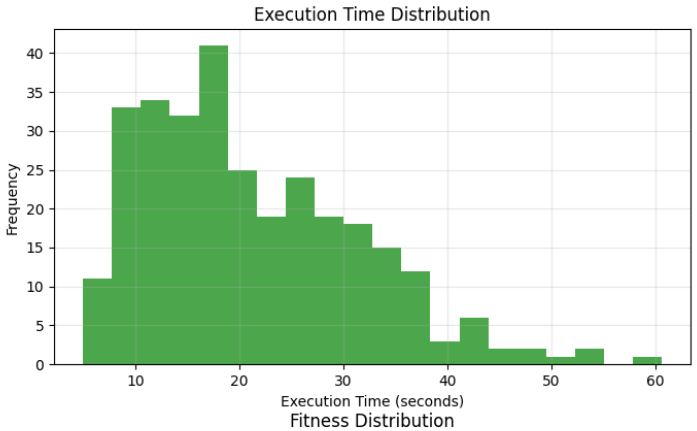
- Swarm Size: 40, 60, 80, 100, 120 (5 values)
- Max Iterations: 250, 350, 450, 550 (4 values)
- Employed Ratio: 0.35, 0.40, 0.45, 0.50, 0.55, 0.60 (6 values)
- Onlooker Ratio: 0.20, 0.25, 0.30, 0.35, 0.40 (5 values)
- Limit: 20, 25, 30, 35 (4 values)

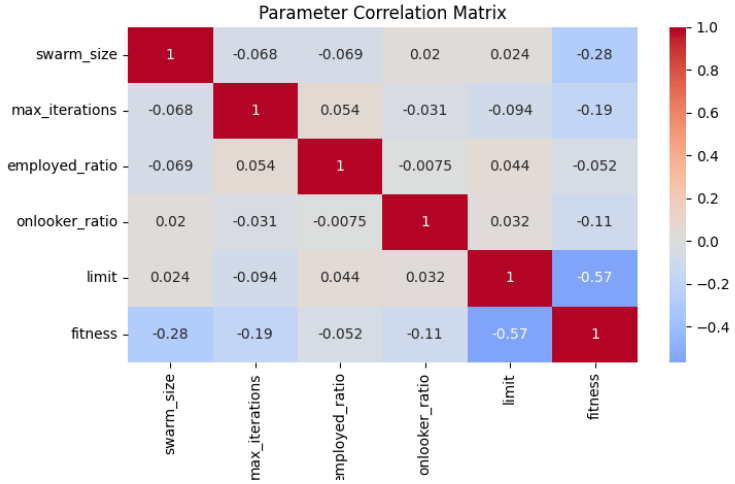
This leads to a total of possible parameter combinations in the full grid.

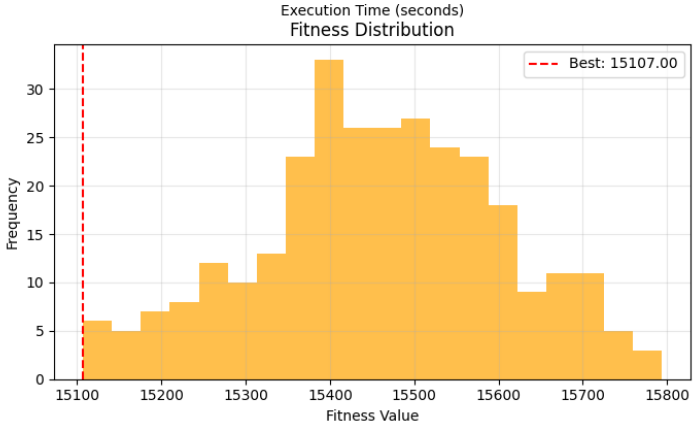
From these, 300 trials were selected for evaluation as a representative sample to effectively explore the parameter space while managing computational resources.

Result:









Best Hyperparameters

- **Swarm Size:** 80
- **Max Iterations:** 450
- **Employed Ratio:** 0.40
- **Onlooker Ratio:** 0.20
- **Limit:** 35

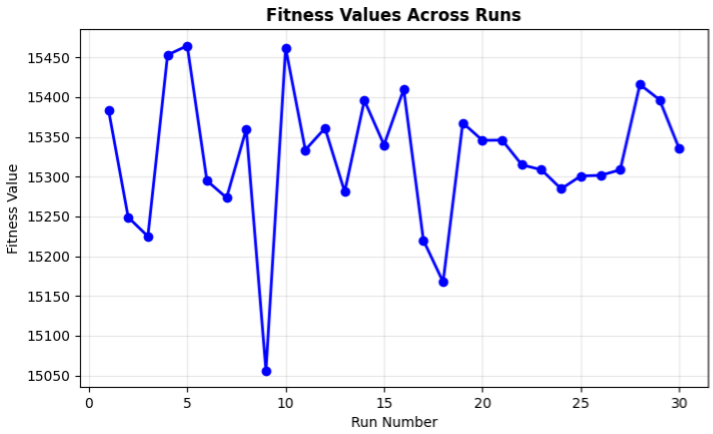
Experiments:

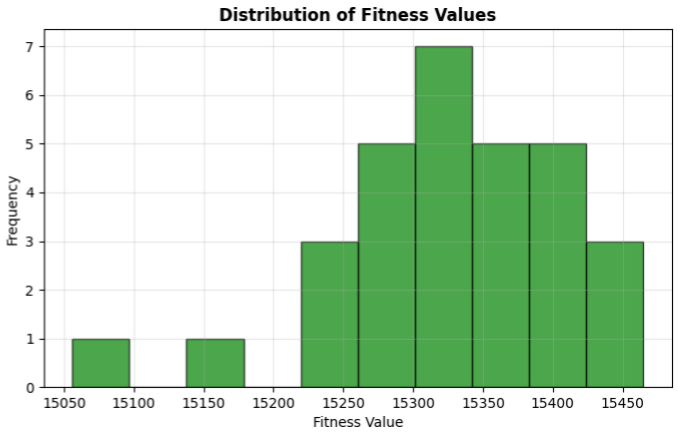
Serial Number	Best Fitness	Number of improvements	Time taken (Sec.)
1	15384.00	28	17.62
2	15249.00	44	17.08
3	15225.00	41	17.01
4	15453.05	32	16.60
5	15464.70	35	16.64
6	15295.00	36	16.63
7	15273.50	36	16.87
8	15360.00	28	17.61
9	15056.00	45	21.87
10	15462.00	24	19.99
11	15333.70	21	21.06
12	15361.05	37	19.36
13	15281.00	44	17.85
14	15396.00	33	17.79
15	15340.00	39	17.63
16	15410.00	36	17.28
17	15220.05	30	17.54
18	15167.70	28	17.21
19	15367.70	24	17.15
20	15345.70	32	17.52
21	15346.00	29	17.41
22	15315.00	36	17.18
23	15308.70	29	17.36
24	15284.70	28	17.33
25	15301.00	40	17.02
26	15301.70	45	18.71
27	15308.70	29	19.28
28	15416.00	25	20.32
29	15396.70	38	19.37
30	15335.05	34	23.51

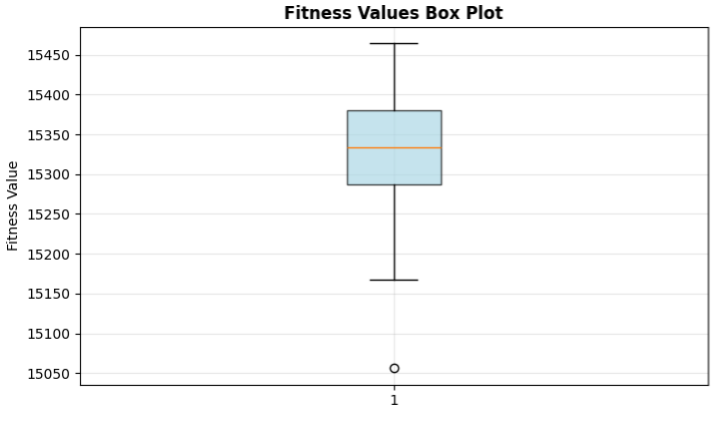
Summary Statistics

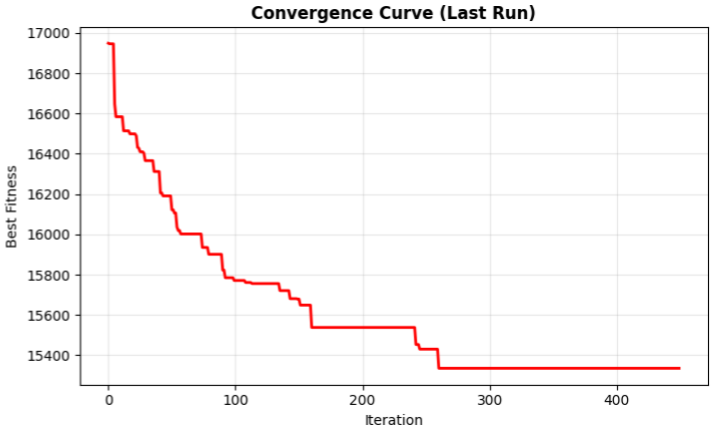
- Total Runs Requested: 30
- Successful Runs: 30
- Success Rate: 100%
- Best Fitness: 15,056.0
- Worst Fitness: 15,464.7
- Mean Fitness: 15,325.29
- Median Fitness: 15,334.38
- Standard Deviation of Fitness: 86.07
- Mean Execution Time (per run): 18.20 seconds
- Total Execution Time: 545.87 seconds

Result:









Hyperparameter tunning with Bayesian Search:

Parameter Grid and Trial Selection

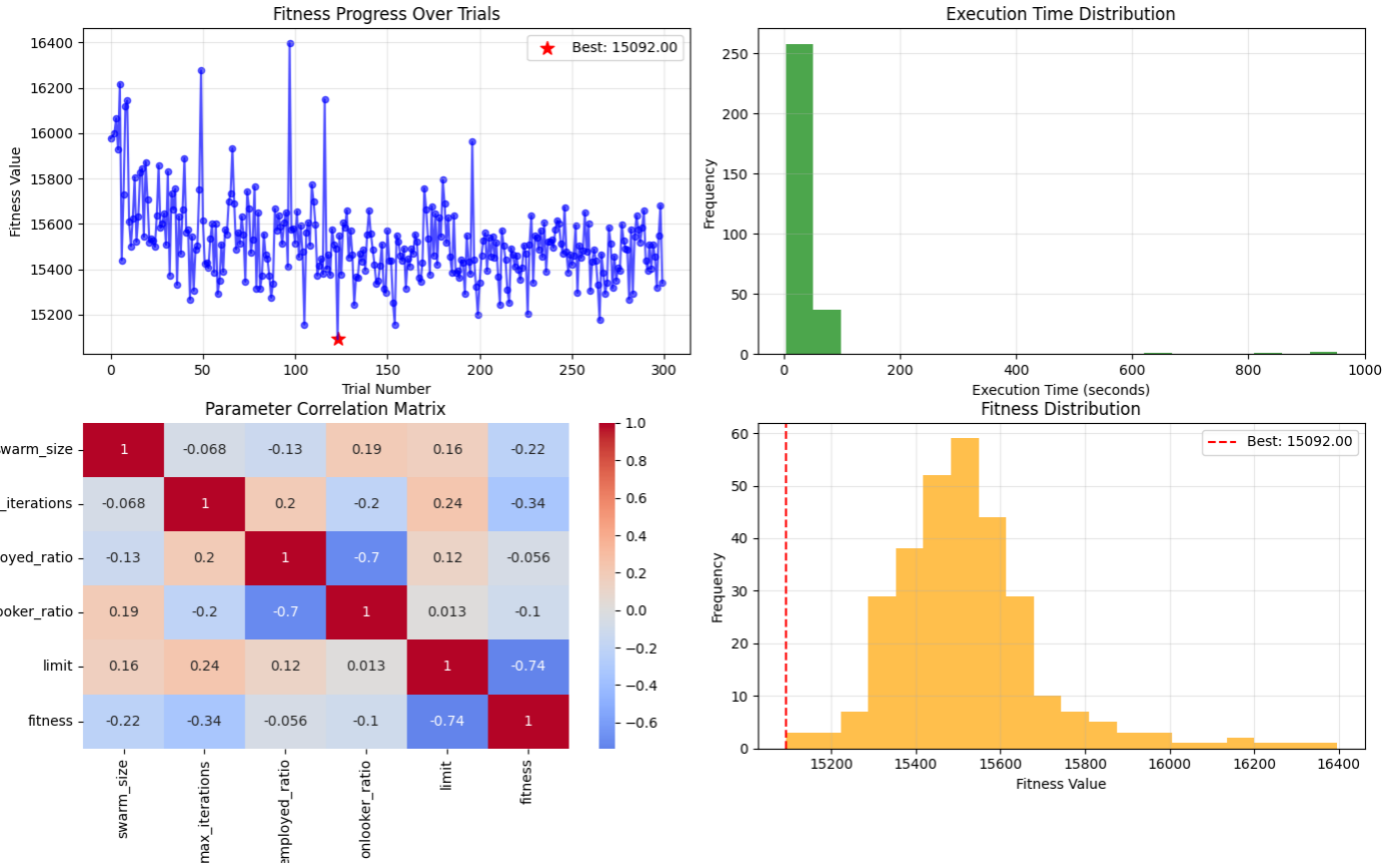
The parameter grid consisted of the following values:

- Swarm Size: 40, 60, 80, 100, 120 (5 values)
- Max Iterations: 250, 350, 450, 550 (4 values)
- Employed Ratio: 0.35, 0.40, 0.45, 0.50, 0.55, 0.60 (6 values)
- Onlooker Ratio: 0.20, 0.25, 0.30, 0.35, 0.40 (5 values)
- Limit: 20, 25, 30, 35 (4 values)

This leads to a total of possible parameter combinations in the full grid.

From these, 300 trials were selected for evaluation as a representative sample to effectively explore the parameter space while managing computational resources.

Result:



Best Hyperparameters

- **Employed Ratio:** 0.50
- **Onlooker Ratio:** 0.35
- **Swarm Size:** 110
- **Max Iterations:** 350
- **Limit:** 25

Experiments:

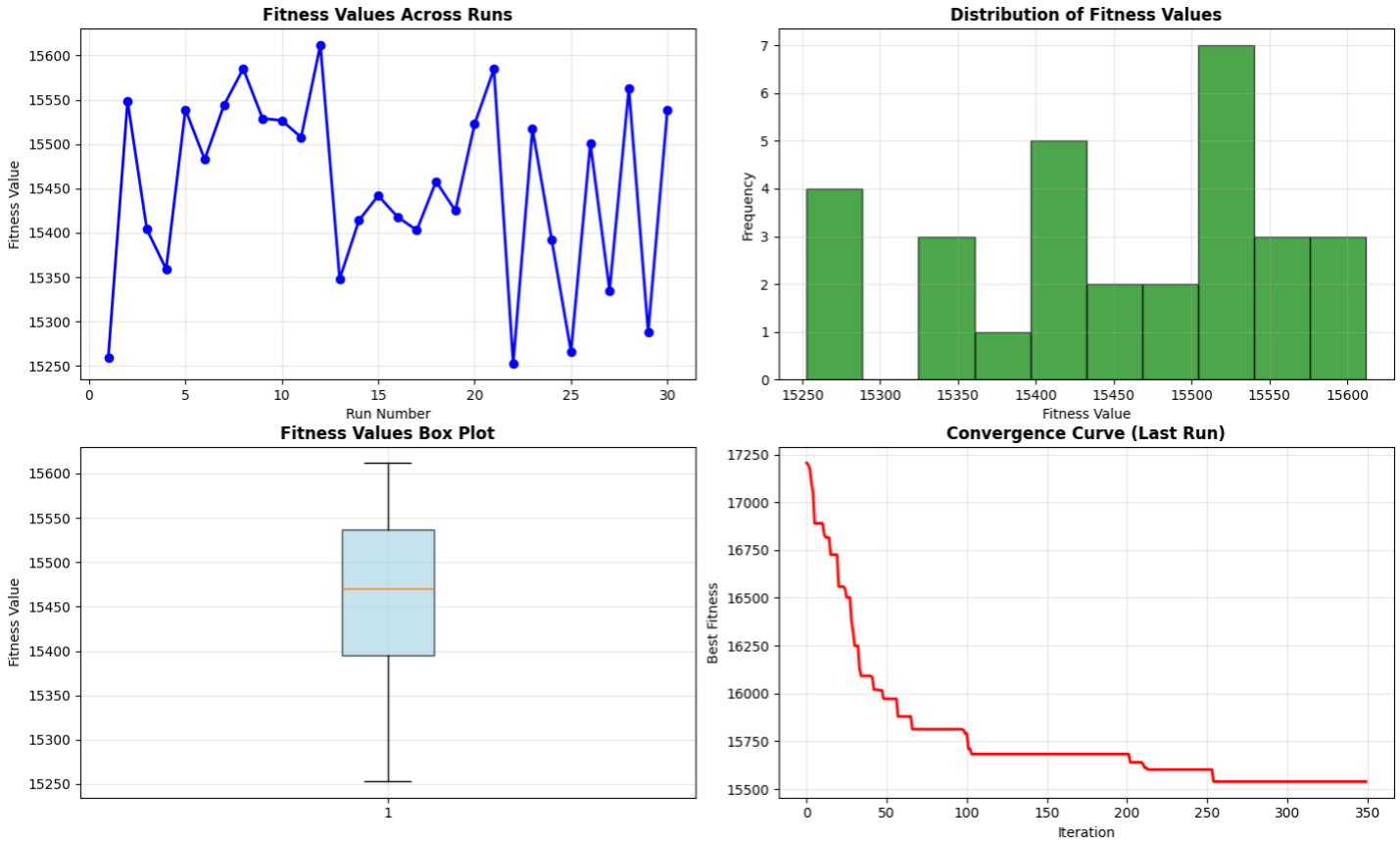
Serial Number	Best Fitness	Number of improvements	Time taken (Sec.)
1	15259.70	29	24.02
2	15548.50	32	23.95
3	15404.05	29	23.45
4	15359.05	21	23.42
5	15539.00	21	23.34
6	15482.75	32	23.34
7	15544.00	26	23.39
8	15585.00	23	23.56
9	15529.00	25	23.40
10	15526.75	30	24.08
11	15507.75	27	24.93
12	15612.00	12	23.79
13	15348.00	34	23.82
14	15414.05	30	23.80
15	15442.00	30	23.66
16	15418.00	23	23.65
17	15403.00	31	23.72
18	15458.00	24	23.93
19	15425.05	27	24.02
20	15522.70	28	23.79
21	15584.70	24	24.28
22	15252.75	22	24.37
23	15517.00	20	24.13
24	15391.75	39	23.84
25	15266.00	33	24.38
26	15501.00	25	23.94
27	15335.00	35	23.98
28	15563.00	34	24.23

29	15288.00	32	24.21
30	15539.00	31	24.49

Summary Statistics

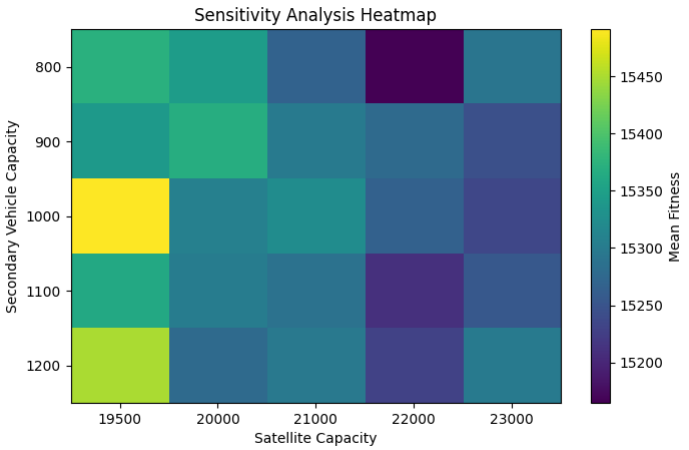
- Total Runs Requested: 30
- Successful Runs: 30
- Success Rate: 100%
- Best Fitness: 15,252.75
- Worst Fitness: 15,612.00
- Mean Fitness: 15,452.22
- Median Fitness: 15,470.38
- Standard Deviation of Fitness: 102.70
- Mean Execution Time (per run): 23.90 seconds
- Total Execution Time: 717.02 seconds

Result:



Sensitivity Analysis:

Satellite Capacity	Secondary Capacity (compartment)	Best Fitness	Mean Fitness	Std Fitness	Mean Time
19500	800	15088.00	15372.15	156.04	16.87s
19500	900	15258.05	15341.24	59.74	16.52s
19500	1000	15336.00	15491.03	86.92	16.52s
19500	1100	15335.00	15361.20	31.07	16.27s
19500	1200	15233.00	15450.10	119.35	16.61s
20000	800	15269.00	15345.10	70.70	16.31s
20000	900	15288.00	15367.75	73.50	16.39s
20000	1000	15153.05	15306.51	98.09	16.28s
20000	1100	15197.70	15302.19	63.75	16.52s
20000	1200	15024.70	15277.62	172.65	16.47s
21000	800	15186.05	15266.71	74.63	16.29s
21000	900	15145.70	15298.74	91.84	16.86s
21000	1000	15160.70	15323.09	89.20	16.83s
21000	1100	15250.00	15287.80	40.84	17.68s
21000	1200	15126.00	15296.95	99.53	18.25s
22000	800	14987.00	15164.68	141.09	19.93s
22000	900	15231.00	15277.92	56.31	18.21s
22000	1000	15171.00	15266.05	55.77	18.53s
22000	1100	14990.00	15209.92	121.89	18.34s
22000	1200	15164.00	15229.04	86.12	19.34s
23000	800	15177.00	15291.30	90.35	19.08s
23000	900	15147.70	15244.77	100.29	18.96s
23000	1000	15174.00	15233.55	74.76	18.75s
23000	1100	15163.70	15254.68	85.12	18.75s
23000	1200	15205.70	15299.35	65.76	18.62s



Optimization Run Results Summary (Run 76)

1. Overall Performance Metrics

Metric	Value	Unit/Notes
Run Number	76	
Timestamp	2025-10-01T19:33:26.653122	
Best Fitness	14979.0	(The best objective function value found)
Execution Time	15.14	seconds
Total Iterations	450	
Improvements Count	26	
Is Solution Valid?	True	(Yes)
Violations	None	

2. Customer Service & Algorithm Parameters

Metric / Parameter	Value	Notes
Total Customers	41	
Customers Served	41	
Service Rate	1.0	(100%)
Swarm Size	80	
Max Iterations	450	
Employed Ratio	0.4	
Onlooker Ratio	0.2	
Limit	35	

```
## 3. Final Routing Plan (Two-Echelon Structure)

### A. Primary Routes (Echelon 1: Depots <-> Satellites)
These routes connect the Depots (D) to the Satellites (S).

Route   Sequence
-----   --------------------------
D1      D1 -> S1 -> S2 -> D1
D2      D2 -> S2 -> S1 -> D2
D3      D3 -> S2 -> S1 -> D3
D4      D4 -> S1 -> S2 -> D4
D5      D5 -> S2 -> S1 -> D5
D6      D6 -> S2 -> S1 -> D6
D7      D7 -> S1 -> S2 -> D7
D8      D8 -> S2 -> S1 -> D8
D9      D9 -> S1 -> S2 -> D9
D10     D10 -> S2 -> S1 -> D10


### B. Secondary Routes (Echelon 2: Satellites <-> Customers)
These routes handle delivery from Satellites (S) to Customers (C).
```

Route Sequence (Start/End at Satellite)

----- ----------

Best Route with fitness value 14979.0 Km (For number of vehicles = 2)

S1 -> C22 -> C28 -> C15 -> C24 -> C4 -> C21 -> C5 -> C9 -> C29 -> C30 -> C13 -> C33 -> C18 -> C23 -> C17 -> C10 -> C25 -> C6 -> C2 -> C19 -> C20 -> C7 -> S1

S2 -> C36 -> C16 -> C32 -> C14 -> C27 -> C1 -> C8 -> C3 -> C31 -> C26 -> C12 -> C11 -> C35 -> C34 -> C37 -> C41 -> C39 -> C40 -> C38 -> S2

Convergence Curve Data

The convergence curve tracks the best fitness value over the 450 iterations.

Best Fitness: 14979.0

Starting Fitness: 16880.0

[16880.0, 16880.0, 16880.0, 16796.0, 16754.0, 16754.0, 16754.0, 16754.0, 16754.0, 16606.0, 16606.0, 16547.0, 16547.0, 16547.0, 16547.0, 16547.0, 16547.0, 16547.0, 16525.0, 16525.0, 16525.0, 16525.0, 16525.0, 16525.0, 16481.0, 16205.0, 16205.0, 16205.0, 16205.0, 16205.0, 16205.0, 16196.0, 16196.0, 16196.0, 16196.0, 16196.0, 16196.0, 16196.0, 16196.0, 16196.0, 16196.0, 16196.0, 16196.0, 16196.0, 16156.0, 16060.0, 16060.0, 16060.0, 16060.0, 16060.0, 16060.0, 16060.0, 16004.0, 16004.0, 16004.0, 16004.0, 16004.0, 16004.0, 16004.0, 16004.0, 16004.0, 16004.0, 16004.0, 15864.0, 15864.0, 15864.0, 15864.0, 15864.0, 15856.0, 15856.0, 15856.0, 15856.0, 15856.0, 15856.0, 15854.0, 15854.0, 15854.0, 15854.0, 15854.0, 15854.0, 15710.0, 15710.0, 15710.0, 15679.0, 15679.0, 15679.0, 15360.0, 15360.0, 15360.0, 15360.0, 15360.0, 15360.0, 15360.0, 15271.0, 15271.0, 15216.0, 15216.0, 15216.0, 15216.0, 15216.0, 15216.0, 15216.0, 15216.0, 15216.0, 15216.0, 15216.0, 15216.0, 15216.0, 15200.0, 15189.0, 15189.0, 15189.0, 15189.0, 15189.0, 15189.0, 15189.0, 15189.0, 15189.0, 15189.0, 15189.0, 15189.0, 15117.0, 15117.0, 15117.0, 15117.0, 15117.0, 15117.0, 15117.0, 15117.0, 15117.0, 15117.0, 15117.0, 15117.0, 15117.0, 15117.0, 15117.0, 15117.0, 15117.0, 15117.0, 15117.0, 15061.0, 15001.0,

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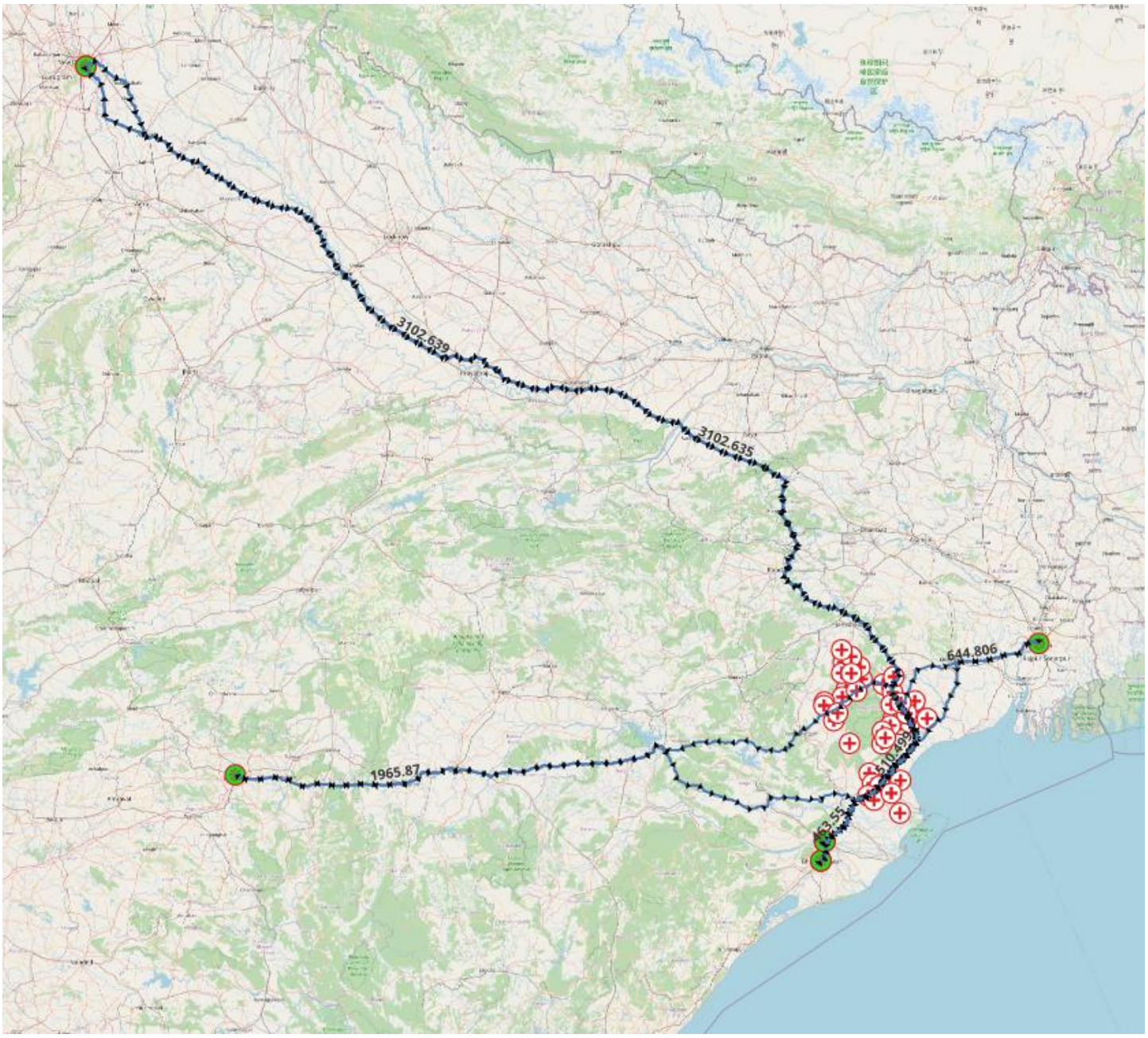
```

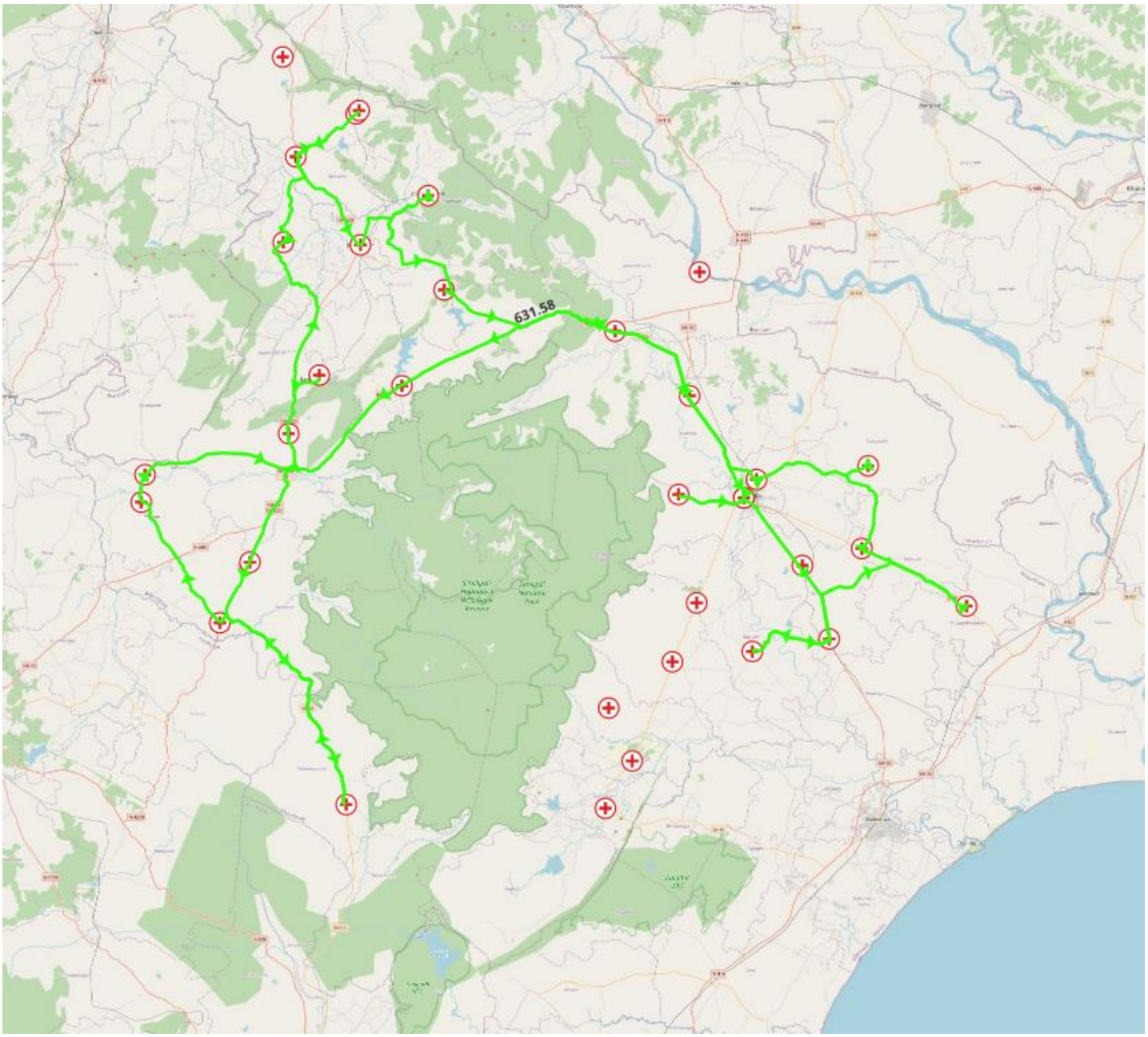
Visualization on Maps

First Echelon. :-

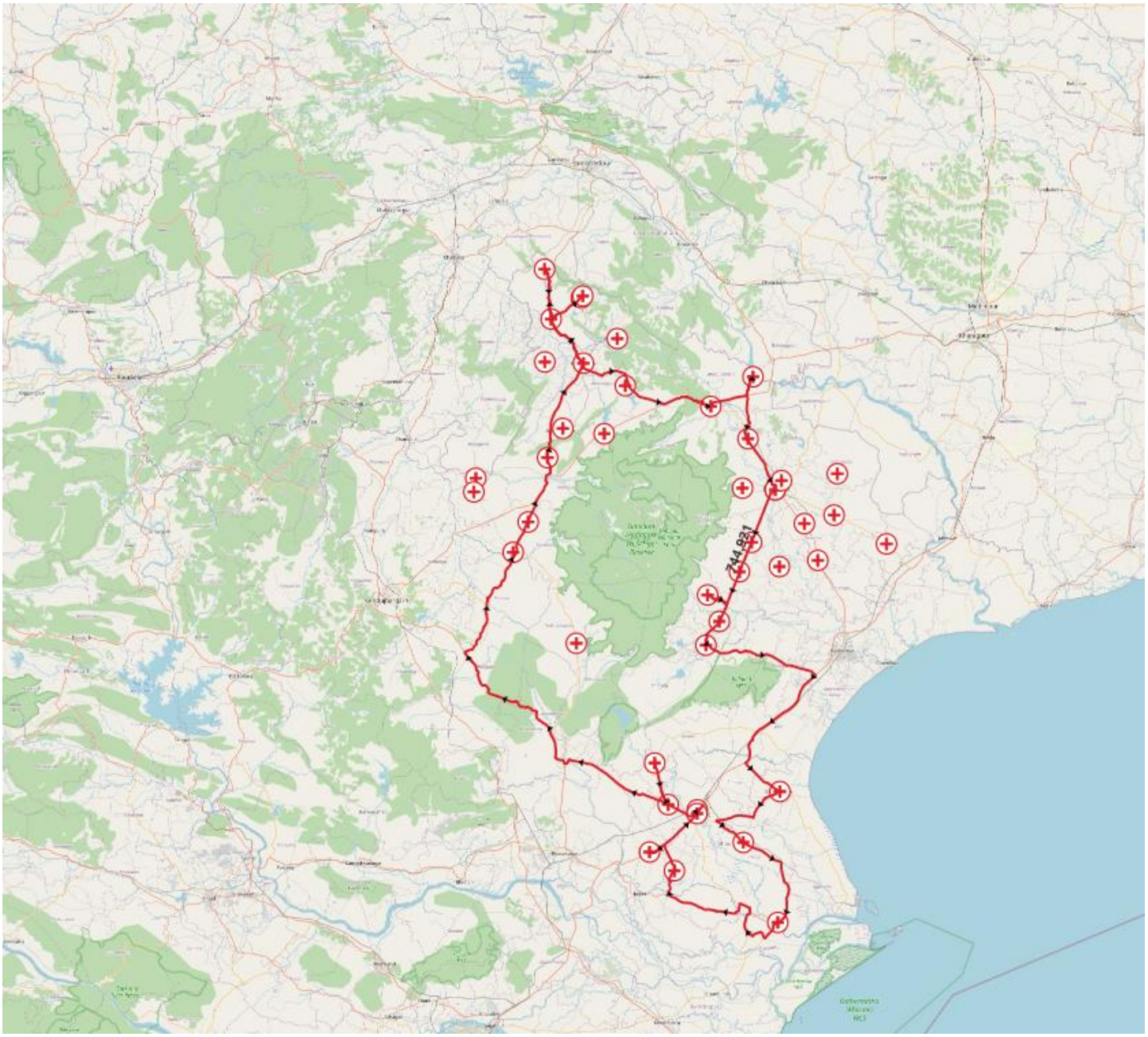


Second Echelon. :-

From Satellite 1st



From Satellite 2nd



Optimal number of vehicles :-

10 Customers:

Vehicles	Mean Fitness	Best Fitness	Success Rate
4	13921.33	13907.00	100%
6	14078.67	14076.00	100%
8	14371.00	14371.00	100%
12	14752.00	14752.00	100%
10	14776.00	14776.00	100%

20 Customers:

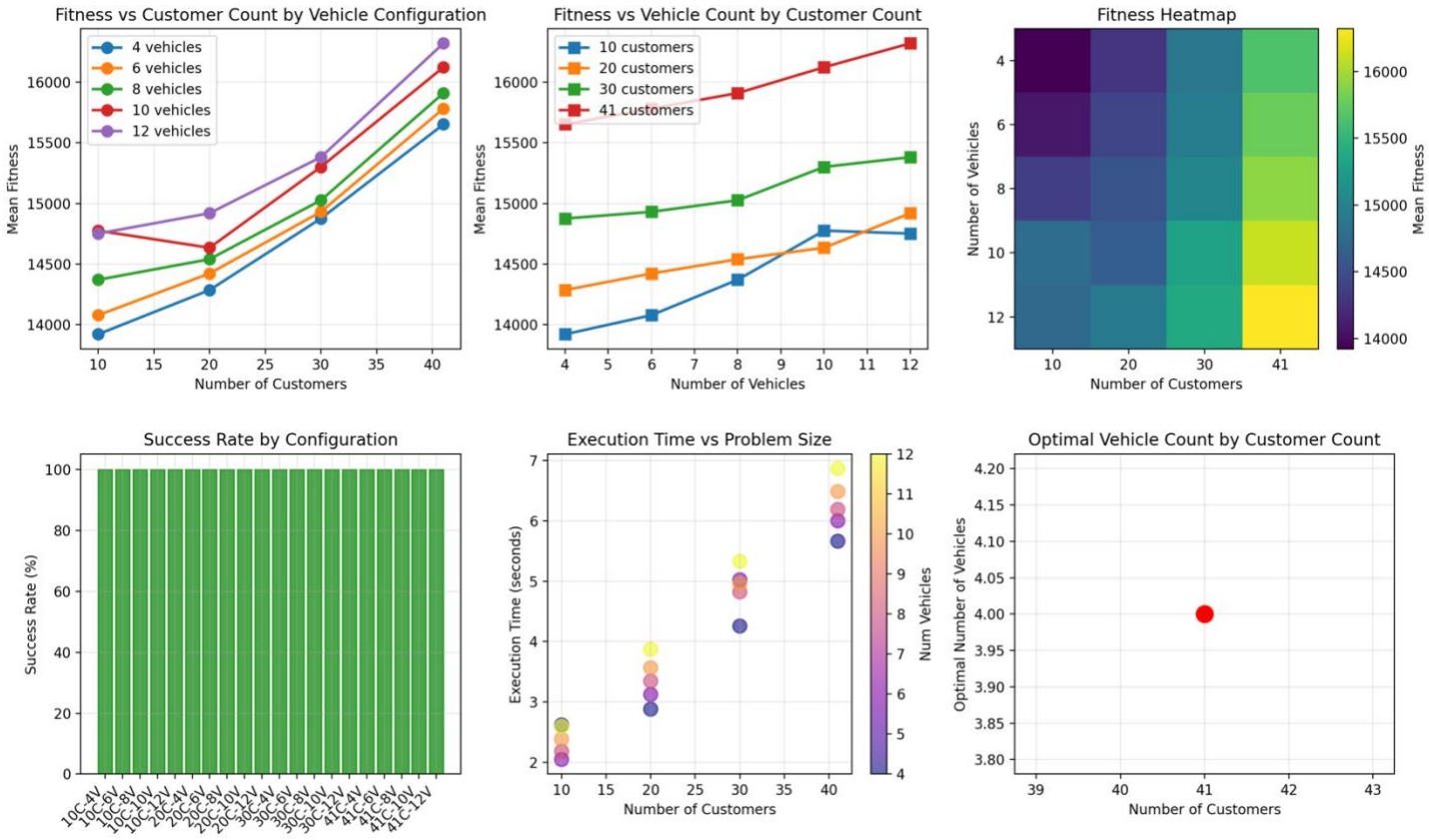
Vehicles	Mean Fitness	Best Fitness	Success Rate
4	14286.05	14276.05	100%
6	14422.38	14365.05	100%
8	14540.38	14498.05	100%
10	14634.73	14539.10	100%
12	14919.73	14892.05	100%

30 Customers:

Vehicles	Mean Fitness	Best Fitness	Success Rate
4	14875.82	14775.75	100%
6	14931.27	14853.75	100%
8	15026.52	14939.75	100%
10	15301.27	15242.75	100%
12	15381.87	15329.75	100%

41 Customers:

Vehicles	Mean Fitness	Best Fitness	Success Rate
4	15652.25	15573.00	100%
6	15781.93	15728.00	100%
8	15909.95	15825.00	100%
10	16123.25	15922.05	100%
12	16320.33	16239.05	100%



Conclusion

Hence we got the minimum distance in all the 3 cases using 10 customers , 20 customers and all 41 customers by using 4 Vehicles.

So we will perform sensitivity analysis using 4 vehicles in further Experiments

Sensitivity Analysis with Capacities (Number of Vehicles = 4)

Experiment 1

CAPACITY IMPACT ANALYSIS

==========

OPTIMAL CAPACITY CONFIGURATION:

Satellite Capacity (W): 22000

Secondary Vehicle Capacity (Q): 900

Mean Fitness: 15232.06 ± 124.28

Best Fitness: 15079.00

Success Rate: 100.0%

📈 SATELLITE CAPACITY (W) IMPACT:

W=19500: Mean Fitness = 15482.32

W=20000: Mean Fitness = 15395.57

W=21000: Mean Fitness = 15374.34

W=22000: Mean Fitness = 15306.86

W=23000: Mean Fitness = 15308.07

📈 SECONDARY VEHICLE CAPACITY (Q) IMPACT:

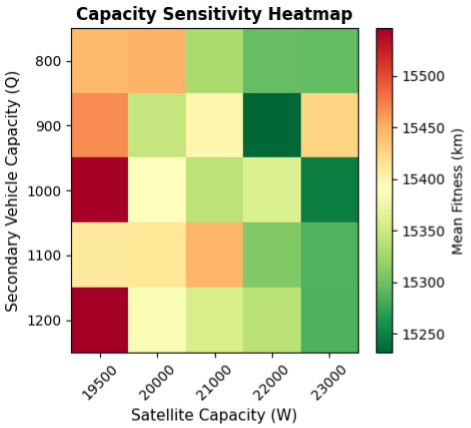
Q=800: Mean Fitness = 15361.87

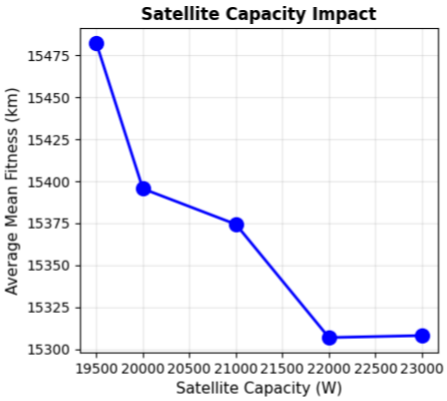
Q=900: Mean Fitness = 15374.38

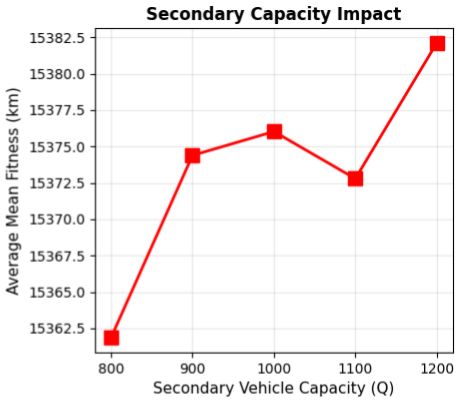
Q=1000: Mean Fitness = 15376.02

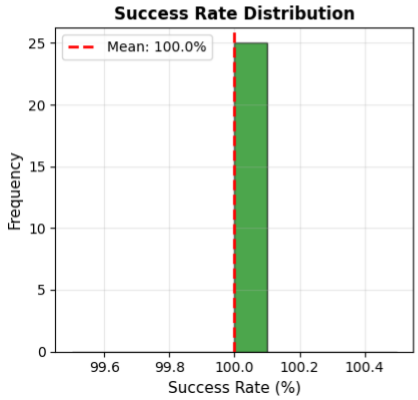
Q=1100: Mean Fitness = 15372.78

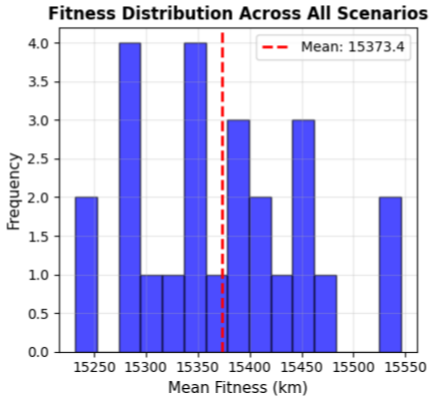
Q=1200: Mean Fitness = 15382.10

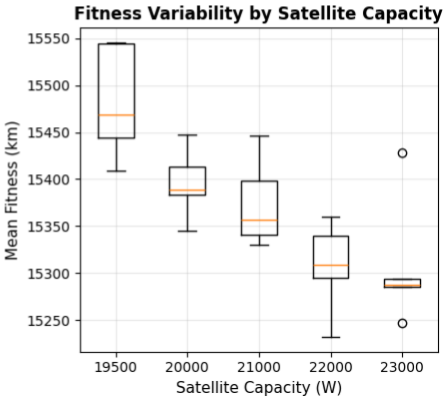

Capacity Sensitivity Heatmap
Secondary Vehicle Capacity (Q)
800
900
1000
1100
1200
19500
20000
21000
22000
23000
Satellite Capacity (W)
Mean Fitness (km)
15500
15450
15400
15350
15300
15250


Satellite Capacity Impact
Average Mean Fitness (km)
15475
15450
15425
15400
15375
15350
15325
15300
19500 20000 20500 21000 21500 22000 22500 23000
Satellite Capacity (W)


Secondary Capacity Impact
Average Mean Fitness (km)
15382.5
15380.0
15377.5
15375.0
15372.5
15370.0
15367.5
15365.0
15362.5
800
900
1000
1100
1200
Secondary Vehicle Capacity (Q)


Success Rate Distribution
Mean: 100.0%
Frequency
25
20
15
10
5
0
99.6
99.8
100.0
100.2
100.4
Success Rate (%)


Fitness Distribution Across All Scenarios
Mean: 15373.4
Frequency
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
15250 15300 15350 15400 15450 15500 15550
Mean Fitness (km)


Fitness Variability by Satellite Capacity
Mean Fitness (km)
15550
15500
15450
15400
15350
15300
15250
19500
20000
21000
22000
23000
Satellite Capacity (W)

Satellite Capacity (W)	Secondary Capacity (Q)	Number of Vehicles	Success Rate	Best Fitness	Mean Fitness	Std. Fitness	Median Fitness	Mean Time (sec.)
19500	800	4	100.0%	15258.75	15443.90	122.11	15454.00	18.26
19500	900	4	100.0%	15369.00	15468.48	92.16	15479.70	17.64
19500	1000	4	100.0%	15458.70	15544.15	43.32	15564.00	18.27
19500	1100	4	100.0%	15304.05	15409.33	104.88	15392.80	17.66
19500	1200	4	100.0%	15475.05	15545.76	60.46	15516.00	17.66
20000	800	4	100.0%	15285.05	15447.70	96.11	15438.70	17.70
20000	900	4	100.0%	15237.00	15345.24	77.01	15367.75	18.43
20000	1000	4	100.0%	15311.00	15388.95	63.96	15394.05	17.74
20000	1100	4	100.0%	15342.70	15412.78	53.75	15422.70	336.58
20000	1200	4	100.0%	15289.00	15383.16	55.52	15384.00	19.05
21000	800	4	100.0%	15174.00	15329.49	107.06	15309.00	17.80
21000	900	4	100.0%	15318.05	15398.36	95.70	15324.00	18.38
21000	1000	4	100.0%	15255.70	15340.51	71.74	15374.70	18.24
21000	1100	4	100.0%	15275.00	15446.36	89.66	15466.00	17.72
21000	1200	4	100.0%	15165.00	15356.97	108.37	15361.05	17.72
22000	800	4	100.0%	15085.75	15294.79	113.64	15325.70	17.94
22000	900	4	100.0%	15079.00	15232.06	124.28	15225.00	17.93
22000	1000	4	100.0%	15224.00	15359.55	70.48	15394.00	18.91
22000	1100	4	100.0%	15191.05	15308.55	103.94	15259.00	18.52
22000	1200	4	100.0%	15257.70	15339.37	52.64	15365.05	18.07
23000	800	4	100.0%	15105.75	15293.45	103.08	15325.00	17.67
23000	900	4	100.0%	15285.00	15427.78	76.35	15450.75	17.74
23000	1000	4	100.0%	15132.05	15246.96	93.69	15230.00	17.74
23000	1100	4	100.0%	15069.05	15286.90	111.72	15322.70	17.77
23000	1200	4	100.0%	15163.70	15285.24	78.54	15293.00	17.70

Experiment 2

CAPACITY IMPACT ANALYSIS

==========

🏆 OPTIMAL CAPACITY CONFIGURATION:

Satellite Capacity (W): 22000

Secondary Vehicle Capacity (Q): 800

Mean Fitness: 15229.04 ± 93.42

Best Fitness: 15062.05

Success Rate: 100.0%

📈 SATELLITE CAPACITY (W) IMPACT:

W=19500: Mean Fitness = 15440.00

W=20000: Mean Fitness = 15391.28

W=21000: Mean Fitness = 15398.62

W=22000: Mean Fitness = 15320.98

W=23000: Mean Fitness = 15313.48

📈 SECONDARY VEHICLE CAPACITY (Q) IMPACT:

Q=800: Mean Fitness = 15362.38

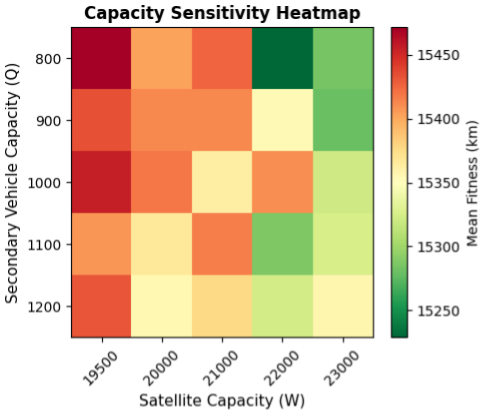
Q=900: Mean Fitness = 15378.44

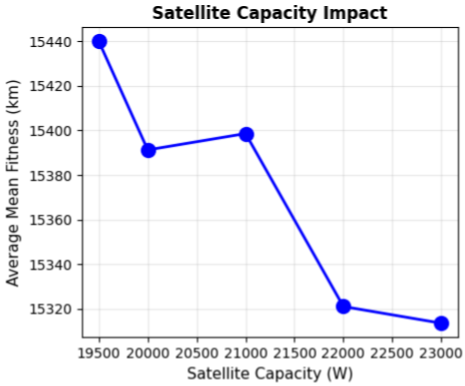
Q=1000: Mean Fitness = 15393.63

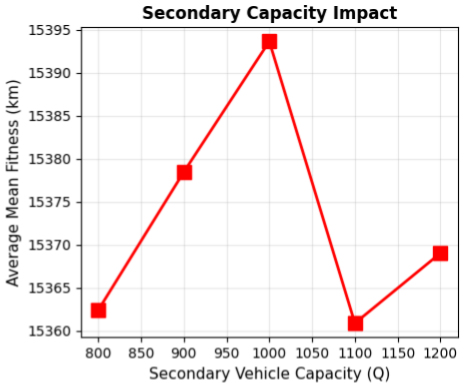
Q=1100: Mean Fitness = 15360.88

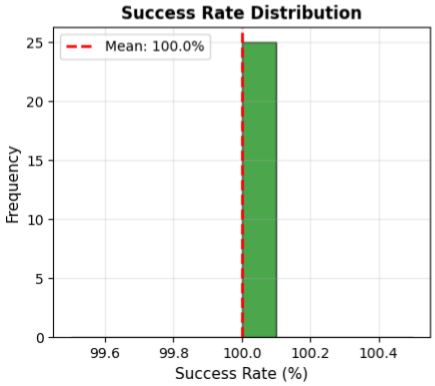
Q=1200: Mean Fitness = 15369.03

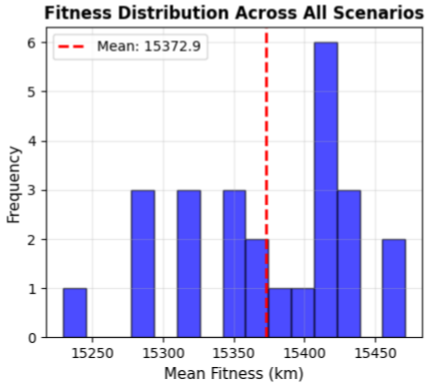
Table CSV: capacity_sensitivity_table_20251202_105127.csv

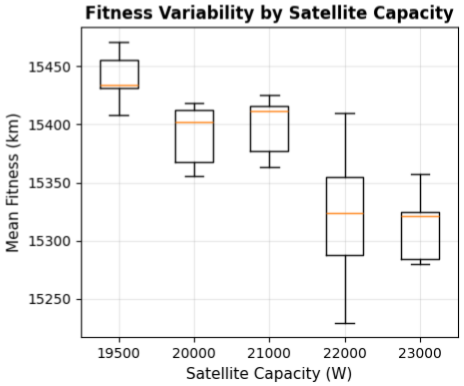

Capacity Sensitivity Heatmap
Secondary Vehicle Capacity (Q)
800
900
1000
1100
1200
19500
20000
21000
22000
23000
Satellite Capacity (W)
Mean Fitness (km)
15450
15400
15350
15300
15250


Satellite Capacity Impact
Average Mean Fitness (km)
15440
15420
15400
15380
15360
15340
15320
19500 20000 20500 21000 21500 22000 22500 23000
Satellite Capacity (W)


Secondary Capacity Impact
Average Mean Fitness (km)
15395
15390
15385
15380
15375
15370
15365
15360
800 850 900 950 1000 1050 1100 1150 1200
Secondary Vehicle Capacity (Q)

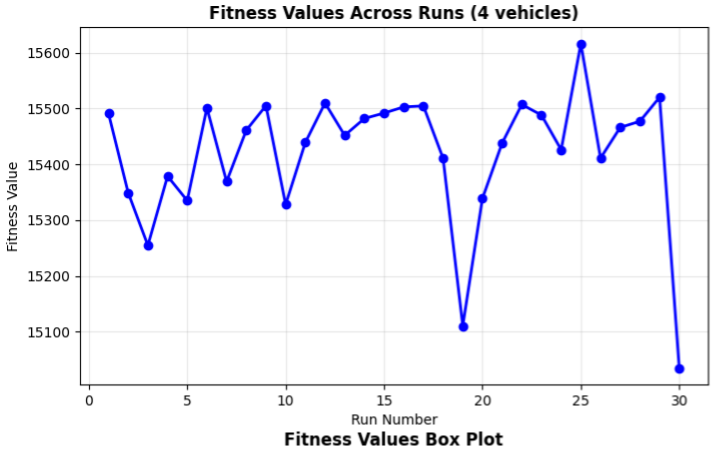

Success Rate Distribution
Mean: 100.0%
Frequency
25
20
15
10
5
0
99.6
99.8
100.0
100.2
100.4
Success Rate (%)

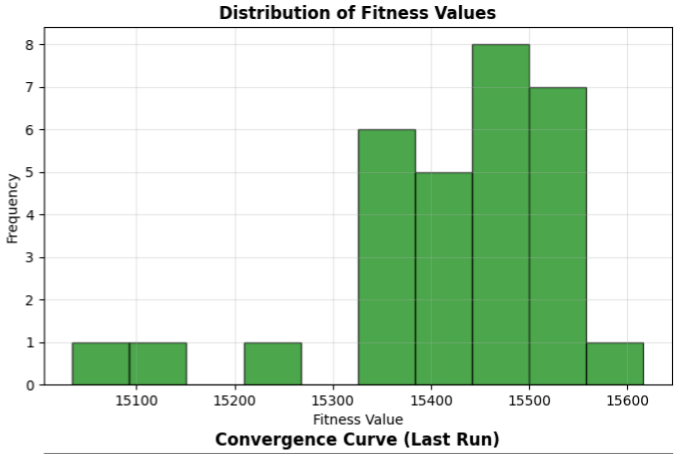

Fitness Distribution Across All Scenarios
Mean: 15372.9
Frequency
6
5
4
3
2
1
0
15250
15300
15350
15400
15450
Mean Fitness (km)

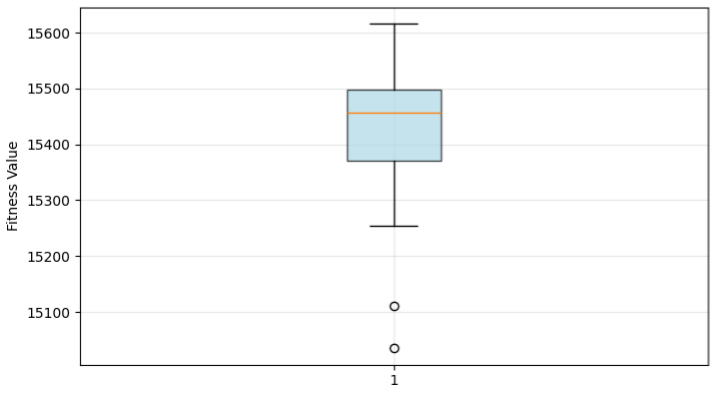

Fitness Variability by Satellite Capacity
Mean Fitness (km)
15450
15400
15350
15300
15250
19500
20000
21000
22000
23000
Satellite Capacity (W)

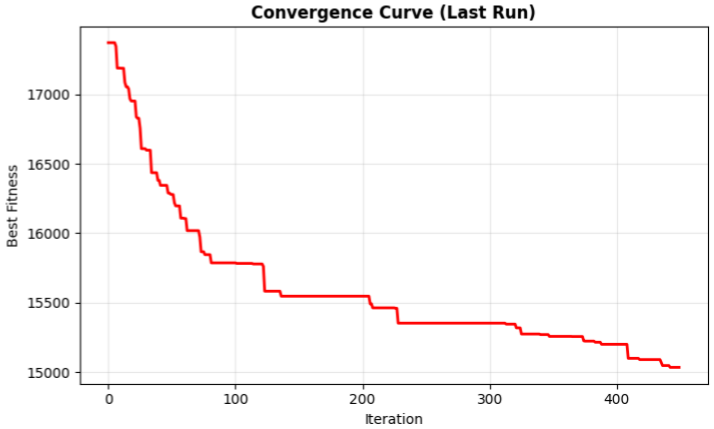
Satellite Capacity (W)	Secondary Capacity (Q)	Number of Vehicles	Success Rate	Best Fitness	Mean Fitness	Std. Fitness	Median Fitness	Mean Time (sec.)
19500	800	4	100.0%	15182.70	15471.28	155.14	15521.00	17.12
19500	900	4	100.0%	15345.00	15434.14	59.60	15453.00	17.21
19500	1000	4	100.0%	15345.75	15455.26	77.71	15453.05	17.36
19500	1100	4	100.0%	15312.00	15407.76	65.82	15398.05	17.49
19500	1200	4	100.0%	15254.00	15431.58	130.78	15414.50	17.37
20000	800	4	100.0%	15265.75	15402.30	75.31	15436.05	17.34
20000	900	4	100.0%	15316.00	15412.03	77.26	15438.05	17.52
20000	1000	4	100.0%	15288.70	15418.45	93.43	15399.00	17.42
20000	1100	4	100.0%	15314.00	15368.09	42.78	15395.00	17.43
20000	1200	4	100.0%	15293.05	15355.55	38.42	15359.70	17.40
21000	800	4	100.0%	15181.70	15425.25	124.37	15474.05	17.93
21000	900	4	100.0%	15327.05	15411.71	70.88	15397.70	17.46
21000	1000	4	100.0%	15240.00	15363.11	76.85	15384.05	17.41
21000	1100	4	100.0%	15323.00	15416.28	101.14	15340.00	17.41
21000	1200	4	100.0%	15219.00	15376.75	100.50	15422.00	17.42
22000	800	4	100.0%	15062.05	15229.04	93.42	15256.00	17.38
22000	900	4	100.0%	15280.75	15354.69	43.23	15362.00	17.37
22000	1000	4	100.0%	15306.00	15410.03	78.94	15442.75	17.41
22000	1100	4	100.0%	15149.00	15287.56	96.94	15296.70	17.41
22000	1200	4	100.0%	15179.05	15323.56	76.73	15341.00	17.40
23000	800	4	100.0%	15053.70	15284.04	142.44	15295.75	17.51
23000	900	4	100.0%	15201.05	15279.64	58.35	15265.70	17.28
23000	1000	4	100.0%	15070.75	15321.32	145.40	15320.05	17.22
23000	1100	4	100.0%	15253.05	15324.70	67.20	15310.75	17.24
23000	1200	4	100.0%	15267.00	15357.69	78.68	15358.75	17.23

Route Analysis :-









🏆 FINAL BEST SOLUTION ROUTES:

🚚 Primary Vehicle Routes (Depots → Satellites):

Vehicle D1: D1 → S2 → S1 → D1 (2 satellites)

Vehicle D2: D2 → S2 → S1 → D2 (2 satellites)

Vehicle D3: D3 → S2 → S1 → D3 (2 satellites)

Vehicle D4: D4 → S1 → S2 → D4 (2 satellites)

Vehicle D5: D5 → S2 → S1 → D5 (2 satellites)

Vehicle D6: D6 → S2 → S1 → D6 (2 satellites)

Vehicle D7: D7 → S1 → S2 → D7 (2 satellites)

Vehicle D8: D8 → S1 → S2 → D8 (2 satellites)

Vehicle D9: D9 → S1 → S2 → D9 (2 satellites)

Vehicle D10: D10 → S1 → S2 → D10 (2 satellites)

🚚 Secondary Vehicle Routes (Satellites → Customers) - Multiple Vehicles:

S1_V1 (from S1): S1 → C10 → C17 → C27 → C2 → C19 → C18 → C33 → S1 (7 customers)

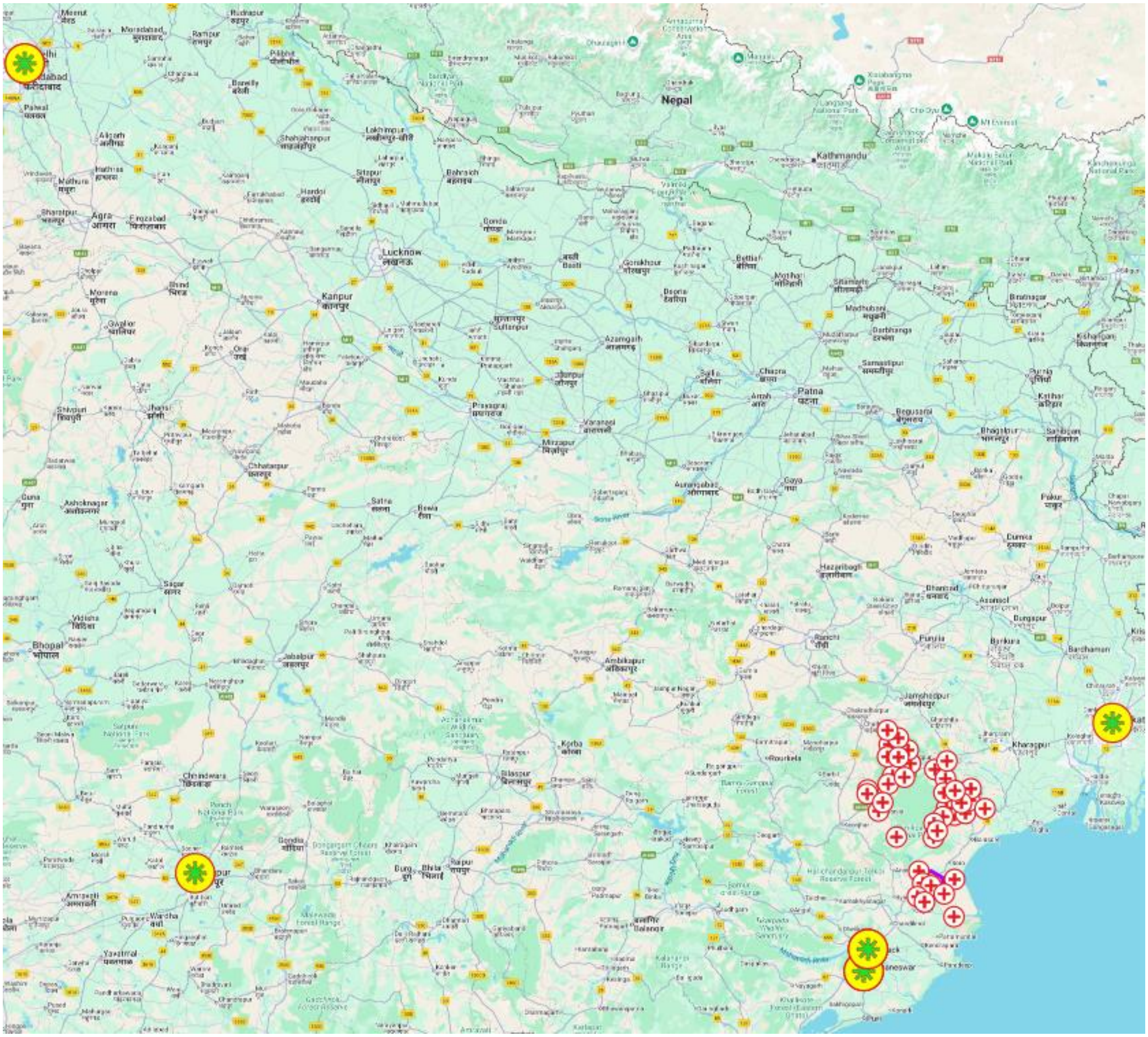
S1_V2 (from S1): S1 → C7 → C9 → C13 → C40 → C35 → C34 → C14 → C23 → C8 → C26 → C20 → C31 → C3 → C22 → C29 → C5 → S1 (16 customers)

S2_V1 (from S2): S2 → C38 → C32 → C16 → C36 → C41 → C39 → S2 (6 customers)

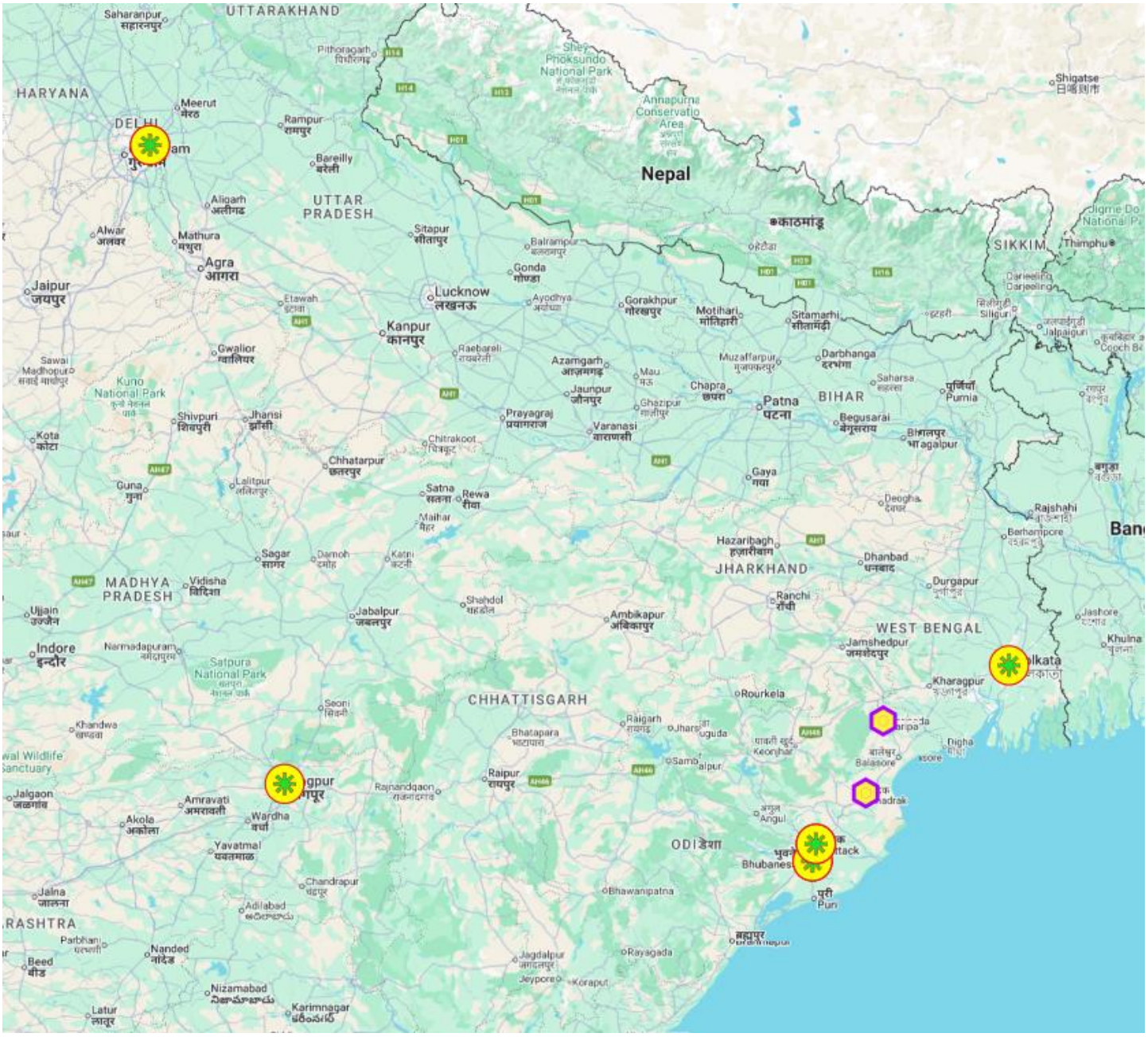
S2_V2 (from S2): S2 → C15 → C30 → C4 → C28 → C24 → C21 → C12 → C11 → C1 → C25 → C6 → C37 → S2 (12 customers)

Run 30: Fitness = 15034.7000 | Served = 41/41 | Vehicles = 4

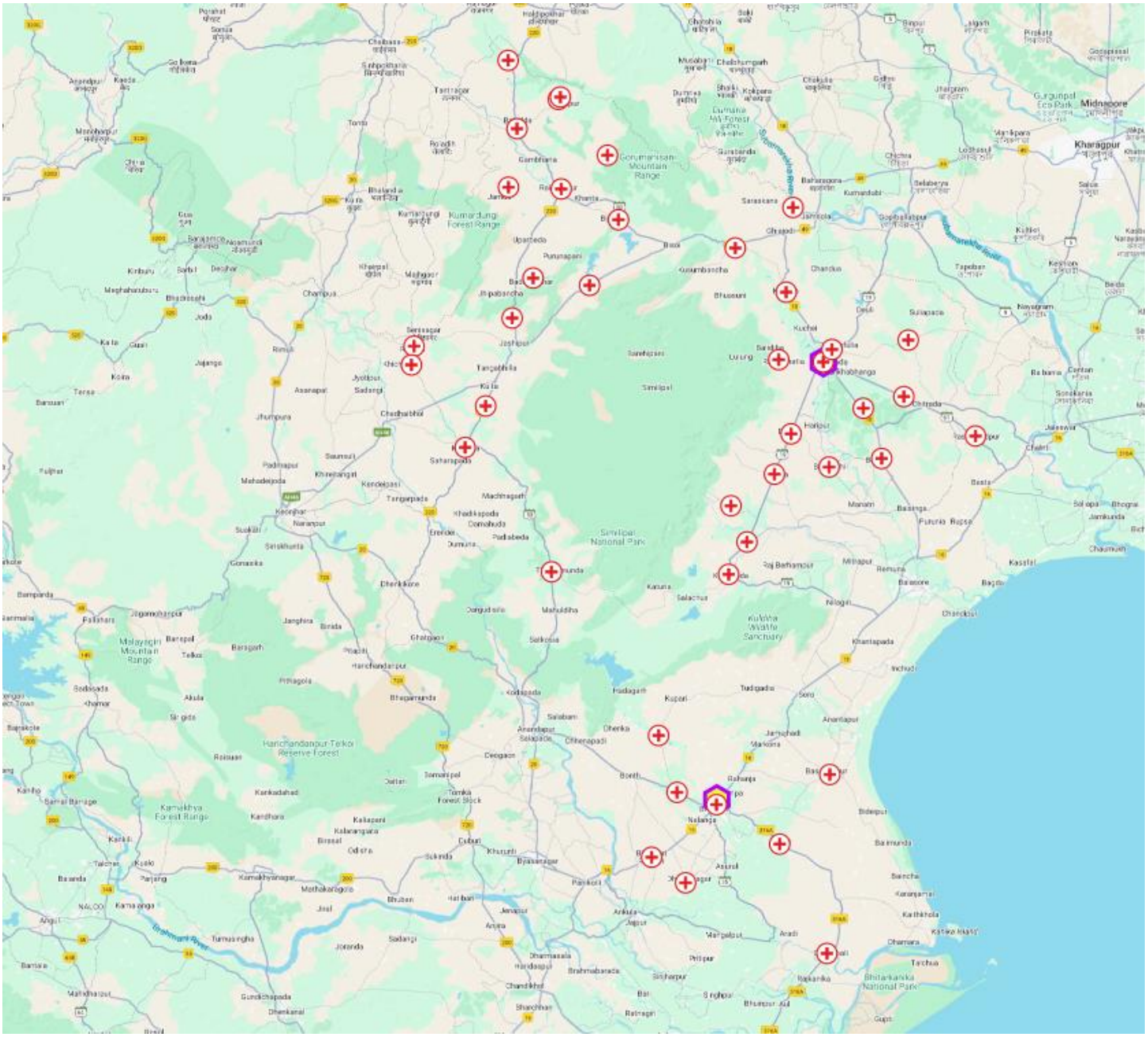
All Coordinates:



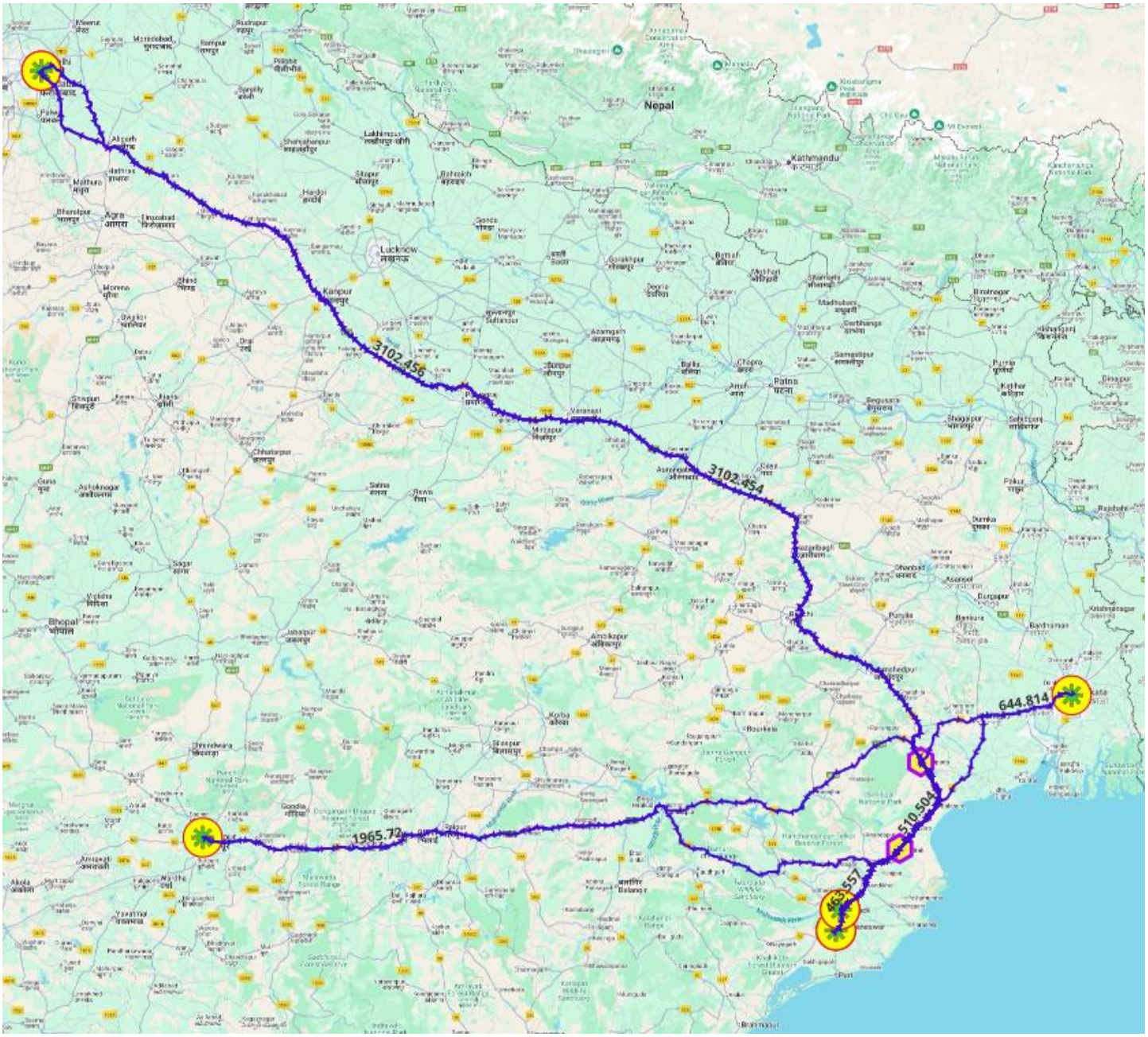
Location of Depots and Satellites :-



Customers and Satellite :-


Kharagpur
Midnapore
Gumamisan Mountain Range
Kumardung Forest Range
Similipal National Park
Kuldiha Wildlife Sanctuary
Malayagiri Mountain Range
Harichandanpur-Telkoi Reserve Forest
Kamakhya Forest Range
Bhitarkanika National Park

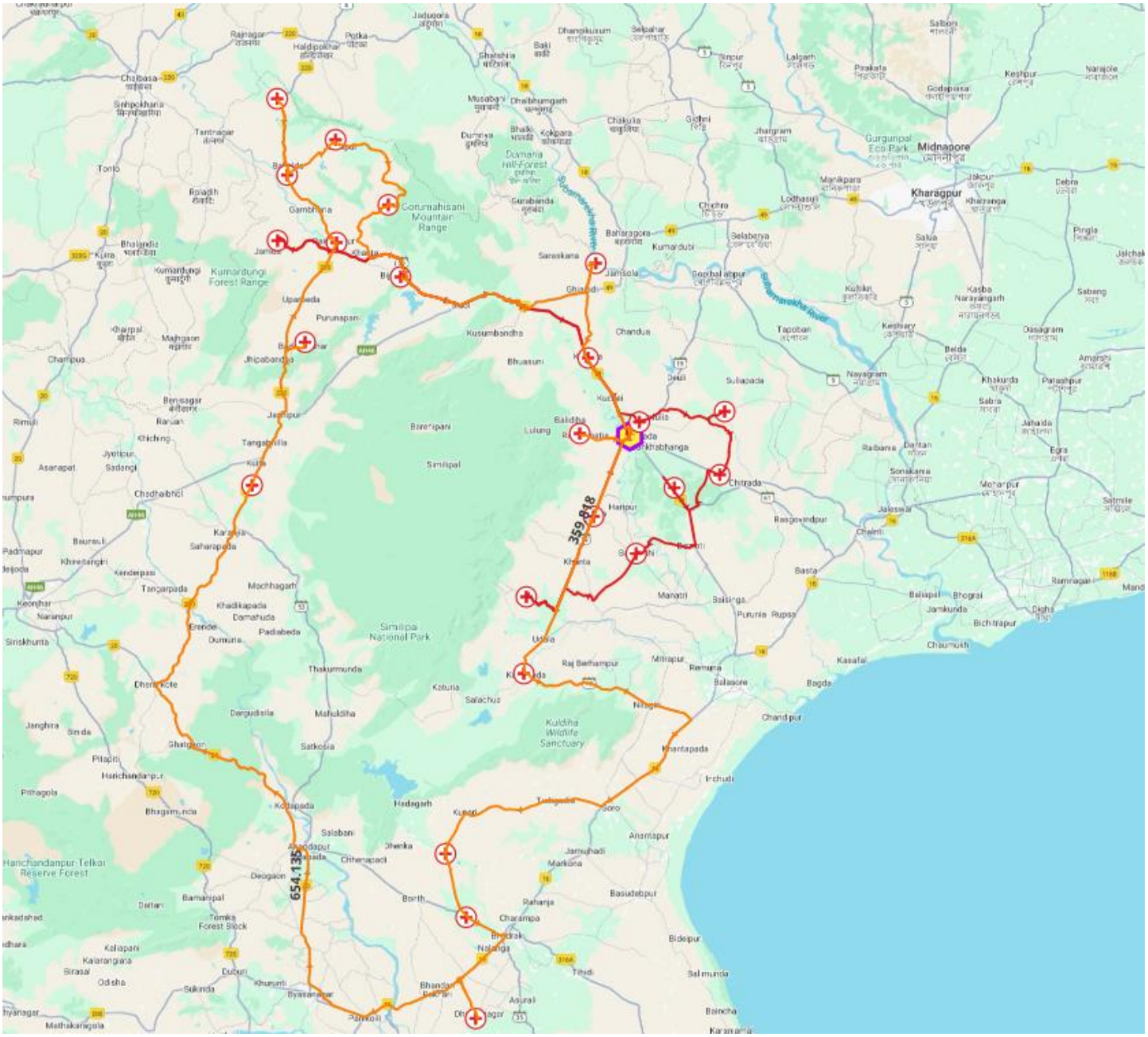
First Echelon. :-



Second Echelon. :-

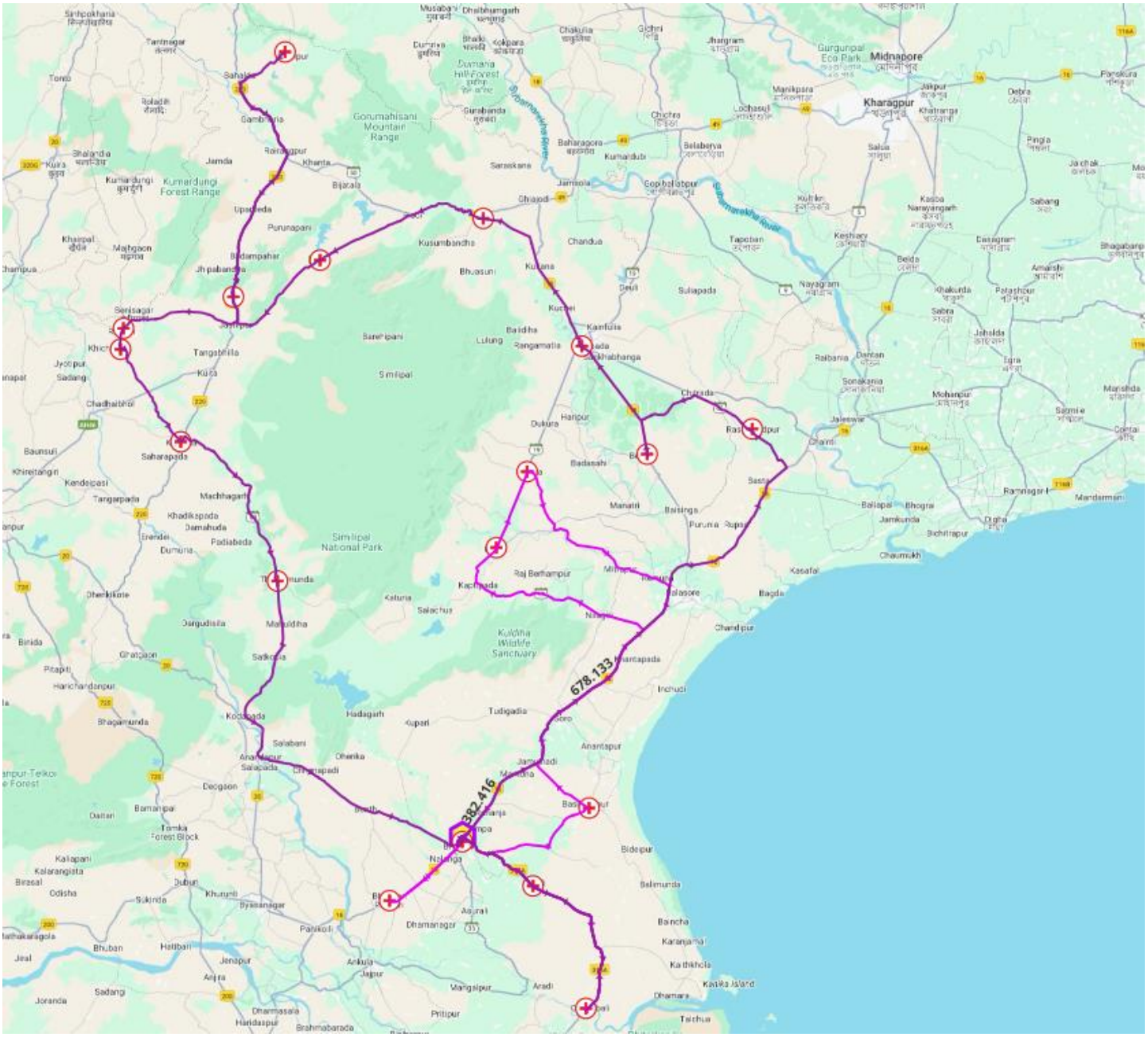
From Satellite 1:

Distance is covered by two vehicles



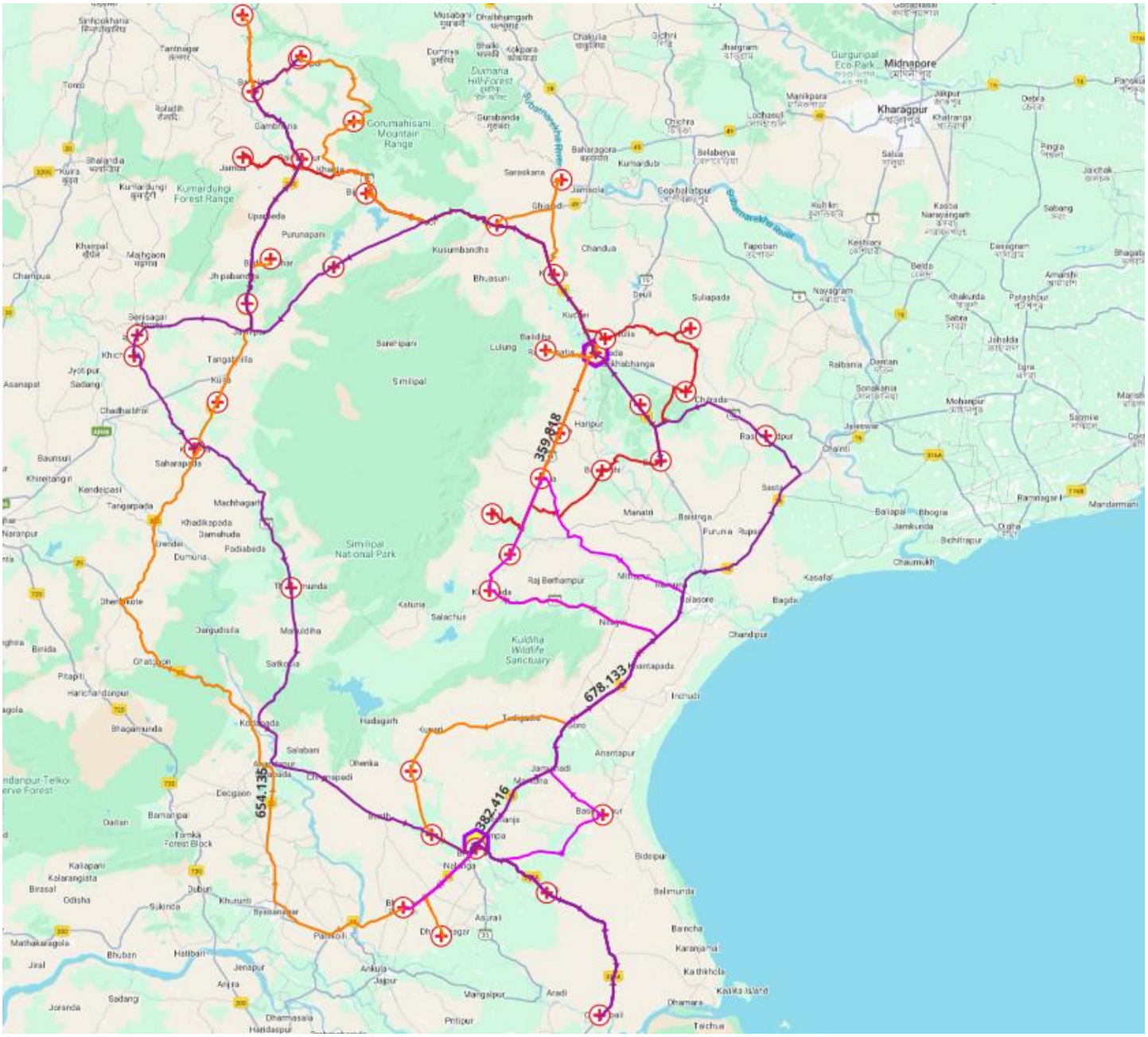
From Satellite 2 :-

Distance is covered by 2 Vehicles

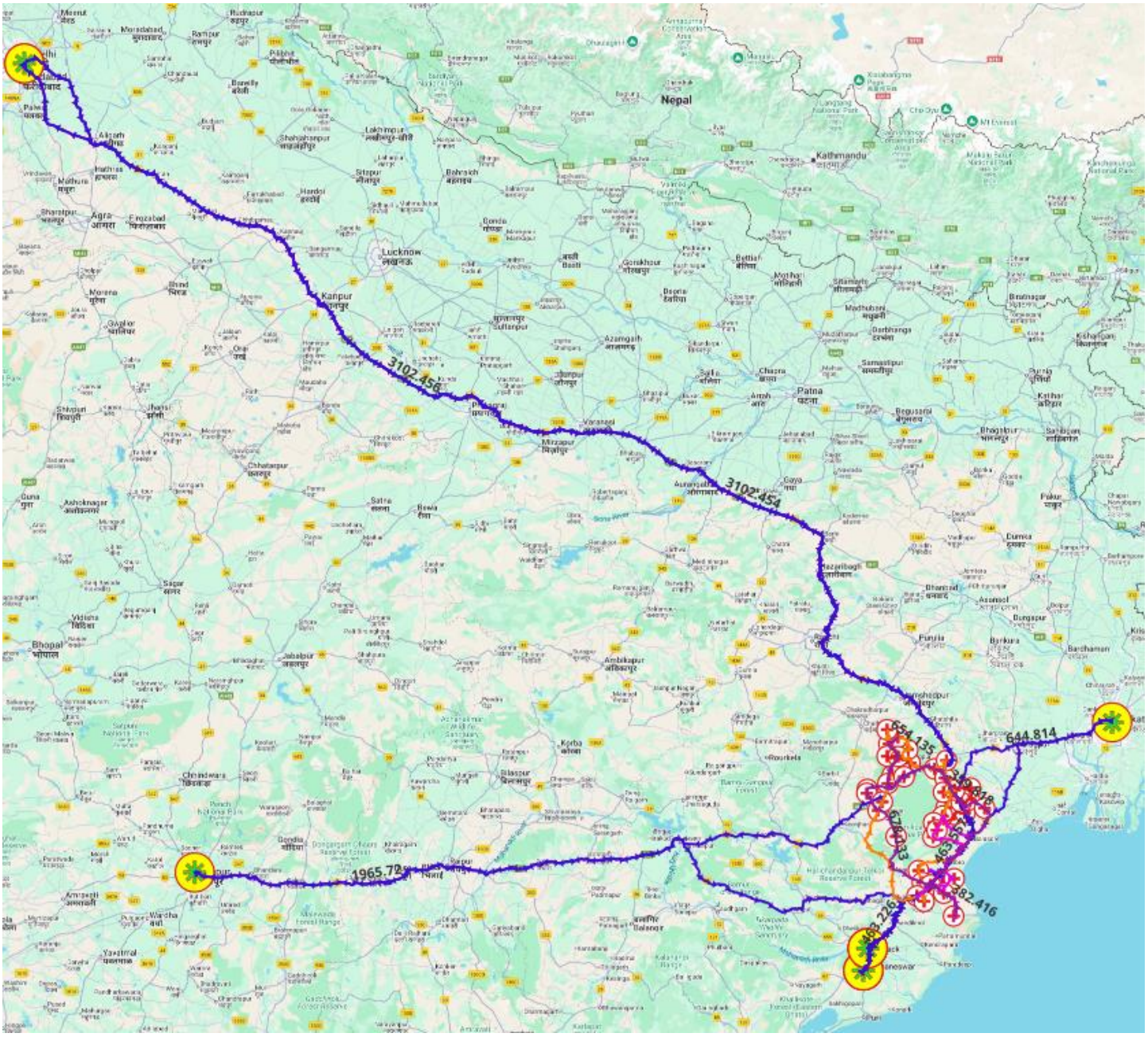


Complete 2nd echelon

Number of Vehicles used is 4



Complete map:



So practically the length of the Route comes out to be **13816 km**