Fleet Sizing for Fractional Ownership of Autonomous Vehicles

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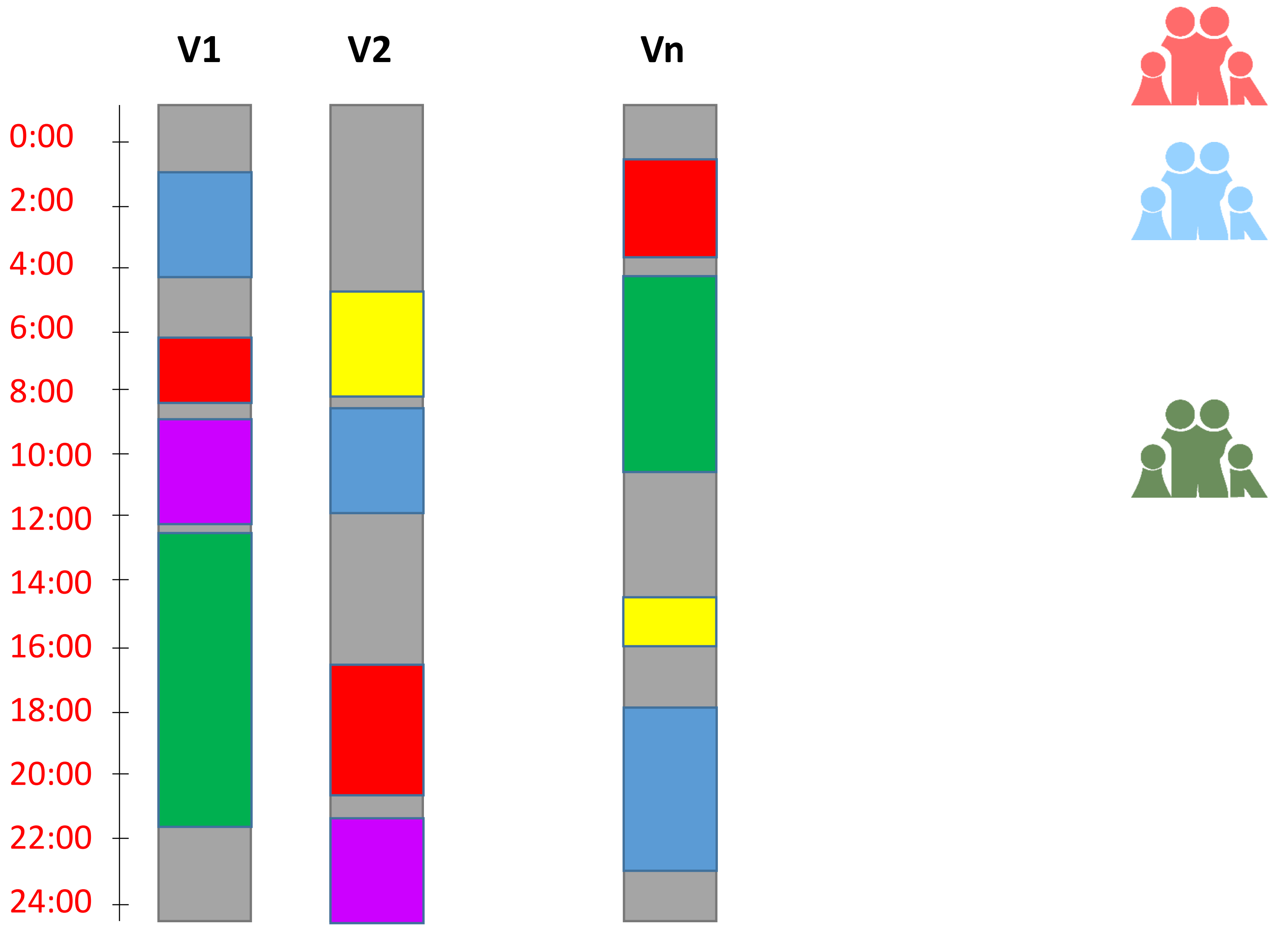
Emerging trends:

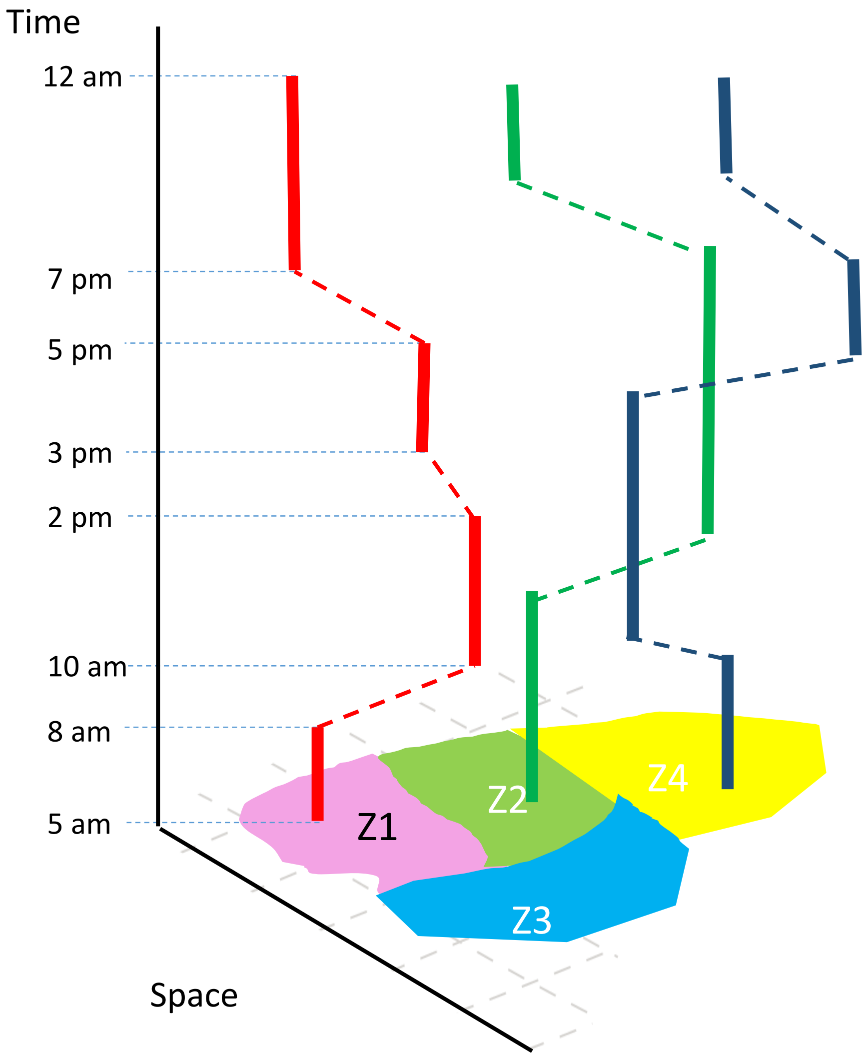
- Collaborative consumption
- Autonomous vehicles (AVs)

Shared Ownership of Vehicles

Problem Statement:



Chains of activities:



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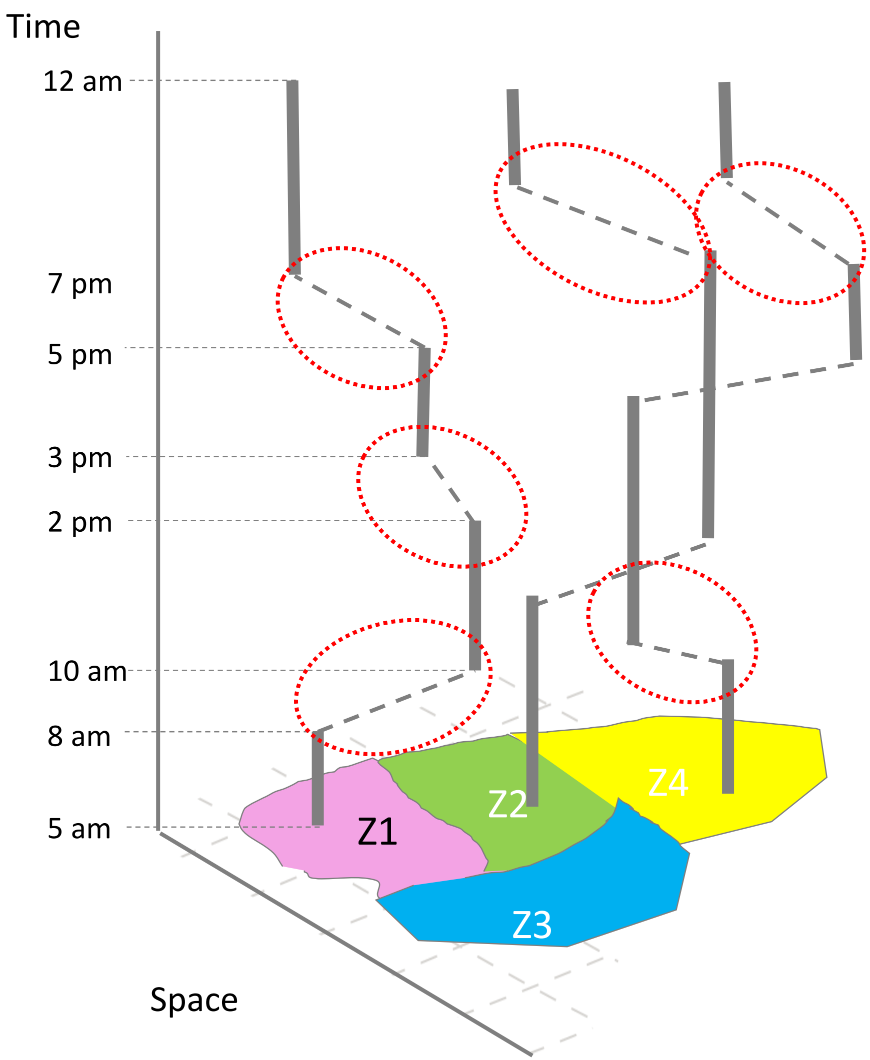
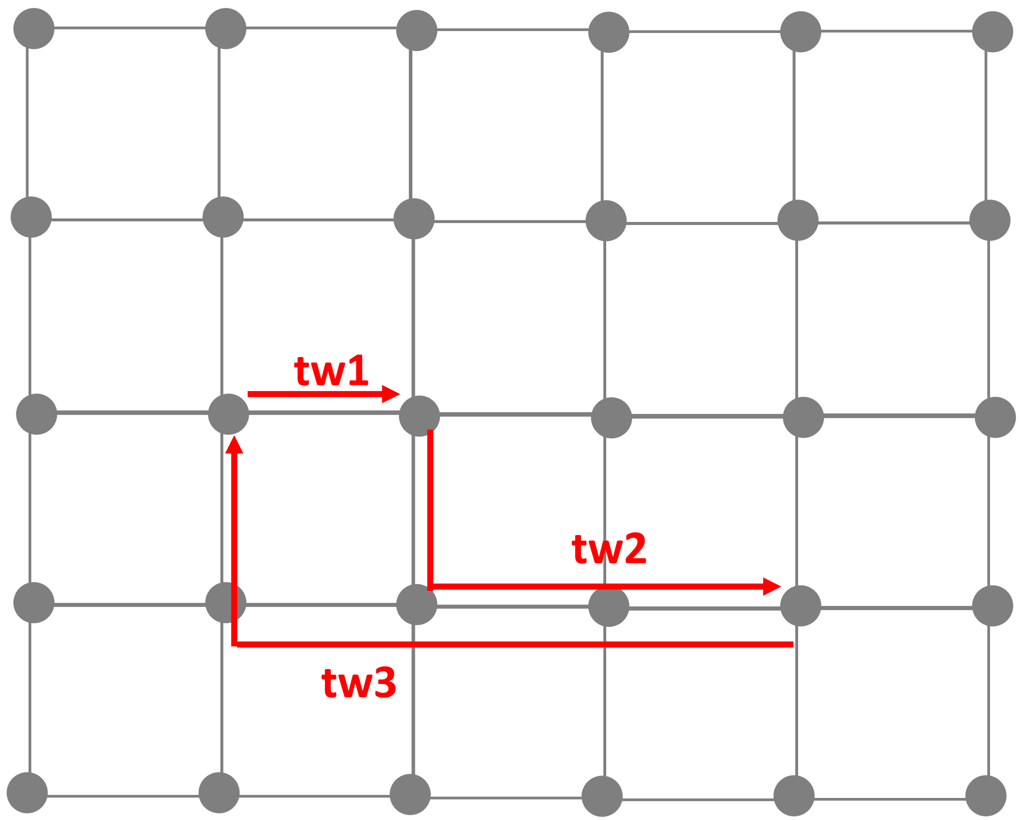


Model formulation:



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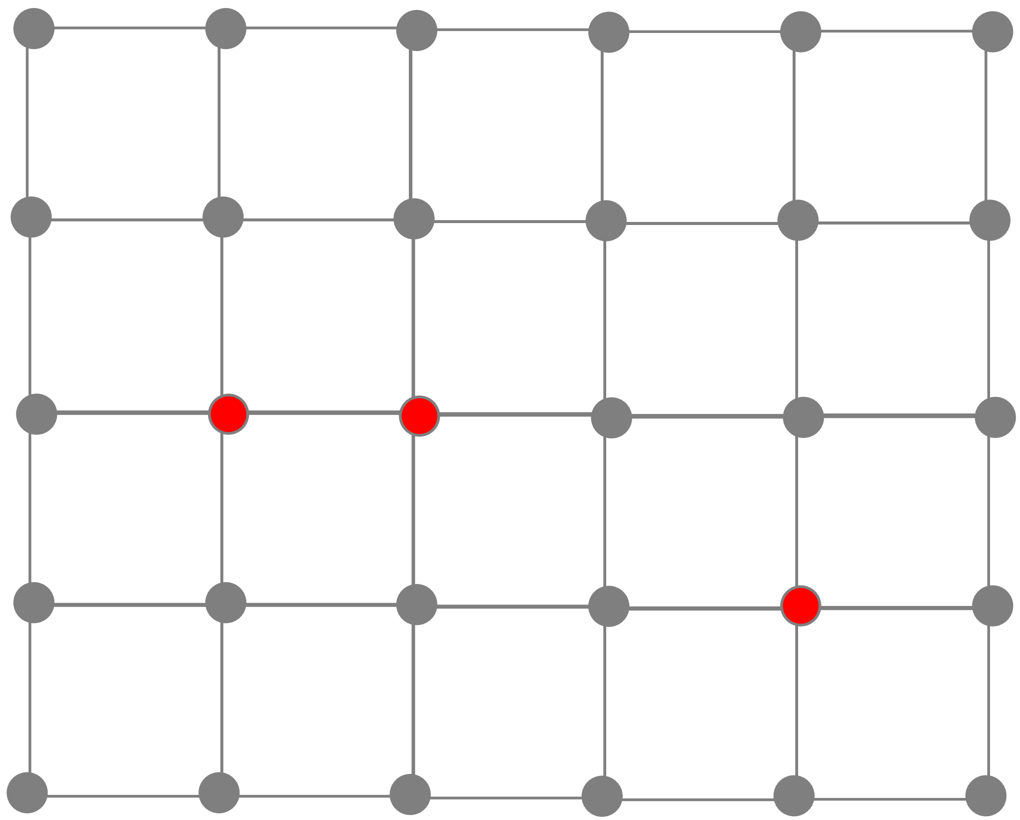

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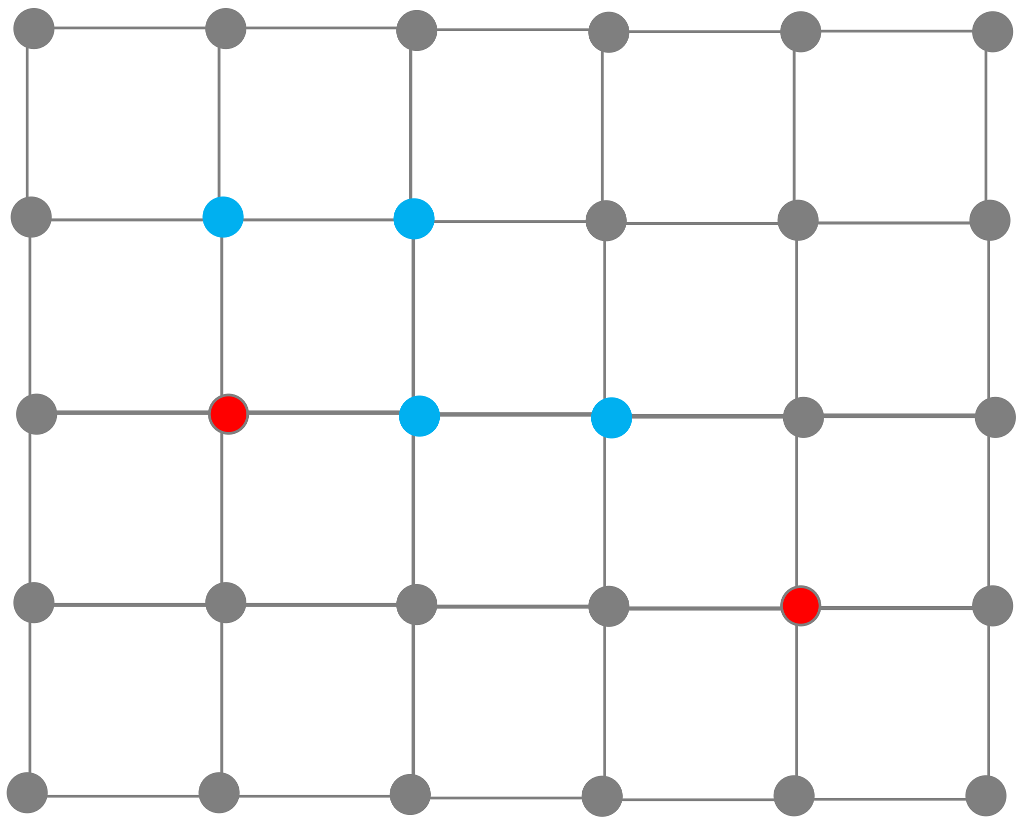

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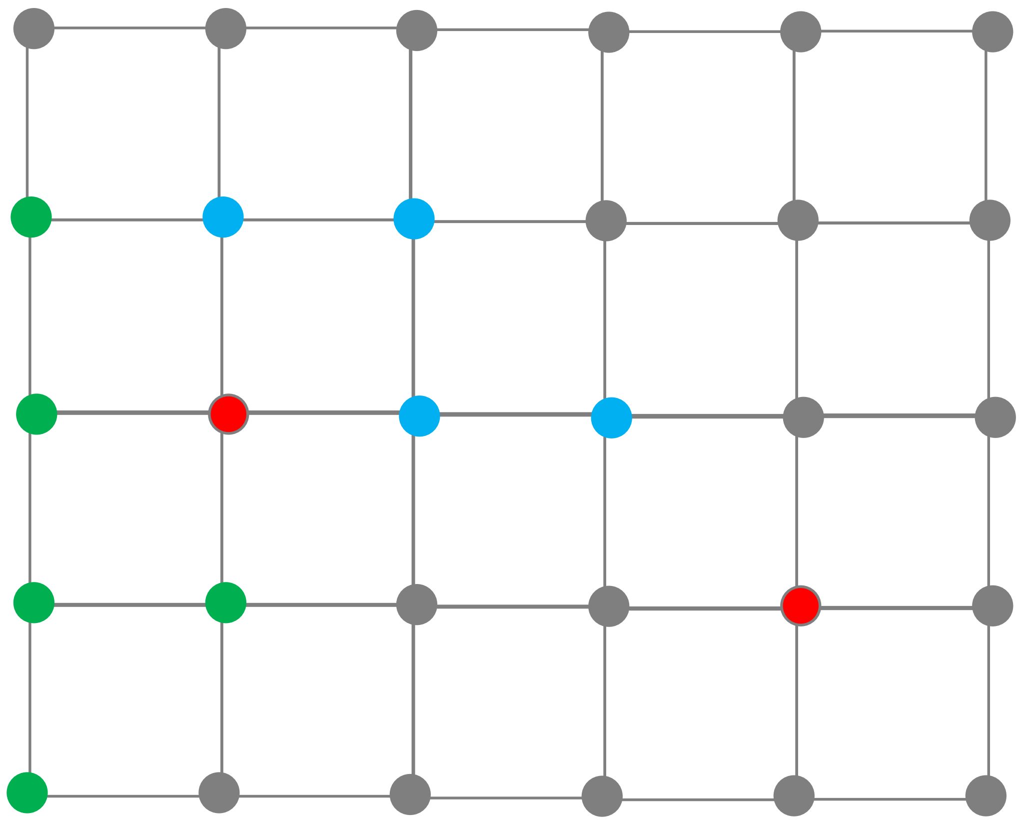

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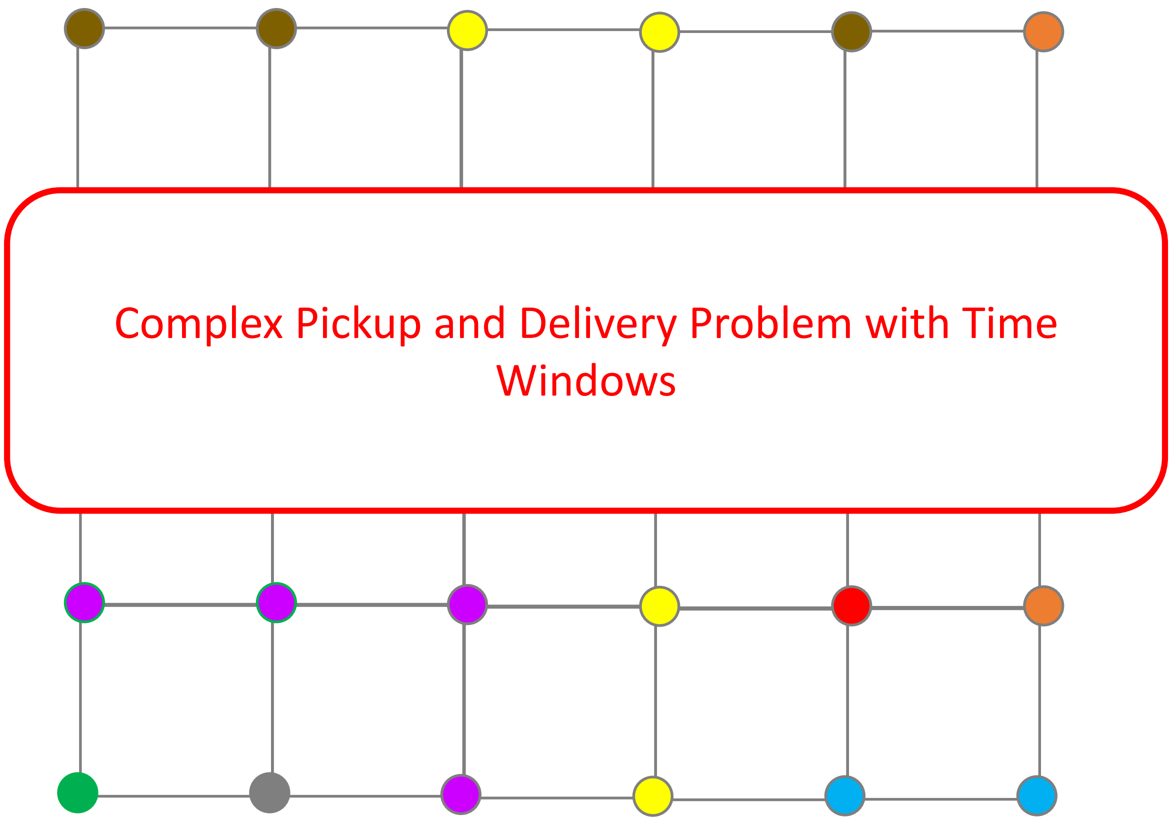


Model formulation:

- Converting PDPTW to VRPTW:
  - Assumptions: Users don't share rides

    P1D1-P10D10-P5D5-....- PnDn

  - Serive time at every dummy node of VRP = travel time between pickup and drop off locations of PDP

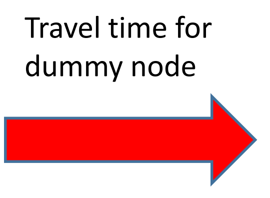
  - Travel time to dummy node in VRP = travel time to pickup node in PDP

  - Travel time from dummy node in VRP = travel time from drop off node in PDP

Model formulation:

- Converting PDPTW to VRPTW:
  - Assumptions: Users don't share rides
    P1D1-P10D10-P5D5-....- PnDn
  - Example:
    - pickup node: 2, drop off node: 5

Travel time		Destination Node					
		1	2	3	4	5	6
Origin Node	1		0.5	0.1	0.8	0.8	0.3
	2	1.0		0.3	1.1	0.8	0.2
	3	1.2	1.2		0.5	1.0	0.6
	4	0.8	1.5	0.7		1.4	1.1
	5	0.8	0.6	1.2	0.9		0.6



Travel time		Destination Node						
		1	2	3	4	5	6	2-5
Origin Node	1		0.5	0.1	0.8	0.8	0.3	0.5
	2	1.0		0.3	1.1	0.8	0.2	
	3	1.2	1.2		0.5	1.0	0.6	1.2
	4	0.8	1.5	0.7		1.4	1.1	1.5
	5	0.8	0.6	1.2	0.9		0.6	0.6
	2-5	0.8	0.6	1.2	0.9		0.6	

Modeling Approach:

- Core model:
  - Household activity pattern generator (Recker, 1995)
- Upper Level Model:
  - Fleet Sizing-Routing-Scheduling Model
- Solution Approach:
  - Benders' Decomposition (Sexton et al, 1985, 1986, Saharidis and Ierapetritou 2009)

Model formulation:

Objective function:

$$Min\, Z = \alpha_1 \sum_{v \in V} f_v \sum_{j \in N} X_{0j}^{v} + \alpha_2 \sum_{v \in V} \sum_{i \in N} \sum_{j \in N} c_{ij} X_{ij}^{v} + \alpha_3 \sum_{v \in V} \sum_{i \in N} \left(T_j^v - T_i^v - t_{ij} \right) X_{ij}^{v}$$

Terms:

- Vehicle acquisition cost
- Total travel cost
- Total idle time of vehicles

Model formulation:

Constraints:

$$\sum_{v \in V} \sum_{j \in N} X_{ij}^{v} = Y_i, \ \forall i = 1, \ldots, n$$ → Node will be visited if a request submitted on it

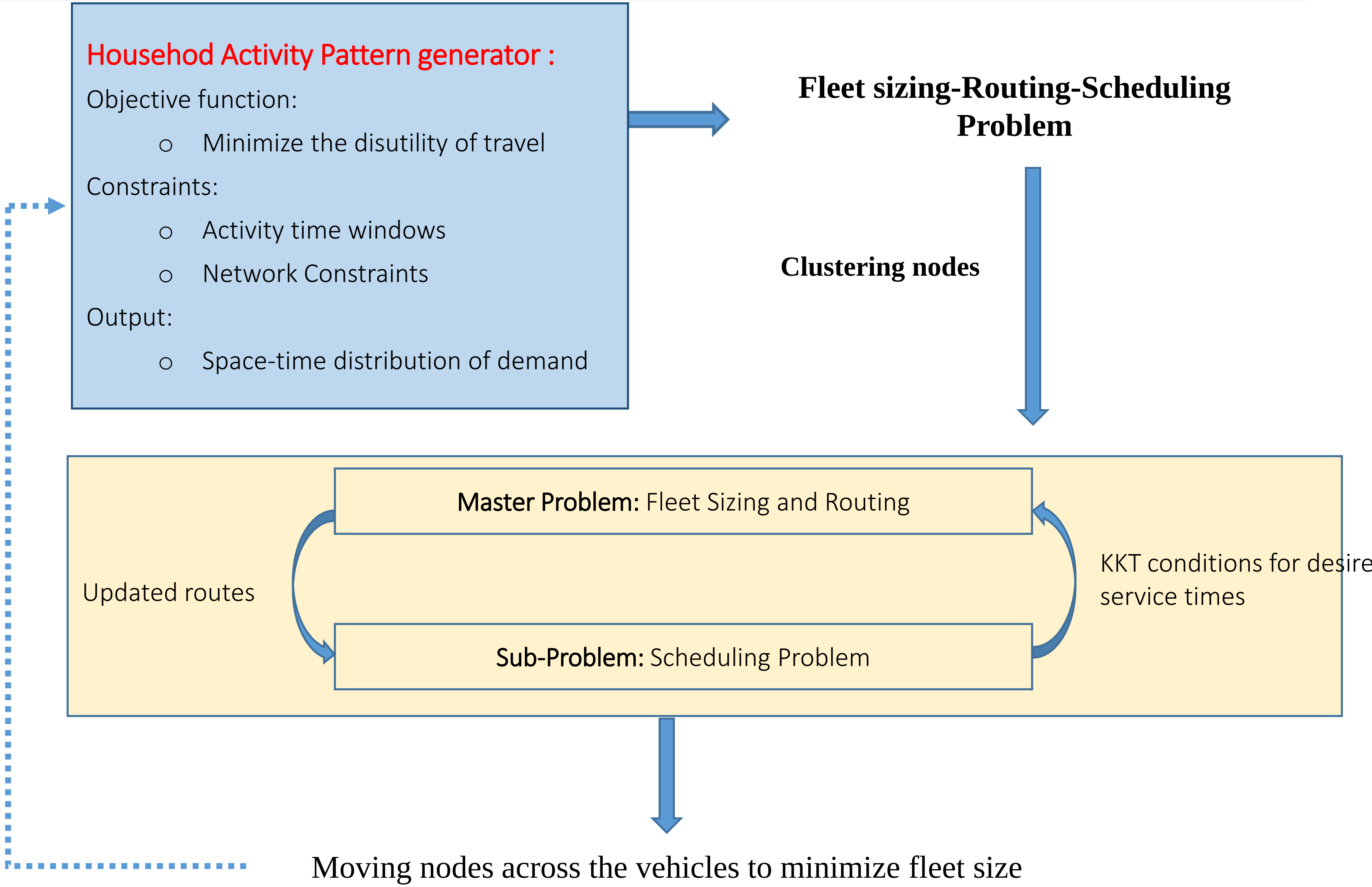
$$\sum_{j \in N} X_{0j}^{v} - \sum_{j \in N} X_{j,n+1}^{v} = 0, \ \forall v \in V$$ → Vehicles should return to depot at the end of the service

$$\sum_{j \in N} X_{ji}^{v} - \sum_{j \in N} X_{ij}^{v} = 0, \ \forall i = 1, \ldots, n; v \in V$$ → Network connectivity

$$T_j^{v} - T_i^{v} - t_{ij} \geq \left(1 - X_{ij}^{v}\right) M, \ \forall i, j \in N, v \in V$$ → Time of the visit is adjusted based on tour information

$$X_{ij}^{v} \in \{0,1\}; Y_i \ \text{integer}; T_i^{v}, TD_i \geq 0$$

$$\{Y_i, TD_i, L_i, P_i\} : \operatorname{argmin}\{HAPP(p;T)\}, \ \forall i = 1, \ldots, n$$


Household Activity Pattern generator :
Objective function:
Minimize the disutility of travel
Constraints:
Activity time windows
Network Constraints
Output:
Space-time distribution of demand
Fleet sizing-Routing-Scheduling Problem
Clustering nodes
Master Problem: Fleet Sizing and Routing
Updated routes
KKT conditions for desire
service times
Sub-Problem: Scheduling Problem
Moving nodes across the vehicles to minimize fleet size

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Household Activity Pattern Generator

$$Min\, Z = \sum_{v\in V}\sum_{u\in N}\sum_{w\in N} t_{uw}^{v} X_{uw}^{v}$$

$$\sum_{v}\sum_{w}(X_{uw}^{v}) = 1 \quad ,\forall u\epsilon P^{+}, v\epsilon V, w\epsilon P^{-}$$

$$\sum_{w} X_{uw}^{v} - \sum_{w} X_{wu}^{v} = 0,\ \forall u\epsilon P, v\epsilon V, w\epsilon P$$

$$\sum_{w} X_{0w}^{v} = 1 \quad ,\forall v\epsilon V, w\epsilon P^{+}$$

$$\sum_{v}\sum_{w} X_{0w}^{v} > 0 \quad ,\forall v\epsilon V, w\epsilon P^{+}$$

$$\sum_{u} X_{u,2n+1}^{v} - \sum_{w} X_{0w}^{v} = 0, \quad ,\forall v\epsilon V, w\epsilon P^{+}, u\epsilon P^{-}$$

$$\sum_{u} X_{uw}^{v} - \sum_{w} X_{w,n+u}^{v} = 0, \forall u\epsilon P^{+}, v\epsilon V, w\epsilon P$$

$$\sum_{w} X_{0,w}^{v} = 0,\ \ \forall v\epsilon V, w\epsilon P^{-},\ \sum_{u} X_{u,0}^{v} = 0,\ \ \forall v\epsilon V, u\epsilon P$$

$$\sum_{u} X_{u,2n+1}^{v} = 0,\ \ \forall v\epsilon V,\ u\epsilon P^{+},\ \sum_{w} X_{2n+1,w}^{v} = 0,\ \ \forall v\epsilon V, w\epsilon P^{-}$$

$$T_u + S_u + t_{u,n+u} - T_w \le T_{n+u},\ \ \forall u\epsilon P^{+}$$

$$T_u + S_u + t_{uw} - T_w \le \left(1 - X_{uw}^{v}\right)M, \quad \forall u,w\epsilon P, \forall v\epsilon V$$

$$T_0^{v} + t_{0w} - T_w \le \left(1 - X_{0w}^{v}\right)M, \forall w\epsilon P^{+}, \forall v\epsilon V$$

$$T_u + S_u + t_{u,2n+1} - T_{2n+1}^{v} \le \left(1 - X_{u,2n+1}^{v}\right)M, \forall v\epsilon V, u\epsilon P^{-}$$

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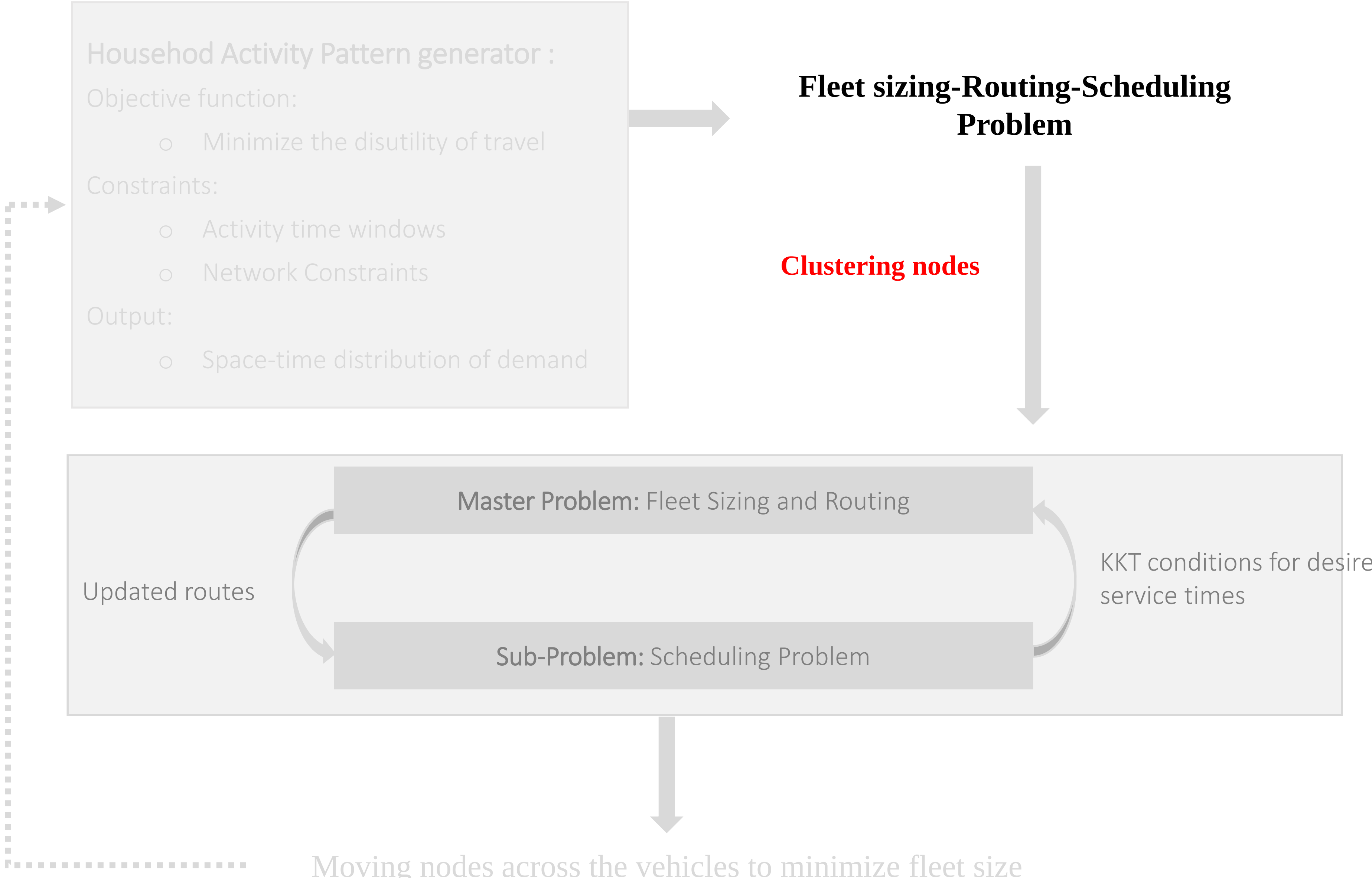
$$a_u \le T_u \le b_u$$

$$T_{u\in N} \ge 0,\ X\ is\, binary.$$

HAPP (Recker, 1995)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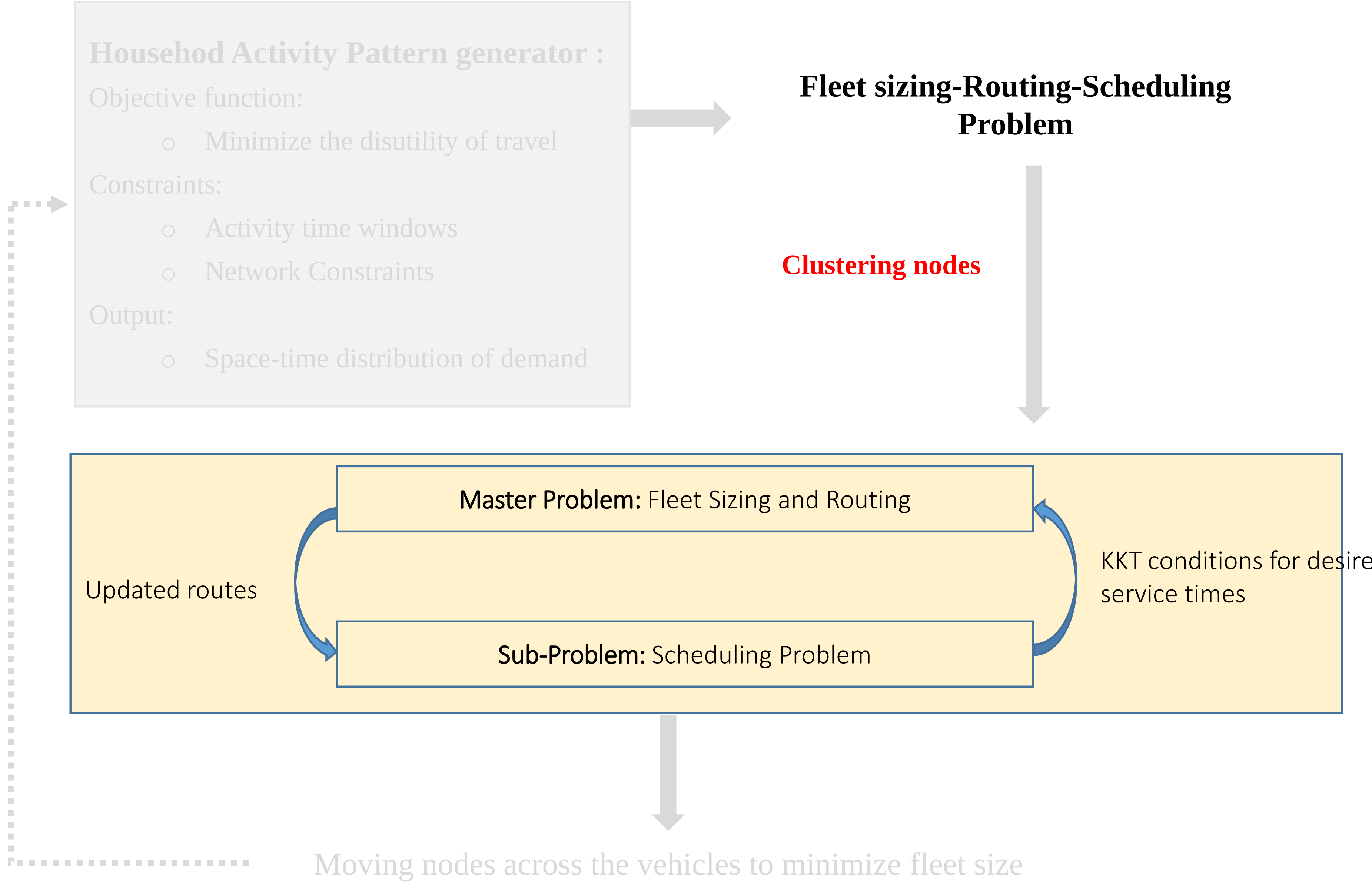
Fleet sizing-Routing-Scheduling Problem

- Clustering Nodes:
  - Spatial considerations
  - Requested service time constraints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Fleet sizing-Routing-Scheduling Problem

Step 0: Initial Routing

Step 1: Solving sub-problem (scheduling problem) given routes

Step 2: Solving Master Problem (Routing Problem) given KKT conditions of sub-problem

Step3: Iterate step 1 and 2 until convergence is occurred

Step 4: Move nodes visited in short tours across to other vehicles to reduce fleet size

Step5: Change the schedule of some activities of HHLDs and compute the corresponding disutility caused for the households and its impact on reducing fleet size.

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Fleet sizing-Routing-Scheduling Problem

Step 0: Initial Routing

For every node, find all the feasible proceeding nodes based on request time:

$\forall j \in Nodes$:

$\forall\, i \in Nodes, i \neq j$:

if$T_i \geq T_j$: $add\ i\ to\ the\ \{Proced_j\}$

Generate set of feasible routes:

$$route_m = \{j, i \in Proced_j, k \in Proced_i, \ldots\}$$

Every node should be visited at least ***once***.

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Step 1: Solving sub-problem (scheduling problem) given routes

$$Min\, S = \sum_{v \in V} \sum_{i \in N} \sum_{j \in N} \left(T_j^v - T_i^v - t_{ij}\right) X_{ij}^v + \sum_{v \in V} \sum_{i \in N} d_i^{+,v} + \sum_{v \in V} \sum_{i \in N} d_i^{-,v}$$

Output of routing model

$$d_i^{+,v} \geq \left(T_i^v - TD_i\right), \forall i \in N, v \in V$$

$$d_i^{-,v} \geq \left(TD_i - T_i^v\right), \forall i \in N, v \in V$$

Desired service time requested by user

$$T_j^v \geq T_i^v + t_{ij} - \left(1 - X_{ij}^v\right) M, \; \forall i, j \in N, v \in V$$

$$T_i^v, d_i^{-,v}, d_i^{+,v} \geq 0, \; \forall i \in N, v \in V$$

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Step 2: Solving Master Problem (Routing Problem) given KKT conditions of sub-problem

$$Min\,Z = \alpha_1 \sum_{v \in V} f_v \sum_{j \in N} X_{0j}^v + \alpha_2 \sum_{v \in V} \sum_{i,j \in N} c_{ij} X_{ij}^v + \alpha_3 \sum_{v \in V} \sum_{i,j \in N} \gamma_i^v X_{ij}^v + \alpha_4 \sum_{v \in V} \sum_{i,j \in N} \left| X_{ij}^v - X_{(iter-1),ij}^v \right|$$

KKT conditions of Scheduling model

$$\sum_{j \in N} X_{0j}^v - \sum_{j \in N} X_{j,n+1}^v = 0, \ \forall v \in V$$

$$\sum_{v \in V} \sum_{j \in N} X_{ij}^v - \sum_{v \in V} \sum_{j \in N} X_{ij}^v = 0, \ \forall i = 1, \ldots, n, \ v \in V$$

$$\sum_{v \in V} \sum_{j \in N} X_{ij}^v = Y_i, \ \forall i \in N$$

Output of pattern generator

$$X_{j0}^v = 0, \ \forall j \in N, \ X_{n+1,j}^v = 0, \ \forall j \in N, X_{ij}^v \in \{0,1\};$$

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Step 4: Move nodes visited in short tours across to other vehicles to reduce fleet size

$\forall j \in Tours$:

$\forall\ length(tour_j < minsize)$:

$\forall node\ 'k'\ \in tour_j, t = T_k$:

$Check\ the\ time\ windows\ constraints\ in\ other\ tours$:

$Adding\ node\ in\ tour_i, i \neq j, violates\ the\ time\ windows\ constraint$:

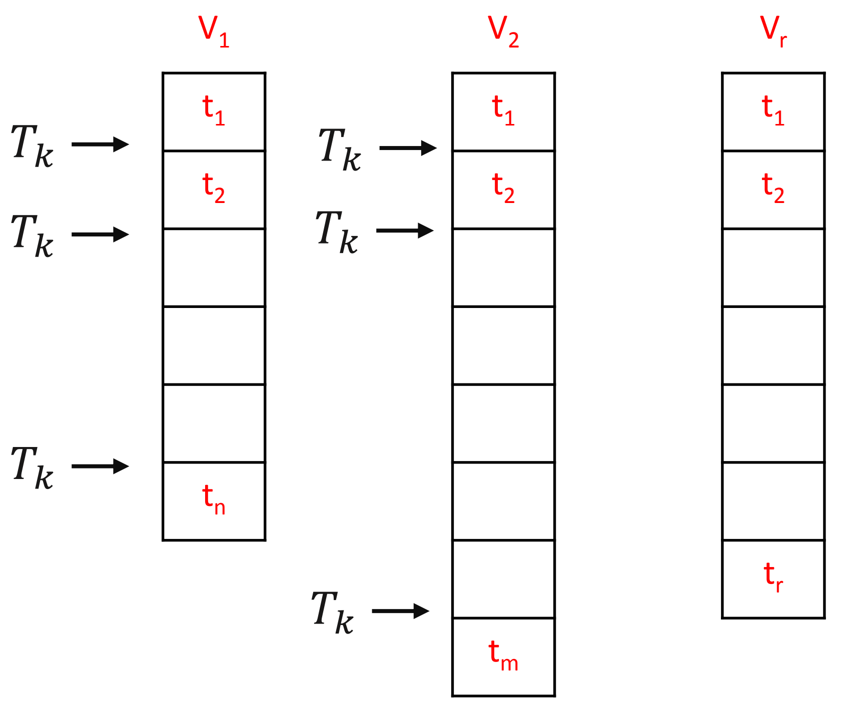
$move\ to\ the\ other\ tour$

$Adding\ node\ in\ tour_i, i \neq j, does\ not\ violates\ the\ TW\ constraint$:

$add\ node\ 'k'\ to\ tour_i$

Fleet sizing-Routing-Scheduling Problem

Step 4: Move nodes visited in short tours across to other vehicles to reduce fleet size



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Household Activity Pattern Generator

$$Min\, Z = \sum_{v\in V}\sum_{u\in N}\sum_{w\in N} t_{uw}^{v} X_{uw}^{v} + \sum_{u\epsilon P^{+}} \left|T_u - T_D\right|$$

$$\sum_{v}\sum_{w}(X_{uw}^{v}) = 1 \quad ,\forall u\epsilon P^{+}, v\epsilon V, w\epsilon P^{-}$$

$$\sum_{w} X_{uw}^{v} - \sum_{w} X_{wu}^{v} = 0, \ \forall u\epsilon P, v\epsilon V, w\epsilon P$$

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$$\sum_{v}\sum_{w} X_{0w}^{v} > 0 \quad ,\forall v\epsilon V, w\epsilon P^{+}$$

$$\sum_{u} X_{u,2n+1}^{v} - \sum_{w} X_{0w}^{v} = 0, \quad ,\forall v\epsilon V, w\epsilon P^{+}, u\epsilon P^{-}$$

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$$\sum_{u} X_{u,2n+1}^{v} = 0, \ \ \forall v\epsilon V, \ u\epsilon P^{+}, \ \sum_{w} X_{2n+1,w}^{v} = 0, \ \ \forall v\epsilon V, w\epsilon P^{-}$$

$$T_u + S_u + t_{u,n+u} - T_w \le T_{n+u}, \ \ \forall u\epsilon P^{+}$$

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$$T_0^{v} + t_{0w} - T_w \le \left(1 - X_{0w}^{v}\right) M, \forall w\epsilon P^{+}, \forall v\epsilon V$$

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$$T_u + S_u + t_{u,2n+1} - T_{2n+1}^{v} \le \left(1 - X_{u,2n+1}^{v}\right) M, \forall v\epsilon V, u\epsilon P^{-}$$

$$T_u = T_{adj}, \quad u \in conflicting\ node$$

$$a_u \le T_u \le b_u$$

$$T_{u\in N} \ge 0, \ X \ is\ binary.$$

HAPP (Recker, 1995)

Numerical Experiments

- Case 1: 4 individuals, 20 activities

Individual ID	***Home_ID***	***Visited Nodes ID***	***Time Windows***	***Duration (hours)***
Ind 1	1	2	[6:00,24:00]	0.5
		3	[8:00,9:00]	7
		4	[6:00,24:00]	2
		5	[16:00,17:00]	0.5
Ind 2	6	7	[12:00,13:00]	1.5
		8	[6:00,24:00]	2
		9	[6:00,24:00]	1
		10	[6:00,24:00]	2
Ind 3	11	12	[08:00, 10:00]	6
		13	[6:00,24:00]	2
		14	[18:00,19:00]	1
		15	[6:00,20:00]	1
Ind 4	16	17	[6:00,20:00]	0.5
		18	[7:00, 9:00]	2
		19	[10:00,12:00]	6
		20	[12:00, 24:00]	1

Numerical Experiments

Travel time	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1		0.54	0.11	0.84	0.78	0.30	0.76	0.64	0.93	0.64	0.98	0.50	0.44	0.57	0.34	1.01	0.55	0.34	0.51	0.79
2	1.01		0.31	1.01	0.83	0.21	1.09	0.70	0.73	0.80	0.95	1.04	0.57	0.27	0.92	0.52	1.03	0.56	1.02	0.37
3	1.19	1.19		0.48	1.01	0.60	1.15	0.96	0.67	1.34	1.18	1.31	0.49	0.60	1.16	1.12	1.20	0.92	0.85	1.03
4	0.82	1.57	0.73		1.42	1.12	1.07	1.67	1.09	1.13	0.84	1.01	1.00	1.58	0.93	1.00	1.10	1.39	0.83	1.56
5	0.78	0.56	1.23	0.96		0.60	0.59	0.90	0.81	1.11	0.44	1.22	1.05	0.51	1.23	0.57	0.98	0.92	0.54	0.38
6	1.06	0.44	0.48	1.00	0.48		0.65	0.99	0.52	0.83	0.77	0.59	0.61	1.09	0.22	0.42	0.59	0.73	1.02	0.61
7	1.40	0.73	1.47	0.68	0.94	1.18		1.25	1.23	1.02	0.72	1.34	0.83	1.24	1.44	0.67	1.56	0.62	1.42	1.42
8	1.74	1.56	1.41	1.19	1.59	1.27	1.46		1.73	1.79	1.83	1.70	0.89	0.89	0.98	1.15	0.91	1.31	1.23	1.43
9	0.52	0.83	0.55	0.95	0.55	0.58	0.57	0.32		0.15	0.97	0.32	0.95	0.80	0.96	1.02	0.23	0.48	1.07	0.73
10	1.33	0.92	0.45	1.06	0.66	0.96	1.16	1.04	1.02		0.68	0.86	0.44	1.04	1.39	0.53	0.47	1.32	0.68	0.44
11	0.13	0.89	0.06	0.93	0.93	0.56	0.16	0.21	0.74	0.87		0.79	0.99	0.38	0.67	0.38	0.25	0.82	0.76	0.31
12	0.79	0.62	0.30	0.23	0.69	0.48	0.54	0.49	0.37	0.60	0.90		0.87	0.65	0.64	0.38	0.40	0.82	0.47	0.76
13	1.80	1.38	1.67	1.23	1.29	1.65	1.82	1.35	1.75	1.56	1.39	1.79		1.78	1.47	1.20	1.30	1.74	0.84	0.98
14	0.80	1.29	1.69	1.07	1.55	1.35	1.54	1.55	0.80	1.03	1.40	1.24	1.72		1.32	1.05	1.00	1.64	1.20	1.56
15	1.32	1.09	1.06	1.34	1.16	0.99	1.33	0.44	0.65	1.37	1.15	0.86	1.06	0.80		0.59	0.76	0.41	0.85	0.71
16	0.91	0.96	0.28	0.14	0.53	0.89	0.53	0.47	0.56	0.18	0.19	0.93	0.66	0.32	0.92		0.52	0.78	0.40	0.46
17	1.43	1.79	1.68	0.97	1.18	1.28	1.76	1.32	1.14	1.50	1.38	1.80	1.83	1.72	1.61	1.64		0.96	1.24	0.90
18	1.18	0.86	0.71	0.58	0.88	0.64	0.42	0.43	0.42	0.76	0.47	0.79	1.25	0.70	0.47	0.92	1.22		0.39	0.49
19	0.79	1.46	1.17	1.38	1.41	1.29	1.34	1.59	1.38	1.59	1.18	0.86	0.78	1.43	1.02	1.39	1.37	1.25		1.22
20	0.59	0.66	0.18	0.78	1.01	0.23	0.56	0.40	1.11	0.73	0.37	0.25	0.67	0.95	0.96	0.95	0.32	0.67	1.00	

Numerical Experiments

Requested service time: output of pattern generator

Node ID	*Time requested*	*Node ID*	*Time requested*
16	6:50	13	16:20
11	7:57	10	16:57
1	8:24	19	17:25
17	8:35	15	17:29
18	10:55	9	17:49
6	13:00	4	18:35
12	14:03	20	19:10
7	15:00	14	19:17
3	15:37	2	20:10
5	16:14	8	20:33

Numerical Experiments

- Vehicle allocation without feedback to pattern generator:

Vehicle 1	
Node ID	***Service time***
16	6:50
17	8:35
18	10:55
6	13:00
12	14:03
7	15:00
5	16:14
19	17:25
20	19:10
2	20:10

Vehicle 2	
Node ID	***Service time***
11	7:57
3	15:37
10	16:57
4	18:35
8	20:33

Vehicle 3	
Node ID	***Service time***
1	8:24
15	17:29
14	19:17

Vehicle 4	
Node ID	***Service time***
13	16:20
9	17:49

Numerical Experiments

- Vehicle allocation with feedback to pattern generator:

Vehicle 1

Node ID	***Service time***
16	6:48
1	8:17
17	8:35
18	10:56
6	13:00
12	14:03
7	15:00
5	16:14
19	17:25
20	19:10
14	19:33
2	20:10

Vehicle 2

Node ID	***Service time***
11	7:57
3	15:38
13	16:54
10	16:58
15	18:03
9	18:24
4	18:35
8	20:33

Numerical Experiments

- Comparison:

Vehicle 1

Node ID	Service time
16	6:48
1	8:17
17	8:35
18	10:56
6	13:00
12	14:03
7	15:00
5	16:14
19	17:25
20	19:10
14	19:33
2	20:10

Vehicle 2

Node ID	Service time
11	7:57
3	15:38
13	16:54
10	16:58
15	18:03
9	18:24
4	18:35
8	20:33

Vehicle 1

Node ID	Service time
16	6:50
17	8:35
18	10:55
6	13:00
12	14:03
7	15:00
5	16:14
19	17:25
20	19:10
2	20:10

Vehicle 2

Node ID	Service time
11	7:57
3	15:37
10	16:57
4	18:35
8	20:33

Vehicle 3

Node ID	Service time
1	8:24
15	17:29
14	19:17

Vehicle 4

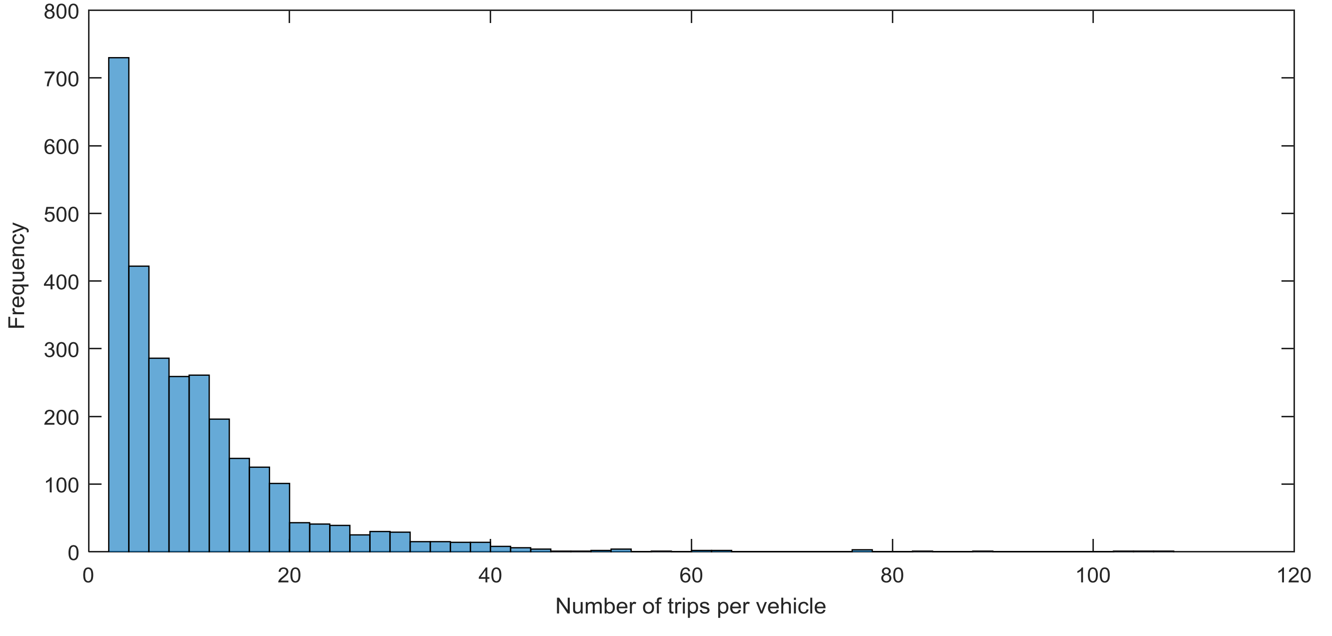
Node ID	Service time
13	16:20
9	17:49

Numerical Experiments

- Case 2: (A test on scalability)
  - Data:
    - *MTA travel survey data, 2008*
      - # of individuals: 12158
      - # of trips: 36921
      - Average number of trips/person: 3.04
      - Average trip duration: 23.91 min
      - Highest % of age group surveyed: 30-36
      - Highest average income group surveyed : 42-52K
      - Females: 60%
      - Average HHLD size: 2.52
      - Average Vehicle in HHLD: 0.67
    - *NYMTC household travel survey data, 2010-2011.*
      - # of individuals: 8904
      - # of trips: 31305
      - Average number of trips/person 3.52
      - Average trip duration: 32.26 min
      - Highest % of age group surveyed : 26-31
      - Highest average income group surveyed : 38-52k
      - Females: 55%
      - Average HHLD size: 2.11
      - Average Vehicle in HHLD: 0.73

Numerical Experiments

- Case 2: (A test on Scalability Test)
  - For this analysis:
    - Number of observation:
      - 25543 daily trip observations
      - Study region: Manhattan Borough
      - Fleet size: 2092 (12.67 trips/vehicle)



Numerical Experiments

- Case 2: (A test on Scalability Test)
  - For this analysis:
    - Number of observation:
      - 25543 daily trip observations
      - Study region: Manhattan Borough
      - Fleet size: 2092 (12.67 trips/vehicle)
    - Computation details:
      - Software: Matlab
      - Number of codes: 12 cores
      - CPU: 2.66 GHZ
      - 86 minutes

Future Extensions:

- Incorporate adjustments to the itineraries for large scale and improve computation efficiency;
- Extension to a more general case: models with ride-sharing or para-transit modes;
- Incorporate household preferences over different types of vehicles.

Thank you ☺

Questions?

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