MONASH University

Improving Time-Dependent Contraction Hierarchy ICAPS 2022

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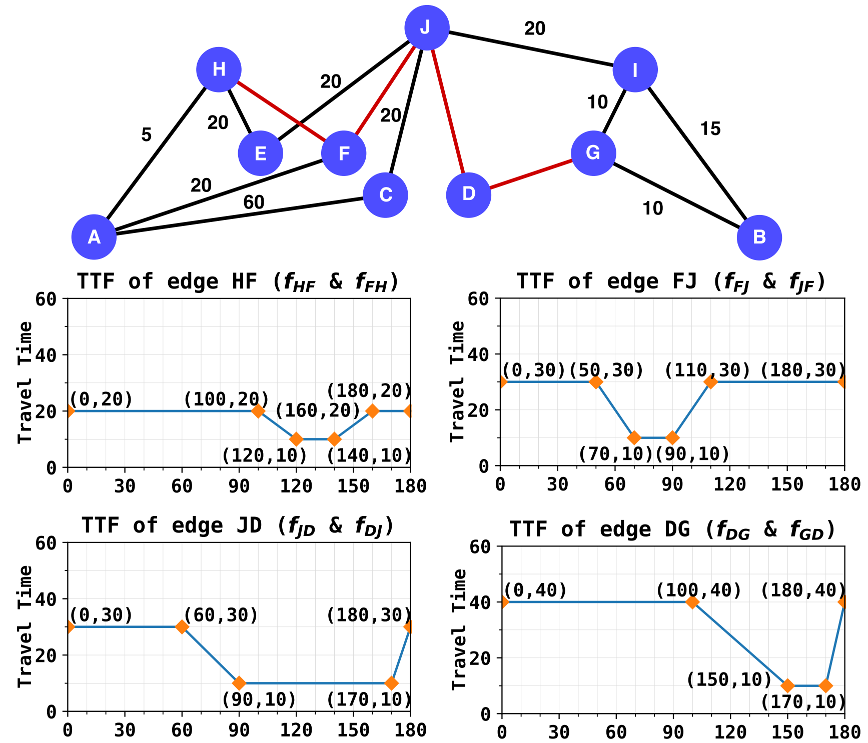
Time Dependent Road Network

- Time Dependent Road Network:
  - A directed graph:
    - A set of vertices: V.
    - A set of edges: $E \subseteq V \times V$.
    - The travel cost of each edge $e \in E$ is represented as a travel time function f (TTF).
      - Each TTF follows FIFO property (i.e., $f(t') + t' \geq f(t) + t \mid \forall e \in E$ and $\forall t' > t \in T$).
  - Objective:
    - Given a start s and destination d.
    - Find the fastest path that minimize the travel time.



An example of an undirected time-dependent graph. TTFs of the red edges are shown below the graph, and the travel cost of the other edges are constant

Background
Compressed Path Databases (CPD) Heuristic [1]

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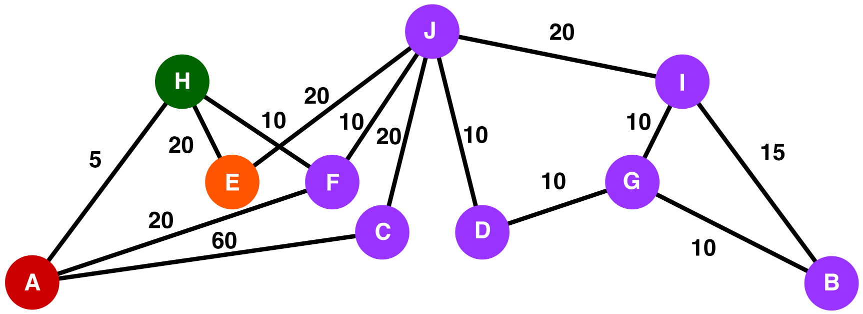
H	*	A	F	F	F	F	F	F	F	E
A	H	*	H	H	H	H	H	H	H	H
J	F	F	F	*	I	D	D	D	C	E



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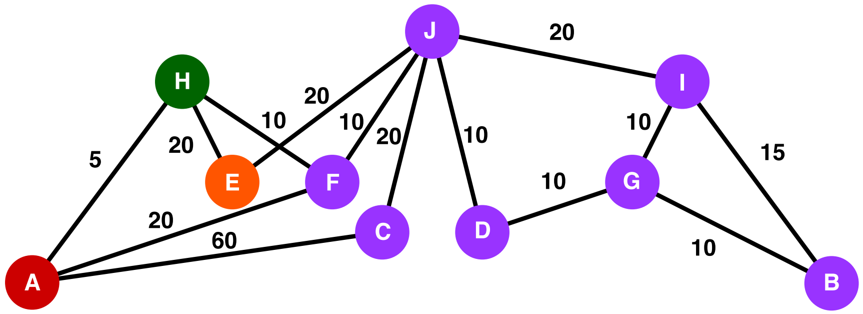

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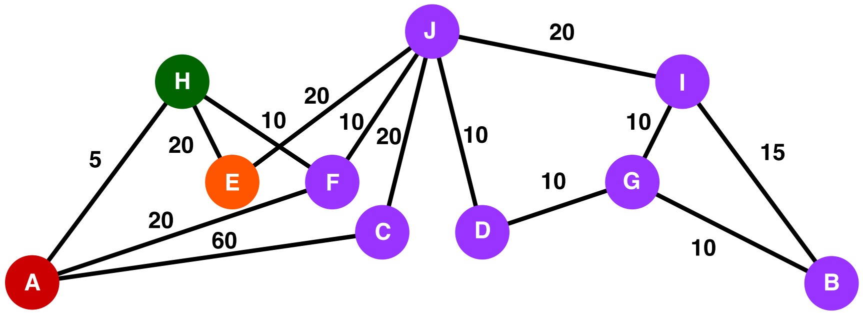
J	F	F	F	*	I	D	D	D	C	E



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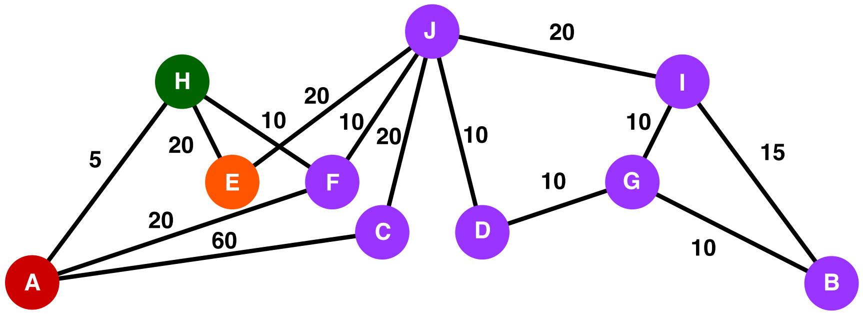

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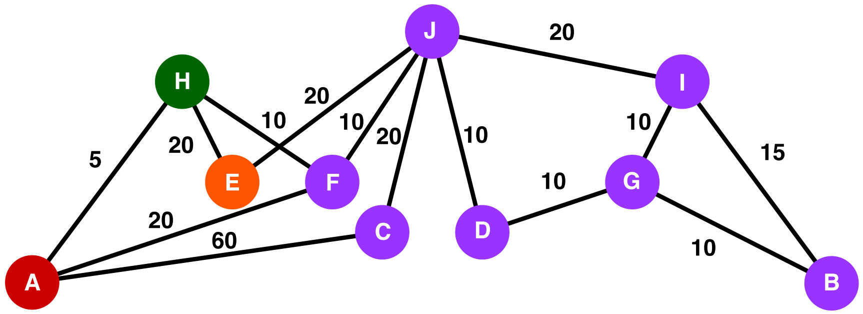
A	H	*	H	H	H	H	H	H	H	H
J	F	F	F	*	I	D	D	D	C	E



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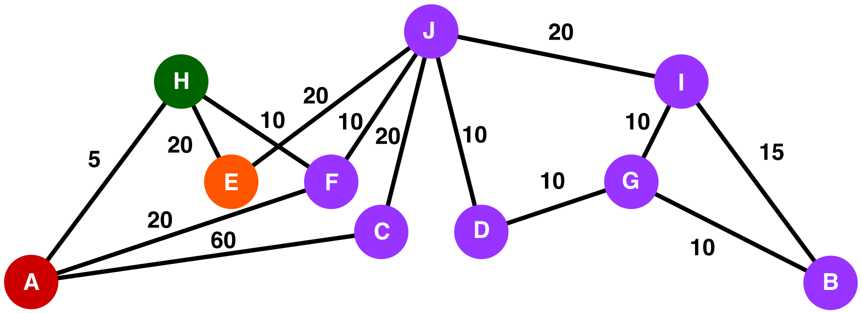
J	F	F	F	*	I	D	D	D	C	E



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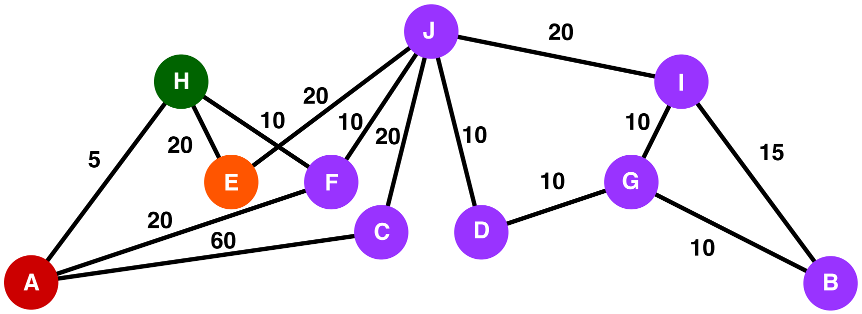
J	F	F	F	*	I	D	D	D	C	E



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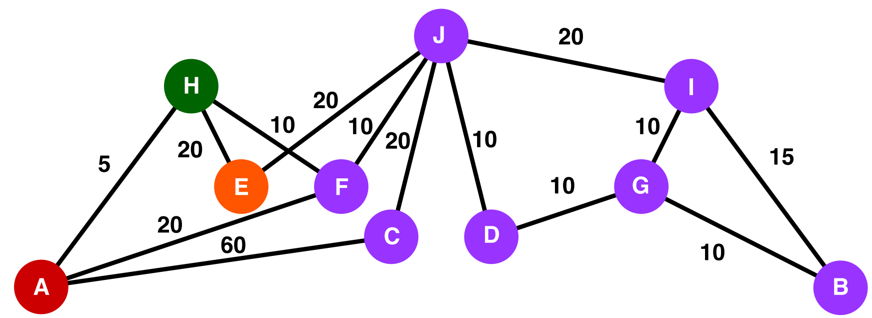
A	H	*	H	H	H	H	H	H	H	H
J	F	F	F	*	I	D	D	D	C	E



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A	A	A	H	F	J	G	D	J	J	H
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A reverse first move table which records the for every d ∈ V , the first move on the shortest path from d to s

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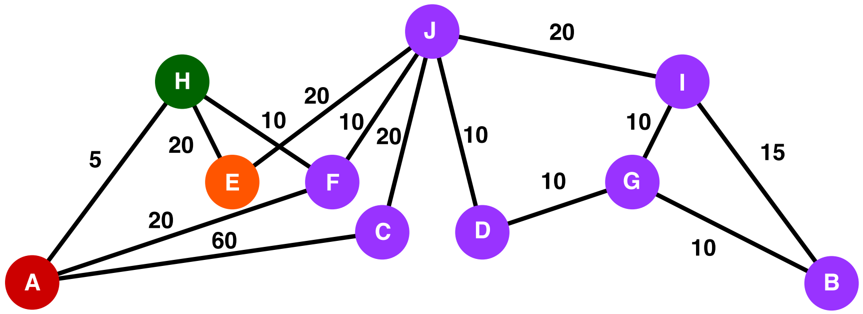
A	H	*	H	H	H	H	H	H	H	H
J	F	F	F	*	I	D	D	D	C	E



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A	A	A	H	F	J	G	D	J	J	H
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  - Construction:
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  - First move extraction:
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- Heuristic:
  - The shortest path extracted from CPD between s and d is a valid lower-bound.

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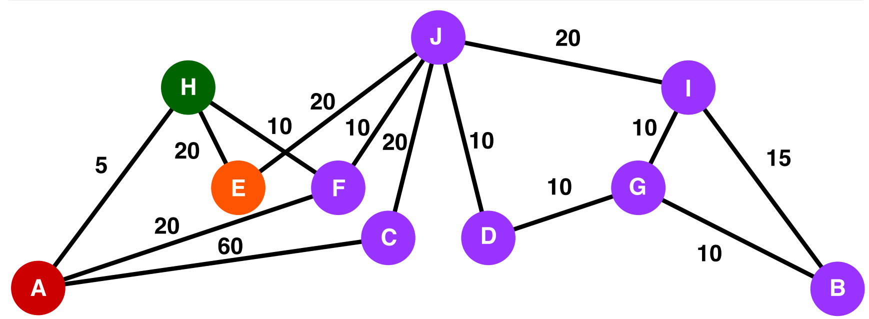
A	H	*	H	H	H	H	H	H	H	H
J	F	F	F	*	I	D	D	D	C	E



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  - Construction:
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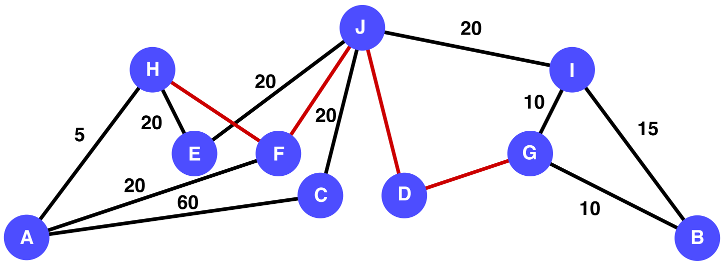

The lex order L is the alphabetical order shown in the figure.

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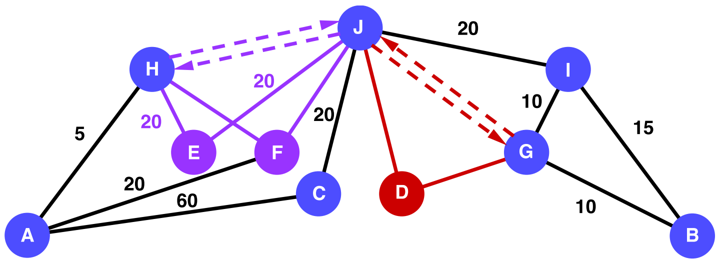

We show the result for contracting nodes E and F in purple, and D in red. Dashed edge are the shortcut edges.

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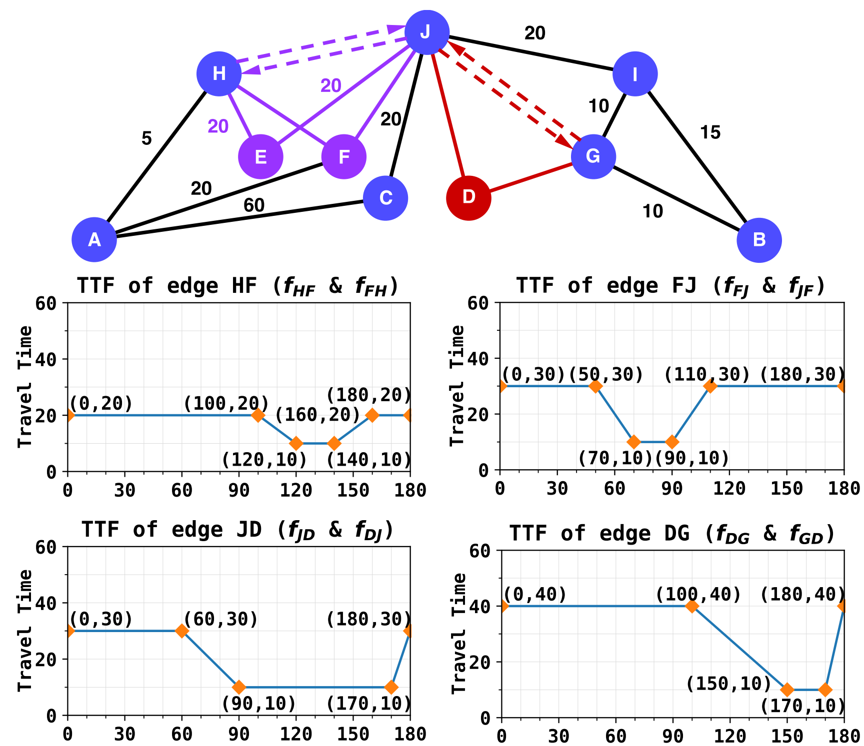
      - » v $<_L$ u & v $<_L$ w.
      - » ∃ t ∈ T, v ∈ sp(u,w,t).



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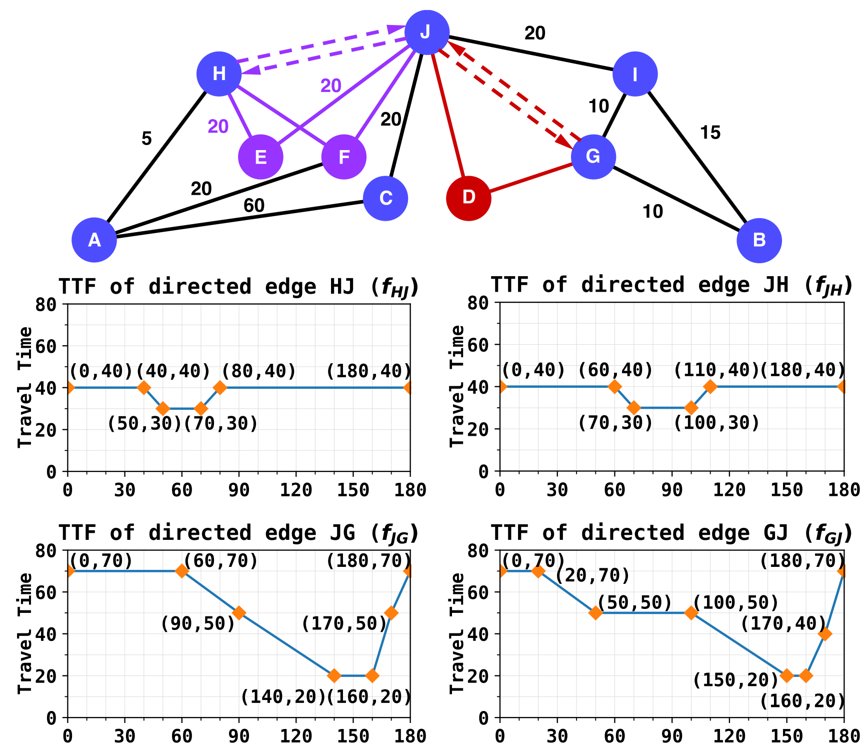
        - » v $<_L$ u & v $<_L$ w.
        - » ∃ t ∈ T, v ∈ sp(u,w,t).
      - When add a shortcut edge (u,w) the TTF is computed as
        - » $fuw = fuv \circ fvw$ or $fuw = \min(fuw', fuv \circ fvw)$ if parallel edges existed.



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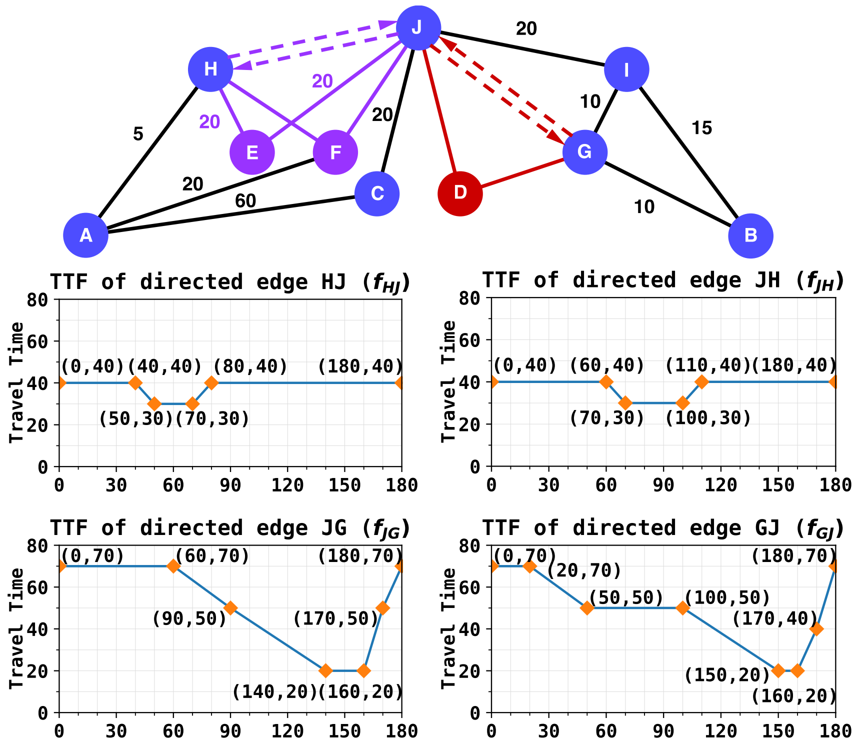

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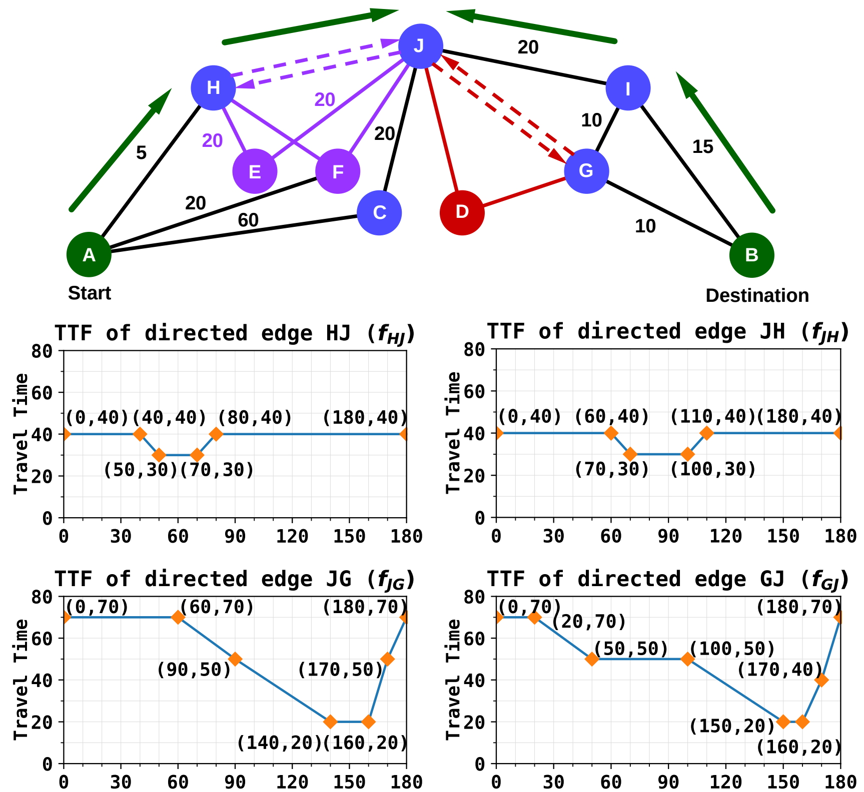

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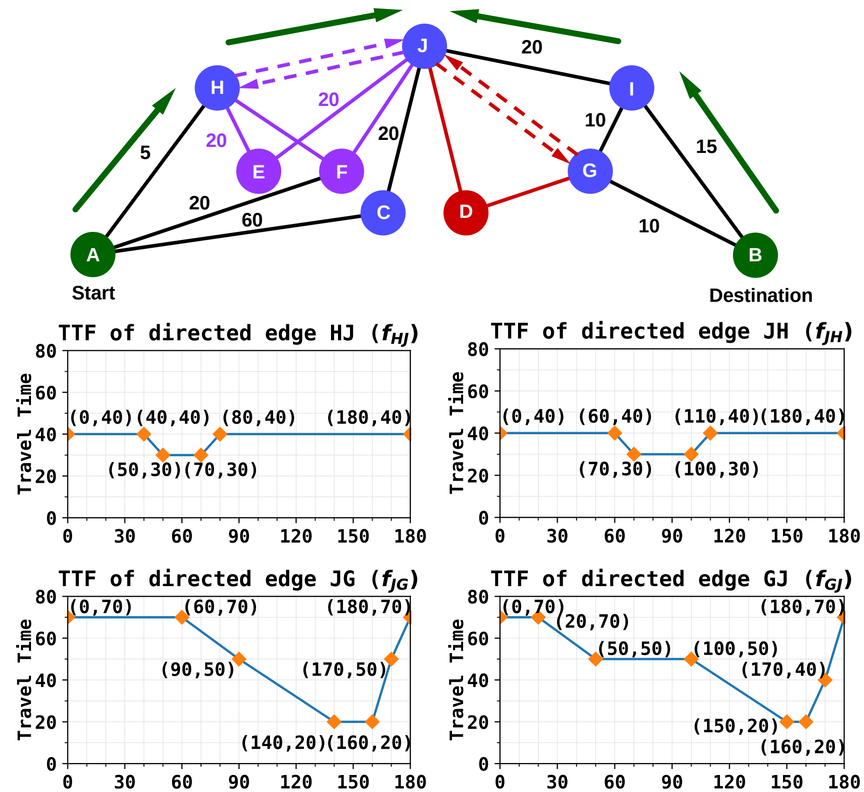

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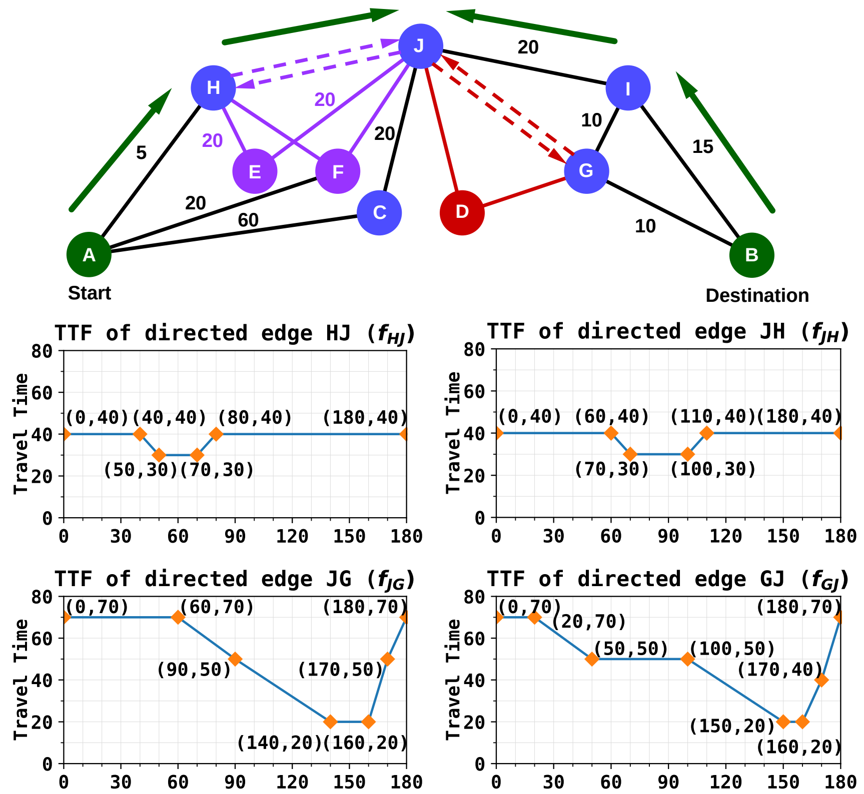

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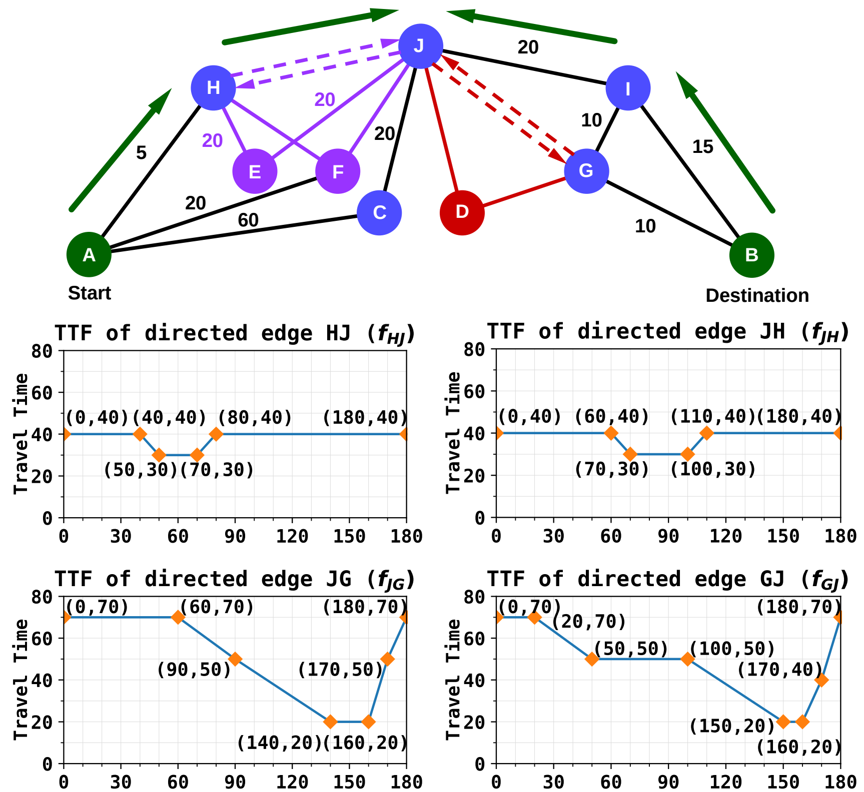
      - When the search meet at k:
        - » Compute the upper-bound
          - fwd(s,k) + upper(k,d)
        - » Compute the lower-bound
          - fwd(s,k) + lower(k,d)



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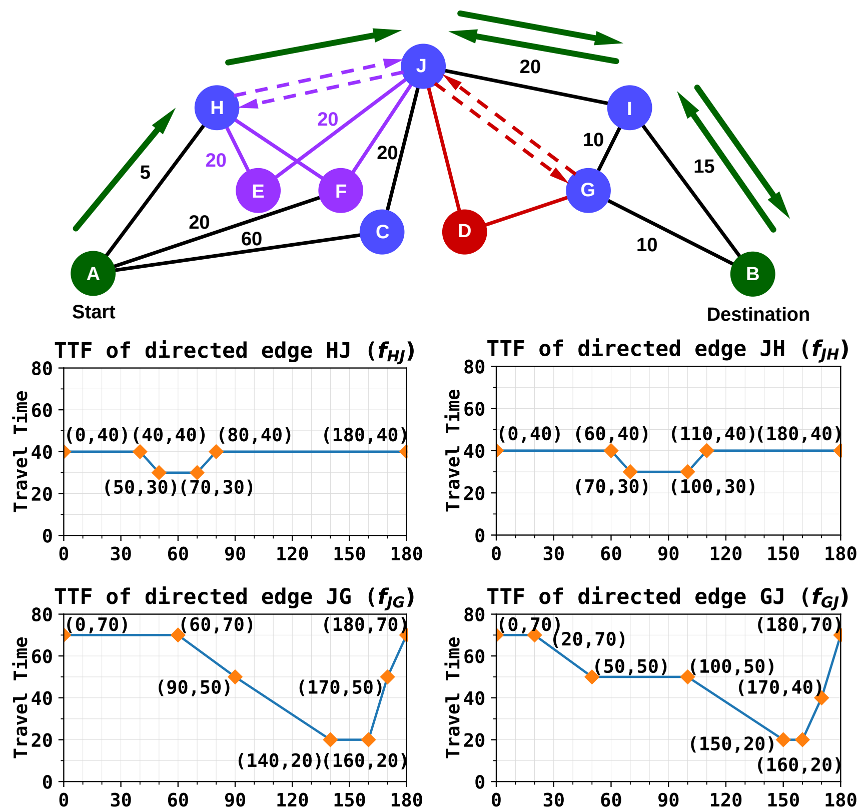

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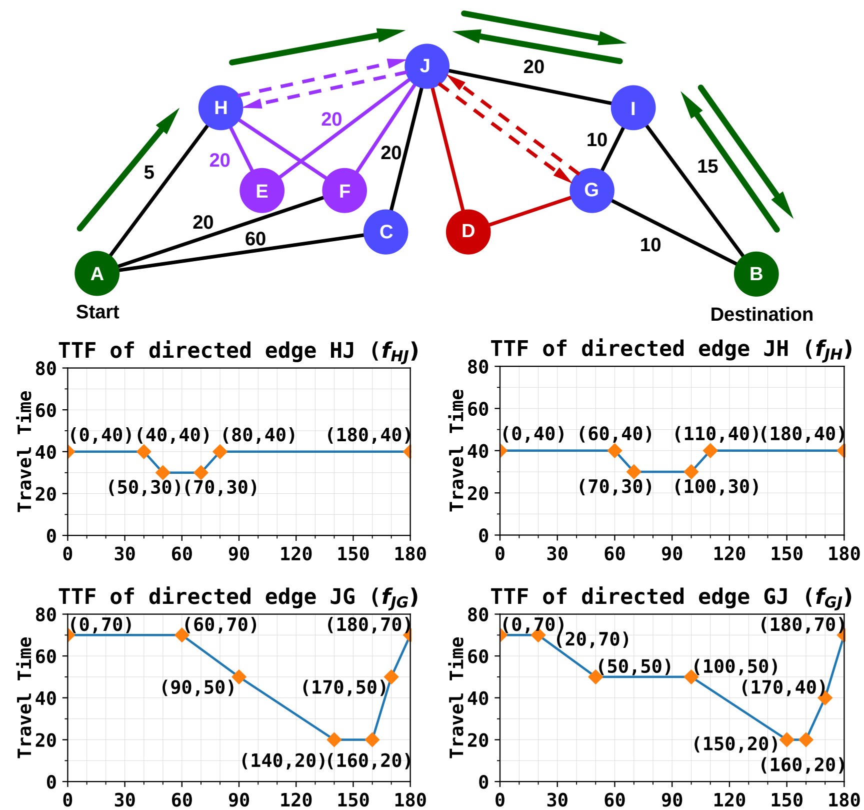

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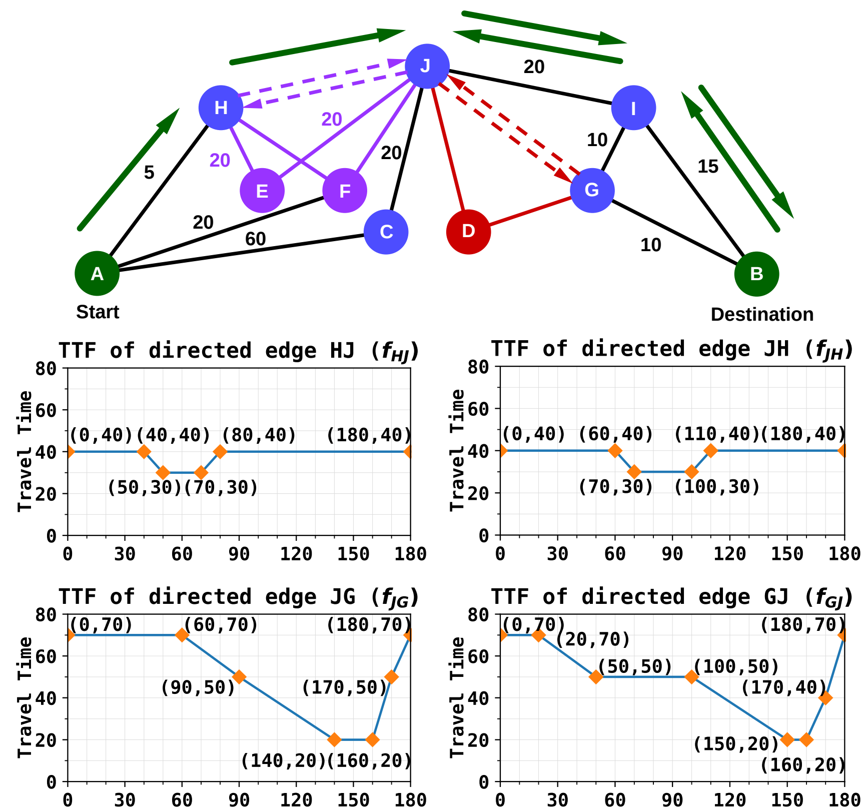
    - Extract the path and unpack.



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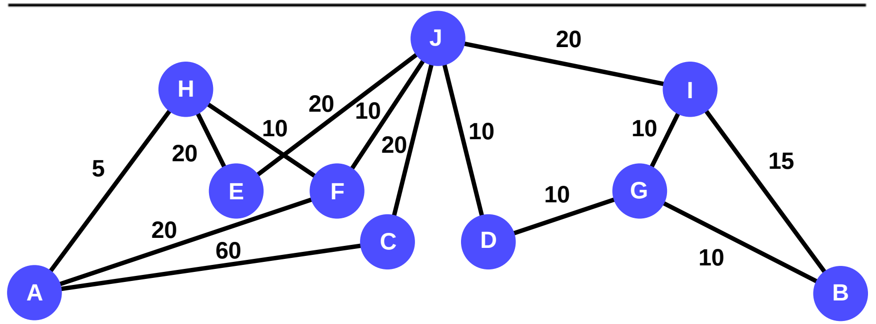
d(A,_), d(_,A)	5	0	15	25	45	55	45	35	45	25
d(B,_), d(_,B)	50	55	40	30	15	0	10	20	50	50
d(J,_), d(_,J)	20	25	10	0	20	30	20	10	20	20



An example of static graph, where the travel cost of each edge is the free-flow cost of corresponding TTF.

- Combing BTCH with landmark:
  - Bi-directional search:
    - landmark heuristic [6]:
      - landmark(vi,vj) = max l∈L {max (d(vi,l) − d(vj,l), d(l,vi) − d(l,vj))}

Ordering	H	A	F	J	I	B	G	D	C	E
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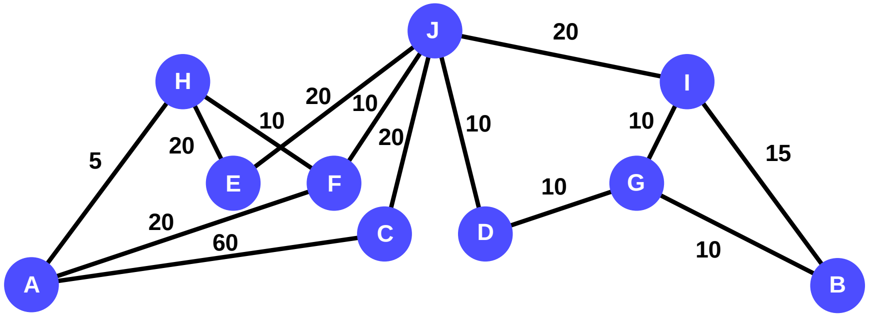
d(J,_), d(_,J)	20	25	10	0	20	30	20	10	20	20



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      - E.g., landmark(H,I) = max(|5 - 45|, |50 - 15|, |20 - 20|) = 35

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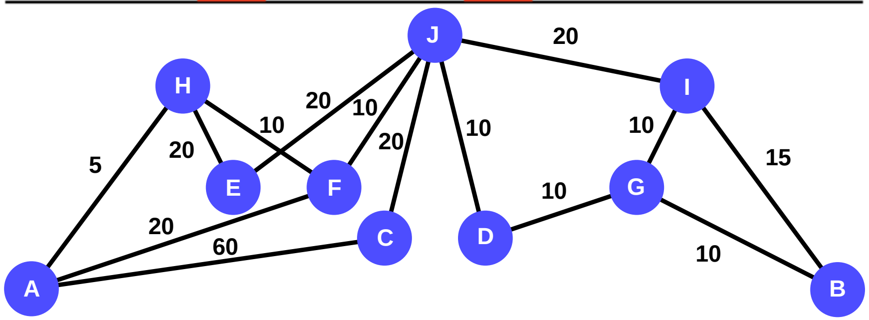

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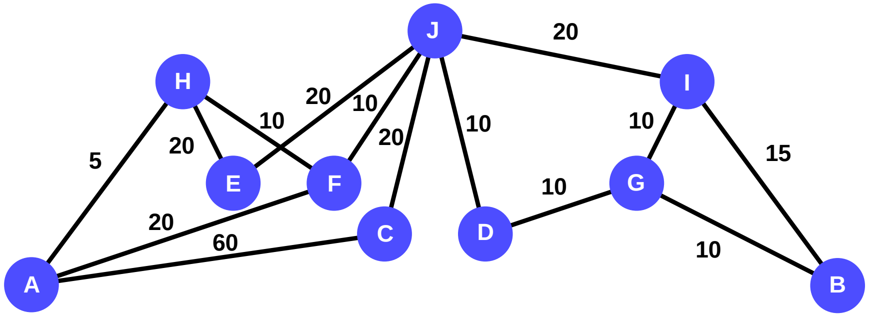
      - E.g., landmark(H,I) = max(|5 - 45|, |50 - 15|, |20 - 20|) = 35
  - Forward search:
    - Heuristic:
      - Directly reuse the lower-bound computed by backward search.

Ordering	H	A	F	J	I	B	G	D	C	E
d(A,_), d(_,A)	5	0	15	25	45	55	45	35	45	25
d(B,_), d(_,B)	50	55	40	30	15	0	10	20	50	50
d(J,_), d(_,J)	20	25	10	0	20	30	20	10	20	20



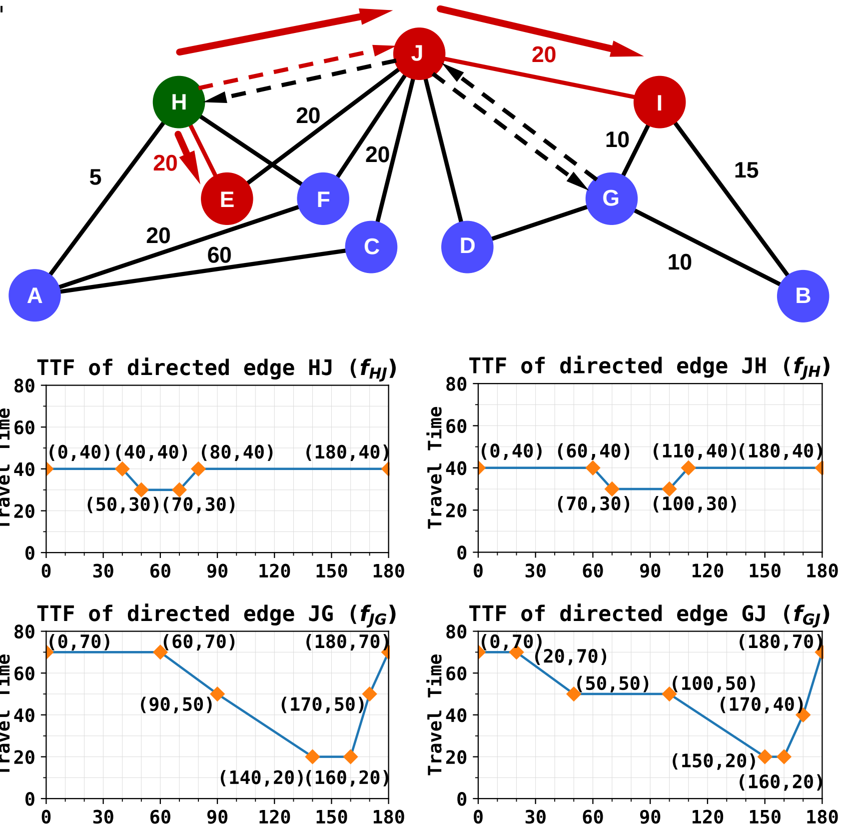
An example of static graph, where the travel cost of each edge is the free-flow cost of corresponding TTF.

Our Approach
Improving TCH using Heuristic

- Combing BTCH with landmark:
- Forward TCH Search with CPD-based Heuristic:

Our Approach
Improving TCH using Heuristic

- Combing BTCH with landmark:
- Forward TCH Search with CPD-based Heuristic:
  - Forward TCH Search:
    - Up-then-Down Policy.



Deconstructing the TCH-path gives following three cases: (i) up TCH-path: <H, J>; (ii) up-down TCH-path: <H, J, I>; (iii) down TCH-path: <H, E>.

- Combing BTCH with landmark:
- Forward TCH Search with CPD-based Heuristic:
  - Forward TCH Search:
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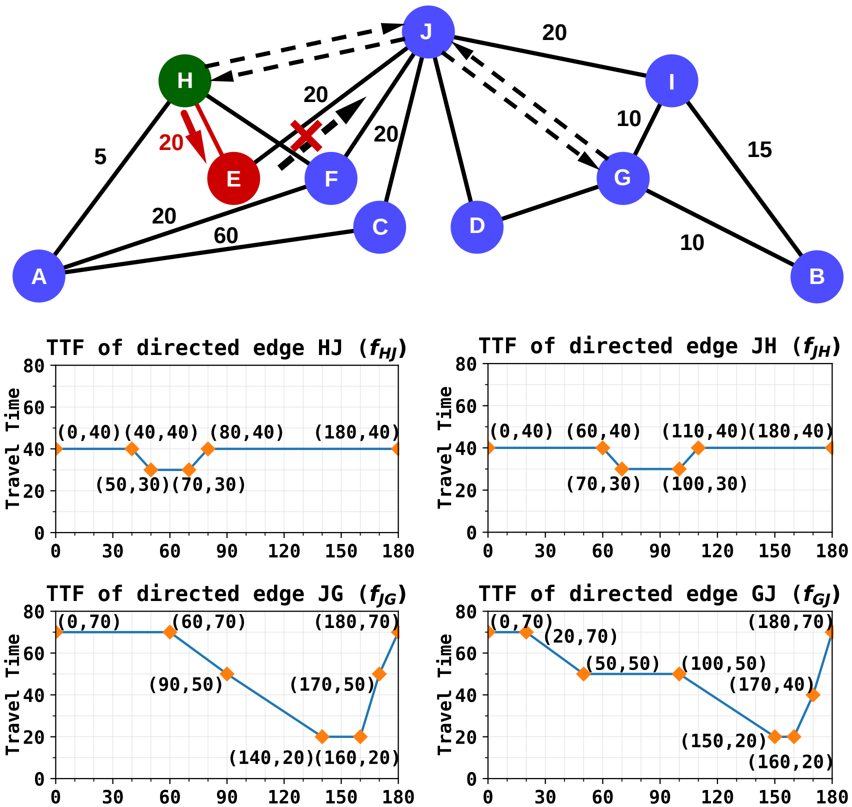
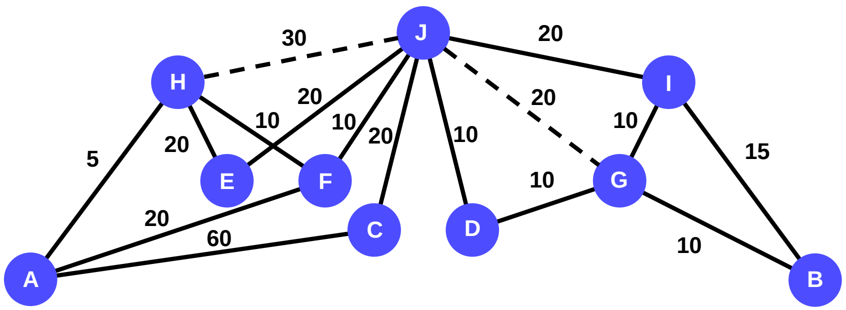


The up-then-down policy: the up successor J of E is pruned, because the predecessor H is lexically larger than E. (i.e., h $>_L$ E).

Our Approach
Improving TCH using Heuristic

- Combing BTCH with landmark:
- Forward TCH Search with CPD-based Heuristic:
  - Forward TCH Search:
    - Up-then-Down Policy
  - Heuristic:
    - TCH-CPD heuristic.



An example of static TCH, where the travel cost of each edge is the free-flow cost of corresponding TTF.

Our Approach
Improving TCH using Heuristic

- Combing BTCH with landmark:
- Forward TCH Search with CPD-based Heuristic:
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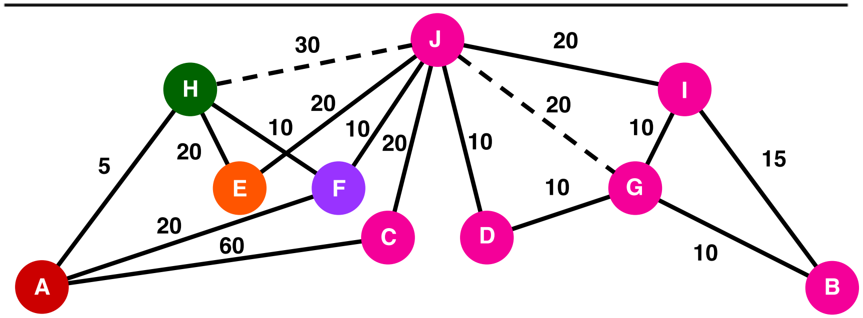
  - Heuristic:
    - TCH-CPD heuristic.
      - Construction:
        - » Run a modified Dijkstra search to compute first move on the optimal TCH-path.

Ordering	H	A	F	J	I	B	G	D	C	E
H	*	A	F	J	J	J	J	J	J	E
A	H	*	H	F	F	F	F	F	F	H
J	H	F	F	*	I	G	G	D	C	E



From the source node H, the optimal first move to any node are A (red), E(orange), F (purple) and J (pink)

Our Approach
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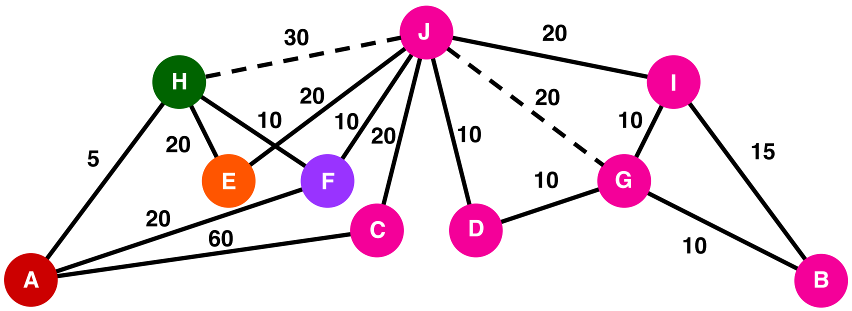
- Combing BTCH with landmark:
- Forward TCH Search with CPD-based Heuristic:
  - Forward TCH Search:
    - Up-then-Down Policy.
  - Heuristic:
    - TCH-CPD heuristic.
      - Construction:
        - » Run a modified Dijkstra search to compute first move on the optimal TCH-path.
        - » Compress by following the same procedures as CPD.

Ordering	H	A	F	J	I	B	G	D	C	E
H	*	A	F	J	J	J	J	J	J	E
A	H	*	H	F	F	F	F	F	F	H
J	H	F	F	*	I	G	G	D	C	E



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Our Approach
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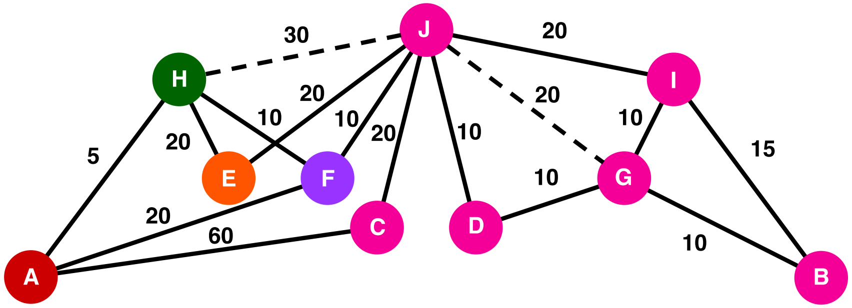
- Forward TCH Search with CPD-based Heuristic:
  - Forward TCH Search:
    - Up-then-Down Policy.
  - Heuristic:
    - TCH-CPD heuristic.
  - Enhancement:

Ordering	H	A	F	J	I	B	G	D	C	E
H	*	A	F	J	J	J	J	J	J	E
A	H	*	H	F	F	F	F	F	F	H
J	H	F	F	*	I	G	G	D	C	E



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Our Approach
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  - Forward TCH Search:
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  - Heuristic:
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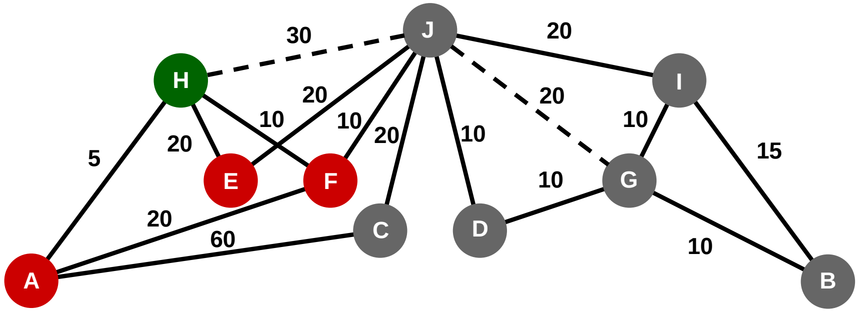
  - Enhancement:
    - Downward successor pruning:
      - Reachability Oracle.

Ordering	H	A	F	J	I	B	G	D	C	E
H	*	T	T	F	F	F	F	F	F	T
A	F	*	F	F	F	F	F	F	F	F
J	T	T	T	*	T	T	T	T	T	T



From the source node H, the downward reachable and non-reachable nodes are colored in red and grey respectively.

Our Approach
Improving TCH using Heuristic

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  - Forward TCH Search:
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  - Heuristic:
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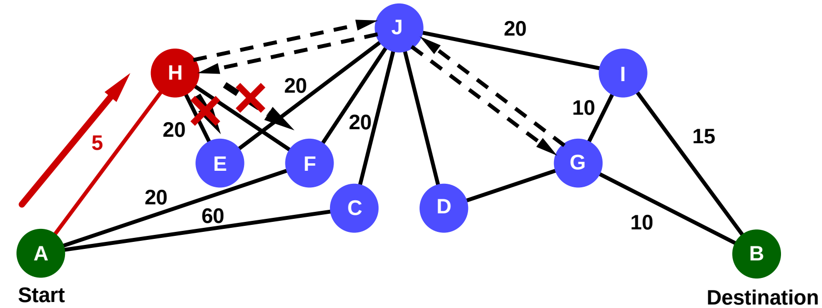
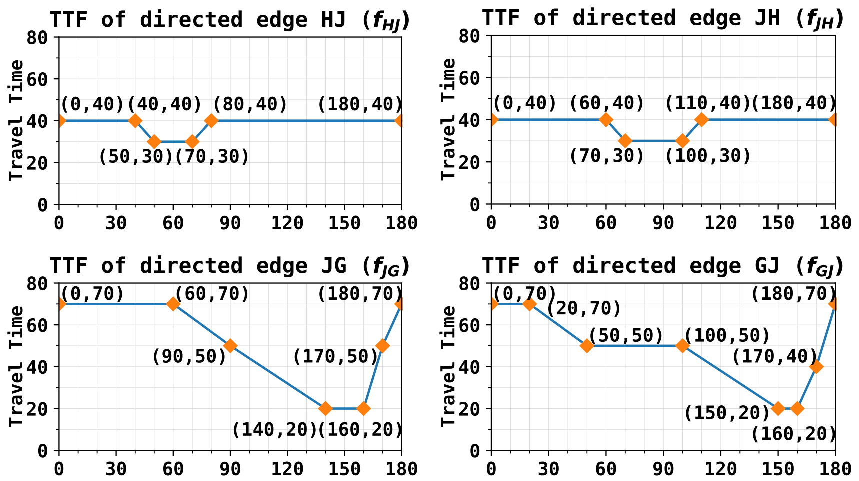
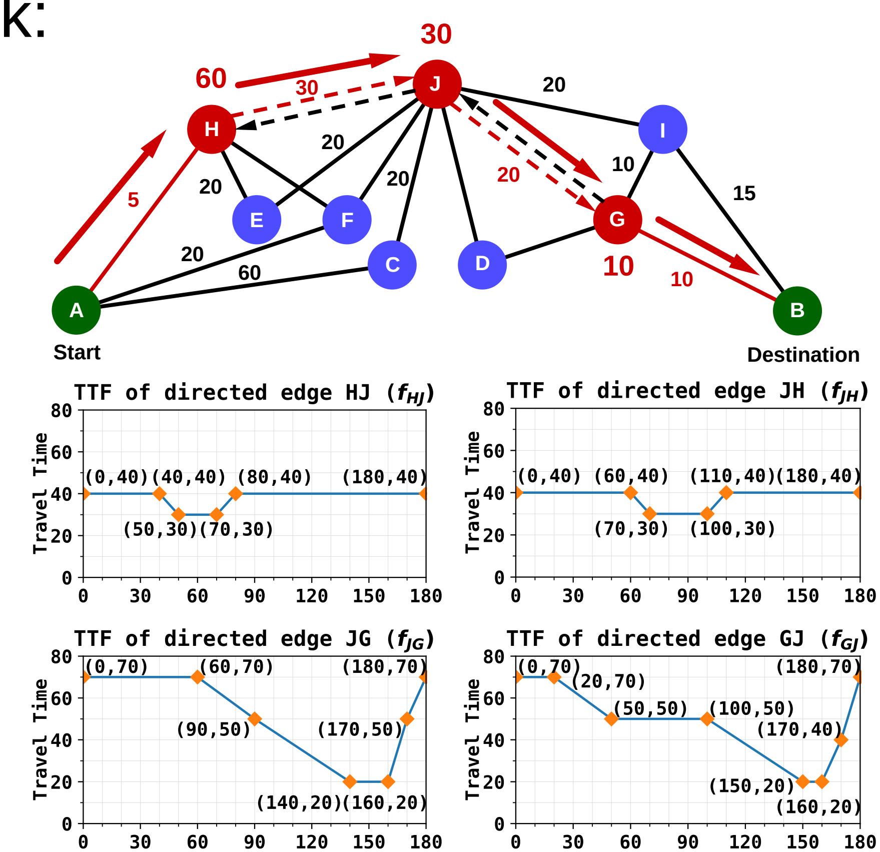
  - Enhancement:
    - Downward successor pruning:
      - Reachability Oracle.
      - During the search, prune the unreachable down successors.





The down successor E and F are pruned, because there exists no down path from E or F can reach the destination B.

- Combing BTCH with landmark:
- Forward TCH Search with CPD-based Heuristic:
  - Forward TCH Search:
    - Up-then-Down Policy.
  - Heuristic:
    - TCH-CPD heuristic.
  - Enhancement:
    - Downward successor pruning:
      - Reachability Oracle.
      - During the search, prune the unreachable down successors.
    - Cost Caching.



When compute the heuristic, we cache distance on each node when extracts the path from H to B.

Our Approach
Improving TCH using Heuristic

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- Combing BTCH with landmark:
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  - Forward TCH Search:
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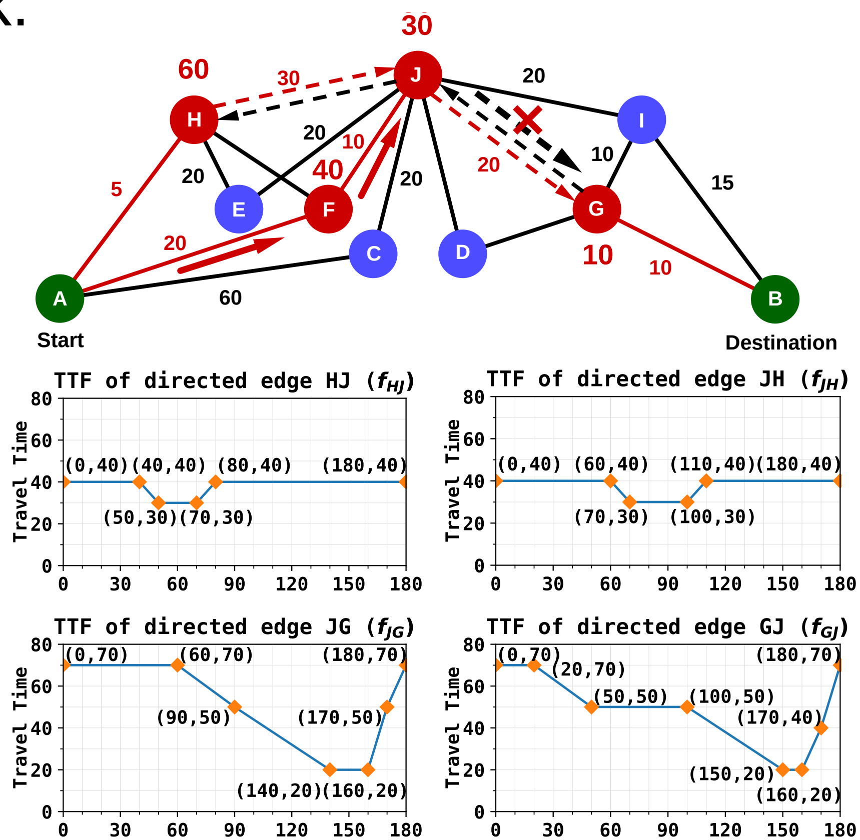
  - Enhancement:
    - Downward successor pruning:
      - Reachability Oracle.
      - During the search, prune the unreachable down successors.
    - Cost Caching.



When compute heuristic for node F, the path extraction terminate at J as we already recorded the distance from J to B.

Our Approach
Improving TCH using Heuristic

- Combing BTCH with landmark:
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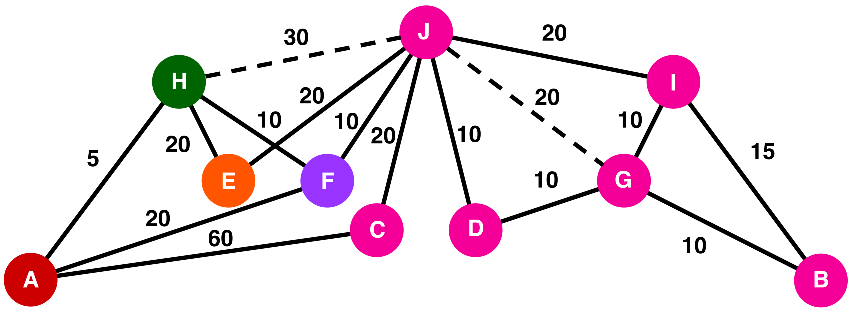
  - Forward TCH Search:
    - Up-then-Down Policy.
  - Heuristic:
    - TCH-CPD heuristic.
  - Enhancement:
    - Downward successor pruning:
      - Reachability Oracle.
      - During the search, prune the unreachable down successors.
    - Cost Caching.
    - Reverse TCH path database.

Ordering	H	A	F	J	I	B	G	D	C	E
H	*	A	F	J	J	J	J	J	J	E
A	H	*	H	F	F	F	F	F	F	H
J	H	F	F	*	I	G	G	D	C	E



From the source node H, the optimal first move to any node are A (red), E(orange), F (purple) and J (pink)

Ordering	H	A	F	J	I	B	G	D	C	E
H	H	H	H	H	J	G	J	J	J	H
A	A	A	H	F	J	G	J	J	J	H
J	J	H	J	J	J	G	J	J	J	J

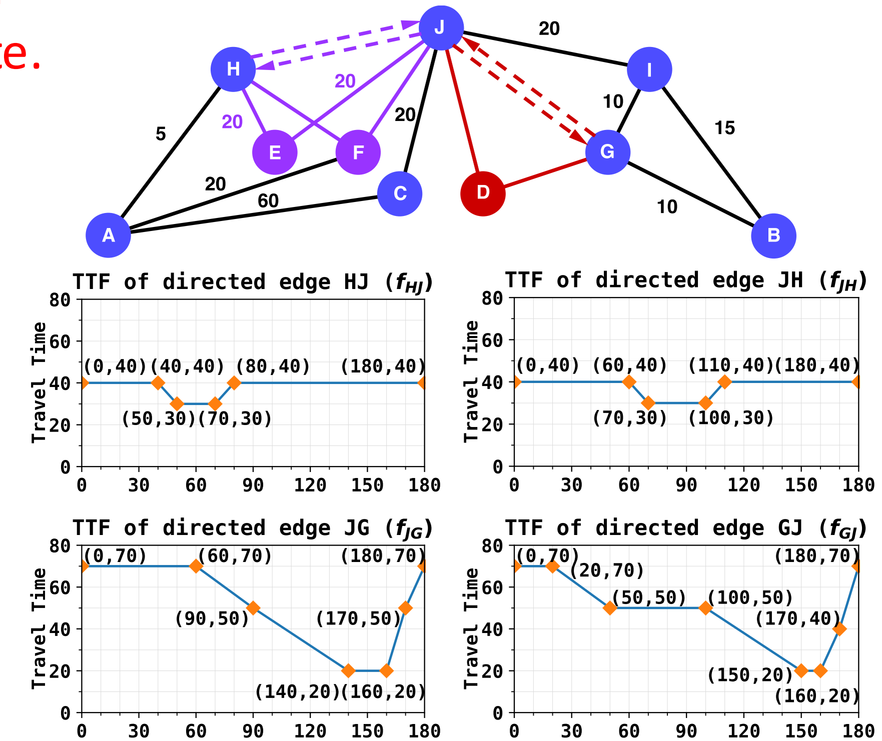
A reverse first move table which records the for every d ∈ V , the first move on the shortest path from d to s

Our Approach
Improving TCH by splitting the time domain

- Drawbacks of TCH:

Improving TCH by splitting the time domain

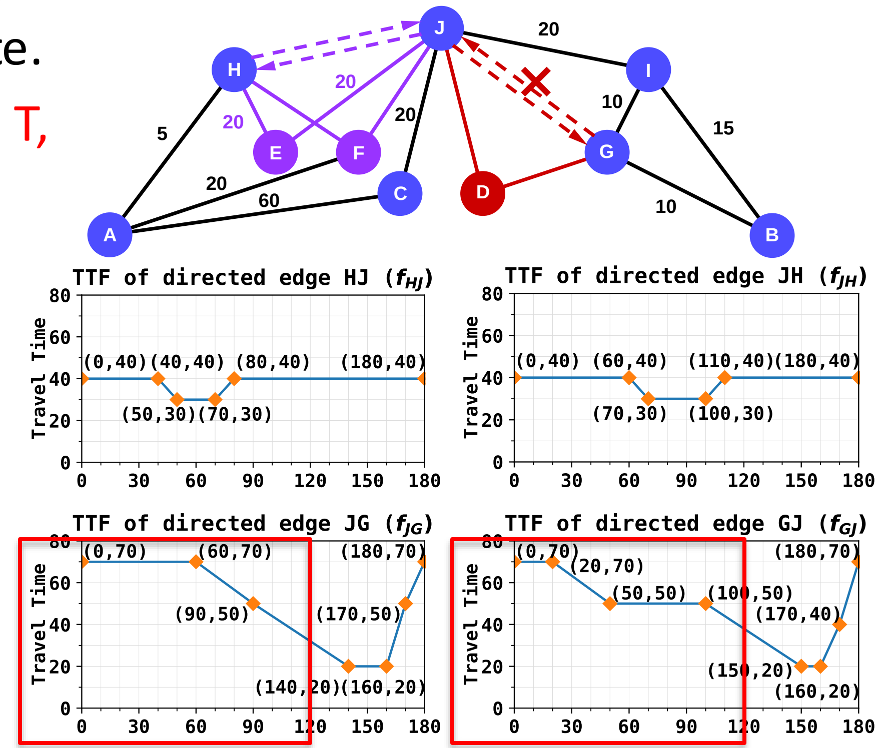
- Drawbacks of TCH:
  - TTF stores all interpolate points for entire T, thus are harder to evaluate.



We show the result for contracting nodes E and F in purple, and D in red. Dashed edge are the shortcut edges and their corresponding TTFs are shown in the figure below.

Improving TCH by splitting the time domain

- Drawbacks of TCH:
  - TTF stores all interpolate points for entire T, thus are harder to evaluate.
  - Shortcut edge are added for entire T, may be unnecessary for T' ⊆ T.



Assume a TCH is built for T = [0, 120], contracting the node D cannot add the shortcut JG, as <J,I,G> is a shorter path than <J,D,G> (i.e., 20 + 10 < min(fJD ∘ fDG)).

Our Approach
Improving TCH by splitting the time domain

- Drawbacks of TCH:
- Single layer TCH (STCH):

Our Approach
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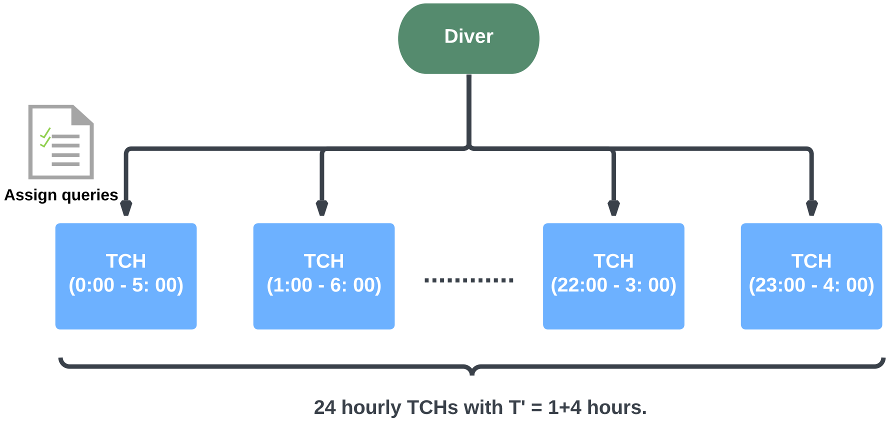
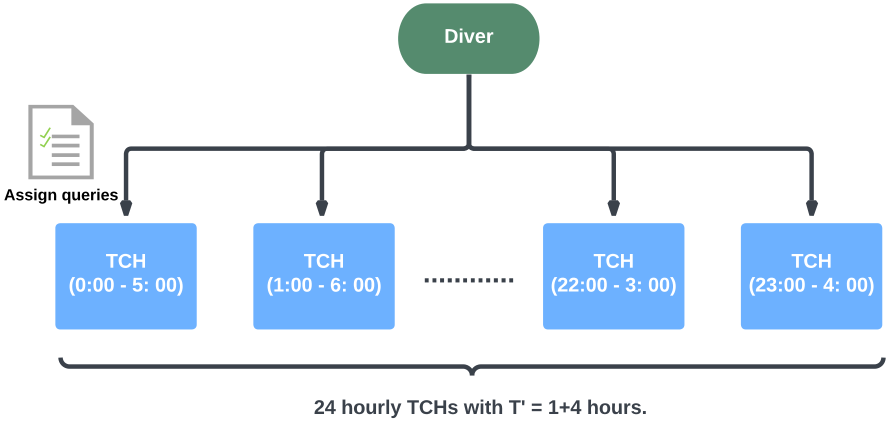


Our Approach
Improving TCH by splitting the time domain

- Drawbacks of TCH:
- Single layer TCH (STCH):
  - Divide the time domain T into n buckets.
  - Built a TCH for each bucket:
    - T’ = T/n + U.



Our Approach
Improving TCH by splitting the time domain

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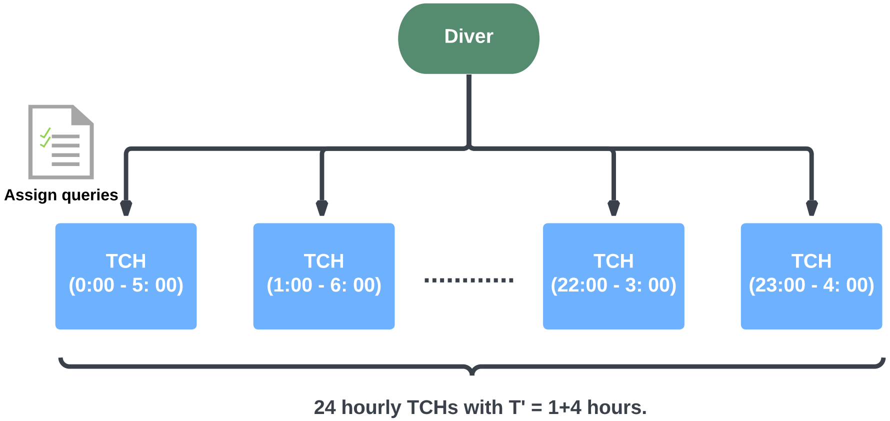
- Drawbacks of TCH:
- Single layer TCH (STCH):
  - Divide the time domain T into n buckets.
  - Built a TCH for each bucket:
    - T’ = T/n + U.
  - Query:
    - Assign queries to the corresponding TCH.



Our Approach
Improving TCH by splitting the time domain

- Drawbacks of TCH:
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- Multi layer TCH (MTCH):

Our Approach
Improving TCH by splitting the time domain

- Drawbacks of TCH:
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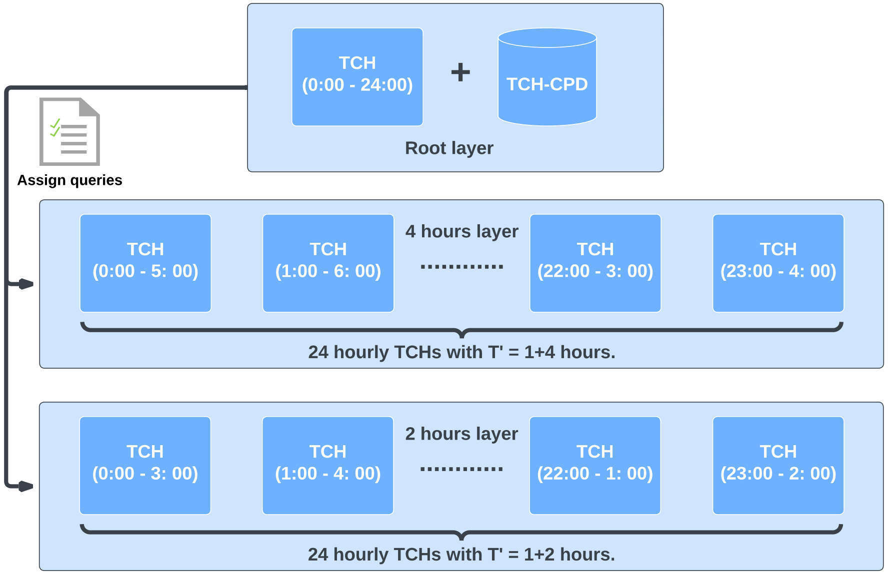
  - Root layer:
    - Build a full TCH and TCH-CPD.



Our Approach
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- Drawbacks of TCH:
- Single layer TCH (STCH):
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  - For each layer under root layer:
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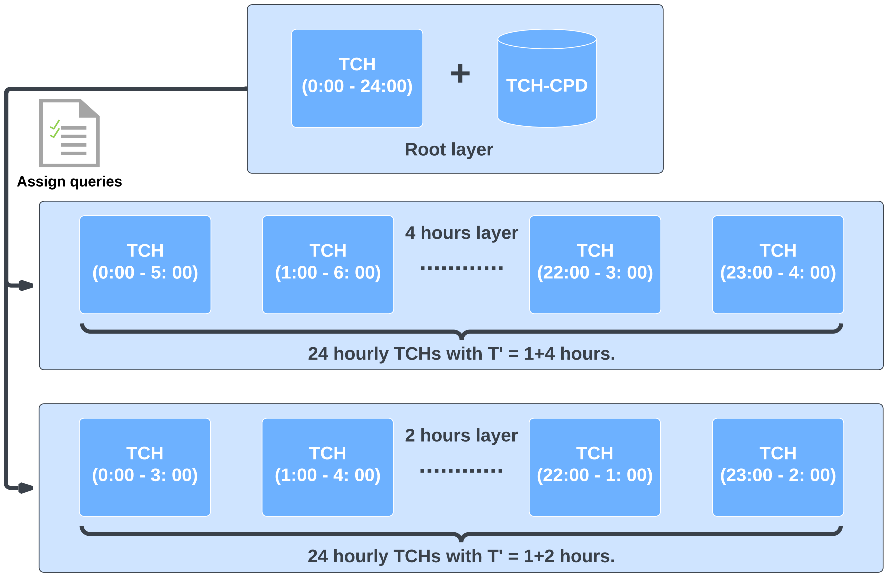

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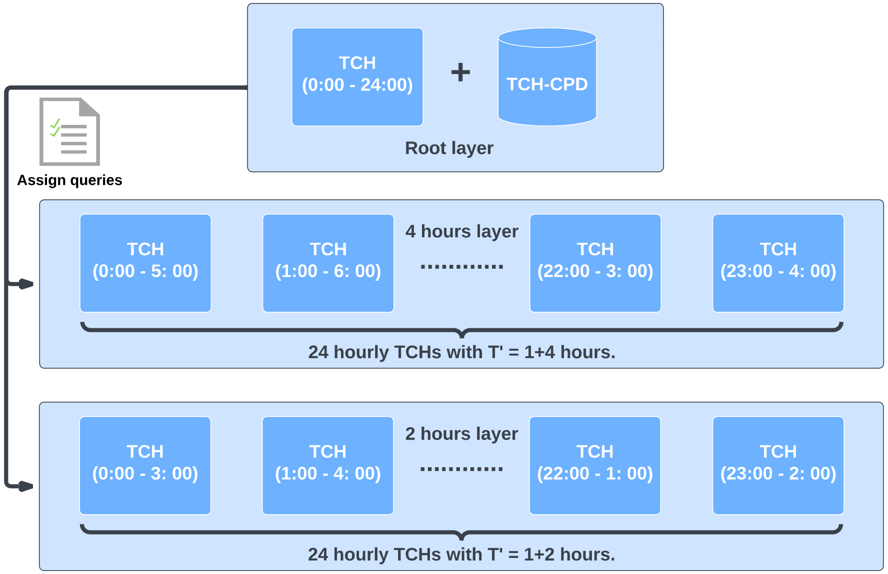
  - Query:
    - TCH-CPD to compute an upper-bound U(s,d).



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- Drawbacks of TCH:
- Single layer TCH (STCH):
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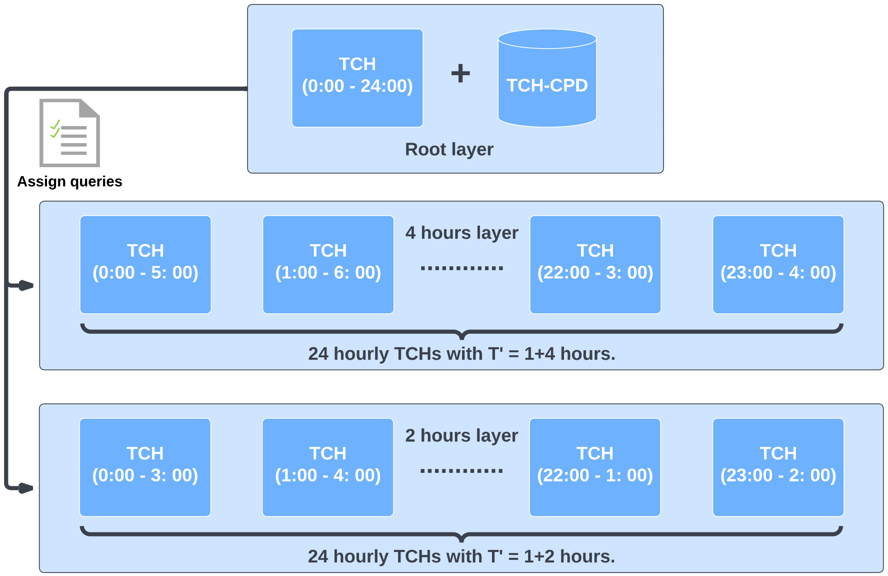
  - For each layer under root layer:
    - Build STCH with any arbitrary U.
  - Query:
    - TCH-CPD to compute an upper-bound U(s,d).
    - Assign queries to the TCH with minimal T' that covers [t, t+U(s,d)]

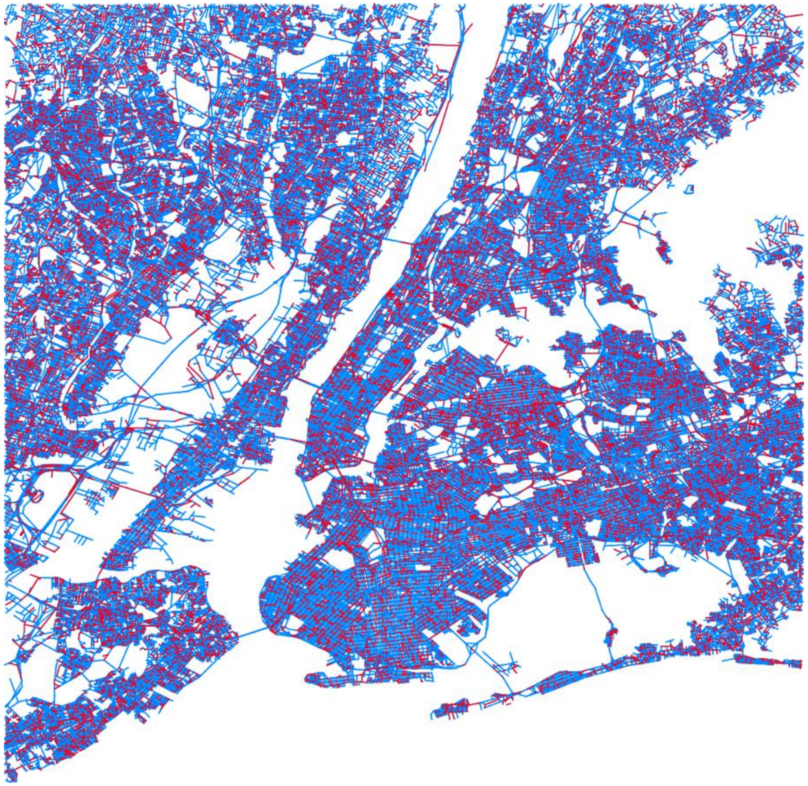


Our Approach
Experimental Results

- Experimental Results:

Our Approach
Experimental Results

- Experimental Results:
  - Benchmarks:
    - Real-world time-dependent road network [7].



Real-world dataset: New York. The edges that have TTF are colored in red.

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- Experimental Results:
  - Preprocessing cost:

Map	#V	#E	Build Time (Mins)								Memory (MB)							
			TCH				STCH		MTCH		TCH				STCH		MTCH	
			-	CPD	TCPD	RTPD	-	TCPD	-	TCPD	-	CPD	TCPD	RTPD	-	TCPD	-	TCPD
NY	96k	260k	1.72	2.92	2.94	3.21	2.99	31.87	9.04	95.12	269	346	353	9596	1279	3286	3193	9198

Our Approach
Experimental Results

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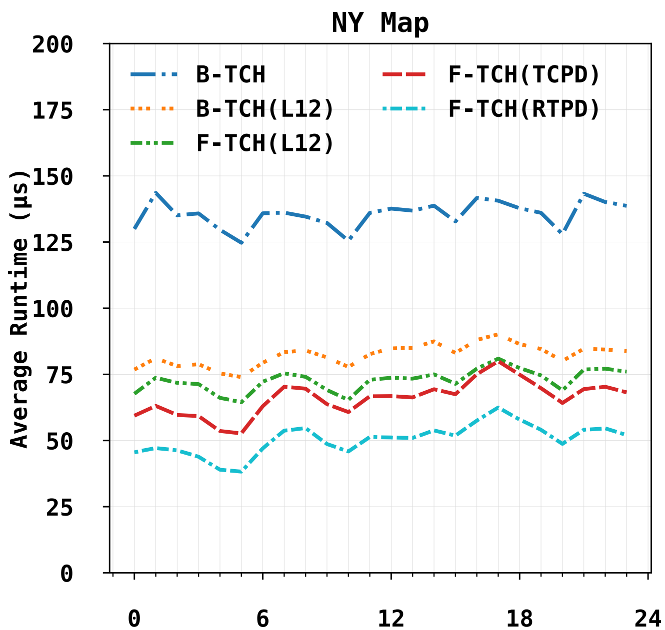
  - Preprocessing cost:

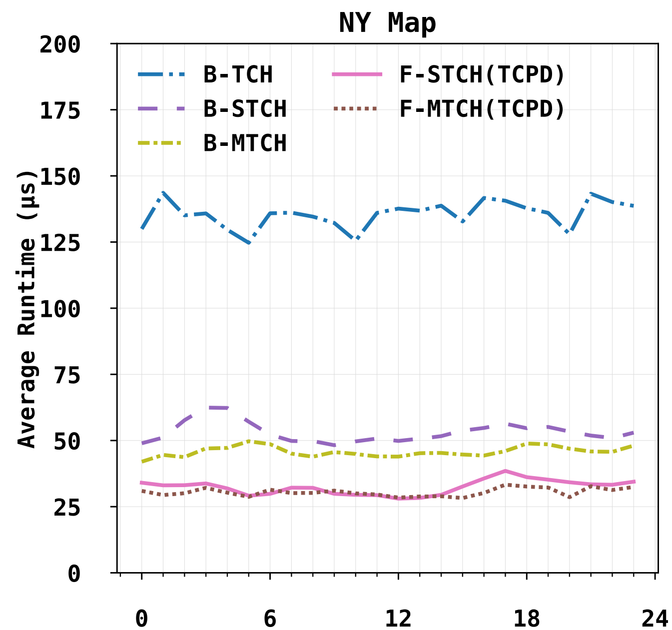
Map	#V	#E	Build Time (Mins)								Memory (MB)							
			TCH				STCH		MTCH		TCH				STCH		MTCH	
			-	CPD	TCPD	RTPD	-	TCPD	-	TCPD	-	CPD	TCPD	RTPD	-	TCPD	-	TCPD
NY	96k	260k	1.72	2.92	2.94	3.21	2.99	31.87	9.04	95.12	269	346	353	9596	1279	3286	3193	9198

  - Query performance:

Heuristic Search



Time Domain Splitting



Our Approach
Experimental Results

- Experimental Results:
  - Preprocessing cost:

Map	#V	#E	Build Time (Mins)								Memory (MB)							
			TCH				STCH		MTCH		TCH				STCH		MTCH	
			-	CPD	TCPD	RTPD	-	TCPD	-	TCPD	-	CPD	TCPD	RTPD	-	TCPD	-	TCPD
NY	96k	260k	1.72	2.92	2.94	3.21	2.99	31.87	9.04	95.12	269	346	353	9596	1279	3286	3193	9198

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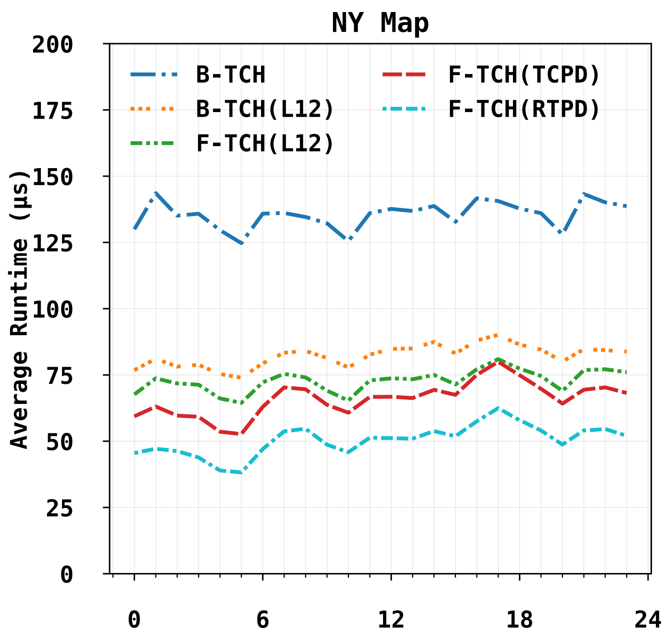

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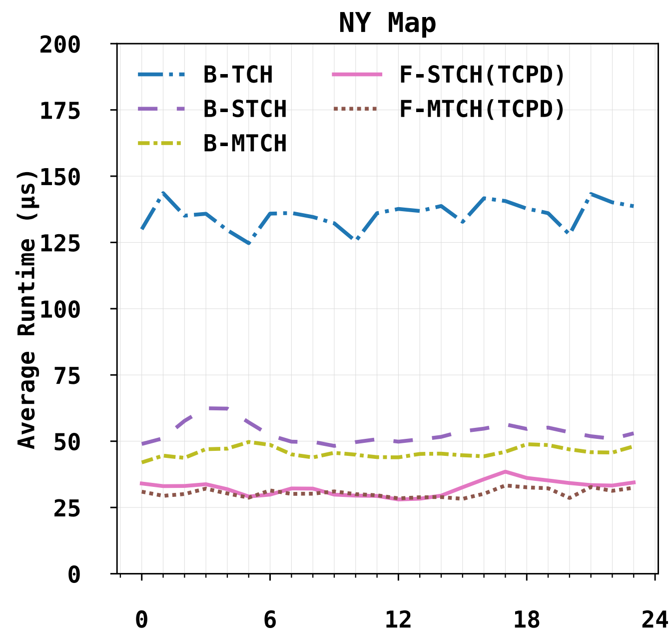

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Map	#V	#E	Build Time (Mins)									Memory (MB)							
			TCH				STCH		MTCH			TCH				STCH		MTCH	
			-	CPD	TCPD	RTPD	-	TCPD	-	TCPD		-	CPD	TCPD	RTPD	-	TCPD	-	TCPD
NY	96k	260k	1.72	2.92	2.94	3.21	2.99	31.87	9.04	95.12		269	346	353	9596	1279	3286	3193	9198

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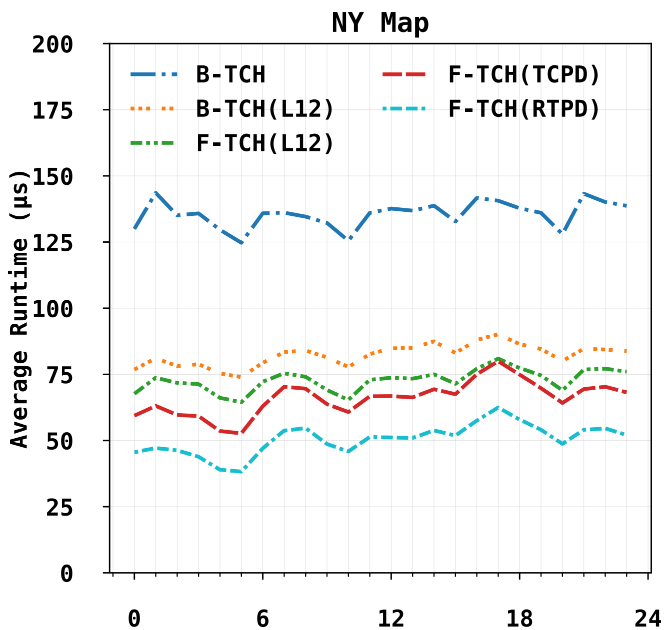
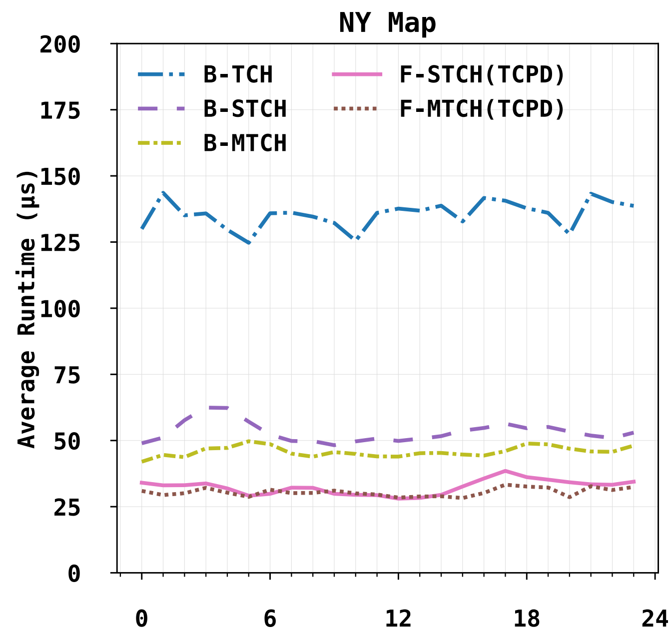


Time Domain Splitting



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[6] Delling, D.; and Wagner, D. 2007. Landmark-Based Rout- ing in Dynamic Graphs. In *Experimental Algorithms, 6th International Workshop, WEA 2007, Rome, Italy, June 6-8, 2007, Proceedings*, volume 4525 of *Lecture Notes in Com- puter Science*, 52–65. Springer.

[7] https://uofi.app.box.com/v/NYC-traffic-estimates.

Thank you for listening