UNIVERSITY OF MACEDONIA

MSc in Artificial Intelligence and Data Analytics

Train-scheduling for railway networks using basic kinematics and A*

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Introduction

- Goal: Automation of train-scheduling for railway networks.
- First algorithm: Computing optimal speed profile over a given path
  - Makes use of various train and path characteristics.
  - Optimizes journey duration.
  - Basic kinematic equations are applied.
  - Approximates real-world conditions.
- Second algorithm: Time-dependent shortest path finding
  - A* search
  - Straight line distance admissible heuristic function

Related Work

- Train scheduling is considered an NP-complete problem.
- Operations research techniques:
  - branch and bound algorithm
  - Lagrangian relaxation decomposition
  - linear programming
  - tabu search
  - Dijkstra algorithm
  - genetic algorithms
  - ant colony optimization
- Machine learning techniques:
  - Reinforcement learning (Q-learning algorithm)
  - Deep neural networks

Problem Formulation (1/2)

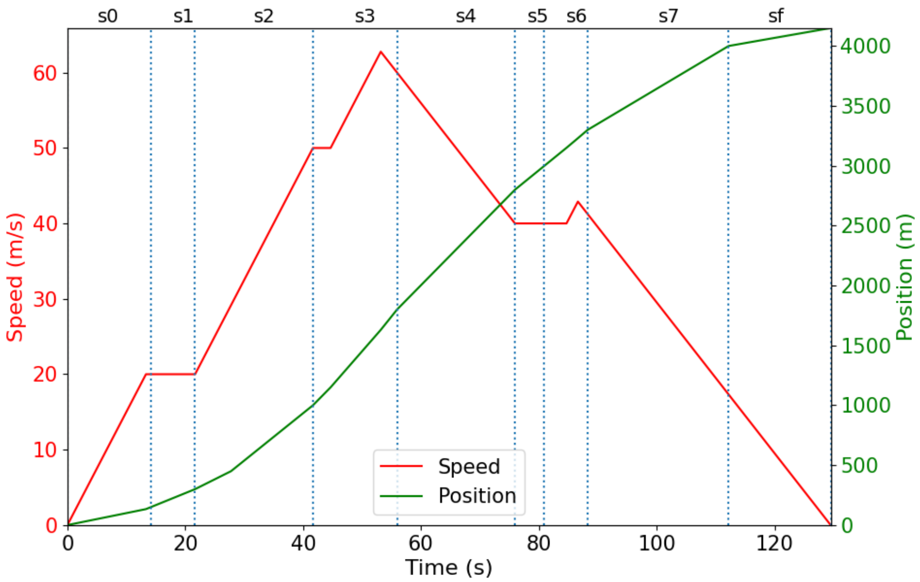
- Railway network graph modeled as an undirected graph G = (V, E).
- Each path is composed of multiple segments.
- Path segment characteristics.
  - length
  - maximum allowed speed
- Train characteristics
  - length
  - maximum speed
  - acceleration
  - deceleration
- State
  - position
    - list of segments
    - remaining distance
  - speed

Problem Formulation (2/2)

- Problem definition: initial and goal state
- Optimal solution: minimum duration speed profile

Parameters	Value
Length $l(T)$	150 m
Maximum speed $vmax(T)$	75 m/s
Acceleration $maxacc(T)$	1.5 m/s^2
Deceleration $maxdec(T)$	1 m/s^2
$init$	$((s_0, 150), 0)$
$goal$	$((s_f, 0), 0)$

Segment s	Length l_s (m)	$vmax(s)$ (m/s)
s_0	150	20
s_1	150	40
s_2	700	50
s_3	800	80
s_4	1000	85
s_5	200	40
s_6	300	60
s_7	700	50
s_f	150	30



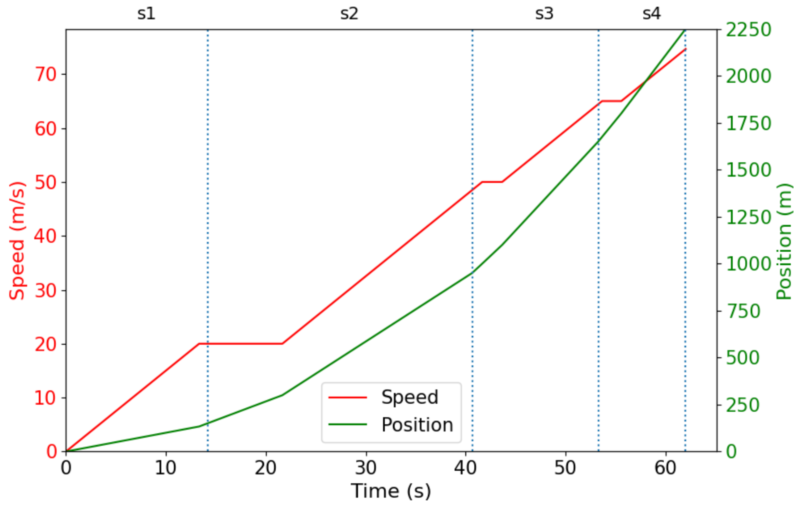
Computing optimal speed profile over a given path (1/6)

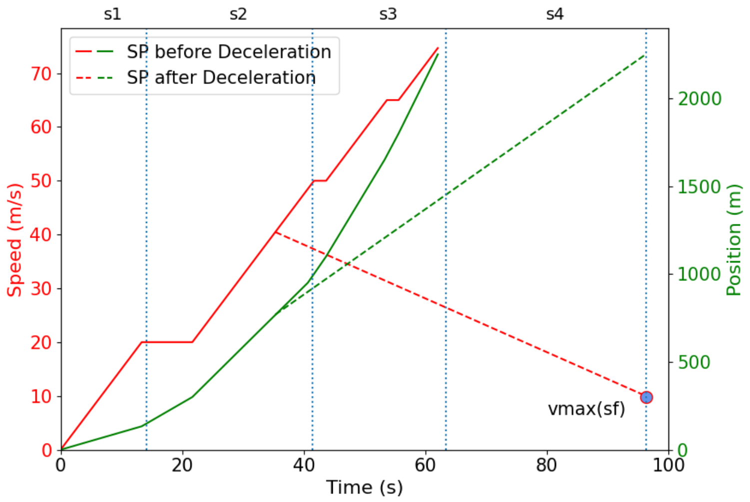
- Input: Path & Train characteristics, initial and goal state.
- Output: Optimal speed profile.
- An event-based approach is applied.
- An event happens when:
  - the train's head enters a new segment.
  - the train's tail exits a segment.
  - the train reaches the (segment or train) speed limit.
- The time to reach each type of event is calculated and the speed profile is adapted accordingly.
- **Difficult case:** When entering a new segment, there might a be speed limit lower than the train's current speed.

Computing optimal speed profile over a given path (2/6)

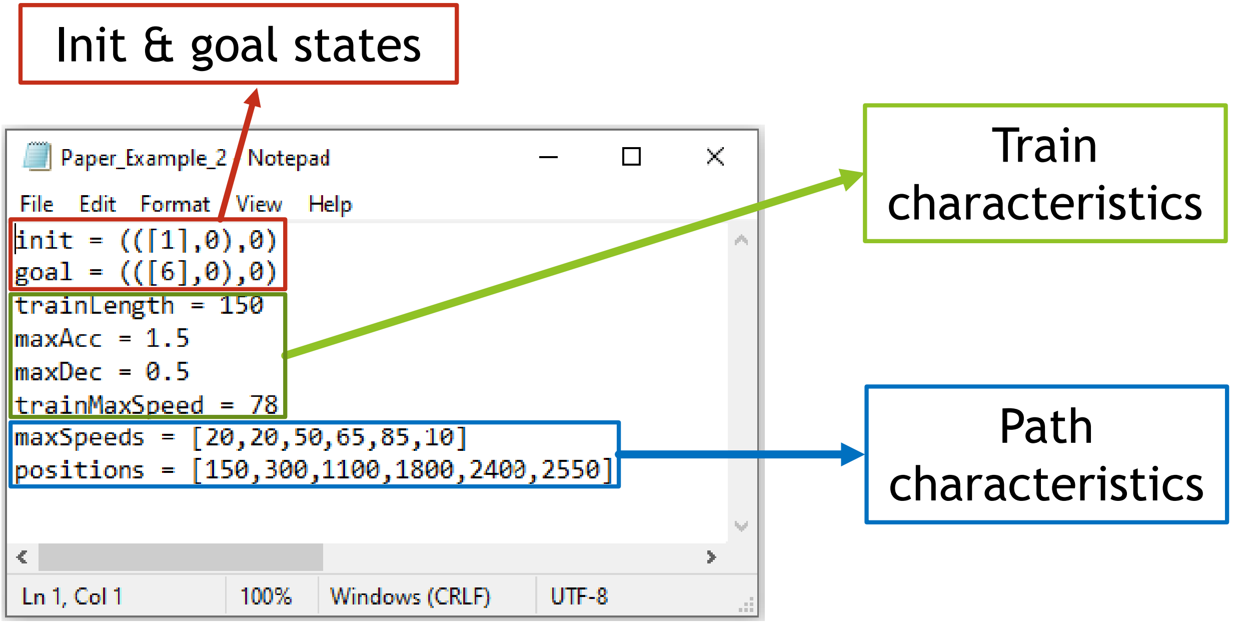
Segment s	Length l_s (m)	$vmax(s)$ (m/s)
s_0	150	20
s_1	150	20
s_2	700	65
s_3	800	70
s_4	1000	78
s_f	150	10

Parameters	Value
Length $l(T)$	150 m
Maximum speed $vmax(T)$	78 m/s
Acceleration $maxacc(T)$	1.5 m/s^2
Deceleration $maxacc(T)$	-0.5 m/s^2
init	$((s_0, 0), 0)$
goal	$((s_f, 0), 0)$





Computing optimal speed profile over a given path (3/6)



Computing optimal speed profile over a given path (4/6)

Input data validation

```
D:\Dissertation>py OptimalPathSpeedProfile.py D:\Dissertation\Paths\Paper_Example_2.txt
Train characteristics are valid.
Path characteristics are valid.
Init and Goal states are valid.

Total time:  121.2427603749243

Optimal Speed profile of the path

State 1: (([1, 2], 150), 0), Time: 0
State 2: (([1, 2], 16.666666666666657), 20.0), Time: 13.333333333333334
State 3: (([2, 3], 800), 20.0), Time: 14.166666666666666
State 4: (([3], 650.0), 20.0), Time: 21.666666666666664
State 5: (([3], 237.5), 40.46603514059662), Time: 35.310690093731075
State 6: (([5, 6], 150), 10), Time: 96.2427603749243
State 7: (([5, 6], 100.0), 10.0), Time: 101.2427603749243
State 8: (([6], 0), 0), Time: 121.2427603749243
```

Path travel time

Optimal speed profile

Computing optimal speed profile over a given path (5/6)

State of the train at the start of the Iteration

Time needed until each event

```
D:\Dissertation>py OptimalPathSpeedProfile.py D:\Dissertation\Paths\Paper_Example_2.txt --debug
Train characteristics are valid.
Path characteristics are valid.
Init and Goal states are valid.
----------------------------------------------------------------------
iterationCounter: 1
speedLimit: 20, currentAcc: 1.5, t1, t2, t3: (14.142135623730951, 14.142135623730951, 13.333333333333334)
current State: (([1, 2], 150), 0)
current time: 13.333333333333334
hExit: 16.666666666666657, tExit: 16.666666666666657
Train moved 133.33333333333334 meters in 13.333333333333334 seconds, CurrentV: 20.0, currentAcc: 1.5
New state: (([1, 2], 16.666666666666657), 20.0)
----------------------------------------------------------------------
```

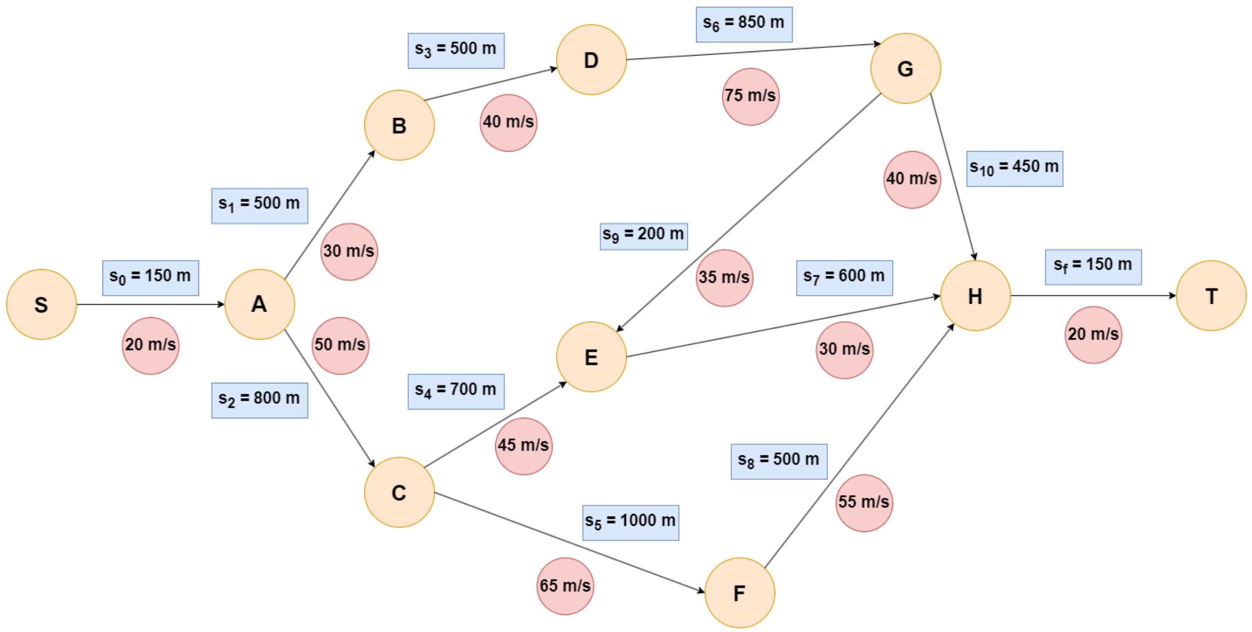
State of the train at the event

Computing optimal speed profile over a given path (6/6)

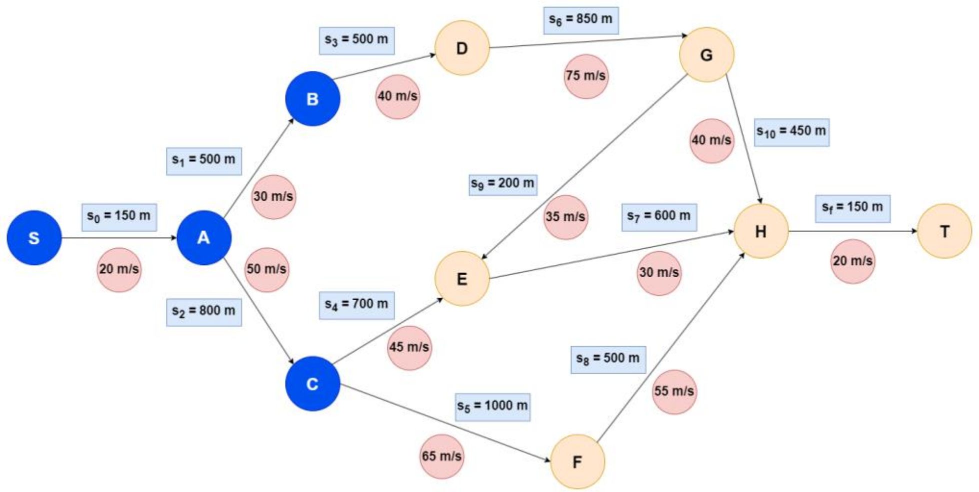
```
D:\Dissertation>py OptimalPathSpeedProfile.py D:\Dissertation\Paths\Impossible_to_decelerate.txt
Train characteristics are valid.
Path characteristics are valid.
Init and Goal states are valid.

No deceleration point could be found. There is no solution!

D:\Dissertation>py OptimalPathSpeedProfile.py D:\Dissertation\Paths\Impossible_to_accelerate.txt
Train characteristics are valid.
Path characteristics are valid.
Init and Goal states are valid.

It is impossible to accelerate to goalV!
```

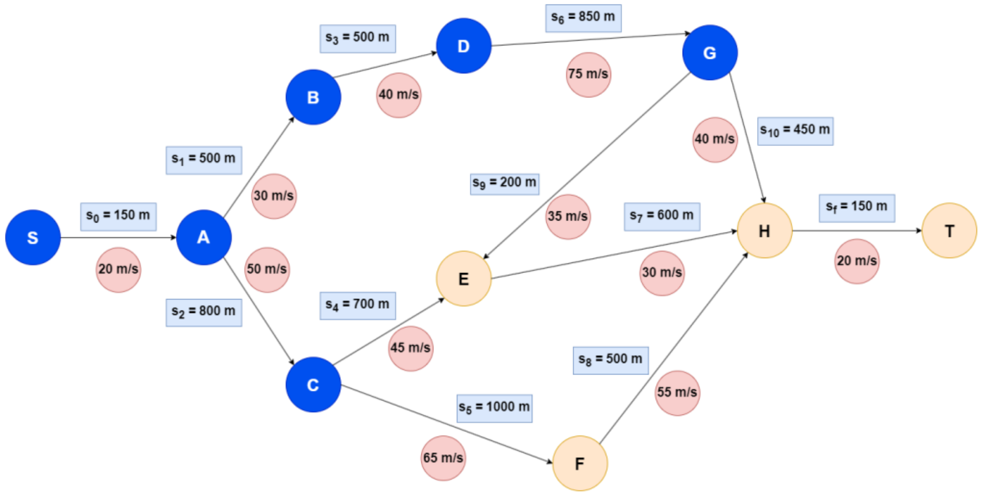
Shortest path finding (1/7)

- Input: G, Train characteristics, initial and goal state.
- Output: Optimal speed profile for the shortest path.
- A* search with a straight-line heuristic.



Shortest path finding (2/7)





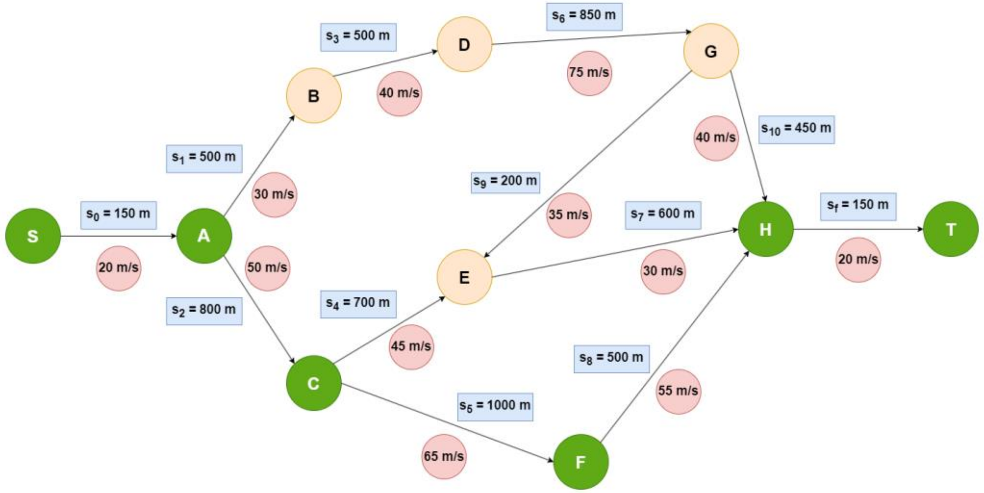
- Detected paths are expanded until the nearest junction where multiple paths meet.
  - Paths [S,A,B] and [S,A,C] are detected.
  - Path [S,A,B] is extended into path [S,A,B,D,G].
- Graph weights: f = g + h
  - G values:

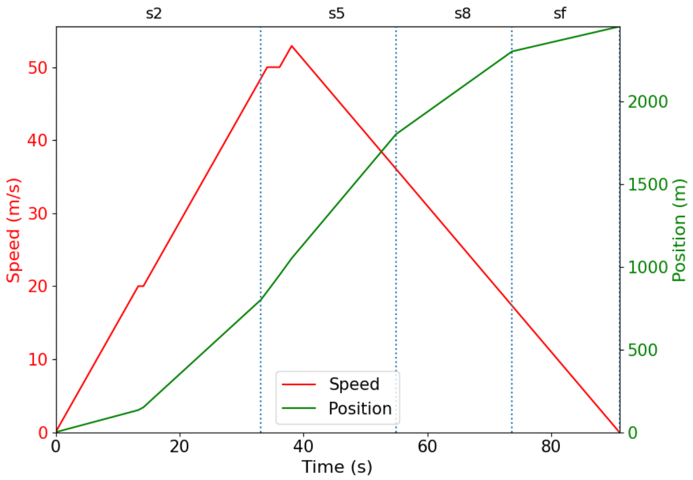
G([S,A,B,D,G]) = 59.16 seconds

G([S,A,C]) = 33.15 seconds

  - H values are the time needed to travel the straight line distance between the last node of a path and the destination node using the train's maximum speed.

Shortest path finding (3/7)





Shortest path finding (4/7)

Paper_Example_3_Characteristics - N...

File Edit Format View Help

```
init = (([1],0),0)
goal = (([12],0),0)
trainLength = 150
maxAcc = 1.5
maxDec = 1
trainMaxSpeed = 75
```

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Paper_Example_3_Network - Notepad

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```
S A {'label':0,'maxspeed': 20, 'length':150, 'straight_line': 2000}
A B {'label':1,'maxspeed': 30, 'length':500, 'straight_line': 1400}
A C {'label':2,'maxspeed': 50, 'length':800, 'straight_line': 1200}
B D {'label':3,'maxspeed': 40, 'length':500, 'straight_line': 900}
C E {'label':4,'maxspeed': 45, 'length':700, 'straight_line': 900}
C F {'label':5,'maxspeed': 65, 'length':1000, 'straight_line': 500}
D G {'label':6,'maxspeed': 75, 'length':850, 'straight_line': 500}
E H {'label':7,'maxspeed': 30, 'length':600, 'straight_line': 50}
F H {'label':8,'maxspeed': 55, 'length':500, 'straight_line': 50}
G E {'label':9,'maxspeed': 35, 'length':200, 'straight_line': 900}
G H {'label':10,'maxspeed': 40, 'length':450, 'straight_line': 50}
H T {'label':11,'maxspeed': 20, 'length':150, 'straight_line': 0}
```

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Computing optimal speed profile over a given path (5/7)

Nodes of the shortest path

```
D:\Dissertation>py ShortestPath.py D:\Dissertation\Networks\Paper_Example_3_Network.txt D:\Dissertation\Networks\Paper_Example_3_Characteristics.txt
Shortest path is:  ('S', 'A', 'C', 'F', 'H', 'T')

Total time:  91.02504370215301

Optimal Speed profile of the path

State 1: (([1, 2], 800), 0), Time: 0
State 2: (([1, 2], 666.6666666666666), 20.0), Time: 13.333333333333334
State 3: (([2], 650.0), 20.0), Time: 14.166666666666666
State 4: (([2, 3], 1000), 48.47679857416329), Time: 33.15119904944219
State 5: (([2, 3], 950.0), 50.0), Time: 34.166666666666664
State 6: (([3], 850.0), 50.0), Time: 36.166666666666664
State 7: (([3], 750.0), 52.91502622129181), Time: 38.1100174808612
State 8: (([5], 0), 0), Time: 91.02504370215301
```

Shortest path travel time

Optimal speed profile of the shortest path

Computing optimal speed profile over a given path (6/7)

Expansion of the current path

```
Current fastest path:  ('S', 'A', 'C')
Generated paths:  dict_keys([('S', 'A', 'C', 'E'), ('S', 'A', 'C', 'F')])
Expanded paths:  dict_keys([('S', 'A', 'C', 'E', 'H', 'T'), ('S', 'A', 'C', 'F', 'H', 'T')])
Calculating g value on path  ('S', 'A', 'C', 'E', 'H', 'T')
----------------------------------------------------------------------
iterationCounter: 1
speedLimit: 50, currentAcc: 1.5, t1, t2, t3: (21.94335081419454, 18.984532382775527, 20.0)
current State: (([2], 650.0), 20.0)
current time: 33.15119904944219
hExit: 0.0, tExit: 150.0
Train moved 650.0 meters in 18.984532382775527 seconds, CurrentV: 48.47679857416329, currentAcc: 1.5
New state: (([2], 0.0), 48.47679857416329)
Train reached a segment with speed limit 45 with a speed equal to 48.47679857416329.
i: 2, v0: 45, v1: 20.0, v2: 48.47679857416329, hExit: 650.0
d: 800, d1: 150.0, xDec: 735.0, v1Hash: 46.42197755374064
The train can accelerate until xDec. New state: (([2], 65.0), 46.42197755374064). Acc time: 17.61465170249376, Dec time: 1.4219775537406392.
----------------------------------------------------------------------
```

G value computation

Computing optimal speed profile over a given path (7/7)

The g values of all paths are equal to infinite.

```
openDict with g values:  {('S', 'A', 'B', 'D', 'G'): inf, ('S', 'A', 'C', 'E', 'H', 'T'): inf, ('S', 'A', 'C', 'F', 'H', 'T'): inf}
Calculating f value on path  ('S', 'A', 'B', 'D', 'G')
g value:  inf
heuristic:  3.3333333333333335
f value:  inf
Calculating f value on path  ('S', 'A', 'C', 'E', 'H', 'T')
g value:  inf
heuristic:  0.0
f value:  inf
Calculating f value on path  ('S', 'A', 'C', 'F', 'H', 'T')
g value:  inf
heuristic:  0.0
f value:  inf
Data after f values computation.
openDict:  {('S', 'A', 'B', 'D', 'G'): inf, ('S', 'A', 'C', 'E', 'H', 'T'): inf, ('S', 'A', 'C', 'F', 'H', 'T'): inf}
SPDict:  {('S', 'A', 'B', 'D', 'G'): [0], ('S', 'A', 'C', 'E', 'H', 'T'): [0], ('S', 'A', 'C', 'F', 'H', 'T'): [0]}
timeDict:  {('S', 'A', 'B', 'D', 'G'): [inf], ('S', 'A', 'C', 'E', 'H', 'T'): [inf], ('S', 'A', 'C', 'F', 'H', 'T'): [inf]}
The problem cannot be solved!
```

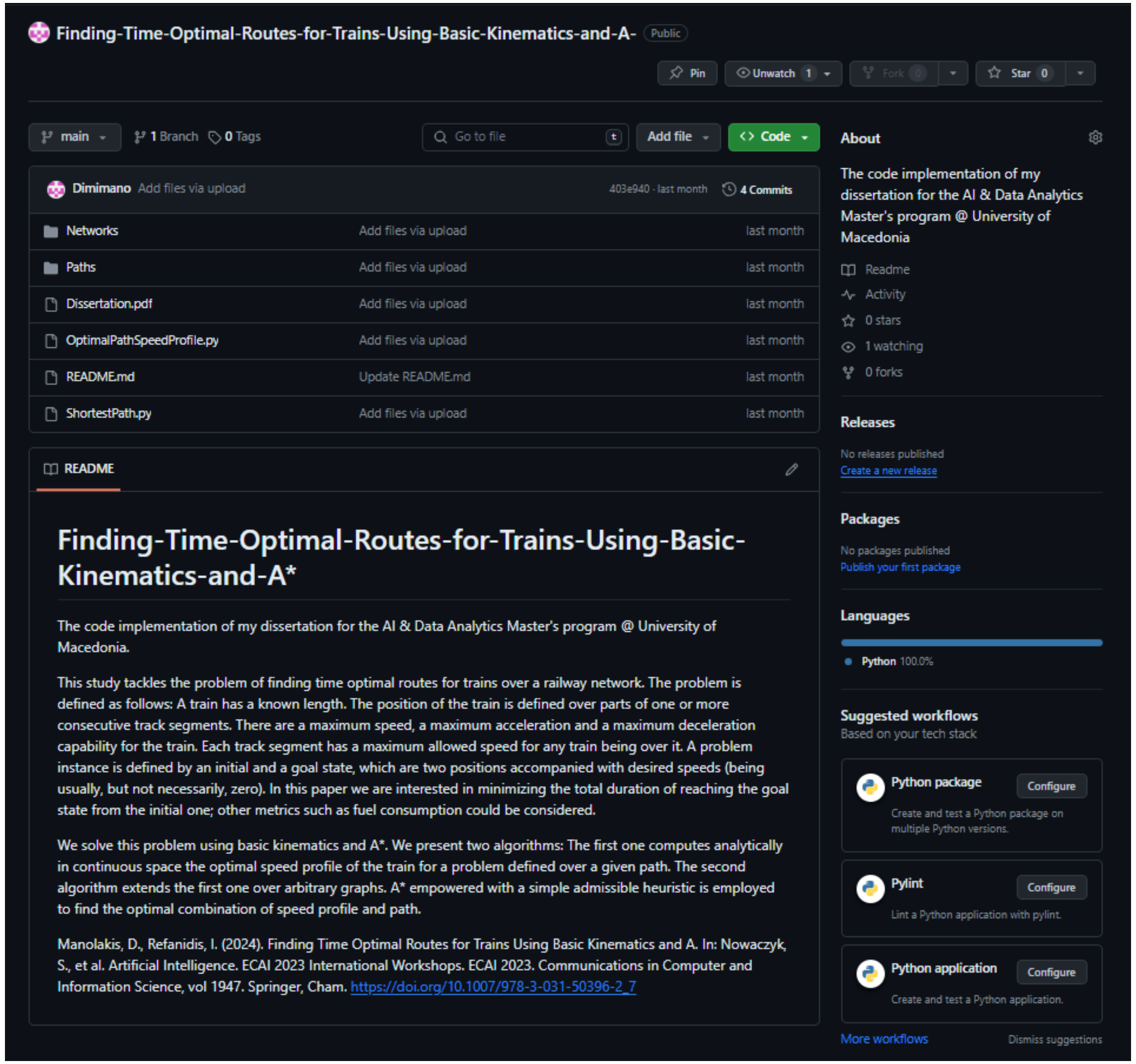
The f values of all paths become equal to infinite.

Hence, the problem cannot be solved!

Conclusions

- Realistic problem formulation.
- Handles the train when at multiple segments.
- Backtracks in previous states when a deceleration is needed.
- Many more train or path characteristics can be added.
- Different optimization criteria can be used.
- Different algorithms can be applied for the fastest route search.
- Problem can be expanded to handle multiple trains in the railway network.
- Real-world data can be used.

Repository



https://github.com/Dimimano/Finding-Time-Optimal-Routes-for-Trains-Using-Basic-Kinematics-and-A-

Thank you for your time!

Questions?