Modeling, Simulation and Optimization Project

Raksha Muddegowdana Koppalu Prakasha

Masters of Science in Data Analytics - Jan 2020

x19193181

Loading the Libraraies to Carry out Simulation

Python simpy package is used to carry out simulation

```
pip install simpy
```

```
Collecting simpy
  Downloading https://files.pythonhosted.org/packages/20/f9/874b0bab83406827db93292a5bbe5acb5c18e3cea665b2f6e053292cb687/simpy-4.0.1-py2.
Installing collected packages: simpy
Successfully installed simpy-4.0.1
```

```
import simpy
import random
import pandas as pd
import numpy as np
import matplotlib.pyplot as plt
from scipy.optimize import minimize
from time import sleep
```

Creating DataFrame

```
data = pd.DataFrame(columns=['FROM', 'TO', 'TIME_SEC', 'BLOCKS', 'DISTANCE'])

data_records = [ pd.Series(['London Old Oak', 'Birmingham Interchange', 'NA', 'NA', 145000], index=data.columns )]

data = data.append(data_records, ignore_index=True)
```

```
data
```

	FROM	TO	TIME_SEC	BLOCKS	DISTANCE
0	London Old Oak	Birmingham Interchange	NA	NA	145000

Defining Utility Functions to carry out value calculation,etc through out the simulation process

```
#To convert distance from meter to Kilometer
def m_to_km(x):
  return round(x/1000, 1)

#To formate Time in HH:mm:ss
def hhmmss(t):
  t=int(t)
  return f"{t//3600:02d}:{(t%3600)//60:02d}:{t%60:02d}"

#To convert time from sec scale to min
def s_to_m(t):
  return round(t/60,2)

def get_sec(time_str):
    """Get Seconds from time."""
    h, m, s = time_str.split(':')
    return int(h) * 3600 + int(m) * 60 + int(s)

def getTravelTimeDistance(a, v):
    t = round(v/a,1)
    d = round((a*t*t)/2)
    # print("timee",t)
    return [t, d]

def getTravelTime(s, d):
    t = round(d/s, 1)
    # print("TravelTime",t)
    return t

def getTravelDistance(s, t):
    d = round(s*t)
    return d
```

Class Train() is created to handle data/information regarding the moving train and their individual train objects.

```
class Train(object):
  def __init__(self, train_num):
    self.number = train_num
    self.pos = 0
    self.traveled_distance = 0
    self.start_time = 0
    self.end_time = 0
    self.travel_time = 0
    self.wait_time = 0
    self.incident_resol_time = 30
    self.incident_status = False
    self.incident_number = 0
```

Class Network() is created to handle movement of trains and signal blocks(pre).

```
class Network(object):
  def __init__(self, num_of_blocks, num_of_trains,induce_winds, pass_dwell):
    self.data = data

    self.st23_num_of_blocks = num_of_blocks
    self.st23_block_length = round(data.loc[0][4]/num_of_blocks,1)
    self.block_list = [0]*(num_of_blocks)
    self.num_ip_trains = num_of_trains
    self.train_count = 0
    self.total_trains = 0
    self.winds = induce_winds
    self.dwell = pass_dwell
    self.broken = False

  def signal_control(self):
    #global block_list
    if self.train_count < self.num_ip_trains and self.block_list[0] == 0:
      return True
    else:
      return False
```

```
  def new_train(self, train_num):
    return Train(train_num)

  def strong_weather_impact(self):
    if self.winds == 1:
      mu, sigma =   3.378, 0.75 # mean and standard deviation
      s = np.random.lognormal(mu, sigma, 1)
      st_i = round(s[0])
      # print("st winds", st_i)
      return st_i #increase in travel time using log normal distribution function                 ##Variation due to bad weather, the delay res
    else:
      return 0

  def dwell_time(self):
    if self.dwell == 1:
      return random.randint(10,20) #increase in travel time by 1.5 * value in scale             ## variation due to passanger onboarding, the r
    else:
      return 0
```

update_train_state() function records the information of each trains travelling for every iteration and updates its current position and travelling time

```
def update_train_status(env, t):
    global trains_list

    t.end_time = env.now
    t.travel_time = env.now - t.start_time
    trains_list[t.number-1] == t
```

Global Constants defined

```
#Global Constants

MAX_VELOCITY = 83.3 #m/s
ACCELERATION = 0.72 #m/s^2
DECELERATION = 0.38 #m/s^2
GRN_SIGNAL_AFT_EXIT = 5 #sec
```

```
TIME = 0

#Global DataFrame is created to store the information of moving trains
m_train = pd.DataFrame(columns= ['TRAIN', 'STATUS', 'STATION', 'TIME'])
#Global Trains List
trains_list = []
```

Double-click (or enter) to edit

run() function is the major process of the simulation and encaptures coding logic for controlling the movement of trains. It includes the logic:

Variability of movement of passengers/dwell_time() is added when Train leaving London Old Oak Commons Station.

Variability of bad weather/ strong_weather_impact() is added for trains between London Old Oak to Birmingham Interchange stations, which will affect the movement/travel_time of a train and schedules of future trains too.

Trains travelling check for 2 subsequent signals, if green, before entering the next block. If it doesn't get 2 green signal it waits for train ahead to pass

```
def run( hs, t):

  global TIME

  global m_train
  while t.pos < len(hs.block_list):
    try:
      update_train_status(env, t)
      ########################### travelling between  London Old Oak Commons  - Birmingham Interchange #################################
      if t.pos == 0:

        time, distance = getTravelTimeDistance(ACCELERATION,MAX_VELOCITY)
        time += getTravelTime(MAX_VELOCITY,hs.st23_block_length - distance)
        a_time = TIME
        wait = hs.dwell_time()
        t.wait_time += wait
        yield env.timeout(wait)

        hs.block_list[t.pos] = t.number
```

```
    record = {'TRAIN':t.number, 'STATUS':'DEPARTED', 'STATION':'LONDON OLD OAK', 'TIME':hhmmss(TIME+env.now)}
    m_train = m_train.append(record, ignore_index=True)
    yield env.timeout(GRN_SIGNAL_AFT_EXIT)
    update_train_status(env, t)

    t.pos += 1

    time = getTravelTime(MAX_VELOCITY,hs.st23_block_length)
    delay = hs.strong_weather_impact()
    # time += delay                                              #Impack of Extrenal factor like bad weather is introduced, affectin
    t.wait_time += delay                                        #is introduced, affecting speed of train
    yield env.timeout(wait)

  elif t.pos >= 1 and t.pos < hs.st23_num_of_blocks:

    hs.block_list[t.pos-1] = 0
    hs.block_list[t.pos] = t.number
    yield env.timeout(time + GRN_SIGNAL_AFT_EXIT)

    update_train_status(env, t)

    t.pos += 1

    if t.pos == hs.st23_num_of_blocks:
      time, distance = getTravelTimeDistance(DECELERATION,MAX_VELOCITY)
      time += getTravelTime(MAX_VELOCITY, hs.st23_block_length - distance)

      hs.block_list[t.pos-1] = t.number
      yield env.timeout(time)
      update_train_status(env, t)
      record1 = {'TRAIN':t.number, 'STATUS':'ARRIVED', 'STATION':'BIRMINGHAM INTERCHANGE', 'TIME':hhmmss(env.now+a_time)}
      m_train = m_train.append(record1, ignore_index=True)
      hs.block_list[t.pos-1] = 0
      update_train_status(env, t)
  else:
      yield env.timeout(1)                                                                                #Inner clock

except simpy.Interrupt:
  yield self.env.timeout(30)
```

delay() function is used to induce the temporary breakdown due to electrical malfunction of the 9am train from London to Birmingham. It takes 30 minutes to fix the problem.

```
def delay(hs, t):                                    # inducing a temporary break down due to electrical
                                                     # malfunction of the 9am train from London to Birmingham. It takes 30 minutes to fix the
                                                     # problem.

  global TIME

  # print(env.now > 32400 and env.now < 32690 )
  # print("time not updated", TIME)
  if (env.now > 32400 and env.now < 32690 ):
    # print("time updated")
    TIME = TIME + 1800
  else:
    yield env.timeout(5*60)

  yield env.timeout(1)
```

train_simulation() process is called to handle the entry of new train into Network, new run() process is called every time a new train is created.

```
def train_simulation(hs,incident):
  print('Simulation Running...',f'\nFor {len(hs.block_list)} blocks and {hs.num_ip_trains} input trains',
        f'each block between LONDON OLD OAK and BIRMINGHAM INTERCHANGE is {m_to_km(hs.st23_block_length)} km in length.')

  global trains_list
  global m_train
  global env
  trains_list = []
  m_train.drop(m_train.index, inplace=True)
  # print("incident", incident)
  while True:
    if hs.signal_control():                            # Check for green signal before starting new train
      hs.train_count += 1
      train = hs.new_train(hs.train_count)             # creating new train object
      train.start_time = env.now
      trains_list.append(train)
```

```
      env.process(run(hs, train))
      yield env.timeout(5*60)                  # Start new train process
      env.process(delay(hs, train))            # Induce Breakdown of 9am train


    yield env.timeout(10)
```

main() function validates the input, sets environment for simulation and start and end time for simulation.

```
def main(num_of_blocks,num_of_trains,induce_winds, pass_dwell, start_time, end_time,incident):
  global env
  #create class object
  hs = Network(num_of_blocks, num_of_trains,int(induce_winds), int(pass_dwell))
  #Setup enviornment
  env = simpy.Environment(initial_time = start_time )
  # if incident == 1:
  #initiate simulation
  env.process(train_simulation(hs,incident))
  #run until 3 hr (3600 sec)
  env.run(until = end_time)
```

Running Simulation for "k" number of blocks and "n" number of trains with variability of bad weather and passenger dwell time introduces. Additionally breakdown of 9 am train because of technical issue

The start_time and end_time of the simulation is also passed to the main() function

```
n_blocks = input('Enter number of blocks to be laid between (London Old Oak - Brimingham Interchange) line of 145 km = \n')
n_trains = input('Enter number of train = \n')

#Validating input
global TIME

TIME = 0

params = [n_blocks, n_trains]
if all(str(i).isdigit() and int(i)>0 for i in params):                   #Check is values are digit and greater than 0
  n_blocks, n_trains = [int(x) for x in params]
else:
```

```
  print('Default, Simulation starts with 10 Block and 10 Trains')
  n_blocks, n_trains = 10,10

# if int(winds) and int(pass_dwell) and int(incident) in [0,1]:                                                    #Checks choice for wind varia
#   if int(winds) and int(pass_dwell) and int(incident) == 1:
#     print("\n***Variablity in speed of trains due to WIND and Passanger Movement and Breakdown by incident is induced in simulation\n\n")
# else:
#   winds, pass_dwell,incident = 0, 0
# print("TIMEe", TIME)
if __name__ == "__main__":
  main(n_blocks, n_trains,1,1, 30600,39600,1)
```

```
Enter number of blocks to be laid between (London Old Oak - Brimingham Interchange) line of 145 km =
14
Enter number of train =
10
Simulation Running...
For 14 blocks and 10 input trains each block between LONDON OLD OAK and BIRMINGHAM INTERCHANGE is 10.4 km in length.
```

Verification of Simulation Results

Dataframe shows the results of the simulation when the number of blocks are 14 and train number is 10.

```
m_train
```

	TRAIN	STATUS	STATION	TIME
0	1	DEPARTED	LONDON OLD OAK	08:30:12
1	2	DEPARTED	LONDON OLD OAK	08:35:28
2	3	DEPARTED	LONDON OLD OAK	08:40:39
3	4	DEPARTED	LONDON OLD OAK	08:45:44
4	5	DEPARTED	LONDON OLD OAK	08:50:59
5	6	DEPARTED	LONDON OLD OAK	08:56:05
6	7	DEPARTED	LONDON OLD OAK	09:31:10
7	1	ARRIVED	BIRMINGHAM INTERCHANGE	09:02:23
8	8	DEPARTED	LONDON OLD OAK	09:36:21
9	2	ARRIVED	BIRMINGHAM INTERCHANGE	09:07:45
10	9	DEPARTED	LONDON OLD OAK	09:41:38

build_train_summary() creates the summary to all trains that entered into Network

```
train_summary = pd.DataFrame(columns=['TRAIN','POSITION','TRAVEL_TIME', 'WAIT_TIME'])
travel_time = pd.DataFrame(columns=['TRAIN','TRAVEL_TIME','DELAY_TIME','POSITION'])

def build_train_summary(trains_list):
  global train_summary
  # print((t.number))
  global travel_time
  train_summary.drop(train_summary.index, inplace=True)
  for t in trains_list:
    if t.pos > 1:

      dep = m_train.TIME[(m_train.STATUS == 'DEPARTED') & (m_train.TRAIN == t.number)].apply(get_sec)
      arr = m_train.TIME[(m_train.STATUS == 'ARRIVED') & (m_train.TRAIN == t.number)].apply(get_sec)
      a = arr.values[0] - dep.values[0]
```

```
        t.travel_time = abs(a+t.wait_time)
        rec = {'TRAIN': t.number,'TRAVEL_TIME': t.travel_time,'DELAY_TIME':t.wait_time,'POSITION':t.pos+1}
        travel_time = travel_time.append(rec, ignore_index=True)
    record   = {'TRAIN':t.number, 'POSITION':t.pos+1, 'TRAVEL_TIME':hhmmss(t.travel_time), 'WAIT_TIME':(t.wait_time)}
    train_summary = train_summary.append(record, ignore_index=True)
```

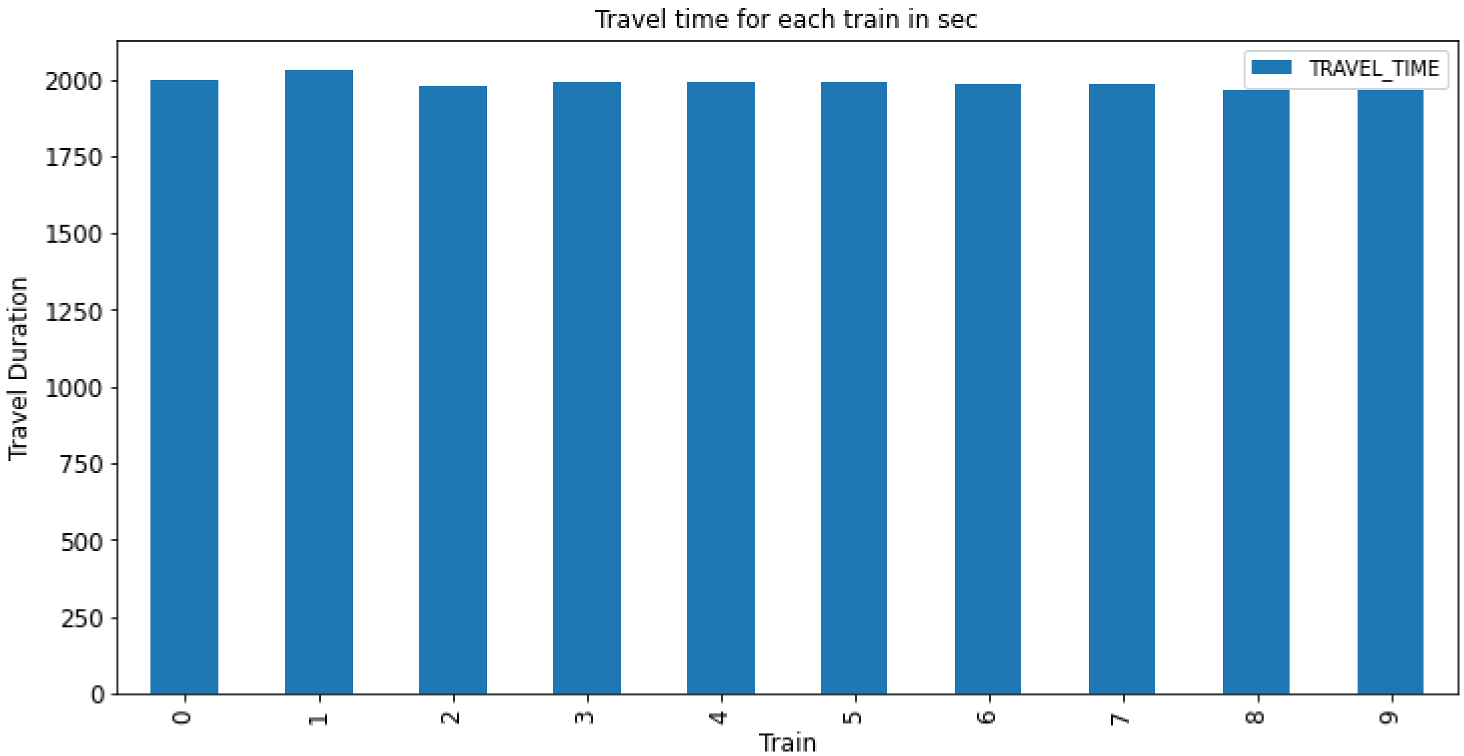
```
build_train_summary(trains_list)
train_summary
```

	TRAIN	POSITION	TRAVEL_TIME	WAIT_TIME
0	1	15	00:33:16	65.0
1	2	15	00:33:47	90.0
2	3	15	00:32:57	39.0
3	4	15	00:33:12	59.0
4	5	15	00:33:09	51.0
5	6	15	00:33:10	56.0
6	7	15	00:33:05	56.0
7	8	15	00:33:02	52.0
8	9	15	00:32:47	30.0
9	10	15	00:32:45	34.0

Bar graph that shows the travel time of each train in the Network.

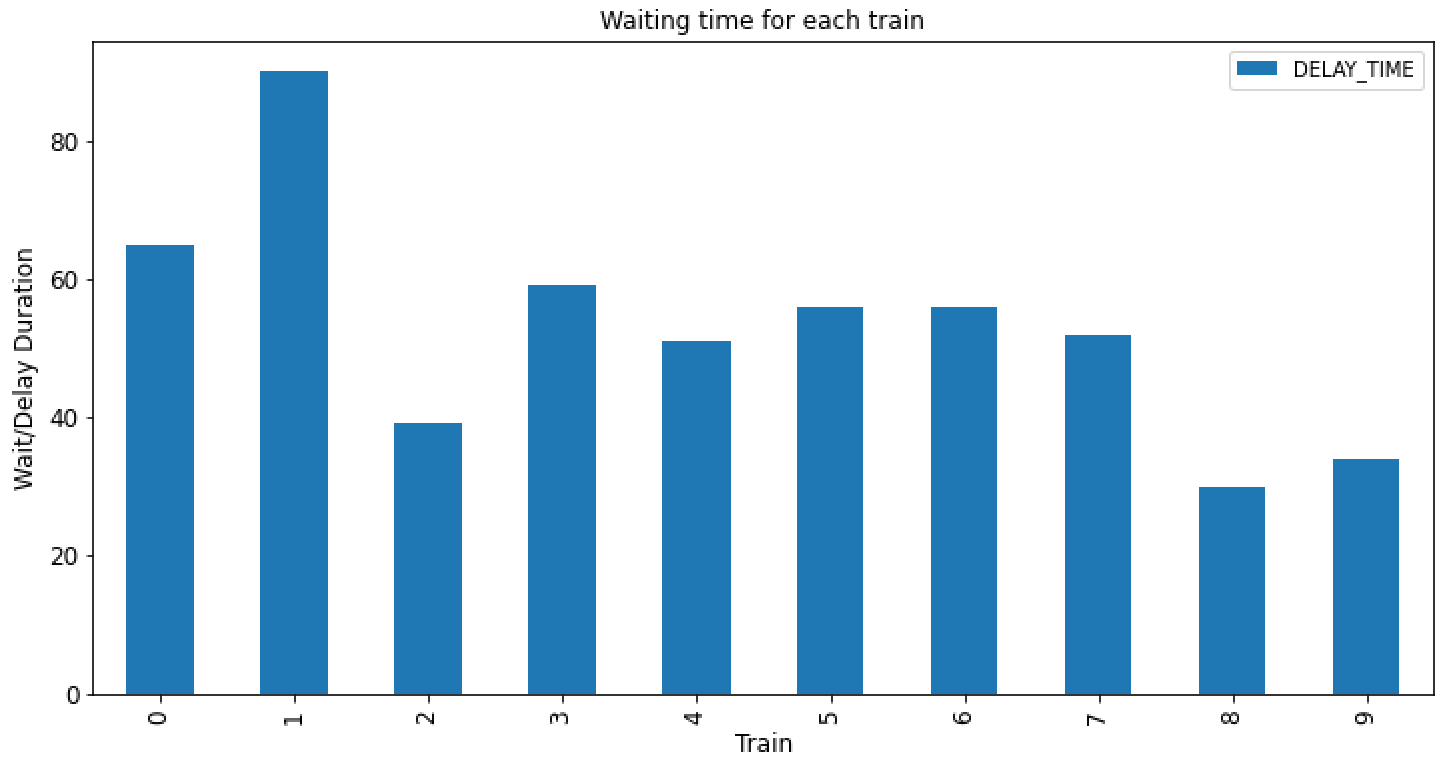
```
ax = travel_time[['TRAVEL_TIME']].plot(kind='bar', title ="Travel time for each train in sec", figsize=(12, 6), legend=True, fontsize=12)
```

```
ax.set_xlabel("Train", fontsize=12)
ax.set_ylabel("Travel Duration", fontsize=12)
plt.show()
```



Bar graph that shows the Waiting/ Delay time of each train in the Network.

```
ax = travel_time[['DELAY_TIME']].plot(kind='bar', title ="Waiting time for each train", figsize=(12, 6), legend=True, fontsize=12)
ax.set_xlabel("Train", fontsize=12)
ax.set_ylabel("Wait/Delay Duration", fontsize=12)
plt.show()
```



.

Average travel time trains in the Network

```
x = travel_time['TRAVEL_TIME'].mean()
print("Overall average travel time of all trains that entered Network line is", hhmmss(x))
```

```
Overall average travel time of all trains that entered Network line is 00:33:07
```

Simulation and Optimization

get_optimal() function calculates the average travel time, average delay time, and throughput for all combination of number of trains ranging from (1...20) and number of blocks ranging from (1...15) between the time 7am - 10pm. Variablity due to bad weather and dwell time due to passenger movement is also induced for optimization problem.

```
optimal = pd.DataFrame(columns=['TRAINS','BLOCKS','OVERALL_AVG_TRAVEL_TIME','OVERALL_AVG_DELAY_TIME','THROUGHPUT'])

def get_optimal():
  global trains_list
  global optimal
  global TIME
  TIME = 0
  optimal.drop(optimal.index, inplace=True)
  for i in range(19):
    for j in range(15):
      if i>0 and j>0:
        trains_list = []
        main(j,i,1,1,25200 ,79200,0)                                        # start time(First Train) = 7 am and Last Train = 10 pm
        build_train_summary(trains_list)
        avg = travel_time['TRAVEL_TIME'].mean()
        # print(avg)
        if avg < 0 :
          break
        else:
          avg1 = travel_time['DELAY_TIME'].mean()
          fin = travel_time[travel_time.POSITION.eq(13)]
          fin_avg = fin['TRAVEL_TIME'].mean()
          record = {'TRAINS':i, 'BLOCKS':j, 'OVERALL_AVG_TRAVEL_TIME':round(avg,2),'OVERALL_AVG_DELAY_TIME':round(avg1,2),'THROUGHPUT':len(trai
          optimal = optimal.append(record, ignore_index=True)


get_optimal()
```

```
Simulation Running...
For 1 blocks and 1 input trains each block between LONDON OLD OAK and BIRMINGHAM INTERCHANGE is 145.0 km in length.
Simulation Running...
For 2 blocks and 1 input trains each block between LONDON OLD OAK and BIRMINGHAM INTERCHANGE is 72.5 km in length.
Simulation Running...
For 3 blocks and 1 input trains each block between LONDON OLD OAK and BIRMINGHAM INTERCHANGE is 48.3 km in length.
Simulation Running...
For 4 blocks and 1 input trains each block between LONDON OLD OAK and BIRMINGHAM INTERCHANGE is 36.2 km in length.
Simulation Running...
For 5 blocks and 1 input trains each block between LONDON OLD OAK and BIRMINGHAM INTERCHANGE is 29.0 km in length.
Simulation Running...
For 6 blocks and 1 input trains each block between LONDON OLD OAK and BIRMINGHAM INTERCHANGE is 24.2 km in length.
Simulation Running...
For 7 blocks and 1 input trains each block between LONDON OLD OAK and BIRMINGHAM INTERCHANGE is 20.7 km in length.
Simulation Running...
For 8 blocks and 1 input trains each block between LONDON OLD OAK and BIRMINGHAM INTERCHANGE is 18.1 km in length.
Simulation Running...
For 9 blocks and 1 input trains each block between LONDON OLD OAK and BIRMINGHAM INTERCHANGE is 16.1 km in length.
Simulation Running...
For 10 blocks and 1 input trains each block between LONDON OLD OAK and BIRMINGHAM INTERCHANGE is 14.5 km in length.
Simulation Running...
For 11 blocks and 1 input trains each block between LONDON OLD OAK and BIRMINGHAM INTERCHANGE is 13.2 km in length.
Simulation Running...
For 12 blocks and 1 input trains each block between LONDON OLD OAK and BIRMINGHAM INTERCHANGE is 12.1 km in length.
Simulation Running...
For 13 blocks and 1 input trains each block between LONDON OLD OAK and BIRMINGHAM INTERCHANGE is 11.2 km in length.
Simulation Running...
For 14 blocks and 1 input trains each block between LONDON OLD OAK and BIRMINGHAM INTERCHANGE is 10.4 km in length.
Simulation Running...
For 1 blocks and 2 input trains each block between LONDON OLD OAK and BIRMINGHAM INTERCHANGE is 145.0 km in length.
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Simulation Running...
```

```
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For 14 blocks and 4 input trains each block between LONDON OLD OAK and BIRMINGHAM INTERCHANGE is 10.4 km in length.
Simulation Running...
For 1 blocks and 5 input trains each block between LONDON OLD OAK and BIRMINGHAM INTERCHANGE is 145.0 km in length.
Simulation Running...
For 2 blocks and 5 input trains each block between LONDON OLD OAK and BIRMINGHAM INTERCHANGE is 72.5 km in length.
Simulation Running...
For 3 blocks and 5 input trains each block between LONDON OLD OAK and BIRMINGHAM INTERCHANGE is 48.3 km in length.
Simulation Running...
For 4 blocks and 5 input trains each block between LONDON OLD OAK and BIRMINGHAM INTERCHANGE is 36.2 km in length.
Simulation Running...
For 5 blocks and 5 input trains each block between LONDON OLD OAK and BIRMINGHAM INTERCHANGE is 29.0 km in length.
Simulation Running...
For 6 blocks and 5 input trains each block between LONDON OLD OAK and BIRMINGHAM INTERCHANGE is 24.2 km in length.
Simulation Running...
For 7 blocks and 5 input trains each block between LONDON OLD OAK and BIRMINGHAM INTERCHANGE is 20.7 km in length.
Simulation Running...
For 8 blocks and 5 input trains each block between LONDON OLD OAK and BIRMINGHAM INTERCHANGE is 18.1 km in length.
Simulation Running...
For 9 blocks and 5 input trains each block between LONDON OLD OAK and BIRMINGHAM INTERCHANGE is 16.1 km in length.
Simulation Running...
For 10 blocks and 5 input trains each block between LONDON OLD OAK and BIRMINGHAM INTERCHANGE is 14.5 km in length.
Simulation Running...
For 11 blocks and 5 input trains each block between LONDON OLD OAK and BIRMINGHAM INTERCHANGE is 13.2 km in length.
Simulation Running...
For 12 blocks and 5 input trains each block between LONDON OLD OAK and BIRMINGHAM INTERCHANGE is 12.1 km in length.
Simulation Running...
For 13 blocks and 5 input trains each block between LONDON OLD OAK and BIRMINGHAM INTERCHANGE is 11.2 km in length.
Simulation Running...
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For 14 blocks and 5 input trains each block between LONDON OLD OAK and BIRMINGHAM INTERCHANGE is 10.4 km in length.
Simulation Running...
For 1 blocks and 6 input trains each block between LONDON OLD OAK and BIRMINGHAM INTERCHANGE is 145.0 km in length.
Simulation Running...
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Simulation Running...
For 13 blocks and 6 input trains each block between LONDON OLD OAK and BIRMINGHAM INTERCHANGE is 11.2 km in length.
Simulation Running...
For 14 blocks and 6 input trains each block between LONDON OLD OAK and BIRMINGHAM INTERCHANGE is 10.4 km in length.
Simulation Running...
For 1 blocks and 7 input trains each block between LONDON OLD OAK and BIRMINGHAM INTERCHANGE is 145.0 km in length.
Simulation Running...
For 2 blocks and 7 input trains each block between LONDON OLD OAK and BIRMINGHAM INTERCHANGE is 72.5 km in length.
Simulation Running...
For 3 blocks and 7 input trains each block between LONDON OLD OAK and BIRMINGHAM INTERCHANGE is 48.3 km in length.
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Simulation Running...
For 9 blocks and 7 input trains each block between LONDON OLD OAK and BIRMINGHAM INTERCHANGE is 16.1 km in length.
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Simulation Running...
For 10 blocks and 7 input trains each block between LONDON OLD OAK and BIRMINGHAM INTERCHANGE is 14.5 km in length.
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For 1 blocks and 8 input trains each block between LONDON OLD OAK and BIRMINGHAM INTERCHANGE is 145.0 km in length.
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Simulation Running...
For 4 blocks and 14 input trains each block between LONDON OLD OAK and BIRMINGHAM INTERCHANGE is 36.2 km in length.
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Simulation Running...
For 5 blocks and 14 input trains each block between LONDON OLD OAK and BIRMINGHAM INTERCHANGE is 29.0 km in length.
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Simulation Running...
For 1 blocks and 15 input trains each block between LONDON OLD OAK and BIRMINGHAM INTERCHANGE is 145.0 km in length.
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For 14 blocks and 15 input trains each block between LONDON OLD OAK and BIRMINGHAM INTERCHANGE is 10.4 km in length.
Simulation Running...
For 1 blocks and 16 input trains each block between LONDON OLD OAK and BIRMINGHAM INTERCHANGE is 145.0 km in length.
Simulation Running...
For 2 blocks and 16 input trains each block between LONDON OLD OAK and BIRMINGHAM INTERCHANGE is 72.5 km in length.
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Simulation Running...
For 1 blocks and 17 input trains each block between LONDON OLD OAK and BIRMINGHAM INTERCHANGE is 145.0 km in length.
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For 2 blocks and 17 input trains each block between LONDON OLD OAK and BIRMINGHAM INTERCHANGE is 72.5 km in length.
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For 4 blocks and 18 input trains each block between LONDON OLD OAK and BIRMINGHAM INTERCHANGE is 36.2 km in length.
Simulation Running...
For 5 blocks and 18 input trains each block between LONDON OLD OAK and BIRMINGHAM INTERCHANGE is 29.0 km in length.
Simulation Running...
For 6 blocks and 18 input trains each block between LONDON OLD OAK and BIRMINGHAM INTERCHANGE is 24.2 km in length.
Simulation Running...
For 7 blocks and 18 input trains each block between LONDON OLD OAK and BIRMINGHAM INTERCHANGE is 20.7 km in length.
Simulation Running...
For 8 blocks and 18 input trains each block between LONDON OLD OAK and BIRMINGHAM INTERCHANGE is 18.1 km in length.
Simulation Running...
For 9 blocks and 18 input trains each block between LONDON OLD OAK and BIRMINGHAM INTERCHANGE is 16.1 km in length.
```

optimal

	TRAINS	BLOCKS	OVERALL_AVG_TRAVEL_TIME	OVERALL_AVG_DELAY_TIME	THROUGHPUT
0	1.0	1.0	1959.08	54.16	1.0
1	1.0	2.0	1959.06	54.15	1.0
2	1.0	3.0	1959.05	54.16	1.0
3	1.0	4.0	1959.04	54.16	1.0

```
optimal[optimal.OVERALL_AVG_DELAY_TIME <= 0.5*5*60]
```

	TRAINS	BLOCKS	OVERALL_AVG_TRAVEL_TIME	OVERALL_AVG_DELAY_TIME	THROUGHPUT
0	1.0	1.0	1959.08	54.16	1.0
1	1.0	2.0	1959.06	54.15	1.0
2	1.0	3.0	1959.05	54.16	1.0
3	1.0	4.0	1959.04	54.16	1.0
4	1.0	5.0	1959.03	54.15	1.0
...	...	...	...	...	...
247	18.0	10.0	1959.22	54.64	18.0
248	18.0	11.0	1959.30	54.66	18.0
249	18.0	12.0	1959.35	54.63	18.0
250	18.0	13.0	1959.41	54.59	18.0
251	18.0	14.0	1959.58	54.65	18.0

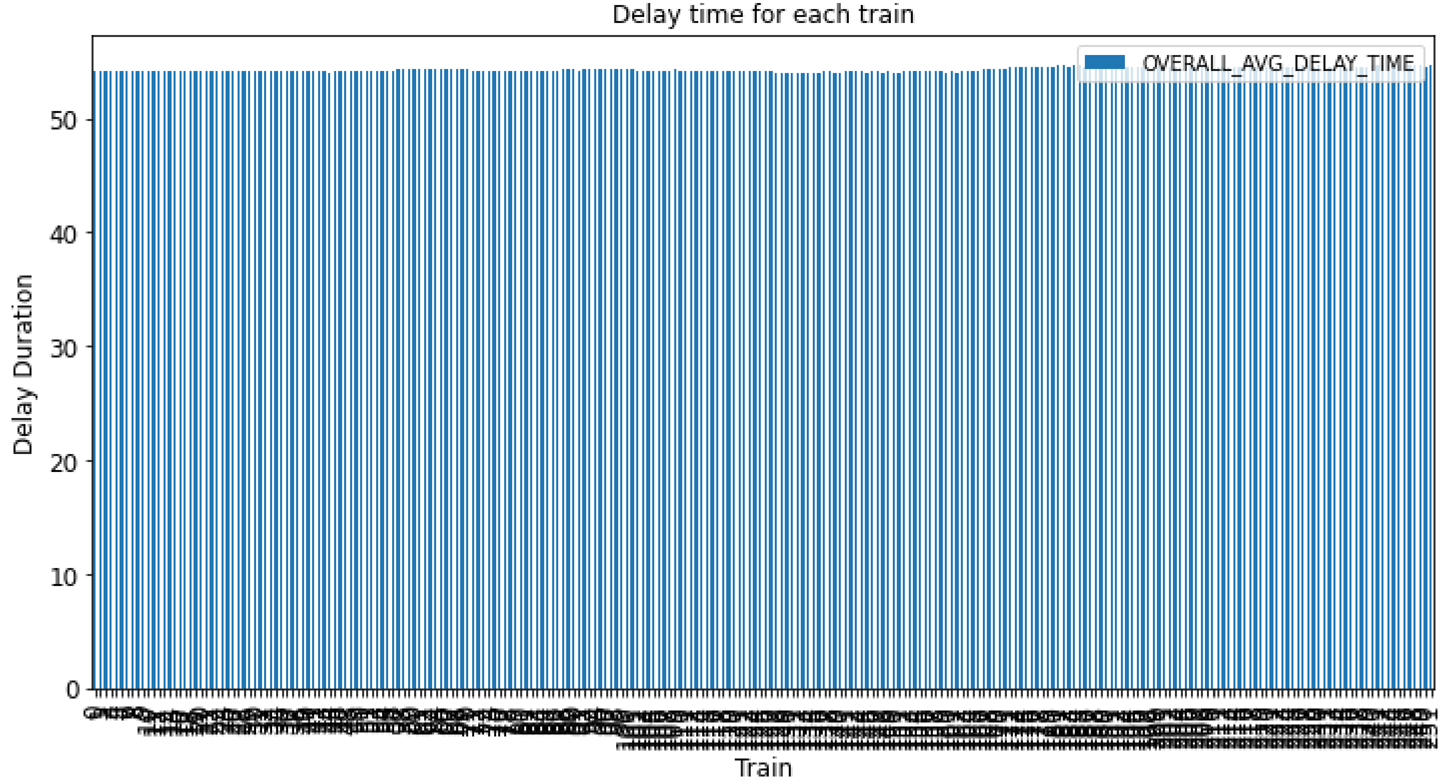
252 rows × 5 columns

```
optimal[optimal.OVERALL_AVG_DELAY_TIME == optimal.OVERALL_AVG_DELAY_TIME.min()]
```

	TRAINS	BLOCKS	OVERALL_AVG_TRAVEL_TIME	OVERALL_AVG_DELAY_TIME	THROUGHPUT
131	10.0	6.0	1958.58	54.01	10.0

Distribution of Delay Times

```
#@title Default title text
ax = optimal[['OVERALL_AVG_DELAY_TIME']].plot(kind='bar', title ="Delay time for each train", figsize=(12, 6), legend=True, fontsize=12)
ax.set_xlabel("Train", fontsize=12)
ax.set_ylabel("Delay Duration", fontsize=12)
plt.show()
```



Train Schedules from London Old Oak to Birmingham Exchange with first train departing London Oak Station at 7 am and last train departing at 10 pm

```
m_train
```

```
#Monte Carlo optimization for minimising travel time
import random
random.seed(0)

def monte_carlo(n, xmin=4, xmax=11, ymin=6, ymax=10):
    x = [ random.randint(xmin, xmax) for i in range(n)]
    y = [ random.randint(ymin, ymax) for i in range(n)]
    xp = [ x[0] ]
    yp = [ y[0] ]
    fmin = f(xp[0], yp[0])

    for i in range(1, len(x)):
        fi = f(x[i], y[i])

        if fi < fmin:
            xp += [x[i]]
            yp += [y[i]]
            fmin = fi

        xs = np.linspace(xmin, xmax, 100)
        ys = np.linspace(ymin, ymax, 100)
        xx, yy = np.meshgrid(xs, ys)
        z=f(xx, yy)

        fig, ax = plt.subplots(1, 1)
        fig.set_figwidth(6)
        fig.set_figheight(5)
        cs = ax.contourf(xs, ys, z, 100)
        fig.colorbar(cs, ax=ax)

        plt.scatter(x, y, c='red', marker='.')
        plt.plot(xp, yp, c='red')

        return len(xp), xp[-1], yp[-1], f(xp[-1], yp[-1])




random.seed(41)
monte_carlo(100)
```

	TRAIN	STATUS	STATION	TIME
0	1	DEPARTED	LONDON OLD OAK	07:00:14
1	2	DEPARTED	LONDON OLD OAK	07:05:21
2	3	DEPARTED	LONDON OLD OAK	07:10:31
3	4	DEPARTED	LONDON OLD OAK	07:15:47
4	5	DEPARTED	LONDON OLD OAK	07:20:52
5	6	DEPARTED	LONDON OLD OAK	07:26:00
6	7	DEPARTED	LONDON OLD OAK	07:31:11
7	1	ARRIVED	BIRMINGHAM INTERCHANGE	07:32:27
8	8	DEPARTED	LONDON OLD OAK	07:36:30
9	2	ARRIVED	BIRMINGHAM INTERCHANGE	07:37:31
10	9	DEPARTED	LONDON OLD OAK	07:41:33
11	3	ARRIVED	BIRMINGHAM INTERCHANGE	07:42:41
12	10	DEPARTED	LONDON OLD OAK	07:46:43
13	4	ARRIVED	BIRMINGHAM INTERCHANGE	07:48:03
14	11	DEPARTED	LONDON OLD OAK	07:51:57
15	5	ARRIVED	BIRMINGHAM INTERCHANGE	07:53:03
16	12	DEPARTED	LONDON OLD OAK	07:57:00
17	6	ARRIVED	BIRMINGHAM INTERCHANGE	07:58:09
18	13	DEPARTED	LONDON OLD OAK	08:02:17
19	7	ARRIVED	BIRMINGHAM INTERCHANGE	08:03:21
20	14	DEPARTED	LONDON OLD OAK	08:07:23
21	8	ARRIVED	BIRMINGHAM INTERCHANGE	08:08:49
22	15	DEPARTED	LONDON OLD OAK	08:12:37
23	9	ARRIVED	BIRMINGHAM INTERCHANGE	08:13:45

24	16	DEPARTED	LONDON OLD OAK	08:17:44
25	10	ARRIVED	BIRMINGHAM INTERCHANGE	08:18:55
26	17	DEPARTED	LONDON OLD OAK	08:22:58
27	11	ARRIVED	BIRMINGHAM INTERCHANGE	08:24:13
28	18	DEPARTED	LONDON OLD OAK	08:28:01
29	12	ARRIVED	BIRMINGHAM INTERCHANGE	08:29:09
30	13	ARRIVED	BIRMINGHAM INTERCHANGE	08:34:33
31	14	ARRIVED	BIRMINGHAM INTERCHANGE	08:39:35
32	15	ARRIVED	BIRMINGHAM INTERCHANGE	08:44:53
33	16	ARRIVED	BIRMINGHAM INTERCHANGE	08:49:57
34	17	ARRIVED	BIRMINGHAM INTERCHANGE	08:55:15

```
# Travel Optimization
simulation_data = optimal
pd.options.mode.chained_assignment = None

import statsmodels.api as sm
from sklearn.linear_model import LinearRegression
import numpy as np
pd.options.mode.chained_assignment = None
target = pd.DataFrame(simulation_data['OVERALL_AVG_DELAY_TIME'])
predictor = pd.DataFrame(simulation_data[['BLOCKS', 'TRAINS']])
predictor = sm.add_constant(predictor)

model = sm.OLS(target, predictor).fit()
predictions = model.predict(predictor)
model.summary()
```

```
/usr/local/lib/python3.6/dist-packages/statsmodels/tools/_testing.py:19: FutureWarning: pandas.util.testing is deprecated. Use the functi
  import pandas.util.testing as tm
```

OLS Regression Results

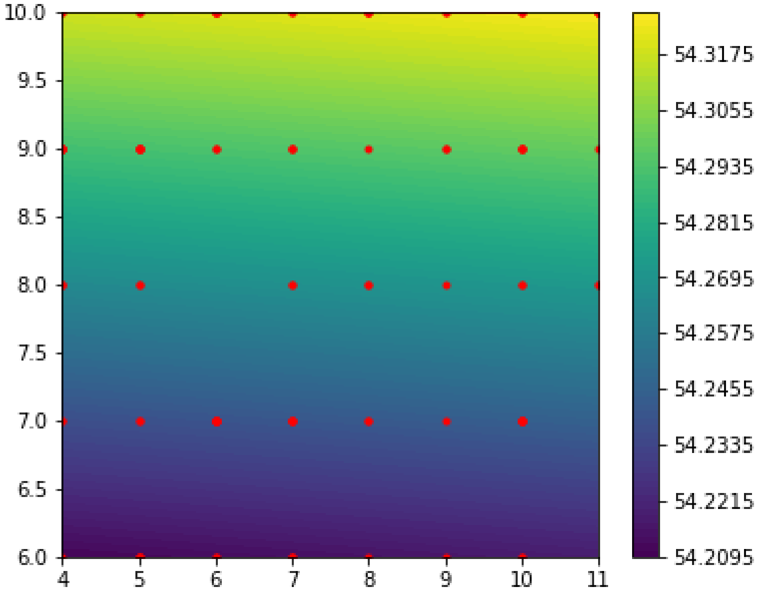
Dep. Variable:	OVERALL_AVG_DELAY_TIME	**R-squared:**	0.535
Model:	OLS	**Adj. R-squared:**	0.531
Method:	Least Squares	**F-statistic:**	143.0
Date:	Tue, 25 Aug 2020	**Prob (F-statistic):**	4.37e-42
Time:	01:37:25	**Log-Likelihood:**	157.15
No. Observations:	252	**AIC:**	-308.3
Df Residuals:	249	**BIC:**	-297.7
Df Model:	2		
Covariance Type:	nonrobust		

	coef	std err	t	P>|t|	[0.025	0.975]
const	54.0454	0.023	2352.195	0.000	54.000	54.091
BLOCKS	0.0011	0.002	0.546	0.586	-0.003	0.005
TRAINS	0.0268	0.002	16.904	0.000	0.024	0.030

Omnibus:	26.800	**Durbin-Watson:**	0.062
Prob(Omnibus):	0.000	**Jarque-Bera (JB):**	33.283
Skew:	-0.889	**Prob(JB):**	5.93e-08
Kurtosis:	2.918	**Cond. No.**	36.6

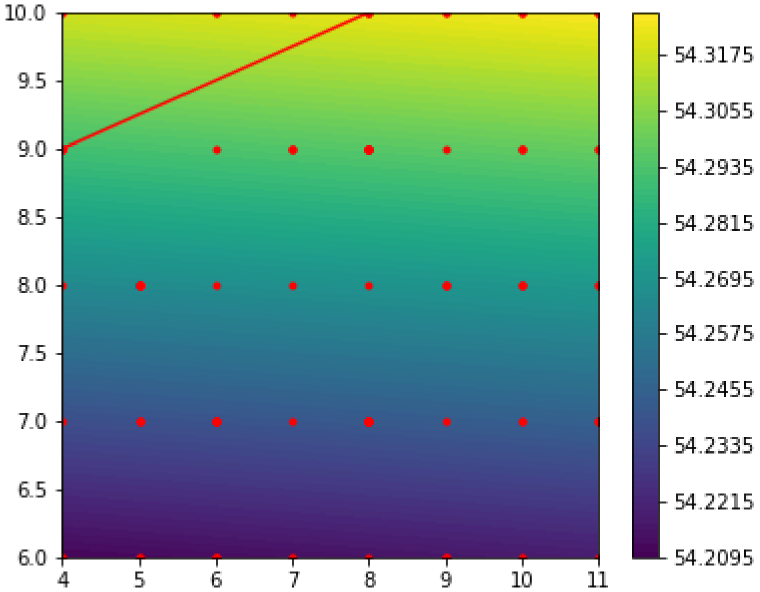
```
#linear regression to find objective function
import matplotlib as mpl
import matplotlib.pyplot as plt
import math
import numpy as np

def f(x,y):
    return 54.0454 + 0.0011*x + 0.0268*y
```

```
(2, 9, 10, 54.3233)
```




```
random.seed(30)
monte_carlo(100)
```

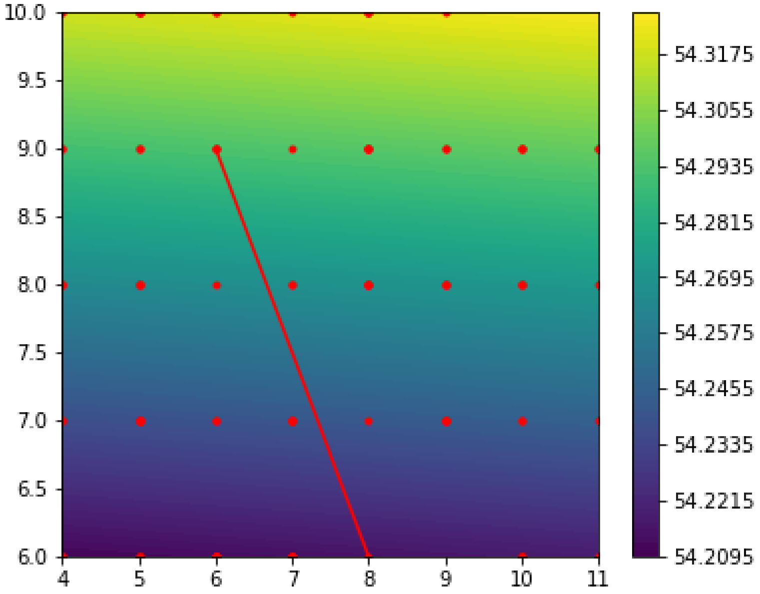
```
(2, 4, 9, 54.291)
```




```
random.seed(20)
```

```
monte_carlo(100)
```

```
(2, 8, 6, 54.215)
```



Conclusion:

In this project, a simulation model was designed to run trains between the stations of London Old Oak and Birmingham Interchange, with signaling blocks. The train travel is simulated for an hour, with variabilities in travel time and delay sue to impact of bad weather, and passenger dwell time is introduced into the simulation process. Additionally, an incident of breakdown due to electric failure in the line for the 9 am train is also introduced into the model. The simulation experiment carried out concluded that 10 trains can be run in an hour between the stations, and the train in overall requires around 32-40 minutes to complete the entire journey. Optimization of the simulation model was carried out to maximize the frequency of trains per hour with a condition that the delay time of the train should not be more than half the scheduled time between the trains. And accordingly, the optimization carried out using optimal() function resulted in a maximum frequency of 10 trains, 6 signaling blocks, and a delay time of 54.01. Monte Carlo optimization was also carried out, which resulted in a maximum frequency of 10 trains, 9 signaling blocks, and a delay time of 54.251.