SIMULATION AND OPTIMISATION OF HS2 LINE FROM LONDON TO BIRMINGHAM

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***Abstract* – Given certain constraints such that the average delay time should not be higher than half the scheduled time between consecutive trains, this paper focused on maximising the number of trains operating per hour. A detailed simulation is captured to reflect train trips from London Old Oak Commons to Birmingham Interchange station. The simulated model in this paper factored in an induced temporary break down due to electrical malfunction with a 30-minute delay for fixing the problem as well as delay caused by random events and reports the distribution of the actual delayed times.**

***Keywords* – Simulation, Distribution, Optimisation, Signalling Blocks, Delay.**

I. INTRODUCTION

One of the typical causes of delay times for high-speed railway (HSR) lines is bad weather (BW). The paper by Yang et al. [1] showed that this type of cause can be explained using candidate distribution selection such as Lognormal, exponential and gamma. Other causes like natural disaster (ND) can be explained using logistic, lognormal and gamma candidate distributions.

$$\text{Lognormal:}\quad f(x,\mu,\sigma)=\frac{1}{x\sigma\sqrt{2\pi}}e^{-(\ln x-\mu)^2/2\sigma^2}$$

where μ and σ are the logarithmic mean and standard deviation of the variables

$$\text{Exponential:}\quad f(x,\lambda)=\begin{cases}\lambda e^{-\lambda x}, & x\geq 0\\ 0, & x<0\end{cases}$$

where λ is the rate parameter that represent the frequency events.

$$\text{Gamma:}\quad f(x,\alpha,\beta)=\frac{x^{(\alpha-1)}(1/\beta)^{\alpha}x^{(-x/\beta)}}{\Gamma(\alpha)}$$

where α is the shape parameter and β is the scale parameter

1. BACKGROUND

Lessan et al. [2] evaluated different distribution models and concluded that Log-logistic probability density function was a better form for inferring arrival delays. Yuan et al. [3] discovered in their research that location-shifted log-normal distribution best estimated the arrival time of trains and its platform track. Cabrera et al. [4] presented an Agent-Based modelling (ABM) simulation and applied exhaustive search (ES) optimization to investigate the optimal emergency departments (ED) staff configuration. Yuan et al. [5] proposed the use of Monte Carlo approach to estimate distribution of departure delays.

Based on reviewed works, the lognormal distribution will be adopted in this paper as well as the Exhaustive Search and Monte Carlo algorithm for optimisation.

2. OBJECTIVES

- To reflect operational conditions for an induced 30-minute delay due to a temporary breakdown caused by either electrical malfunction of the 9am train from London to Birmingham.
- To maximise the number of trains operating per hour under the constraint that the average delay time should not be higher than half the scheduled time between consecutive trains.

II. SIMULATION

Simulation of the HS2 train line of 145 km (London Old Oak Commons to Birmingham Interchange) was modelled with stations, signalling blocks and by introducing variability of travelling times using a suitable distribution on events.

A single queue single server system was used for this modelling. The signalling blocks are represented as the servers, while the trains are on a queue and get served one at a time by a signalling block. The event graph diagram is shown below.

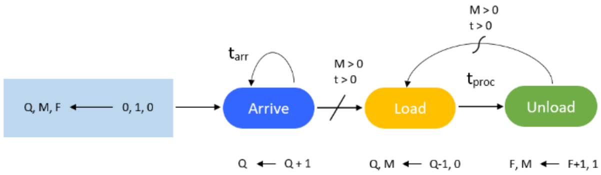

Fig. 1. Event graph

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Fig 1. Shows the event graph diagram for the simulation of the HS2 Line.

1. Dataset

The given information was represented with specific variables for carrying out the simulation.

	Line	From	To	Travel_Time	Blocks
0	HS2	London Old Oak Common	Birmingham Interchange	1684	12

Fig. 2. Loaded data

Fig 2. Shows the loading data for the simulation of the HS2 Line.

2. Train Process Flow

- The train drives from depot to the London Old Oak Commons station, waits to depart, then requests for the signalling block.
- If the signalling block is empty, then and only then can the train drive into the track (k), else the train waits till the signalling block is empty before it can proceed.
- The train continues its journey by entering each block. When the train gets to the final station (Birmingham Interchange), it notifies that the train has reached the destination.
- The train name, time of departure and time of arrival for each train are all recorded in a table (dataframe).

3. Assumptions

- The trains travel at the same speed. This way the signally blocks can be tested effectively without variation in train speed.
- The signalling blocks have all equal length.
- There is a train depot and 2 stations.
- It takes 30 seconds for each train to drive from the depot to the first station (London Old Oak Commons).

4. Simulation Tests

The simulation test was carried out in three phases.

- **Test without any constraint**

The simulation was tested without inducing a 30-minute delay or random event (delay). The result from the simulation validated the average travel time of 1684 seconds, obtained from the maximum speed of 310km/h at 145km and yielded an average delay time of 0.0.

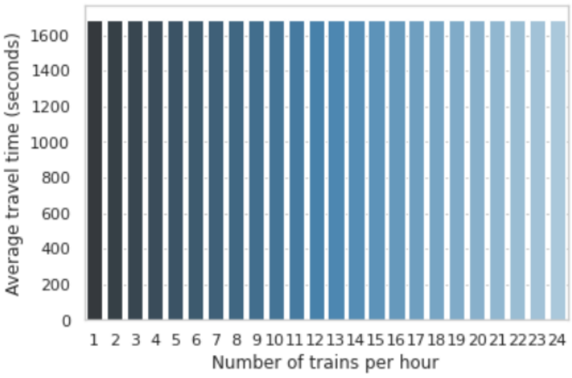

Fig. 3. Varied number of trains per hour against average travel time

Fig 3. Shows that by varying the number of trains per hour without any added constraint, the travel time remains constant (1684 seconds), with no delay time.

- **Test with 30-minutes delay only**

The simulation was tested with inducing a 30-minute delay caused by temporary break down due to electrical malfunction of the 9am train from London to Birmingham but without the addition of a random event (delay). A random simulation test was carried out using 15 trains and 6 signalling blocks, this produced an average travel time of 7798.67 seconds, while the average delay time was 6114.67 seconds. This then led to testing the simulation across a range of values for number of trains per hour (n) as well as signalling blocks (k).

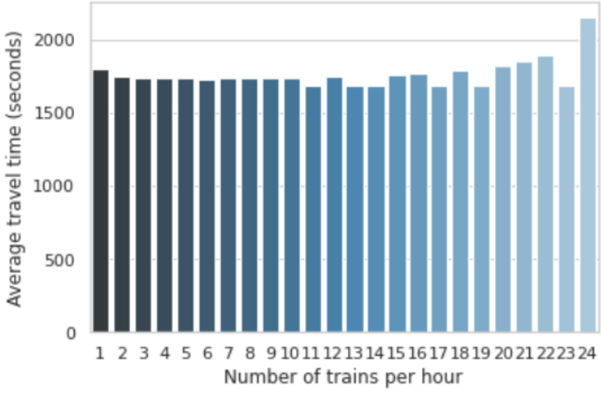

Fig. 4. Varied number of trains per hour against average travel time

Fig. 4. Shows that by varying the number of trains (n), shows that at a constant of 12 signalling blocks, lesser average travel time is achieved with the following number of trains per hour **(n = 11, 13, 14, 17, 19 and 23)**. Due to the restricted entry of one train per time for each signalling block, there will be an increase in the number of trains waiting in-line per hour for a limited number of signalling blocks.

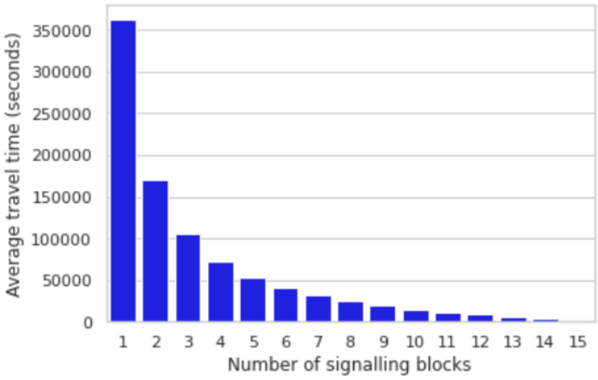

Fig. 5. Varied number of signalling blocks against average travel time

Fig 5. Shows that by varying the number of signalling blocks (k) from 1 to 15 at a constant number of trains per hour (n=30), the higher the number of signalling blocks, the lesser the average travel time.

III. OPTIMISATION

From the simulation created earlier, an optimisation is carried out for the track consisting of k signalling blocks of equal length and a fixed train schedule of n trains per hour.

1. Train Schedule

The train schedule was initiated at 7am for the first train and the last train departed at 10pm. The time format was converted to seconds to carry out the simulation effectively. This duration spans across 15 hours.

- 7 am = 25230 seconds
- 10 pm = 78990 seconds

	departure_time	arrival_time	Train
0	25230	26920.6	[Train 0]
1	25470	27289.9	[Train 1]
2	25710	27576.8	[Train 2]
3	25950	27858.4	[Train 3]
4	26190	28146.5	[Train 4]
...	...	...	...
220	78030	92177.6	[Train 220]
221	78270	92459	[Train 221]
222	78510	92754.4	[Train 222]
223	78750	93037.9	[Train 223]
224	78990	93321.8	[Train 224]

225 rows × 3 columns

Fig. 6. Train schedule from 7 am to 10 pm

2. Test with 30-minutes delay only

Once again, the simulation was tested with 30 minutes delay only without the addition of a random event delay, to evaluate the range of optimised number of trains and signalling blocks.

a) Exhaustive Search

This is a problem-solving technique and algorithmic paradigm that systematically enumerates all possible variations for the solution and checks if each satisfies the problem statement. This algorithm was used to obtain the optimum number of trains and optimum number of signalling blocks to minimise overall delay time. This was carried out using n ∈ {1, ..., 24} and k ∈ {1, ..., 16}.

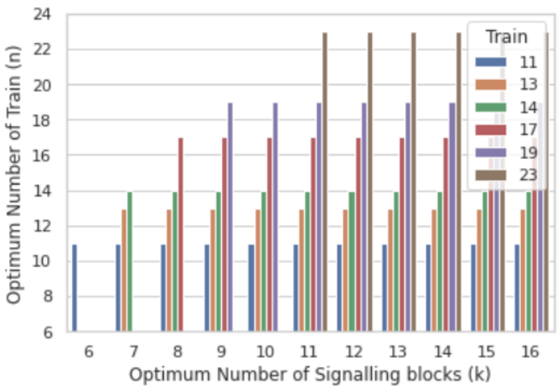

Fig. 3. Optimisation for combination of n and k

Signalling Blocks	Number of Trains						Total combination
6	11						1
7	11	13	14				3
8	11	13	14	17			4
9	11	13	14	17	19		5
10	11	13	14	17	19		5
11	11	13	14	17	19	23	6
12	11	13	14	17	19	23	6
13	11	13	14	17	19	23	6
14	11	13	14	17	19	23	6
15	11	13	14	17	19	23	6
16	11	13	14	17	19	23	6

Table I: Optimisation for combination of n and k

Fig 3. and Table I both shows 54 possible combinations of the optimum number of trains and signalling blocks that can yield an average delay time of zero (0).

b) Monte Carlo Method

The Monte Carlo algorithm was used to run simulation of 100 iterations for a search space of [1, 24, 1, 16]. This provided an optimised result of n=14, k=12 & dt = 39.84.

Where 1 = minimum number of trains; 24 = maximum number of trains; 1 = minimum number of signalling blocks and 16 = maximum number of signalling blocks

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1 optimum_delaytime
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(5, 14, 12, 39.84)
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3. Test with 30-minutes delay and random event delay

The simulation was tested with 30 minutes delay and the addition of a random event delay to evaluate the range of optimised number of trains and signalling blocks.

- **Distribution of travel time**

The simulation test was carried out using 11 trains and 14 signalling blocks. A histogram and distribution curve were plotted to evaluate the distribution of the travel time. This plot is shown in Fig. 7. below.

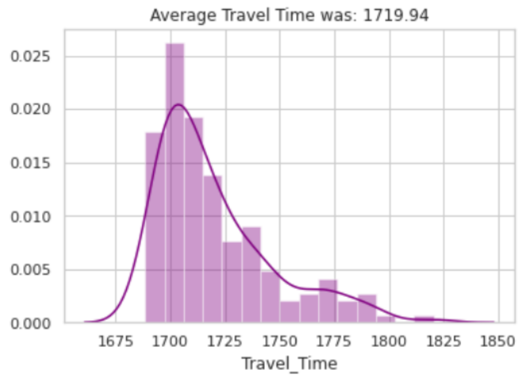

Fig. 7. Distribution of travel time

- **Distribution of delayed time**

The simulation test was carried out using 11 trains and 14 signalling blocks. A histogram and distribution curve were plotted to evaluate the distribution of the delayed time. This plot is shown in Fig. 8. below.

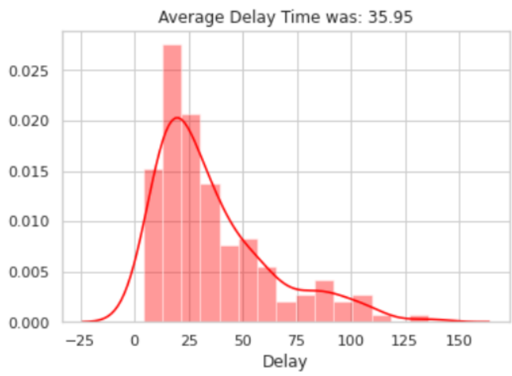

Fig. 8. Distribution of delay time

- **Varying the number of trains (Delay Time)**

  A simulation was run to vary the number of trains between London and Birmingham for a **range of 1 to 24** within an hour while the signalling blocks was **kept constant at 12**.

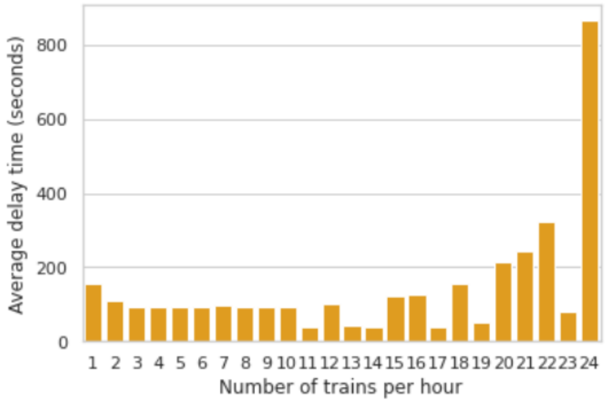

Fig. 9. Varied number of trains against average delay time

Fig. 9. Shows that by varying the number of trains (n), shows that at 14 signalling blocks, lesser average delay time is achieved with the following number of trains per hour **(n = 11, 13, 14, 17, 19 and 23)**.

- **Varying the number of signalling blocks (Delay Time)**

  A simulation was run to vary the number of signalling block between London and Birmingham for a **range of 1 to 15** within an hour while the number of trains was **kept constant at 30.**

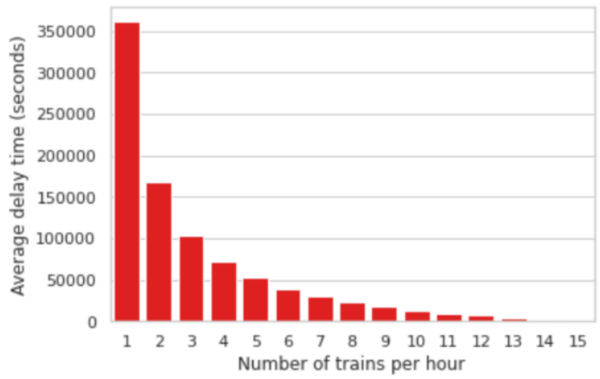

Fig. 10. Varied number of signalling blocks against average delay time

Fig 10. Shows that by varying the number of signalling blocks (k), the higher the number of signalling blocks, the lesser the average delay time.

a. Exhaustive Search

A constraint was set that the average delay time should not be higher than half the scheduled time between consecutive trains using a conditional statement. The exhaustive search algorithm produced an optimised result of 11 trains and 14 signalling blocks, with an average delay time of 32.7 seconds.

Fig 11. Shows the optimum number of trains per hour and signalling blocks.

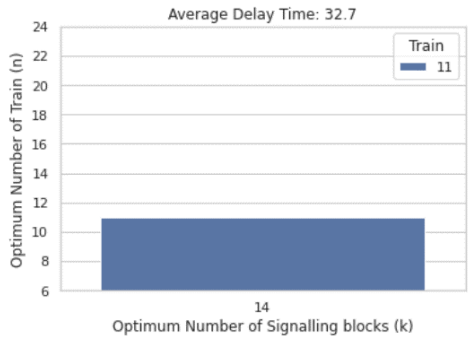

Fig. 11. Optimum number of trains per hour and signalling blocks

b. Monte Carlo Method

The Monte Carlo algorithm produced an optimised result of 13 trains and 13 signalling blocks, with an average delay time of 36.83 seconds. This algorithm is less computationally intensive.

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1 optimum_delaytime
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(19, 13, 13, 36.83)
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IV. RESULTS

As seen from the optimisation carried out, the results obtained using the exhaustive search algorithm for the entire search space of n ∈ {1, ..., 24} and k ∈ {1, ..., 16} provided better optimum result than Monte Carlo algorithm.

Some of the challenges faced in this project was with replicating the simulation operation with the random event delay. Also, though the random event delay was successfully induced, the delay could not be directly attributed to an actual event in a real-life scenario, as it was obtained using the *np.random* function.

- **Recommendation for the Track Layout**

  To maximise the number of trains operating per hour under the constraint that the average delay time should not be higher than half the scheduled time between consecutive trains, the recommended **number of trains (n) operating per hour should be 11, while the number of signalling blocks (k) should be 14, to achieve the lowest average delay time of 32.7 seconds**.

V. CONCLUSION

The simulation task with induced delay in time for trains commuting from London Old Oak Commons to Birmingham Interchange via the HS2 train line was successfully carried out. Also, the optimum number of trains operating per hour and signalling blocks under a given constraint was also obtained.

The comparison of the two methods of optimisation applied showed that Exhaustive Search algorithm yielded a better optimised result compared to Monte Carlo algorithm. However, exhaustive search algorithm is more computationally intensive.

VI. REFERENCES

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