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Eco-conscious decision-support model for optimizing stopping patterns in the mass transit system

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Abstract

The existing train operational efforts focus on need-based criteria for serving passenger demand while maintaining travel time satisfaction. Although mass transit contributes to reduced private vehicle fuel consumption, the current mass transit operations reveal a lack of environmental consciousness. This study introduced a newly developed model for optimizing sustainable train scheduling based on skip-stop operations. The model was applied based on the genetic algorithm technique to identify optimal stopping patterns for the Bangkok Mass Transit System (BTS) on the SkyTrain Silom Line in Bangkok, Thailand. The results presented a wide range of optimal or near-optimal solutions for environmentally friendly stopping patterns for trains and illustrated the tradeoff relationship between the passenger travel time and environmental impacts. This optimization model should prove useful as a decision-support tool for train operation agencies when implementing energy-efficient and environmentally friendly train schedules to improve sustainability.

Keywords: Train stopping pattern, Environmental impact, Travel time, Energy consumption, Optimization

1. Introduction

According to the Department of Alternative Energy Development and Efficiency (DEDE), the total electric energy consumed by the transportation sector in Thailand accounted for 215 GWh in 2019. This reflected a continuing growth trend, with a more than 100% increase between 2014 and 2019 [1]. In general, this trend resulted from the significant expansion of electric rail transportation networks in the Bangkok metropolitan region. According to the Mass Rapid Transit Authority of Thailand, there were 85 kilometers of electric rail system in 2014, and it is planned to extend this to more than 550 kilometers by 2029 [2]. As such, the magnitude of energy consumption in the electric rail transportation sector is expected to increase substantially in the next decade.

In addition to energy consumption, train operations also affect the environment [3]. Givoni et al. [4] reported emissions of 554 g of CO_2 per kWh from electric train operations, which suggests that annual CO_2 emissions due to electric train operations in Thailand will exceed 120 million kg of CO_2. Moreover, they are forecast to reach more than 543 million kg of CO_2 within the next decade. Therefore, to reduce electric energy consumption, proficient operational patterns are vital for electric railways. Many technical and research studies have acknowledged the benefits of using different train operation techniques to mitigate energy consumption, such as skip-stop operation, frequency operation, and driving control strategies. Among these techniques, skip-stop operational planning is important as it is correlated with the electric energy consumption of trains [5-10] and associated with environmental impacts [11]. Consequently, the effective operation of electric rail transportation systems can contribute substantially to reducing electric energy consumption and environmental impacts on society.

Importantly, the operation of trains also affects the passenger travel time, which is an essential basic measurement index of the level of service and efficiency of rail transportation systems [12]. Although passenger satisfaction regarding travel time has been improved, the issue of unserved passenger demand due to train operations still exists. As a result, many railway transportation agencies have attempted to apply effective train operation schedules to meet passenger demand with acceptable travel times to deter passengers from using other transportation modes [13]. Thus, there is an urgent need for proficient train operational patterns that are capable of simultaneously minimizing the passenger travel time and energy consumption, and thus also reducing the environmental impacts.

Many studies have considered the planning of train operational patterns. For example, the passenger travel time has been estimated for different train timetable schedules [14-21]. Some studies have introduced a variety of driving strategies for train operation to minimize the electric energy consumption [7, 17, 21-27]. Some train operational patterns were also optimized to serve predetermined purpose(s) in Freyss et al. [5], Gao et al. [28], Robenek et al. [29], Sun et al. [8], and Yang et al. [20]. However, no previous works have focused on optimizing train operational patterns with the aim of simultaneously minimizing the passenger travel time and the environmental impact of electric rail transportation systems. Accordingly, this study proposed the development of a sustainable decision-support model to optimize train operational strategies that focus on skip-stop operation to tackle this research gap.

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2. Model development framework

This section introduces a conceptual framework of the model development, as illustrated in Figure 1, with the list of parameters summarized in Table 1. The developed model consists of three main modules with capabilities in: (1) evaluating the impact of skip-stop operation on the passenger travel time for entire rail transportation networks, (2) estimating the environmental impacts due to train energy usage and the mode change of unserved passengers, and (3) optimizing train operational strategies to identify the optimal stopping pattern that can simultaneously minimize the passenger travel time and environmental impacts. The details of these modules are then provided in the following sections.

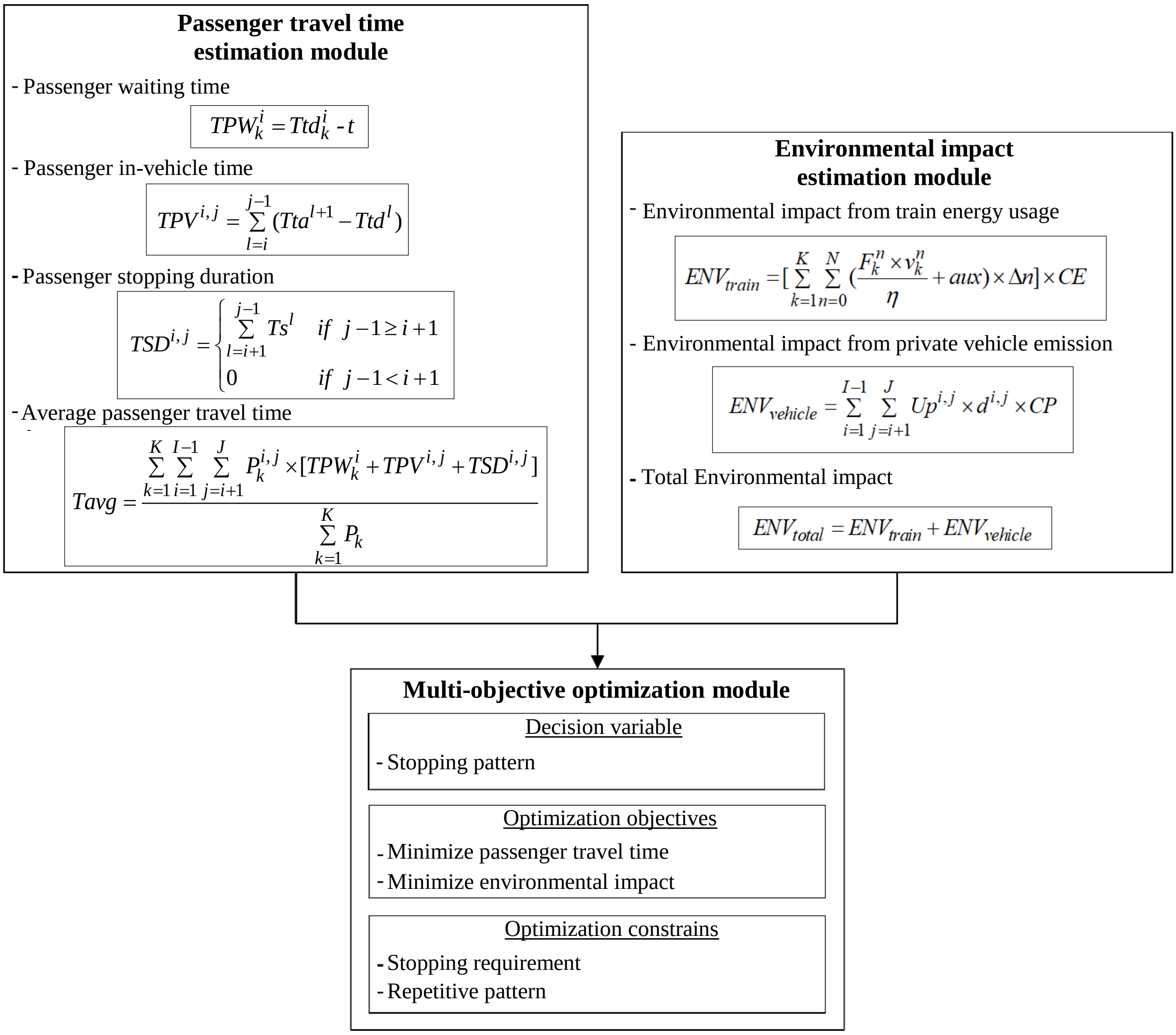

Figure 1 Sustainable train stopping pattern optimization model

Table 1 Lists of parameters in this study

Symbol	Definition
S	Set of stations, $l \in S$
i, j	Station indexes for $(i, j) \in S$
k	Train number
TPW_k^i	Total waiting time of a passenger using train k at station i
Ttd_k^i	Departure time of train k at station i
t	Passenger arrival time
$TPV^{i,j}$	Total passenger in-vehicle time from station i to j
Tta^{l+1}	Train arrival time at station $l + 1$
Ttd^l	Train departure time at station l
$TSD^{i,j}$	Total stopping duration of passenger from station i to j
Ts^l	Stopping duration at station l
$Tavg$	Average passenger travel time of entire system
$P_k^{i,j}$	Number of passengers wanting to travel (passenger demand) from station i to j
P_k	Number of passengers traveling by train k

Table 1 (continued) Lists of parameters in this study

Symbol	Definition
ENV_{train}	Environmental impact from train energy usage (g of CO_2e)
n	Time step
F_k^n	Tractive force (N) at time step n in train k
V_k^n	Traveling speed (km/h) at time step n in train k
η	Efficiency (%) of mechanical output power
aux	Constant load for train facilities (kW)
Δn	Time interval
CE	CO_2 conversion factor for train electricity usage (g of CO_2e per kWh)
$ENV_{vehicle}$	Environmental impact due to private vehicle usage (g of CO_2e)
$Up^{i,j}$	Number of unserved passengers traveling from station i to j (person)
$d^{i,j}$	Unserved passenger travel distance (km) from station i to j
CP	CO_2 conversion factor for vehicle fuel usage (g of CO_2e per passenger-km)
ENV_{total}	Total environmental impact (g of CO_2e)

To make the model more practical, the train stopping patterns in this study are considered over a one-hour period with repetitive patterns, in order to avoid difficulties for the operators with their train scheduling management and confusion of passengers wanting to catch a train. The patterns were set up to be repeated, with the first train of an operating hour always making all stops, but the next three trains following a set of patterns that would be the same.

To complete the model analysis, three main categories of input parameters are required for computation, namely (1) passenger travel data, (2) train operational data and characteristics, and (3) emission-related factors. Their detailed explanations are provided as follows:

(1) Passenger travel data are associated with the passenger demand, passenger traveling distance (origin and destination train stations), and passenger arrival time at the origin station. The volume of passengers traveling between any stations were collected in the form of an O-D matrix based on the statistical data of average passenger demand per day from BTS [30]. The traveling distance of a passenger was individually calculated based on the actual distance between stations retrieved from Google Maps. The passenger arrival time, which is the time at which a passenger arrives at the origin station, was randomly applied by presuming the range of the possible time difference between two consecutive trains based on the value of the train headway obtained from BTS [31].

(2) Train operational data and characteristics are used mainly for estimating the passenger travel time and train energy consumption. The basic attributes are related to the train stopping duration, train travel speed, and some train characteristics. The train stopping duration can be applied based on the actual service of train operators, for which this paper has adopted the actual data collected in the same case study by Sumpavakup et al. [32]. In addition, the operating speed of the train at every time interval is needed to calculate the energy consumption. The train speed profiles are then needed in order to know the vehicle speed along the distance, based on the actual data collection. However, this paper refers to the train speed profiles from Sumpavakup et al. [32].

Moreover, the train characteristics, such as the train capacity, maximum acceleration rate, and effective mass, etc., affect the estimation of the passenger travel time and train energy consumption. These parameters are the specific technical characteristics of train operations and need to be directly requested from the train operators. Accordingly, this paper has used the actual data from the same case study in BTS [30] and Sumpavakup et al. [32].

(3) Emission-related factors are needed to estimate the pollution in terms of CO_2 emissions as a result of train energy consumption and private vehicle usage by unserved passengers due to changes of their transportation mode. Thus, two parameters are acquired from BEIS [33] and used in this paper to convert the train electricity usage and private vehicle usage into the expected amount of CO_2 emissions generated into the environment.

It should be noted that the passenger-related data can be categorized into two main groups. The first group is the input parameters, as aforementioned, which require data from the real operational system or train operators. The other group, not defined as primary input parameters, are intermediate parameters that require further calculation based on the values of the primary ones. These parameters are the passenger waiting time, in-vehicle time, and departure time. The passenger waiting time is calculated based on the difference between the train departure time and passenger arrival time, while the passenger departure time is identified as equal to the train departure time at a station. In addition, to calculate the passenger in-vehicle time between stations, the operating speed of the train needs to be incorporated with the traveling distance. In fact, for the train speed profiles it is necessary to know the vehicle speed along the distance, or the actual data collection to measure the in-vehicle duration. However, this paper refers to the value of passenger in-vehicle time from Sumpavakup et al. [32], as it provided ready-to-use data available from the same case study.

3. Passenger travel time estimation module

The purpose of this module is to estimate the passenger travel time with a variety of train stopping patterns. Freyss et al. [5] reported a greater benefit in reducing the travel time due to the skip-stop operation and a reduction in the stopping duration. Three essential components are normally taken into account to evaluate the impacts of train stopping patterns on the passenger travel time [34]: (1) passenger waiting time (TPW_k^i), (2) passenger in-vehicle time ($TPV^{i,j}$), and (3) passenger stopping duration ($TSD^{i,j}$). Figure 2 provides a graphical representation of the difference between the stopping duration and passenger in-vehicle time. The first term refers to the period when the train is stopping at the station and waiting for passengers to be onboard. Skipping will mean the stopping duration at such a station is zero, leading to a decrease in the total passenger travel time. On the other hand, the second term is defined as the travel time when passengers are traveling between two stations, counting from when the train starts to depart from the station until it arrives and stops at the next station. Skipping a station can enable the train to maintain a constant speed and avoid an allowance time for speed acceleration that could sometimes lead to a significantly shorter in-vehicle time. In some cases, however, the passenger in-vehicle time can be the same if the time required for speed acceleration is insignificant.

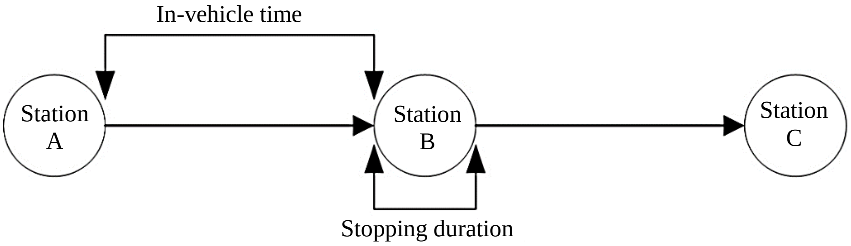

Figure 2 Passenger in-vehicle time and stopping duration

The passenger waiting time is a function of the train departure time and passenger arrival time (Equation (1)), while the passenger in-vehicle time is estimated based on the train travel time between stations (Equation (2)). The passenger stopping duration accounts for the total stopping duration of a passenger as an accumulation of the train's stopping durations at all stations along the trip (Equation (3)), under the classification of two possible cases: (1) when traveling for more than one station ($j-1 \geq i+1$) and (2) when traveling for only one station without any stopping durations ($j = i+1$). Finally, the impacts of the three components are considered over the dimension of passenger demand to calculate the average passenger travel time ($Tavg$) for the entire system, as shown in Equation (4).

$$TPW_k^i = Ttd_k^i - t \tag{1}$$

$$TPV^{i,j} = \sum_{l=i}^{j-1} (Tta^{l+1} - Ttd^l) \tag{2}$$

$$TSD^{i,j} = \begin{cases} \sum_{l=i+1}^{j-1} Ts^l & if \ j-1 \geq i+1 \\ 0 & if \ j-1 < i+1 \end{cases} \tag{3}$$

$$Tavg = \frac{\sum_{k=1}^{K} \sum_{i=1}^{I-1} \sum_{j=i+1}^{J} P_k^{i,j} \times [TPW_k^i + TPV^{i,j} + TSD^{i,j}]}{\sum_{k=1}^{K} P_k} \tag{4}$$

where TPW_k^i denotes the total waiting time of a passenger using train k at station i, Ttd_k^i denotes the departure time of train k from station i, t denotes the passenger arrival time, $TPV^{i,j}$ denotes the total passenger in-vehicle time from station i to j, Tta^{l+1} denotes the train arrival time at station l+1, Ttd^l denotes the train departure time at station l, $TSD^{i,j}$ denotes the total stopping duration of a passenger from station i to j, Ts^l denotes the stopping duration at station l, $Tavg$ denotes the average passenger travel time of the entire system, $P_k^{i,j}$ denotes the number of passengers wanting to travel (i.e. passenger demand) from station i to j, and P_k denotes the number of passengers traveling by train k.

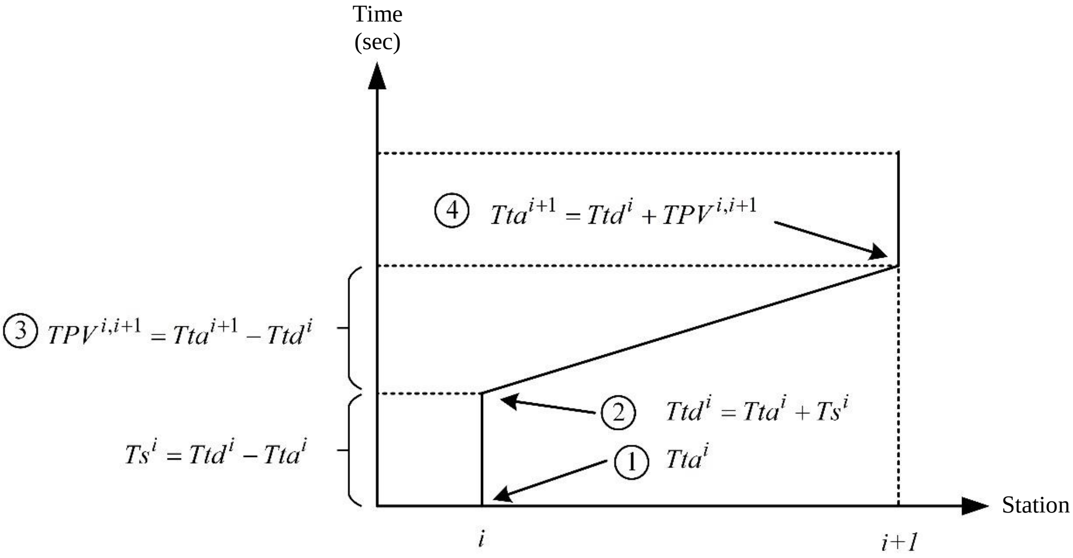

Figure 3 Determination of train timetable

Typically, knowing these three main components can also contribute to establishing the train timetable. Figure 3 demonstrates how to determine the timetable from the stopping patterns. The procedure for a train starts from the known value of the arrival time at the first station (Tta^i) (see Figure 3, Step 1). Then, the departure time of the train from the first station (Ttd^i) can be computed from the predetermined stopping duration at the first station (Ts^i), as shown in Figure 3, Step 2. After that, the train running time, which is equal to the in-vehicle time of passengers traveling from the first station to the next-stop station ($TPV^{i,i+1}$), will be determined, as indicated by the inclined line at Step 3. In fact, several techniques can be implemented to find the train running time, which include taking an actual ride with a timer counter, and using speed profile data and the distance between stations. As a result, the arrival time at the next-stop station (Tta^{i+1}) can be calculated, as shown in Step 4. The steps will be repeated for all stations and all trains being operated over a time period.

4. Environmental impact estimation module

This module aims to estimate the environmental impact due to different train stopping patterns. In this study, the environmental impact was analyzed in terms of the carbon dioxide equivalent emissions (CO_2e) by considering two critical sources: (1) the environmental impact due to electricity consumption during train operations and (2) the environmental impact of unserved passengers changing their transportation mode to use private vehicles. The following paragraphs briefly describe each aspect.

4.1 Environmental impact from train energy

The objective of this section is to estimate the environmental impacts as a result of the energy consumption of trains operating over the entire system. Two main sub-sections are presented here to provide the basic concepts in (1) calculating train movement and energy consumption and (2) estimating the environmental impacts due to train operation energy use, as follows:

4.1.1 Train movement and energy consumption calculation

According to Kim and Chien [35], there are four typical motion regimes for train operations (motoring, cruising, coasting, and braking). First, motoring indicates the period during which a train accelerates from standstill until reaching cruising speed. Second, cruising indicates the time during which a train operates at a constant speed. Third, coasting represents the period during which a train moves without using any engine power. Braking then applies when a train stops at a train station.

Figure 4 demonstrates the impact of the skip-stop activity on train energy consumption in each train motion regime. Considering the trip from Stations A to C, two different alternatives are proposed. Alternative #1 presents the case in which the train stops at all stations (all-stop), while Alternative #2 introduces the skip-stop pattern by skipping Station B. The figure reveals that skipping helps the train to maintain a constant operating speed, leading to a reduction in train energy usage.

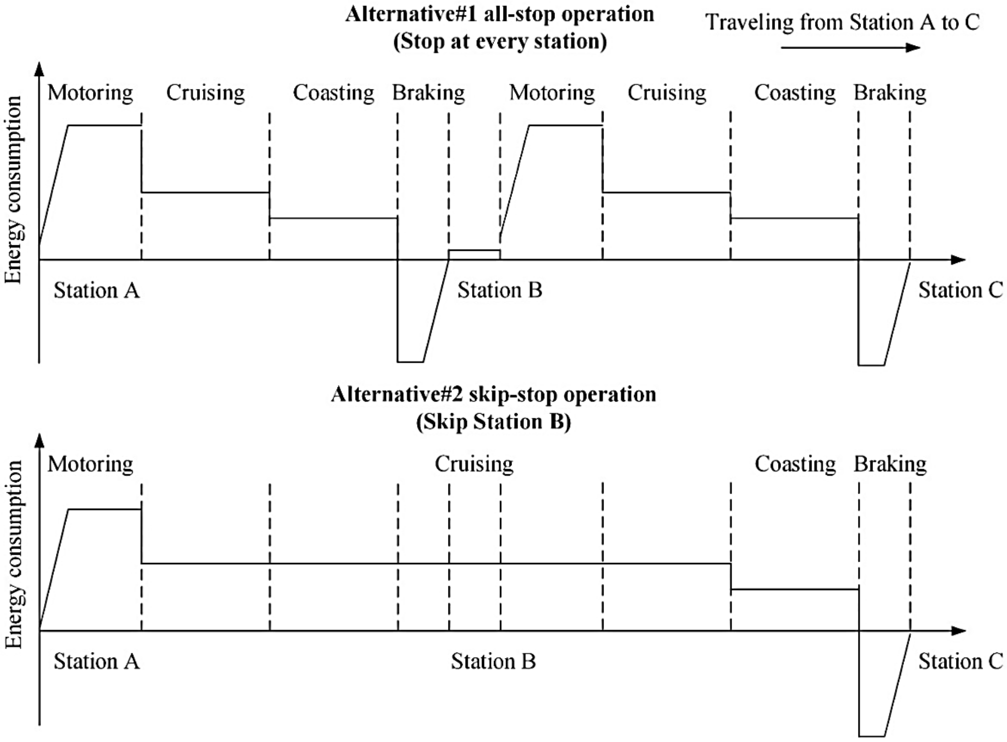

Figure 4 Impacts of different train patterns on energy consumption

All four of the previously mentioned motion patterns result in different types of energy: traction, auxiliary, and regenerative energy. Traction energy is the most common energy type, which is required for propelling the train. Auxiliary energy is used to power on-board facilities, such as lighting and air conditioning. Regenerative energy is the recycling energy generated during braking mode, and it supports future operation of the train. Theoretically, the motoring and cruising activities are associated with traction and auxiliary energy. The coasting regime consumes auxiliary energy, while the braking mode uses auxiliary energy but also generates regenerative energy.

For train operation, the traction energy in each time interval will vary depending on the train operating speed and its tractive effort. The concept of train motion regimes is the basis for calculating the tractive effort, which is the net force in moving a train. Theoretically, the train movement calculation applies Newton's laws of motion [32, 35, 36]. As previously mentioned in the Model Development Framework section, all trains in this study were considered to have insignificant differences in train mass, gradient resistance, and curve resistance for their operations. Accordingly, the train movement calculation has only focused on the tractive effort, train acceleration rate, and train resistance, as shown in Equation (5), with the graphical illustration of the train motion concept shown in Figure 5.

$$F = M_{eff}\alpha + R \tag{5}$$

where F denotes the tractive force (N) of the train, M_{eff} denotes the effective mass (kg) of the train, α denotes the train acceleration rate (m/s^2), and R denotes the overall resistance force (N) of the train, which can be estimated based on the vehicle speed according to [32].

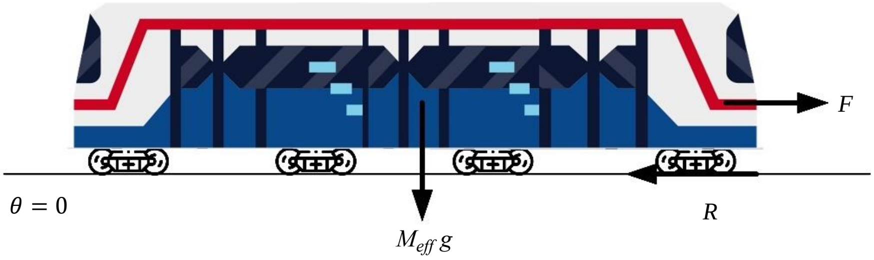

Figure 5 Concept of train movement calculation

4.1.2 Environmental impact estimation due to train energy

Although there are no CO_2 emissions resulting directly from the train operations, the electricity consumed by the train operations indirectly results in CO_2 emissions during the electricity generation process [33]. Equation (6) demonstrates the simple calculation of environmental impacts from train operations based on the consumption of traction and auxiliary energy of all the trains operating over the entire network, and therefore the emission rate in g of CO_2e per kWh. Regenerative energy was excluded from this study because there is no storage system currently used for storing the recycled energy in Thailand. This type of energy from the braking mode will thus be lost in the network. The theoretical framework and a detailed explanation of train energy consumption estimation are described in the study by Sumpavakup et al. [32].

$$ENV_{train} = [\sum_{k=1}^{K}\sum_{n=0}^{N}(\frac{F_k^n \times v_k^n}{\eta} + aux)\times\Delta n]\times CE \tag{6}$$

where ENV_{train} denotes the environmental impact due to train electricity usage (g of CO_2e), k denotes the train number, n denotes the time step, F_k^n denotes the tractive force (N) of train k at time step n, V_k^n denotes the train speed (km/h) of train k at time step n, η denotes the efficiency (%) of the mechanical output power, aux denotes the constant load for the train facilities (kW), Δn denotes the time interval, and CE denotes the CO_2 conversion factor between electricity usage and CO_2 emissions (g of CO_2e per kWh).

4.2 Environmental impact from private vehicle emissions

The environmental impact of the private vehicle usage by unserved passengers ($ENV_{vehicle}$) amounts to indirect emissions resulting from the identified skip-stop operational pattern that could not sufficiently serve the passenger demand. Based on the literature, unserved passengers usually change their trips by using other transportation modes for greater satisfaction and comfort, such as the value of time and the cost of using their personal means of transportation [37]. Indeed, the value of time is a significant concern for passengers [38], making some of them choose faster transportation modes, such as taxicabs and motorcycle taxis. In order to determine the maximum impact that could be expected on the environment, the travel mode change of unserved passengers was evaluated based on the conditions of using private passenger vehicles on the road network alongside the rail line due to easy accessibility and greater comfort. Using private vehicles has severe impacts on the environment due to the extra CO_2 emissions from burning fossil fuels. The associated pollution then takes into account the travel distance of each unserved passenger, as shown in Equation (7).

$$ENV_{vehicle} = \sum_{i=1}^{I-1}\sum_{j=i+1}^{J} Up^{i,j} \times d^{i,j} \times CP \tag{7}$$

where $ENV_{vehicle}$ denotes the environmental impact due to the fuel consumption by private vehicles (g of CO_2e), $Up^{i,j}$ denotes the number of unserved passengers traveling from station i to j (person), $d^{i,j}$ denotes the unserved passenger travel distance (km) from station i to j, and CP denotes the CO_2 conversion factor for vehicle fuel usage (g of CO_2e per passenger-km).

Finally, the total environmental impact (ENV_{total}) can be measured as a combination of two main components, the environmental impact due to electricity consumption during train operations and the environmental impact of unserved passengers changing their transportation mode to use private vehicles, as shown in Equation (8).

$$ENV_{total} = ENV_{train} + ENV_{vehicle} \tag{8}$$

5. Multi-objective optimization module

This module aims to optimize the train stopping patterns for electric rail transportation to identify the optimal stopping patterns that are capable of simultaneously minimizing the passenger travel time and the environmental impacts. In this paper, the optimization module was developed to facilitate decision-making by train operators to determine optimal or near-optimal solution(s) under the decision variable of the stopping pattern, subject to the restricted conditions of the stopping requirement constraint. Their details and explanations are as follows:

The stopping pattern was defined as the decision variable here in terms of the skip-stop operation, meaning that a train is designed to stop at or skip some stations based on a predetermined schedule. This decision variable is assigned with an integer number of zero or one, representing skipping and stopping by a train at a station, respectively. The skip-stop affects the passenger travel time, as passengers are required to spend more time when a train stops at a station. Skipping some stations also facilitates maintaining a constant train operating speed, resulting in a reduction in electric energy consumption [24, 25], but adversely impacting the number of unserved passengers who may change their transportation mode from mass transit to other transportation modes due to their demand being insufficiently served.

On the other hand, the stopping requirement was first set up as the constraints to satisfy the passenger demand and the level of passenger satisfaction. The stopping requirement is important in restricting the operation at some specified train stations. The requirement was determined based on passenger demand at train stations to guarantee the effectiveness of serving a significant number of passengers, resulting in a train stopping at or skipping small-sized or medium-sized stations, but always stopping at stations with high passenger demand. Some trains were also assigned to always stop at the first station at the predetermined frequency. Therefore, they are probably required to stop at the first station, even if the number of passengers is small, in order to maintain the level of service and passenger satisfaction. Furthermore, the repetitiveness of train patterns was taken into consideration in order to simplify the train timetable to be more practical and realistic, as well as to avoid difficulties for train operators and passengers as mentioned before.

In addition, the stopping duration, which defines how long a train stops at a station, was assigned depending on the size of the station and the number of passengers. This assignment defined the minimum stopping duration at small-sized and medium-sized stations, while the large-sized stations were planned with the maximum stopping duration to serve the high passenger demand.

The problem was considered to represent a multi-objective optimization in a huge search space. Numerically, the set of possible solutions in the search space can be as large as 10×2^{10}, given that 10 trains can operate over 13 stations with the stopping requirement constraint in a one-hour time span. As such, this study applied the genetic algorithm, which has been widely used in decision-making, including planning of train operations [8, 9, 32, 34]. The non-dominated sorting genetic algorithm II (NSGA-II) proposed by Deb et al. [39] was applied to identify the optimal stopping patterns due to its superior capabilities and its fast operating procedure of non-dominated sorting, converging near the Pareto-optimal front, and in obtaining diverse solutions.

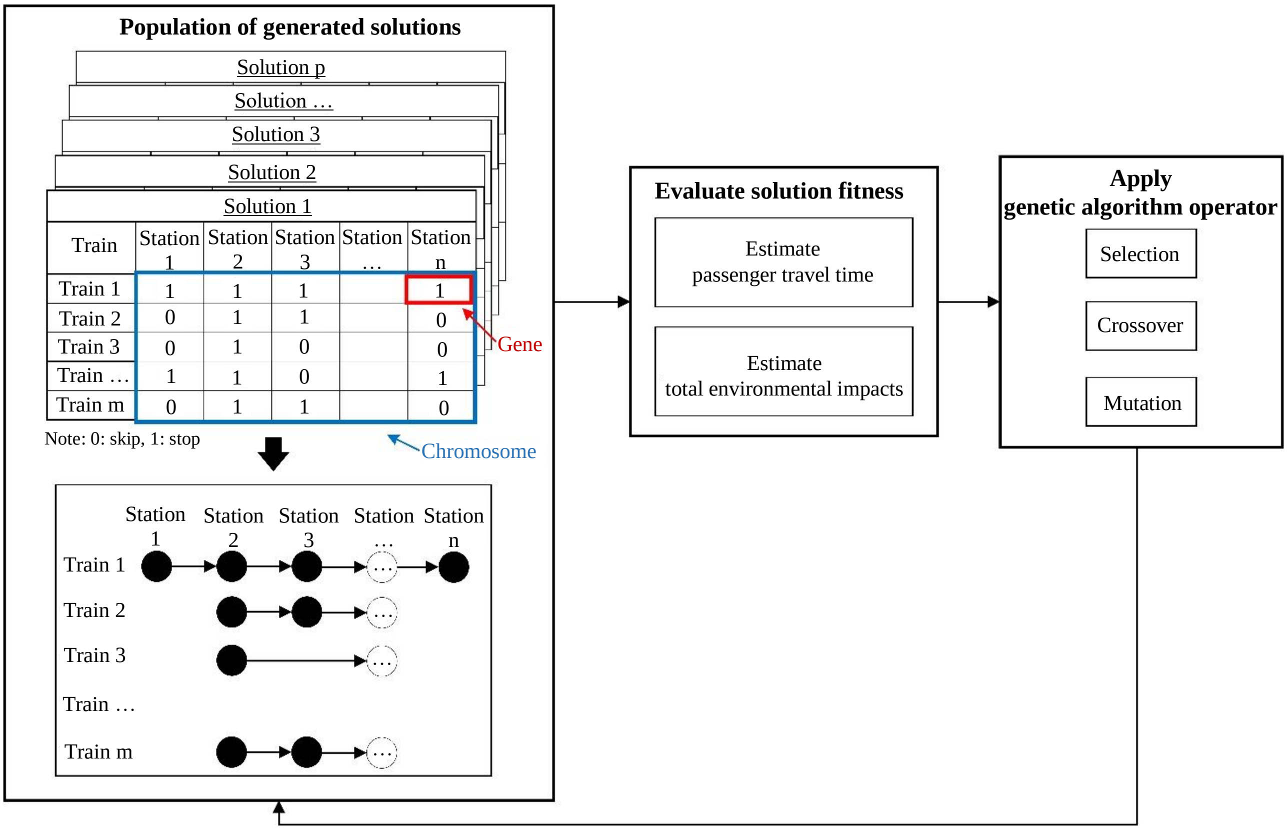

Figure 6 GA procedure for train stopping patterns optimization model

The genetic algorithm (GA) is a search heuristic technique that mimics the evaluation process using natural operators, and has a promising performance in terms of searching speed, reliability, and accuracy in solving hard and complex problems [40]. The GA principle commences with chromosomes, which represent a possible solution. The chromosomes consist of genes, in which one of them represents a decision variable. A set of chromosomes or solutions, called the population, will be used to establish a new population, according to the fitness evaluation of the planning objectives [40]. The main GA operators include selection, crossover, and mutation, which are patterns modeled on the genetic mechanisms of biological organisms [41]. At the beginning, the first set of population will be initialized and evaluate the fitness. Then, the selection will be executed with two chromosomes (called parents) according to their fitness. After that, crossover and mutation will be applied to form new chromosomes (called offspring or children) [42]. The process is repeated until the predetermined analysis conditions are satisfied. Then, the optimal or near-optimal solutions can be obtained. Figure 6 depicts the GA procedure for optimizing the train stopping patterns in this study.

6. Application example

The train stopping pattern optimization model developed was implemented on an application example of the BTS SkyTrain Silom Line in Bangkok, Thailand, to illustrate its capabilities and performance. The case study involved approximately 14 kilometers with 13 train stations [31]. In this example, the model was considered based on a one-way trip from Station W1 to S12, as shown in Figure 7, and the developed optimization model was tested during off-peak operation hours (10-11 AM). The volume of passengers traveling during the test period was set at 22,270 based on actual data from BTS [30].

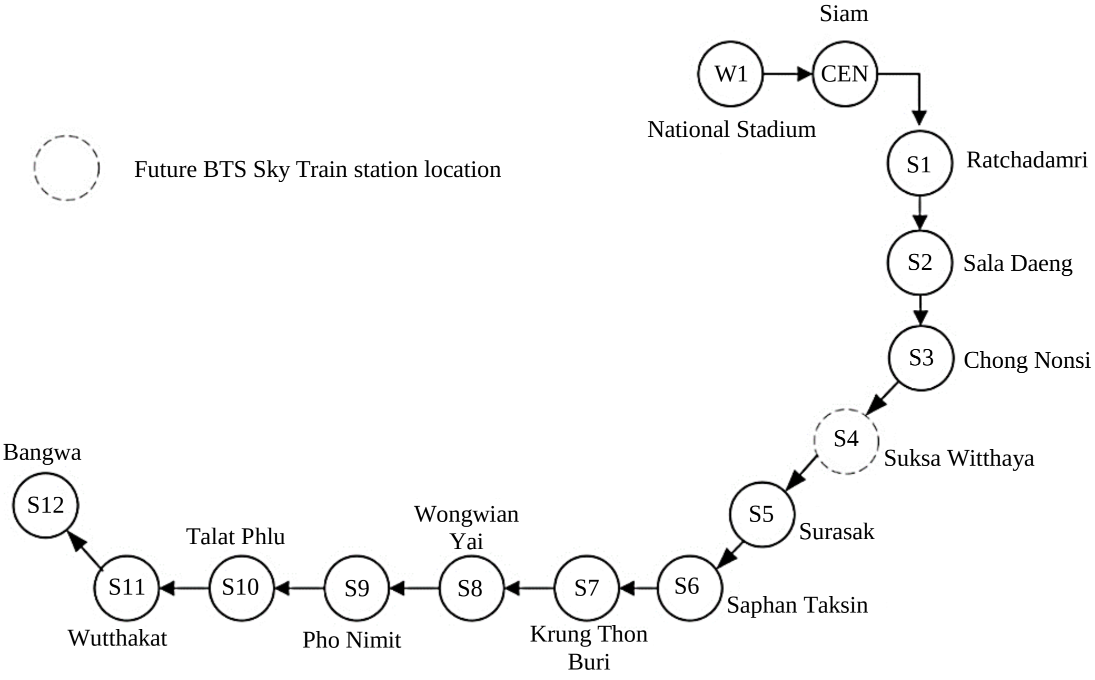

Figure 7 Route map of the Bangkok Mass Transit System (BTS)-Silom Line

Table 2 Origin-destination matrix developed for the BTS-Silom line in this study

Station		**Origin**												
		W1	**CEN**	**S1**	**S2**	**S3**	**S5**	**S6**	**S7**	**S8**	**S9**	**S10**	**S11**	**S12**
Destination	**W1**	0	0	0	0	0	0	0	0	0	0	0	0	0
	CEN	315	0	0	0	0	0	0	0	0	0	0	0	0
	S1	35	234	0	0	0	0	0	0	0	0	0	0	0
	S2	212	968	105	0	0	0	0	0	0	0	0	0	0
	S3	147	695	72	609	0	0	0	0	0	0	0	0	0
	S5	72	387	35	331	270	0	0	0	0	0	0	0	0
	S6	266	1,189	132	1,056	899	503	0	0	0	0	0	0	0
	S7	62	343	29	290	235	120	814	0	0	0	0	0	0
	S8	82	428	40	367	301	159	985	292	0	0	0	0	0
	S9	19	167	8	132	97	41	462	79	181	0	0	0	0
	S10	41	257	19	213	168	82	642	152	306	55	0	0	0
	S11	33	225	15	184	142	67	578	126	261	44	186	0	0
	S12	83	433	40	372	306	161	996	296	552	116	401	453	0

The passenger origin-destination matrix is displayed in Table 2. The possible values of stopping durations at each station were selected as between 30 and 40 seconds according to the data extracted by Sumpavakup et al. [32]. The case study estimated a traveling distance of each unserved passenger individually based on the trip between a passenger's origin and destination. As mentioned earlier, the stopping requirement constraint was determined based on the size of each train station. Thus, a train station was classified based on the passenger demand at that station according to Geurs et al. [43]. A large station (ST-L) was defined as having more than 3,500 passengers, so all trains must stop there. A medium-sized station (ST-M) was defined as having 1,001-3,500 passengers, while a small station (ST-S) was defined as having up to 1,000 passengers. The trains passing through the latter two types of stations had the flexibility of either stopping or not. The stopping requirements on the BTS-Silom Line for the 13 stations are shown in Table 3.

Table 3 Stopping requirement and duration at each station

Station number	Station	Abbreviation	Station type	Stop/skip	Stopping duration (sec)
1	National Stadium	W1	ST-S	[0,1]	30
2	Siam	CEN	ST-L	[1]	40
3	Ratchadamri	S1	ST-S	[0,1]	30
4	Sala Daeng	S2	ST-L	[1]	40
5	Chong Nonsi	S3	ST-M	[0,1]	30
6	Surasak	S5	ST-S	[0,1]	30
7	Saphan Taksin	S6	ST-L	[1]	40
8	Krung Thon Buri	S7	ST-M	[0,1]	30
9	Wongwian Yai	S8	ST-M	[0,1]	30
10	Pho Nimit	S9	ST-S	[0,1]	30
11	Talat Phlu	S10	ST-M	[0,1]	30
12	Wutthakat	S11	ST-S	[0,1]	30
13	Bang Wa	S12	ST-M	[0,1]	30

Note: 0 = skip, 1 = stop.

According to BTS [31], ten four-carriage trains operate along the rail line. The headway between each train is six minutes. The arrival times of all the trains at Station#1 (W1) are shown in Table 4. Each train has the capacity to carry around 1,490 passengers [31]. The application example was applied during off-peak hours due to the higher efficiency of examining the skip-stop operational pattern during this period. The total unserved passengers were assumed to switch mode to private vehicle usage due to a decreased efficiency in serving passenger demand when using skip-stop operation.

Table 4 Arrival time at Station#1 (W1) for each train

Train number	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Arrival time	10:00	10:06	10:12	10:18	10:24	10:30	10:36	10:42	10:48	10:54

Tables 5 and 6 provide the technical data for analyzing the optimal or near-optimal train stopping patterns for the BTS-Silom Line. In this paper, the passenger in-vehicle time was calculated as the train travel time between each station based on the train arrival time and the train departure time, which were referred to in Sumpavakup et al. [32]. The parameters for train operation, train characteristics, and CO_2 emission conversion factors, which are necessary for the optimization, are shown in Table 6. In addition, the energy losses from the traction substations were considered, which is approximately around 5% [32].

Table 5 Travel time between stations

Station		Travel time (sec)
Origin	Destination	
National Stadium (W1)	Siam (CEN)	46
Siam (CEN)	Ratchadamri (S1)	128
Ratchadamri (S1)	Sala Daeng (S2)	175
Sala Daeng (S2)	Chong Nonsi (S3)	128
Chong Nonsi (S3)	Surasak (S5)	150
Surasak (S5)	Saphan Taksin (S6)	67
Saphan Taksin (S6)	Krung Thon Buri (S7)	59
Krung Thon Buri (S7)	Wongwian Yai (S8)	52
Wongwian Yai (S8)	Pho Nimit (S9)	56
Pho Nimit (S9)	Talat Phlu (S10)	64
Talat Phlu (S10)	Wutthakat (S11)	50
Wutthakat (S11)	Bang Wa (S12)	80

Table 6 Input parameters for optimizing train stopping patterns

Description	Parameter	Value	Reference
Train operation	Stopping duration ($TSD^{i,j}$)	[30,40] sec	[32]
Train characteristics	Train capacity (C)	1,490 persons	[30]
	Effective mass (M_{eff})	228 ton	[32]
	Maximum acceleration rate (α)	0.87 m/s^2	[32]
	Maximum speed (v)	80 km/h	[32]
	Auxiliary power (aux)	270 kW	[32]
Environmental impacts	Conversion factor from electricity to CO_2 emissions (CE)	275 g of CO_2e/kWh	[33]
	Conversion factor from passenger-km to CO_2 emissions (CP)	145 g of CO_2e/passenger-km	[33]

Figure 8 shows a comparison of train operational speeds between the all-stop and skip-stop patterns. Profile (a) represents the currently used speed profile for the BTS-Silom Line with the all-stop pattern from Sumpavakup et al. [36] and Profile (b) depicts an example of the modified speed profile when some train stations are skipped based on the concept of energy characteristics for different train motion regimes. Skipping a station replaces the effects of the coasting and braking regimes with those of the cruising regime, which results in the train maintaining a constant speed for a longer time, thus lowering its energy consumption due to less acceleration (see the skipped stations at S3, S7, S10, and S11). As skipping a station prolongs the cruising motion of the train under a constant speed, the dissimilar skip-stop pattern will result in different train motion for each train, causing it to have a different speed profile due to its own motion patterns. To calculate the environmental impact from train energy consumption, the case study was analyzed by presuming an equal train mass, gradient resistance, and curve resistance for all train operations.

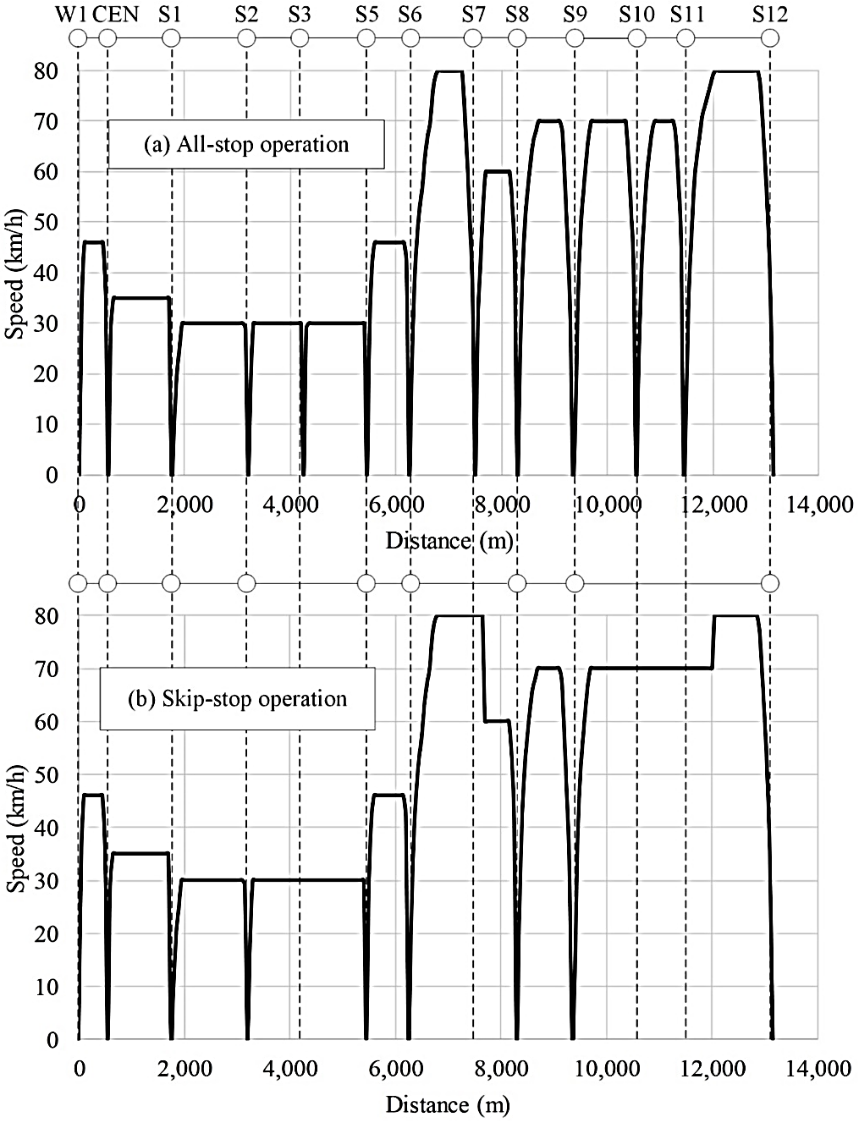

Figure 8 Train speed profiles of the BTS-Silom Line using all-stop and skip-stop patterns

7. Results and discussion

The analysis indicated the capability of the model to generate sets of optimal or near-optimal train skip-stop patterns. Figure 9 illustrates a wide range of 19 optimal solutions, each one representing stopping patterns for all trains traveling over a one-hour off-peak period at 10-11 AM. The solutions are considered optimal when their skip-stop patterns have satisfied the planning objectives in simultaneously minimizing both the passenger travel time and the environmental impacts. It is noticeable that all the optimal solutions presented in Figure 9 have no other pattern dominating them when considering the two predetermined planning objectives. Each solution can be used to create a train timetable identifying stations for stopping and skipping for each train as well as the arrival and departure times at each station.

Solution 1 in Figure 9 represents the stopping pattern with the lowest passenger travel time, while, in contrast, Solution 19 is a sustainability-oriented pattern. The numerical results of all the solutions were also extracted (Table 7) as they illustrate the impacts of the skip-stop patterns on the unserved passengers, the environmental impacts of the trains, the environmental impact of private vehicles, the total environmental impacts, and the average passenger travel time.

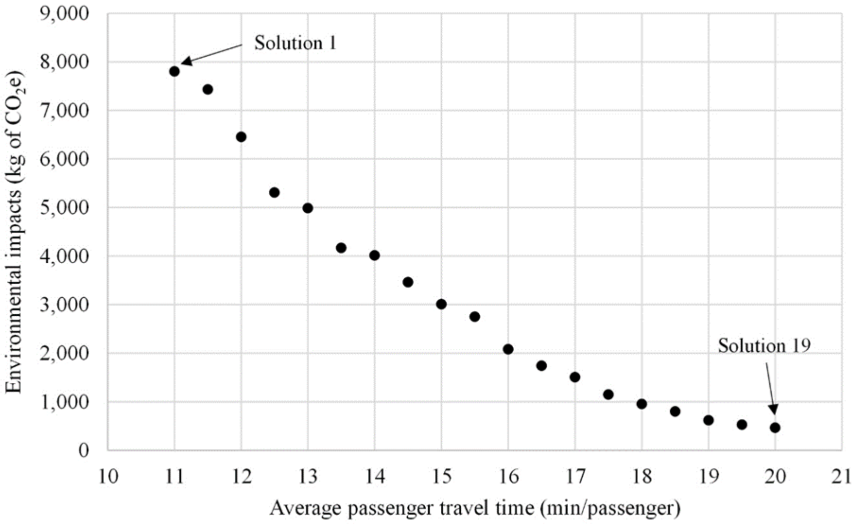

Figure 9 Tradeoff between passenger travel time and environmental impacts

Table 7 Detailed data of each solution from analysis results

Solution	Unserved passengers (passenger-km)	Environmental impact from trains (kgCO$_2$e)	Environmental impact from private vehicles (kgCO$_2$e)	Total environmental impacts (kgCO$_2$e)	Average passenger travel time (min/passenger)
1	51,318	363	7,441	7,805	11.0
2	48,625	380	7,051	7,431	11.5
3	41,799	394	6,061	6,455	12.0
4	33,452	458	4,851	5,309	12.5
5	31,143	470	4,516	4,986	13.0
6	25,746	436	3,733	4,169	13.5
7	24,664	437	3,576	4,013	14.0
8	20,823	441	3,019	3,460	14.5
9	17,590	458	2,551	3,009	15.0
10	15,805	459	2,292	2,751	15.5
11	10,983	488	1,593	2,081	16.0
12	8,659	485	1,256	1,741	16.5
13	6,870	509	996	1,505	17.0
14	4,767	459	691	1,150	17.5
15	3,107	502	451	953	18.0
16	1,900	525	275	800	18.5
17	1,078	464	156	621	19.0
18	254	490	37	527	19.5
19	0	463	0	463	20.0

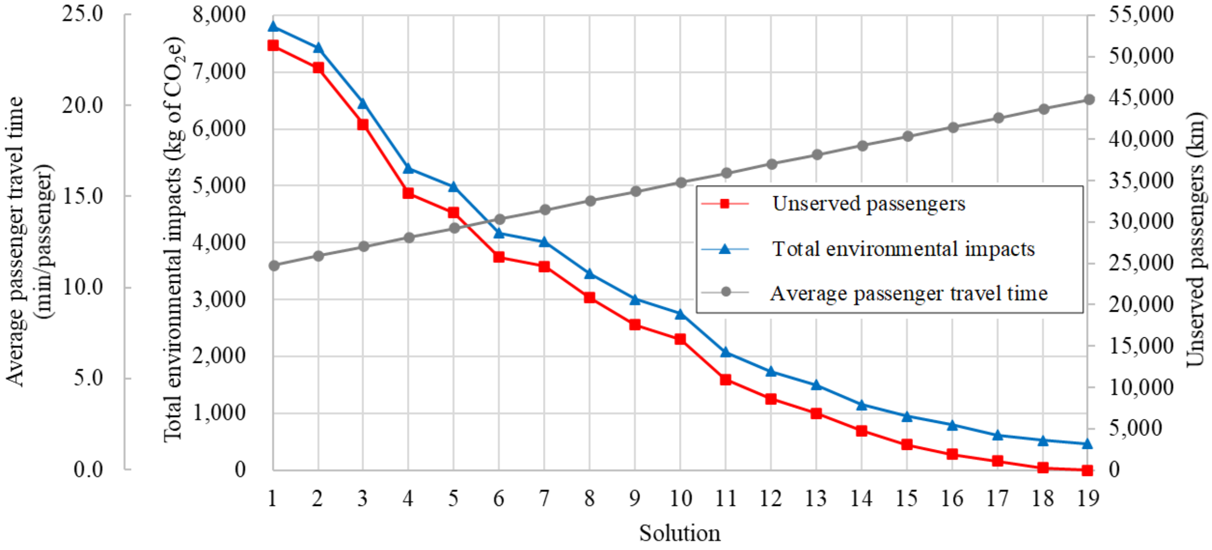

Figure 10 Relationships between passenger travel time, environmental impacts, and unserved passengers

The unserved passengers, environmental impacts, and average passenger travel time from Table 7 were plotted to investigate their trends and correlations, as shown in Figure 10. The analysis revealed that the unserved passengers crucially influenced the total environmental impacts. The trends in unserved passengers and total environmental impacts were similar, suggesting a strong correlation between them. In fact, the mass transit system contributes to serving the transportation needs of people by reducing the use of private vehicles and by reducing air pollution due to decreased traffic congestion [44].

Clearly, Solution 19 seems to be an environmentally promising solution if the average travel time is kept at an acceptable level of passenger satisfaction. It resulted in the lowest total environmental impacts among all the solutions. Solution 19 generated CO_2 emissions and an average travel time of approximately 463 kg of CO_2e and 20 minutes per passenger, respectively, over the one-hour operation at 10-11 AM during the off-peak period. In contrast, Solution 1 generated significantly more CO_2 emissions at 7,805 kg of CO_2e due to a substantial number of unserved passengers at 51,318 passenger-km in the system, while averagely 11 minutes of travel time per passenger. Practically, operator agencies must consider the tradeoff, allowing an increase in the environmental impacts and unserved passengers if a lower passenger travel duration is required.

Nevertheless, for this study, Solution 19 seems to be more promising pattern compared to the others in two aspects. First, Solution 19 is the skip-stop pattern that can efficiently serve all passengers in the system by requiring a shorter average passenger travel time than the all-stop pattern, which are mainly being operated by the service provider. The all-stop pattern requires a longer time at 21 minutes per passenger although the same capability in serving all passengers. Second, for the case study, the magnitude of difference in saving travel time seems to be incomparable with the number of unserved passengers who are probably being left in the system. Decreasing by only 30 seconds in Solution 18 adversely results in more than 250 passenger-km of unserved passengers. This effect tends to be enormous if a larger saving time desired, leading to an unsatisfactory of a significant number of passengers. In reality, service provider agencies are, however, recommended to select their operational patterns by giving the preference weights on the planning objectives in order to ensure the operations toward the organization strategic plan.

Moreover, the graphs in Figure 10 suggested a lower passenger travel time for Solution 1. This results from a higher number of skipped stations (see Figure 11), which can also lead to a larger number of unserved passengers, with associated environmental impacts. In contrast, Solution 19 has a higher number of stopping stations (see Figure 12), which increases the capability of serving more people and reduces the total environmental impacts. However, this sustainability-oriented pattern tends to prolong the passenger travel time in the system. Freyss et al. [5] and Pan et al. [45] confirmed the impacts of the skip-stop operation on the passenger waiting time. Moreover, the results of the current study were consistent with one of the sensitivity analyses performed by Pan et al. [45], showing a tendency for a shorter passenger waiting time with regard to higher numbers of stopping trains and stations. Figures 11 and 12 illustrate the train stopping patterns of Solutions 1 and 19, respectively, along with their corresponding timetables. The timetables were created by interpreting the values of the decision variables in the proposed solutions to practically communicate train schedule to the operators and passengers.

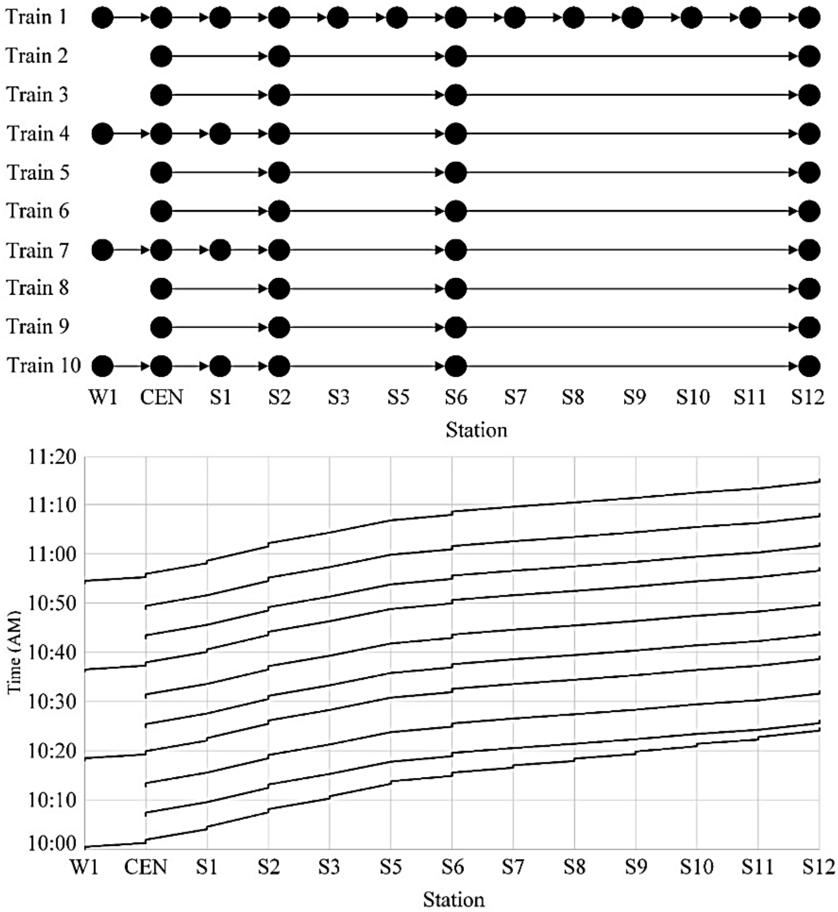

Figure 11 Stopping pattern of Solution 1

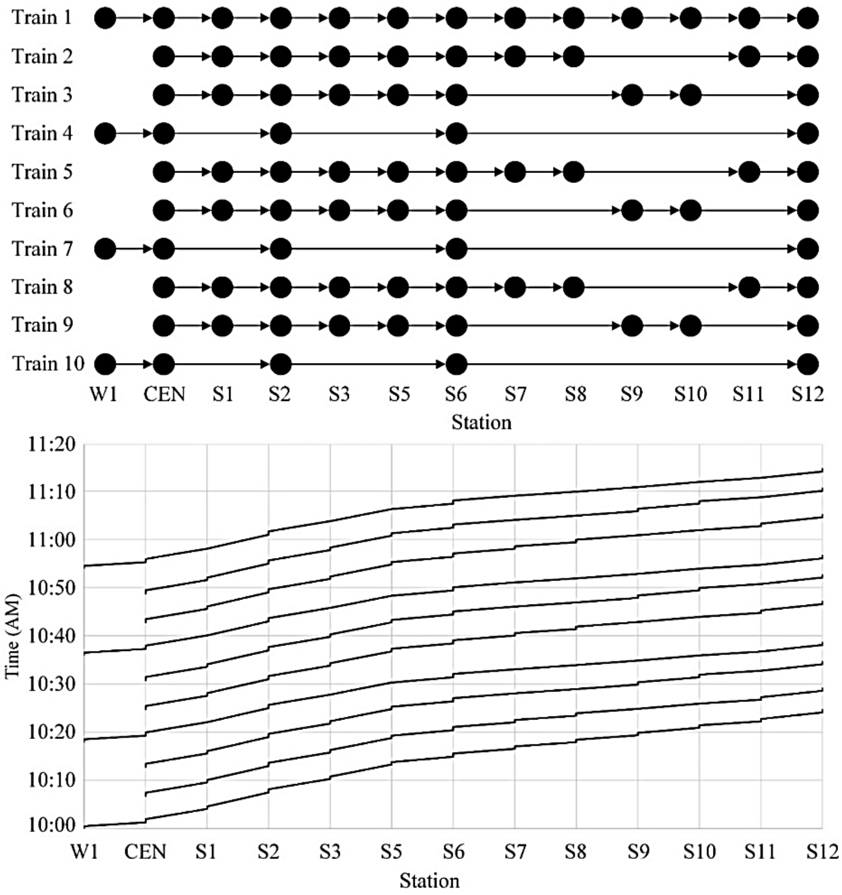

Figure 12 Stopping pattern of Solution 19

Further investigation confirmed that the different skip-stop patterns are less significant for the environmental impacts of train energy usage than the number of unserved passengers. Although some past studies [46, 47] investigated the impacts of train scheduling on the train energy usage and unserved passengers, they separately presented the impacts based solely on their own point of interest and neither determined the magnitude nor undertook any comparison. The curves in Figure 13 confirm an increment in the CO_2 emissions equivalent when the unserved passengers increased. Interestingly, the results revealed that there was no substantial impact of the skip-stop patterns on the electric energy usage by the trains, as there is an almost horizontal line with the increase in the number of unserved passengers.

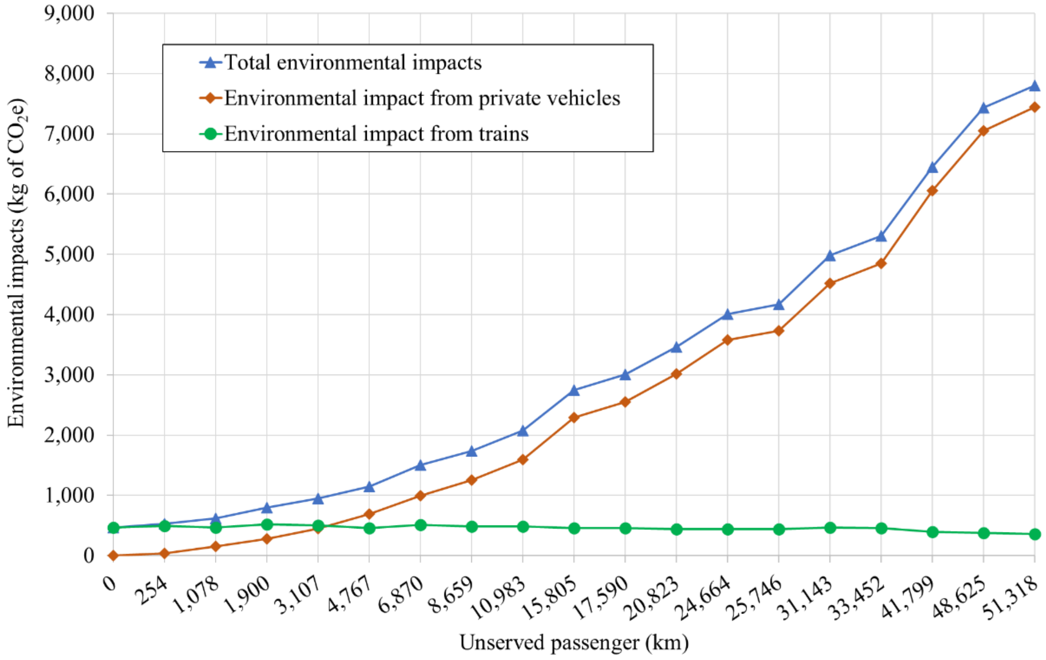

Figure 13 Environmental impacts and unserved passengers at different stopping patterns

Lastly, a qualitative validation was performed by comparing the findings in this study with other research works, as presented in Table 8. The check mark (✓) in the table shows consistency between the results in this paper and the literature. Their similarities and dissimilarities were investigated in three different aspects, which are travel time, energy consumption, and environmental impacts. This revealed an alignment among those findings as most of the consistencies identified came under the time-oriented objective, which is a primary goal for train operations. Correlations on the aspects of energy consumption and environmental impacts were found to be fewer in terms of the number of papers due to the lower number of sustainability-oriented research studies on train scheduling management recently developed.

Table 8 Summary result comparison between the existing literature works and this study

Literature	Descriptions	Analysis technique	Similarity of results on		
			Travel time	Energy consumption	Environmental impact
This paper	➢ The train stopping pattern optimization model was developed to reduce passenger travel time and total environmental impacts. ➢ The results presented a tradeoff between passenger travel time and environmental impact (lower environmental impact required longer travel time). ➢ Skip-stop operation can help reduce passenger travel time but could affect number of unserved passengers. ➢ Skip-stop operation can contribute to reducing train energy consumption.	Genetic algorithm			
Dong et al. [48]	➢ The model contributes to identify an optimal timetable and train stopping plans, accounting for the operator's cost and passenger travel efficiency. ➢ The result showed that optimizing the timetable and stop plan decreases the passenger waiting and train running times.	Adaptive large neighborhood search metaheuristic	✓		
Freyss et al. [5]	➢ Increasing the operating speed by using skip-stop operation was mentioned to reduce operating cost and travel time. ➢ It found less effect of skip-stop operations on travel time for a short rail line with a lower stopping duration.	Sensitivity analysis	✓		
Gao et al. [28]	➢ The comparison of stop mode between express/local stop mode and all-stop mode was introduced to illustrate the efficacy of reducing energy consumption and travel time. ➢ The analysis showed the tradeoff between travel time and energy consumption for express/local mode. ➢ The result showed the reduction in travel time and train energy consumption.	Linear programming	✓	✓	
Jiang et al. [49]	➢ The study investigated the impacts of adding or removing stops on the departure time from the origin station to maximize the number of scheduled trains. ➢ Total travel time reduces when using skip-stop operation.	Adaptive large neighborhood search metaheuristic	✓		
Sharma and Mathew [50]	➢ The network design model was developed focusing on minimizing travel time and vehicle emissions. ➢ The result showed the tradeoff between travel time and emission (lower emission required a longer travel time).	Integer linear programming, Heuristic algorithm	✓		✓
Yang et al. [51]	➢ The optimization model was developed under concept of skip-stop operation to determine timetable and speed profile for reducing energy consumption and train running time. ➢ The result showed a reduction in energy consumption and train running time under skip-stop operation when compared with the all-stop operation.	Quadratic programming optimization model	✓	✓	

8. Conclusions

An environmentally friendly decision support optimization model was developed to facilitate mass transit operational scheduling considering sustainability and passenger satisfaction. Sustainability was assessed in terms of the CO_2 emissions equivalent resulting from train energy usage and the vehicle fuel consumption resulting from unserved passengers using their private vehicles. The model was designed to manage train skip-stop patterns by (1) evaluating the impact of different operational patterns on the passenger travel time, (2) estimating the environmental impacts due to the energy consumption of the trains and the unserved passengers' vehicle usage, and (3) identifying the optimal train stopping patterns capable of concurrently minimizing the passenger travel time and the environmental impacts. An application example based on the BTS SkyTrain Silom Line located in central Bangkok, Thailand, was applied to demonstrate the model's performance and efficiency in optimizing train stopping patterns.

The analysis revealed the effectiveness of the skip-stop schedules in managing train operations during off-peak hours when passenger demand is not overwhelmed. Passenger demand during peak hours at a station tends to be in excess of train capacity and so is likely to induce all-stop patterns on the rail line. However, the analysis disclosed reduced efficacy for skip-stop operation on a short rail line with a small number of stations. Greater effectiveness can be realized if the headway can be substantially minimized, leading to increased train frequency over the whole system.

The results of this study present a wide range of optimal or near-optimal stopping patterns for trains that provide suitable tradeoffs between the objectives of being environmentally friendly and having an acceptable travel time for passengers. All the possible solutions represented skip-stop patterns for all trains operating over all stations in the rail network, so the train operation agency could select a preferred train timetable schedule. Furthermore, the results identified the substantial impact of unserved passengers on the total environmental impact and the importance of ordering train stops when considering passenger travel time reduction. In addition, the findings revealed the major effect of the different skip-stop patterns on unserved passengers and the travel time and its lesser effect on train electric energy consumption. It is noteworthy that the sustainability-oriented pattern was suggested in this paper due to the fulfillment in the research objective, its dissimilarity in serving passengers with more superior travel time comparing to all-stop patterns, and the differences of magnitude in saving passenger travel time and the number of unserved passengers.

Overall, the developed optimization model can be useful as a decision-support tool for train operation agencies regarding the implementation of eco-friendly train schedules. The most promising sustainable train schedule can be synthesized based on a possible range of optimal schedules given by implementation of the model. The model can also provide informative and practical guidance for agencies responsible for train scheduling to achieve an index of sustainability, as an emerging performance measure recently adopted by the transportation industry. Also, this research enhances the current body of knowledge on train scheduling for favorable environmental outcomes. The findings from this study should help develop and quantify effective train scheduling and resource allocation to adequately serve passenger demand, by providing not only commuter satisfaction but also reduced overall environmental impacts.

Some recommendations can further improve the scientific contributions and practical implications of this study. First, the application example was only applied to a one-way trip on a double-track SkyTrain line. However, further development can comprehensively improve the train scheduling at the network level with interchange stations. Second, this study developed a model based on the actual available resources from the associated transportation operation agency and the data on the number of trains and carriage capacities needed for predetermined runs. However, the practical implications can be enhanced for resource allocation and planning by, for example, analyzing the suitable number of trains. Third, the optimization of the train stopping patterns can be more efficient if temporal passenger demand data can be acquired. Using the average passenger demand statistics provided by the transportation agency would be useful for providing perceptions on the impacts; however, collecting data on timely passenger demand is recommended for agencies to facilitate developing more promising train schedule plans. Finally, in addition to taxicabs, the mode-change travel options for unserved passengers could include other means of transportation, such as buses and motor taxis, to expand the evaluation of the environmental impacts.

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