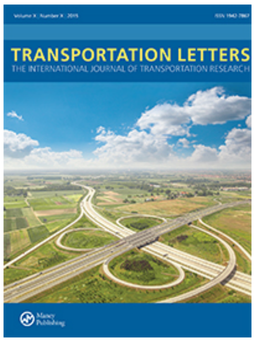

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Freight transportation using high-speed train systems

M. A. Ertem[1] and M. Keskin Özcan[2]

This study investigates the use of high-speed trains (HSTs) for transporting freight, such as small cargo and mail. A HST scheduling model is constructed to observe the effects of including freight in a passenger-only system. The proposed mathematical model is tested with an experimental study using the Turkish State Railways high-speed rail network and train sets. Freight transportation is analyzed in two cases, namely, adding separate freight trains to the system and using passenger trains for freight transportation. It can be concluded that dividing the sequences of cities into two allows for the completion of train services earlier in the day, and using the same train for transporting both passengers and freight provides more time saving in the system.

Keywords: Scheduling, Mixed-traffic systems, Mixed-integer programing model, Timetabling

Introduction

Trains can be classified into two types: (1) conventional trains and (2) high-speed trains (HSTs). The history of conventional trains date back to the eighteenth century, whereas HST technology has been developed only within the past 50years. Although there is not a single widely accepted definition for HST services, it can be said that they run on specially equipped tracks allowing speeds exceeding 250kmph (TSI HS Infrastructure 2002). High-speed train technology has aimed to increase railway capacity and reduce travel time compared to conventional trains. Japan was the first country in the world to operate HSTs in (1964) (UIC High Speed Department 2013). High-speed trains have since become a competitive mode of transportation in Japan, France, Germany, Spain, Italy, and China (UIC Definitions 2013).

In the countries where adopted, HSTs are mostly used for passenger transportation (Ziolkowski 2012). Freight transportation using HSTs is not widespread, and it is not an easy task to implement. This is because it requires additional efforts in terms of adjustments to schedules of freight and passenger traffic, determining a standard speed, setting the weight and way of transporting freight, etc. High-speed trains could become an effective way to transport time-sensitive shipments, such as mail and express freight, in the future. The motivation behind using HSTs for freight transportation is that doing so proves to be cheaper than airway transportation and faster than highway transportation.

Although not widespread, examples of HST implementations for freight transportation can be given from various countries. Passenger train technology is used for most implementations, and some vehicles are even directly derived from passenger trains, such as French TGV Postal, which is the fastest freight train in the world since 1984 with a speed of 270kmph and a capacity of 75ton per train (Troche 2005). Freight versions of the ICE1 passenger trains (since 1990), CargoSprinter, and DB Inter-Cargo-Express Container Wagon in Germany; Postal Railcar Class 325 Royal Mail in the UK; and Green Cargo “B-mail” Wagon in Sweden are other examples of freight transportation using HSTs (Troche 2005).

The operational problem lies in the coordination of freight and passenger traffic (i.e., mixed traffic) for these HST implementations. Timetabling and capacity problems arise, and these problems affect service quality. Currently, courier goods are loaded and unloaded at passenger stations. This is convenient because passenger stations are usually located in city centers. Moreover, these stations are used for transshipment of letter and parcel mail and, to this end, extensive adaptations are not required because the item sizes tend to be small. Mail offices have been located close to stations, and passenger trains have been scheduled together with mail wagons. Infrastructure, such as tunnels and elevators, were used to connect platforms and mail terminals (Troche 2005). Such use can be extended to small, lightweight cargo shipments as well.

Future HST infrastructure is advised to be constructed to allow both for freight and passenger transportation (Ziolkowski 2012). The practicality of this viewpoint is exemplified by the investments in Turkey (Railroad Sector Report 2013) and the methodology followed in our study. In Turkey, conventional trains are used to transport both passengers and freight, but HSTs are used only to transport passengers.

The objective of this study is to investigate factors influencing HST efficiency, such as the timetables of freight and passenger traffic, and standard speed and way of transporting freight, by using a mixed-integer programing model to generate schedules. The developed mathematical model for freight transportation by HSTs is analyzed using the lines currently in operation (Ankara–Eskişehir, Ankara–Konya) and in construction (Eskişehir–İstanbul, Ankara–Sivas) in Turkey. The

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remainder of this study is organized as follows. The next section provides a review of the relevant studies in the literature. In the third section, mixed traffic in HST systems is explained and a scheduling model is presented. The fourth section presents the results of a scenario-based experimental study. Finally, the paper is concluded with implications for practice and future work.

Related literature

Several researchers studied optimization models on transportation by conventional trains (Cordeau, Toth and Vigo 1998). Some studies on conventional trains are concentrated on passenger transportation (Carey and Lockwood 1995), whereas some are concentrated on freight transportation (Ergin and Çekerol 2008; Kuo, Miller-Hooks and Mahmassani 2010; Cacchiani, Caprara and Toth 2010; Crevier, Cordeau and Savard 2012). Our study is on mixed traffic similar to Cacchiani *et al.* (2010).

Mathematical models aiming to minimize deviation between the actual and preferred timetables are seen in some studies (Carey and Lockwood 1995; Cacchiani *et al.* 2010). Our study differentiates itself from these studies by not taking a predefined timetable as given. Moreover, Cacchiani *et al.* (2010) aimed to add extra freight trains to the existing mixed-traffic system, whereas our study aims to add freight trains to a passenger-only system.

Compared to research on transportation by conventional trains, research on HSTs is limited in the literature (Espinosa-Aranda, García-Ródenas, Cadarso and Marín 2014). Some studies on passenger transportation by HSTs focus on socio-economic analysis (Givoni 2006), cost of infrastructure (Campos and De Rus 2009), pricing (Yang and Zhang 2012), and competition among transportation modes (Dobruszkes 2011; Clewlow, Sussman and Balakrishnan 2014), whereas others focus on operational problems, such as timetabling (Xie, Luo and Peng 2009) and capacity planning (Espinosa-Aranda *et al.* 2014). Although most studies are on passenger transportation by HSTs, our study is on adding freight transportation to the HST system.

Mathematical models of freight transportation using HSTs are not investigated as much as those of passenger transportation by rail. Troche (2005) presented freight transportation on high-speed rail by considering the speed, type of cargo, operating principle, vehicle type, terminal, loading unit, and trans-loading technique. Ways of coordinating passenger and freight traffic on HSTs are explained in Troche (2005). Authors benefited from Troche (2005) in their study while determining the possible ways of coordinating mixed traffic. Pazour, Meller and Pohl (2010) developed a mathematical model to solve a strategic level problem of freight network design for HSTs, whereas our study is at the operational level.

As can be inferred from the aforementioned studies, most scheduling models are designed for passenger transportation on conventional trains and with predefined timetables. Models with predefined timetables (e.g., Carey and Lockwood 1995; Cacchiani *et al.* 2010) would not be applicable when there is no actual schedule for freight transportation by HSTs (such as the case in Turkey). The objective of a model for this situation cannot be minimizing the deviation between the actual and preferred schedules. Based on the best of our knowledge gained from the related literature, it can be stated that freight transportation using HSTs has not been analyzed without a predefined timetable thus far. The contribution of this paper to the literature would be to fill this gap.

Methodology

Mixed traffic in HST systems

Based on rail and train types, there are four general methods of operating freight trains (Campos and De Rus 2009). These operational methods are summarized in Table 1. They were developed considering all combinations when tracks or trains are either high speed or conventional. The focus of this study is using high-speed tracks for running HSTs (i.e., *italic* quadrant in Table 1).

To achieve freight transportation on high-speed tracks by HSTs, the following important factors should be considered:

- *Timetable:* construction of a timetable is needed because both passengers and freight will be transported on the same line (i.e., mixed traffic). The timetable of freight-transporting trains should be determined.
- *Capacity*: transportation can be performed in conformity with line capacity. Available space to load freight onto HSTs should be determined. Number of trains/wagons necessary for transporting freight should be calculated.
- *Speed:* the pressure applied on the line because of the weight difference between freight and passenger trains should be determined. This should be used to calculate suitable train speeds such that any damage to the line is avoided.
- *Way of transporting the freight*: line density should be considered, and it should be analyzed whether to transport freight on the same train as passengers or in a separate HST.

Usually, HSTs are used to transport passengers. Transporting freight by HSTs is a concept that should be elaborated from many aspects. Construction of a *timetable* is essential if both passengers and freight are to be transported on the same line. Some trains can be used only for freight transportation, whereas some trains can be used for transporting both freight and passengers. Passenger train *capacity* should be checked to determine whether there is empty space for freight. If there is space, freight can be transported using passenger trains, but the sharing of passenger platforms with freight and loading/unloading can result in extended stopping times at stations. If there is not space, freight can be transported using separate trains, but in coordination with the passenger timetable. In this case, freight transportation is done after completing passenger transportation for the day. This method prevents the disruption of passenger transportation and collisions between freight and passenger trains.

Speed of HSTs differs according to *the way of transporting freight*. Therefore, travel times differ, too. There are four different ways of coordinating high-speed freight and passenger traffic according to Troche (2005), and these are named as Cases A, B, C, and D (see Fig. 1). Case A and C in Fig. 1 correspond to the methods addressed in this paper, which are (Case A) transportation of freight and passenger using the same train and (Case C) transportation of freight using different trains, but in coordination with passenger traffic. Case C provides the

Table 1. Different ways in terms of rail track and train types to operate freight trains (adapted from Campos and De Rus 2009)

	Track	
	High speed	Conventional
High-speed train	*Freight transportation by HST on high-speed tracks*	Freight transportation by HST on conventional tracks
Conventional train	Freight transportation by conventional train on high-speed tracks	Freight transportation by conventional train on conventional tracks

opportunity to load and unload freight at different times and to stop at stations other than passenger stations. However, in Case C, an extra driver is needed. Case B represents transportation of freight and passenger in separate trains that can be multi-coupled and allows these trains to have different starting points and destinations. Case D represents freight transportation that is fully independent from passenger traffic.

Mathematical model

Scheduling models are used in both the manufacturing and service industries. In the service industry, the number of service stations (e.g., cashier, registrar) is limited, and a service receiver (e.g., customer) would not like to wait to receive service. Scheduling models are needed to assign the limited number of service stations to customers. Transportation scheduling models represent a subset of service scheduling models, and they are developed to help vehicle (e.g., bus, plane, and train) controllers schedule transportation services. In these models, a vehicle is similar to a machine in the manufacturing environment, and a trip (i.e., job in manufacturing environment) must take place within a given time. A train schedule consists of arrival and departure times for each train at each station. These events occur with a certain frequency within a planning horizon T. The schedule must satisfy system requirements, such as demands and minimum distances between trains, and accommodate the schedule of passenger trains.

The assumptions for the mathematical model proposed here are as follows. (1) There are enough platforms for arrivals and departures at stations. (2) The daily timetable obtained from this model is valid for all days of the week. (3) For safety reasons, it is necessary to determine the minimum time intervals between arrivals and departures of two consecutive trains (e.g., taken as 15min in the experimental study). (4) It is necessary to determine a minimum dwell time between the arrival time of a train at a station and the departure time of that train from that station for loading/unloading and maintenance (e.g., taken as 45min in the experimental study). (5) There exist two different lines for two different directions between city pairs. (6) Trains should return to their starting station after completing the assigned daily trips.

Let J denote the set of links, such that a link j joins station $j-1$ to station j. The stations are repetitive in our model to create a sequence of stations (i.e., cities). Arrival to and departure from a city are represented by separate links. Let I denote the set of trains with a fixed sequence. Service times (i.e., trip durations) for freight and passenger trains are given. Speed of freight trains is assumed lower than that of passenger trains; thus, service times for freight trains are higher. Service times for different city pairs are known. Figure 2 shows the relationship between the sets of links, stations, and trains.

The mixed-integer programming model is presented in the following.

Parameters

T: Planning horizon (i.e., number of minutes in a day)

$D_{\min}$: Minimum departure time allowed during T

$D_{\max}$: Maximum departure time allowed during T

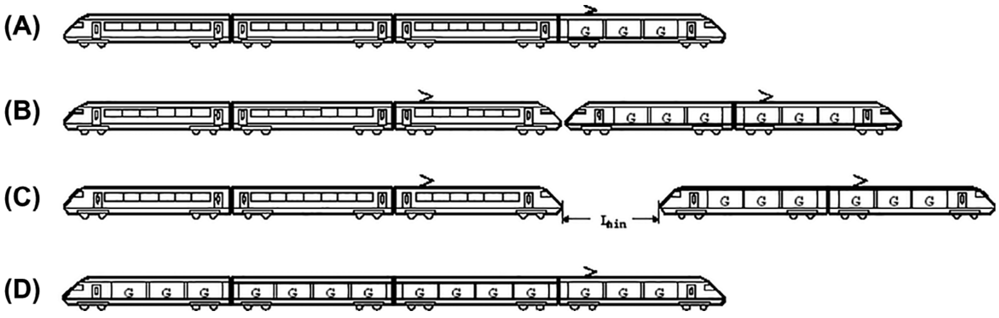
$A_{\min}$: Minimum arrival time allowed during T

$A_{\max}$: Maximum arrival time allowed during T

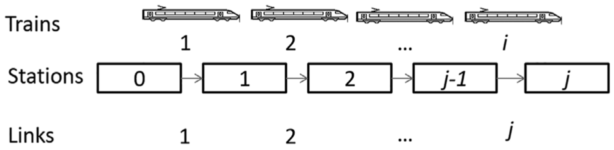
S_{ij}: Service time (i.e., transit) of train i on link j

I_A: Minimum headway time between arrivals of two consecutive trains

I_D: Minimum headway time between departures of two consecutive trains



1 Ways of coordinating high-speed freight and passenger traffic (Troche 2005)



2 Stations and links as considered in the model

I_{AD}: Minimum dwell time between the arrival and departure times of a train at a station

M: Sufficiently large positive integer

Decision variables

A_{ij}: Arrival time of train i at station j (Arrival time of train i at a station after completing travel on link j)

D_{ij}: Departure time of train i from station j − 1 (Departure time of train i to travel on link j)

X_{hij}:
$$\begin{cases} 1, \text{iftrainhimmediatelyprecedestrainionlinkj} \\ 0, \text{otherwise} \end{cases}$$

C_{max}: Maximum of all arrival times for all trains and on all links

In mixed-traffic lines, daytime is usually reserved for passenger traffic and night time is usually reserved for freight traffic (Campos and De Rus 2009). Therefore, the aim of the proposed model is to maximize the time remaining to operate freight-only trains at night after completing any mixed or passenger-only traffic during the day. The objective function and the constraints of the model are as follows

$$\mathrm{Max}\left(T - C_{max}\right)$$

subject to

$$X_{hij} + X_{ihj} = 1\ \forall\, \mathrm{h,i,jandi} \neq \mathrm{h} \tag{1}$$

$$D_{min} \le D_{ij} \le D_{max}\ \forall\, \mathrm{i, j} \tag{2}$$

$$A_{min} \le A_{ij} \le A_{max}\ \forall\, \mathrm{i, j} \tag{3}$$

$$D_{ij} + S_{ij} = A_{ij}\ \forall\, \mathrm{i,j} \tag{4}$$

$$A_{hj} + I_{A} \le A_{ij} + \left(1 - X_{hij}\right) M\ \forall\, \mathrm{h,i,jandi} \neq \mathrm{h} \tag{5}$$

$$D_{hj} + I_{D} \le D_{ij} + \left(1 - X_{hij}\right) M\ \forall\, \mathrm{h,i,jandi} \neq \mathrm{h} \tag{6}$$

$$A_{ij} + I_{AD} \le D_{i,j+1}\ \forall\, \mathrm{i,j} \tag{7}$$

$$A_{ij} \le C_{max}\ \forall\, \mathrm{i,j} \tag{8}$$

$$A_{ij}, D_{ij}, C_{max} \ge 0\ \forall\, \mathrm{i,j} \tag{9}$$

$$X_{hij} \in \{0, 1\}\ \forall\, \mathrm{h,i,jandi} \neq \mathrm{h} \tag{10}$$

Constraint (1) guarantees that if train *h* immediately precedes train *i* on link *j*, the reverse is impossible. Constraints (2) and (3) specify the upper and lower bounds of departure and arrival times during *T*. Constraint (4) specifies the travel time constraint. It guarantees that after the departure of train *i* to travel on link *j*, a service time must pass before the train's arrival at station *j*. Constraint (5) forbids arrival of the next train after arrival of a train if the minimum time interval has not passed. Constraint (6) forbids departure of the next train after departure of a train if the minimum time interval has not passed. Constraint (7) stipulates that if a train arrives at a station, it cannot depart from there unless the minimum dwell/maintenance time has passed. Constraint (8) gives the latest arrival times of all trains at all stations. Constraint (9) is a non-negativity constraint for decision variables, and constraint (10) specifies binary variables. The model in this paper is inspired from the one in Carey and Lockwood (1995). Carey and Lockwood (1995) used two constraints to ensure that each train has one and only one immediate predecessor on a link, and that the train in question is the immediate predecessor of one and only one other train. In the model proposed herein, a single constraint (i.e., constraint (1)) ensures this. Another difference between Carey and Lockwood (1995)'s model and our model is that we do not use a predefined timetable because we do not aim to minimize deviation between the preferred and actual timetables.

Experimental study

Experimental setting

High-speed train systems are costly investments and they must be used efficiently. One way to increase the HST utilization is using them for freight transportation in addition to passenger transportation. The model proposed herein is tested with some real-life scenarios inspired from operations of Turkish State Railways (TCDD-*Turkish abbreviation*). The Turkish HST system can be given as an example for recent investments in various countries. The first HST service was started officially between the cities of Ankara and Eskişehir in 2009. Later, an HST service was started between Ankara and Konya in 2011 (TCDD 2012). The Eskişehir–İstanbul and Ankara–Sivas lines are in process of construction (TCDD 2010). Based on several meetings with TCDD and cargo companies, 21 scenarios are constructed for freight transportation on existing lines and on lines under construction. Figure 3 shows a map of the lines used for scenario analysis (i.e., Ankara–Konya, Ankara–Eskişehir, Ankara − İstanbul, and Ankara–Sivas).

There are 12 HSTs in Turkey. One is used for rail measurements, 4 are reserved for emergencies, and the remaining 7 HSTs are used for 36 services in a day. Twenty of these services are performed using four HSTs between Ankara and Eskişehir and 16 services are performed by using three HSTs between Ankara and Konya. The model parameters are chosen in such a way that frequent departures are achieved in a day to ensure efficient system use and to save time for freight-only transportation at night. The minimum time interval between departures (I_D) is taken as 15min. To increase the number of train services in a day, 45min is taken as the minimum dwell/maintenance time interval between arrival and departure times of a train at a station (I_{AD}). The minimum time interval between arrivals (I_A) is taken as 20min. The earliest departure time (D_{min}) of a train can be 5 : 00 am in a day (300th minute of 1440 ($T = 60 \times 24$) minutes, which corresponds to the total number of minutes in a day). The latest arrival time at a station can be taken as 1400 ($A_{\max}$), which corresponds to the end of the day. Travel times between city pairs are taken from real life, where available, and extrapolated to the lines under construction. In Table 2, service times and average speeds of freight and passenger trains are listed for each city pair considered in the experimental study.

To illustrate the functionality of the model with a simple example, the proposed model is solved for the Ankara–Eskişehir line for a 1-day period to compare results with the case in real life. In real life, four HSTs are used on this line, and each of them completes five services within a day. In Fig. 4, the daily services of only one train set are analyzed to observe the differences and similarities between real life and model output. It is seen that in the model, daily services of a train are completed before the case in real life. This is because the proposed model is constructed to increase system utilization and finish passenger services as early as possible. Notably, the sequence of arrivals and departures between the cities is the same as that in real life.

Given that the number of existing lines is limited, some assumptions are made to represent the possible future scenarios. If a train departs from Ankara station toward İstanbul station, it can only travel after stopping at Eskişehir station. Similarly, after departure from Konya station, the train should first arrive at Ankara station to go to Sivas station, or vice versa. In these scenarios, arrival and departure between pairs of cities (Ankara–Eskişehir, Eskişehir–İstanbul, Ankara–Konya, and Ankara–Sivas) are considered in a sequence, as shown in Fig. 5. This figure shows only one of the scenarios tested here, and arrival and departure between city pairs are represented by separate links. To clarify, if link one in Fig. 5 represents traveling from Ankara to Eskişehir, then link two represents returning from Eskişehir to Ankara. After arriving at Ankara, the next service of the train set is from Ankara to Konya. At the end, the train arrives at Ankara station, which is the start of the journey for that train set. Thus, there is a closed loop (e.g., A–E–A–K–A, where the initials represent the city names) in all scenarios. This is required for nightly maintenance operations. Right now, TCDD has a maintenance station only in Ankara.

Each HST comprises six wagons and can transport up to 419 passengers (TCDD 2010). However, the average capacity utilization in 2012 on the Ankara–Eskişehir line and Ankara–Konya line stood at 66 and 62%, respectively (Railroad Sector Report 2013). These figures are annual averages for all departure times during the day. Capacity utilization on the Ankara–Eskişehir line varies between 87% (6 pm service) and 47% (7 am service); for the Ankara–Konya line, it varies between 81% (9 am service) and 45% (1 pm service). Thus, different numbers of wagons can be emptied for freight transportation at different times of the day. Without loss of generality, we assume that on average, at least one of the six wagons can be emptied per trip and passengers can travel in five wagons. Hence, in our model, it is assumed that one of the wagons can be used for freight transportation when freight and passengers are transported on the same train.

It has been reported that HST systems are an important alternative to air transportation (Clewlow *et al.* 2014) but do not have as much of a demand decreasing effect on cars and buses (Givoni 2006). High-speed train lines in operation do not create an alternative for airline passenger demand in Turkey because, currently, there is no direct flight from Ankara to either Eskişehir or Konya. For the lines in construction (i.e., Eskişehir–Istanbul and Ankara–Sivas extensions), HST might act as an alternative to air transportation, but the figures have not been realized yet. By contrast, HST lines in operation act as alternatives to car and bus transportation, especially between Ankara and Eskişehir. The share of railway transportation for passengers increased from 8 to 72% (Railroad Sector Report 2013).

Three sets of experiments are conducted herein. First, the model is solved for (I) passenger-only transportation. Then, freight transportation is added to the model in two cases, namely, (II) Case C (separate trains) and (III) Case A (same train). When the model is solved to evaluate a schedule for passenger transportation, the objective is to maximize the time (minutes) left for freight transportation in a day. All models for the scenarios are solved using GAMS CPLEX Solver 11, and the results are summarized in Table 3.

Map of lines used for the scenario analysis

Table 2. Service times and average speeds of freight and passenger HSTs

	Service times between cities				
Test cases	A–E(*) (min)	A–K (min)	E–İ (min)	A–S (min)	Average speed (km h^{-1})
Only passenger	90	115	105	170	165
Case A	100	125	120	190	145
Case C	120	155	145	230	120

(*)initials represent the city names; A: Ankara; E: Eskişehir; K: Konya; İ: İstanbul; S: Sivas.

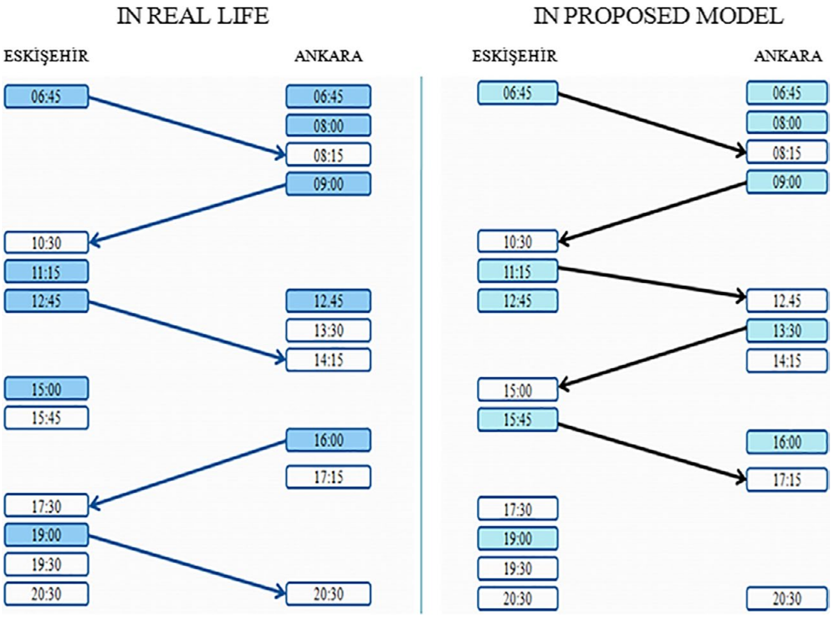
Scenario analysis

Seven scenarios are tested for passenger-only transportation. They vary based on the sequence of cities (represented by the initials of city names) and allocations of available HSTs to these sequences during a day. As can be inferred from Table 3, Scenarios 1, 2, and 3 allocate all trains to the same sequence of cities, whereas Scenarios 4, 5, 6, and 7 are obtained by dividing the sequence of cities and then allocating the trains to these sequences. The trains are allocated to divided sequences of cities by following two approaches. First, three trains are used on the lines among Ankara, Eskişehir, and İstanbul because of the high population density along these lines, and one train is reserved to be used on the lines among Ankara, Konya, and Sivas. Second, the number of trains is divided into two halves. Thus, two of the four trains are used on the Ankara–Eskişehir–İstanbul lines, and the other two trains are used on the Ankara–Konya–Sivas lines.

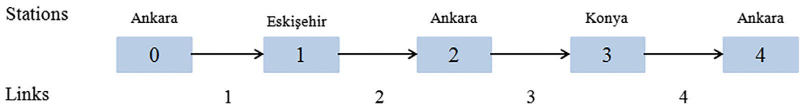
In mixed-traffic experiments, freight transportation is added to the current passenger-only HST system. While adding freight to the current system, two cases are considered. In Case C (see Fig. 1), freight trains travel separately from passenger trains. Scenarios for Case C are constructed in such a way that freight transportation is done after passenger services to avoid passenger delays and benefit from late hours within the day for freight transportation. In Case A, the same train is used to transport both freight and passengers, and only one of the six wagons is allocated for freight loading.

Separate trains in addition to passenger trains are added to the system. This case is tested with two approaches. In the first approach, if the sequence of cities is not divided, two freight trains are added after passenger trains. In the second approach when the sequence of the cities is divided into two, one freight train is added to one of the sequences and another freight train is added to the other sequence. In total, two freight trains are added to the system. The freight trains operate after passenger trains. When freight trains are added to the model, the values of all objective functions decrease. Scenarios 8–14 in Table 3 represent Case C – freight and passengers on separate trains.

Freight transportation by the same train as passengers, Case A (see Fig. 1), is also tested. Case A is operationally more difficult than Case C because a balanced single speed has to be



4 Comparison of the real life and proposed model schedule for Eskişehir–Ankara line



5 A sample sequence among pairs of cities used in scenarios

Table 3. Results of scenario analysis

			Number of trains			Number of train sets allocated to the sequence of cities		
	Scenario number	Number of links	Passenger	Freight	Sequence of cities (initials of city names)	Passenger	Freight	Objective function (min)
Passenger-only transportation	1	4	4	0	A–E–A–K–A	4	0	535
	2	6	4	0	A–E–İ–E–A–K–A	4	0	235
	3	8	4	0	A–E–İ–E–A–K–A–S–A	4	0	N/A (*)
	4	6	4	0	A–E–İ–E–A	3	0	575
					A–K–A	1	0	
	5	6	4	0	A–E–İ–E–A	2	0	595
					A–K–A	2	0	
	6	8	4	0	A–E–İ–E–A	3	0	435
					A–K–A–S–A	1	0	
	7	8	4	0	A–E–İ–E–A	2	0	415
					A–K–A–S–A	2	0	
Freight on separate trains from passengers	8	4	4	2	A–E–A–K–A	4	2	360
	9	6	4	2	A–E–İ–E–A–K–A	4	2	N/A (*)
	10	6	4	2	A–E–İ–E–A–K–A–S–A	4	2	N/A (*)
	11	6	4	2	A–E–İ–E–A	3	1	420
					A–K–A	1	1	
	12	6	4	2	A–E–İ–E–A	2	1	440
					A–K–A	2	1	
	13	8	4	2	A–E–İ–E–A	3	1	220
					A–K–A–S–A	1	1	
	14	8	4	2	A–E–İ–E–A	2	1	200
					A–K–A–S–A	2	1	
Freight on the same trains with passengers	15	4	6		A–E–A–K–A	6		455
	16	6	6		A–E–İ–E–A–K–A	6		125
	17	8	6		A–E–İ–E–A–K–A–S–A	6		N/A (*)
	18	6	6		A–E–İ–E–A	4		505
					A–K–A	2		
	19	6	6		A–E–İ–E–A	3		525
					A–K–A	3		
	20	8	6		A–E–İ–E–A	4		355
					A–K–A–S–A	2		
	21	8	6		A–E–İ–E–A	3		335
					A–K–A–S–A	3		

(*) It is not possible to complete this sequence of cities within a day.

determined. Travel times of trains in Case A are lower than those of trains in Case C, but higher than those in the passenger-only case. Because freight is added to the trains, the values of all objective functions decrease in all scenarios when compared with the passenger-only experiments. Scenarios 15–21 in Table 3 represent Case A – freight on the same train as passengers.

A comparison of three sets of experiments is needed. Comparable scenarios should be chosen from each of the three sets of experiments. For example, Scenarios 1, 8, and 15 can be selected for comparison. Scenario 1 is of the passenger-only type with an A–E–A–K–A city sequence using four passenger trains. Scenario 8 is from Case C experiments for the same city sequence with four passenger trains, but two added freight trains. Scenario 15 is from Case A experiments, also for the same city sequence but with six combined trains holding one freight and five passenger wagons each. The results indicate that the passenger-only experiments have the highest objective function values. Transporting freight by the same trains as passengers leads to higher objective function values than transporting freight by separate freight trains. This means that freight transportation by the same train as passengers is more beneficial than the other case in all scenarios, i.e., using six trains in common for freight and passengers provides greater time saving than the case in which four passenger trains and two freight trains are used separately. However, it should be noted that when six trains are used in common, the number of freight wagons is six because one wagon of each train is separated for freight. In the other case (i.e., Case C), the number of freight wagons is 12 (6 wagons × 2 trains) because two separate freight trains are used, and each train has six wagons. Although time saving is higher when using the same train for freight and passenger transportation, the number of freight wagons is lower. Moreover, an extra driver is needed when freight and passenger trains are separated. This consideration should be balanced by the decision-makers in TCDD during operations on different lines with varying freight demand.

Conclusion

This study presents a mathematical model for adding freight trains on HST systems. A scheduling model is constructed to determine the effects of freight transportation on the current passenger-only system. The model is tested with real life data from the TCDD HST system via passenger-only and mixed-traffic experiments.

When mixed traffic is of concern, the construction of a timetable is essential. If there is empty room for freight transportation on a HST, freight and passengers can be transported using the same train by emptying one of the six wagons of a train for freight loading and by reducing the train speed. The feasibility of this case is high because average fill rate of HSTs is about 64% (on existing lines). If not, freight can be transported by separate trains, having lower speeds than those in the first case, after passenger transportation is completed in a day.

The mixed-integer programing model presented here yields departure and arrival times of trains. The objective function gives the time left in a day after completion of daily services. Various scenarios are considered to test the model's applicability. These scenarios were created considering the Ankara–Eskişehir, Ankara–Konya, Ankara–Sivas, and Eskişehir–İstanbul lines. In the scenarios, the sequence of cities that trains must complete each day is extended and divided into two if the number of minutes in a day is not enough to realize that sequence. The trains are allocated to these sequences in different ways to see the effect on the objective function. When freight is added to the system, the time left in a day after completion of services is reduced in both cases (i.e., freight transportation by the same train as passengers and by separate train). For the first case of transporting freight by separate freight trains, two freight trains are added to the system with four passenger trains.

Dividing the sequence of cities into two and allocating the trains to these sequences always yielded better solution in the scenarios. Daily train services finished much earlier. However, although in some scenarios, better allocation of trains' sequences equally was achieved, worse solutions were obtained in other scenarios. Therefore, the results for allocating an equal number of trains to each sequence cannot be generalized.

For the scenario of freight transportation by the same train as passengers, it can be concluded that transporting freight using the same train as that for passengers is more advantageous than using separate trains for transporting freight. This means that using six trains in common for freight and passengers requires lesser time than using four passenger trains and two freight trains separately.

The sequences of cities are not comprehensive in the experimental settings here. The complete set of possible city pairs will be covered in future studies. Allocating different numbers of trains to different sequences for freight and passengers is not analyzed in a full experimental setting. Only selected scenarios were investigated. Future studies should search for all alternatives, including expected future demand rates on non-existing (i.e., planned) lines.

Using HSTs for freight transportation increases the capacity of railway systems substantially thanks to their high speed and up-to-date signaling systems. Therefore, it can be advantageous to use HSTs in transportation of freight, such as postal mail and small cargo. Nevertheless, freight transportation by HST systems is a complex task and requires consideration of many factors, such as capacity, speed, timetabling, and operational method. This study is an initial attempt to tackle this complex task.

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