INFORMS Railway Applications Section
2022 Problem Solving Competition
Problem description
Version 2.4

Designing real-time traffic management for an urban rail transit system – London’s new Elizabeth line, UK

1 Problem description

As a global rail operator, MTR is working with TrenoLab in the development of a state of the art Decision Support Tool, which will be used in helping build resilience into London’s new railway – the Elizabeth line.

The Elizabeth line (formally known as Crossrail) will stretch more than 60 miles from Reading and Heathrow in the west through central tunnels across to Shenfield and Abbey Wood in the east. It will ultimately provide a seamless transit service between the East and West parts of the British capital city, with several connections to the railway and underground networks, as well as with the Heathrow international airport.

The rail network features the shape of an “horizontal X”, with four extremity terminals: Reading and Heathrow airport on the West side, and Abbey Wood and Shenfield on the East one. Planned services will originate/terminate from/at these terminals as well as from intermediate stations. An illustration of the network is provided by Figure 1.

At the full planned regime, more than 1000 daily trains will be operated by the Train Operating Company (TOC) MTR Elizabeth line on behalf of Transport for London (TfL), resulting in a minimum service headway (time between consecutive trains in the same direction) of 150 s in the central section of the network, where all services between different origins/destinations share the same tracks. In this part of the network a Communication Based Train Control system will allow for a nominal minimum technical headway of about 90 s, while in the peripheric branch a conventional signaling system will allow for an approximate minimum technical headway of 240 s.

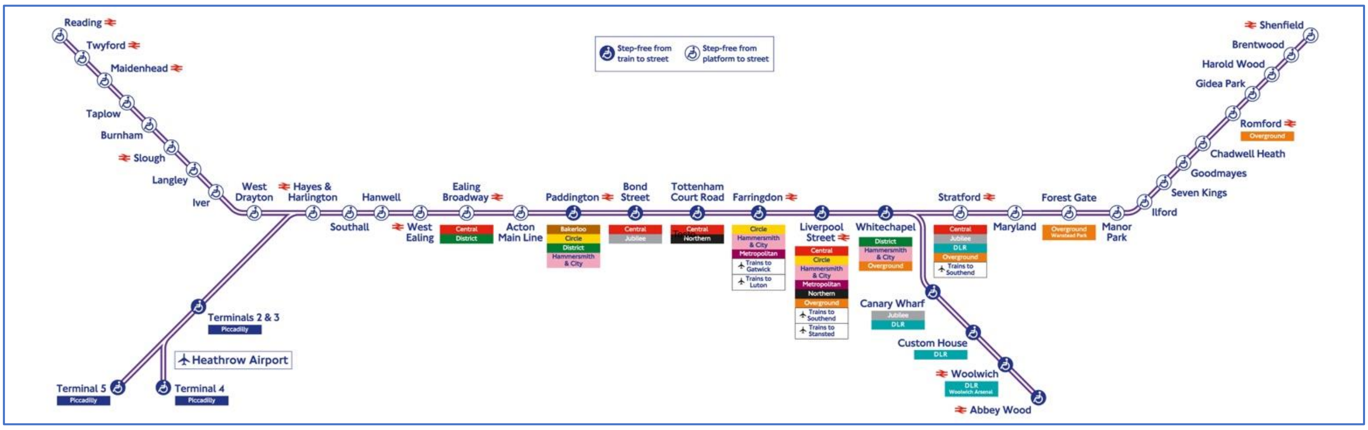


Figure 1. The Elizabeth line.

On a such densely used system, even minor disturbances, especially during peak hours, could result in major implications on the planned timetable and rapid delay spread and potential service cancellations because of two main factors:

- Congestion in the central section;
- Strong interweaving of courses at terminal stations due to rolling stock circulation.

Timetable disruptions ultimately result in a loss of service quality for passengers, for which the TOC will have to pay an economic fee. A set of penalty KPIs is defined to this purpose, in general depending on time and space (e.g., scarcely frequented stations during off-peak hours accounts less than heavily used ones in peak hours).

To maintain a given level of service, and thus, to minimize the economic penalty to be paid, the TOC can perform an active dispatching of the traffic, resulting in a set of timetable amendments. Timetable amendments are actions which modify the planned timetable in real-time during operations. Therefore, from that time on, trains will have to run following the amended timetable instead of the originally planned one. In general, amendments do not come free, meaning that they do involve a certain amount of penalty. Possible amendments could be train retiming, choosing a different platform, skipping a stop, cancelling a service. An effective amendment set is that which involves a total penalty (computed on the amended timetable) minor than the penalty to be paid in case of no amendments are applied.

Finally, amendments must be designed in such a way that they ensure a feasible rolling stock circulation, possibly resorting to calls for available reserve units in depots.

The aim of the competition is to develop a method to compute the optimal sets of amendments for a given set of timetable disruption scenarios using a Decision Support Tool. A disruption can be caused by disturbances of traffic as well as speed reductions on railway track.

Section 2 introduces the input data, which are then discussed in detail in subsequent sections. Section 3 describes the model for infrastructure and timetable. Section 4 explains how the disruptions are structured and described. Section 5 illustrates possible amendment types while Section 6 deals with the computation of the economic penalties. Finally, Section 7 describes the objective of the competition including the expected deliverables.

2 Input data

The input dataset provided to participants is composed by:

- A planned daily timetable;
- The planned rolling stock duties;
- Infrastructure data, i.e., minimum run times and headways (minimum time separation between two trains) for the concerned rolling stock type on the considered network;
- A set of problem instances. Each instance is a disrupted timetable, which is qualified by the realized timetable until a certain time and by a set of conditions such as slowdowns which are expected to occur after that time. These conditions are potential causes of additional delays which must be properly handled.
- A set of KPIs for computing the economical penalty due to actual traffic diverging from the planned timetable. These KPIs consider:
    - Skipped stops;
    - Destination delays;
    - Headways in the central section of the network, between Whitechapel and Paddington.

The data is in two equivalent formats, an Excel spreadsheet and a Microsoft Access database. Both formats were provided to make it easier to use, and both formats can be read in from various languages (e.g., Python, R, C#) and environments (Windows and Linux). A formal data dictionary is in the Excel spreadsheet.

3 Infrastructure/timetable model

3.1 General assumptions

Due to the nature of the considered case study, we can adopt the following simplifications:

- One type of rolling stock only (345 class EMUs) is used for the all considered services and for the empty moves to/from depots. Split-and-join operations (more than one EMUs operating the same train) are not considered.
- The whole considered network is double-track. Certain stations may have more than two tracks. Part of the problem should consider maintenance-of-way considerations when a section of double track is reduced to a single track for a limited time.

3.2 Infrastructure model

We adopt a macroscopic model for infrastructure and operations, based on a graph $G = (V, E)$.

Nodes are the macroscopic timing locations (stations, junctions, halts and control points) in the rail network.

The nodes are found in the NODE table. Table 1 is a relevant small example.

Table 1. Example of the NODE table.

NAME	CODE	NODE CATEGORY	EB_TRACKS	WB_TRACKS	LATITUDE	LONGITUDE	ST_EB	ST_WB
BOND STREET	BONDST	STATION	2	1	51.514299	-0.149002		
FISHER ST EAST	FRNDFST	CONTROL_POINT	2	1	51.520161	-0.104616		
FARRINGDON CROSSRAIL	FRNDXR	STATION	2	1	51.520280	-0.098256		
LONDON LIVERPOOL STREET	LIVST	STATION	17	17	51.518166	-0.081768		3
LIVERPOOL ST CROSSRAIL	LIVSTLL	STATION	1	2	51.517409	-0.082537		
PADDINGTON CROSSRAIL	PADTLL	STATION	1	2	51.519868	-0.177073		
LONDON PADDINGTON	PADTON	STATION	11,12	11,12	51.517702	-0.178155	3	
FISHER ST WEST	TOTCFST	CONTROL_POINT	2	1	51.520780	-0.107688		
TOTTENHAM COURT ROAD	TOTCTRD	STATION	2	1	51.516269	-0.130838		
WHITECHAPEL CROSSRAIL	WCHAPXR	STATION	2	1	51.519470	-0.057691		
VALENCE ROAD	WCHAVRD	CONTROL_POINT	2	1	51.518384	-0.062900		

The CODE field will be used throughout the remainder of the data and will be called NODE in other tables. As a side note, this field is internally called TIPLOC.

The node category field was supplied as information. A STATION is node where a train can pickup/drop off passengers. One use of this field is to help the user creates network graphs that display nodes with different formats depending on the node category.

Figure 2. Georeferenced example of the Elizabeth line network in central London.

The name, latitude and longitude are useful for locating the nodes on a map. Figure 2 provides a relevant example located in central London.
For each node we define:

- A set of tracks for each direction. Each track is identified by a comma separated alphanumeric string, unique within each station;
- A minimum separation time between the end of the occupation of a track by a train and the beginning of the occupation of the same track by the following one tg_ℓ, providing that each track can be used by at most one train at a time.

Finally, the columns "ST_EB" and "ST_WB" contains information relevant to short-turning. These columns apply to EB and WB trains respectively. For each row (node) of the table, these columns can contain the following values:

- Empty: the node cannot be used for short-turning trains;
- 1: The node can be used for short-turning trains, using the station tracks defined for the relevant direction;
- 2: The node can be used for short-turning trains, using the station tracks defined for the opposite direction;
- 3: The node can be used for short-turning trains, using all the station tracks defined both the directions.
- SA: Short turning with Satellite Area. See below for description.

These values depend on the microscopic track configuration of each node, which is not included in the problem dataset. For the sake of clarity, we add here a couple of relevant examples, pointing out that on UK double track lines trains run on the left-hand track.

Table 2. Example of two short-turning locations from the NODE table.

NAME	CODE	NODE_CATEGORY	EB_TRACKS	WB_TRACKS	LATITUDE	LONGITUDE	ST_EB	ST_WB
CUSTOM HOUSE	CUSTMHS	STATION	A	B	51.5096458	0.025834262	3	1

FOREST GATE	FRSTGT	STATION	1	2	51.54930472	0.025673584	2	

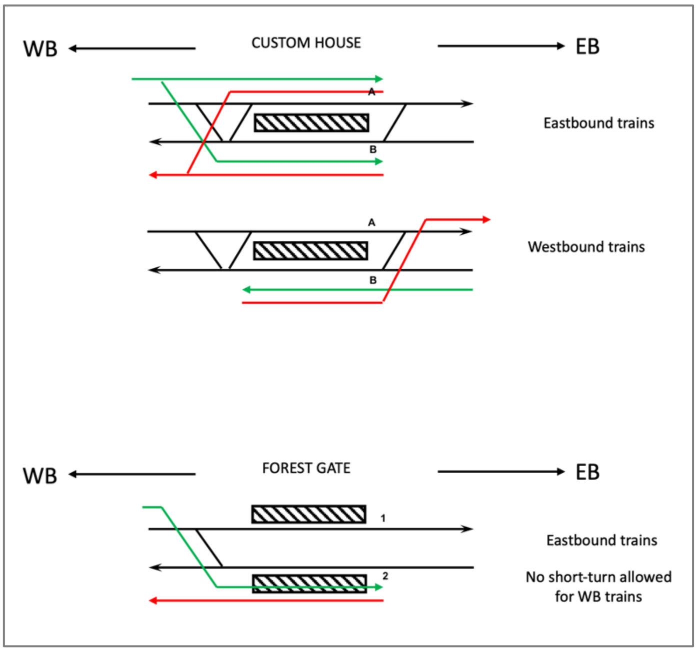


Figure 3. Short-turning examples at Custom House and Forest Gate stations. Green and red lines represent arriving and departing movements respectively.

At Custom House station, thanks to the double cross-over on the WB side, trains running in the EB direction can utilise both tracks to reverse. The ST_EB column value is therefore 3. Differently, trains running in the WB direction, can utilise just track B to this purpose.
At Forest Gate station, short-turning is allowed for EB trains only. They must use track 2 to do this.

Finally, in two cases the short-turning operations must involve more than one network node. This applies at Gidea Park and Chadwell Heath. In these locations, short-turning may take place using sidings or spurs tracks belonging to different nodes (called Satellite Areas), according to the microscopic infrastructure displayed in the following figure.

In particular, EB trains can reverse at Gidea Park using not only the relevant station track in GIDEA PARK station node, but also the track of the node GIDEA PARK MIDDLE SIDING. The relevant reversing movements are displayed in the Figure.

At Chadwell Heath, trains cannot use the tracks in the CHADWELL HEATH station node for reversing. To this purpose, they must use the track in the CHADWELL HEATH TURNBACK node.

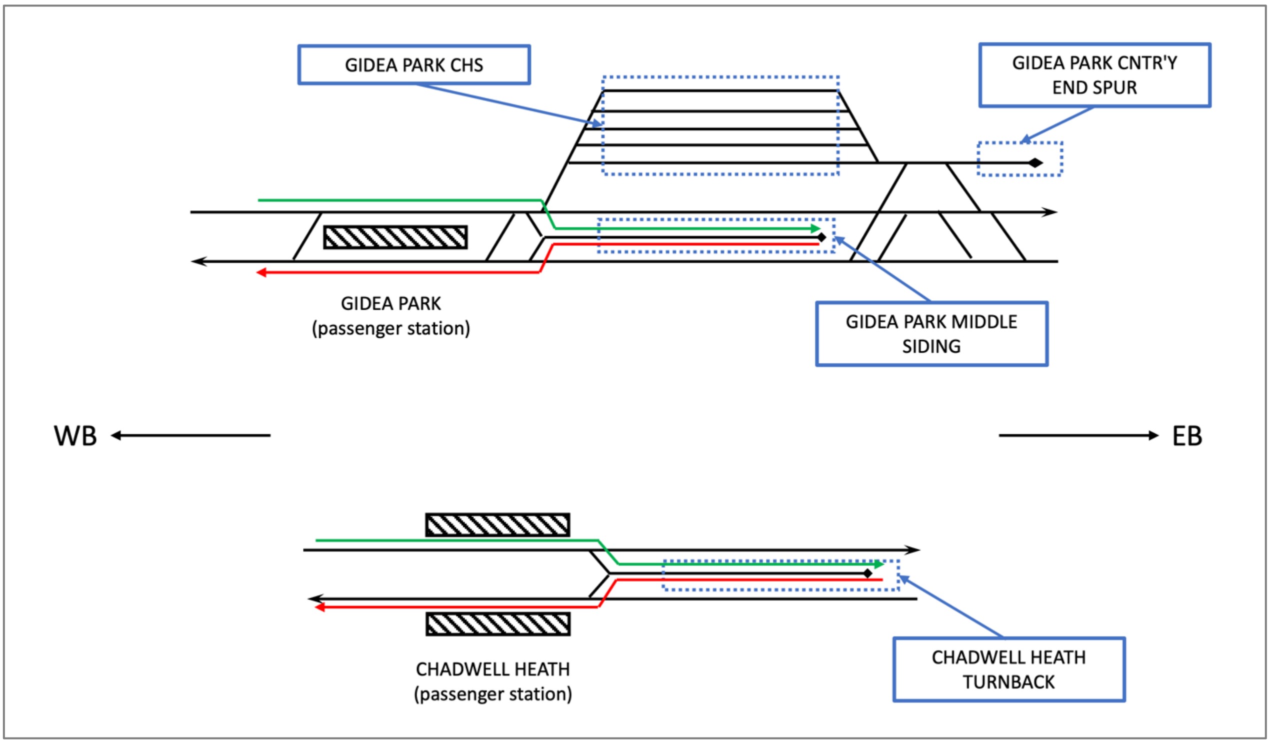


Figure 4. Short-turning movements at Gidea Park and Chadwell Heath. Green arrows represent arriving movements, red arrows represent departing movements.

Edges connect adjacent nodes and are in the LINK table. A relevant example is provided by Table 3.

Table 3. LINK table example.

START_NODE	END_NODE	DIRECTION	DISTANCE_METERS
BONDST	PADTLL	WB	250
BONDST	TOTCTRD	EB	1034
FRNDFST	FRNDXR	EB	1064
FRNDFST	TOTCFST	WB	81
FRNDXR	FRNDFST	WB	1064
FRNDXR	LIVSTLL	EB	1166
LIVST	WHELSTJ	EB	250
LIVSTLL	FRNDXR	WB	1166
LIVSTLL	WCHAVRD	EB	1675
PADTLL	BONDST	EB	250
PADTLL	ROJAOJN	WB	250
PADTON	ROYAOJN	WB	250
TOTCFST	FRNDFST	EB	81
TOTCFST	TOTCTRD	WB	1112
TOTCTRD	BONDST	WB	1034
TOTCTRD	TOTCFST	EB	1112
WCHAPXR	WCHAVRD	WB	341
WCHAVRD	LIVSTLL	WB	1675
WCHAVRD	WCHAPXR	EB	341

Notice that for every adjacent pair of nodes, there are two edges. For example, BONDST and PADTLL are adjacent. There is a BONDST to BONDST link in the westbound direction and a BONDST to BONDST link in the eastbound direction. In both directions, the distance (in meters) is the same.

A few edges are denoted as having direction BOTH. These are for edges that have a degree-1 end and that trains could leave from that end to other parts of the network in either direction.
A train can cross each extremity node with two different activities, i.e. passing or stopping. The running time on an edge depends on the activities at the corresponding nodes, i.e. pass/pass, pass/stop, stop/pass, stop/stop. It is assumed that a train can stop only on nodes, i.e. stops within edges are neglected.

On an edge we have a technical minimum run time depending on the direction it is travelling (which is implicit in the LINK_START_NODE/LINK_END_NODE and on the pair of activities in the extremity nodes. Table 4 provides an example from the MINIMUM_RUN_TIME table. In this example, it appears that each stop increases the run time by 15 seconds, although that is not a firm rule everywhere in the network so this table must be used.

Table 4. MINIMUM_RUN_TIME table example.

LINK_START_NODE	LINK_END_NODE	START_ACTIVITY	END_ACTIVITY	MINIMUM RUN TIME SECONDS
TOTCFST	FRNDFST	PASS	PASS	4
TOTCFST	FRNDFST	PASS	STOP	19
TOTCFST	FRNDFST	STOP	STOP	34
TOTCFST	FRNDFST	STOP	PASS	19
FRNDFST	TOTCFST	PASS	PASS	6
FRNDFST	TOTCFST	PASS	STOP	21
FRNDFST	TOTCFST	STOP	STOP	36
FRNDFST	TOTCFST	STOP	PASS	21
PADTLL	BONDST	PASS	PASS	150
PADTLL	BONDST	PASS	STOP	165
PADTLL	BONDST	STOP	STOP	180
PADTLL	BONDST	STOP	PASS	165
BONDST	PADTLL	PASS	PASS	150
BONDST	PADTLL	PASS	STOP	165
BONDST	PADTLL	STOP	STOP	180
BONDST	PADTLL	STOP	PASS	165

There is also a minimum head-to-head headway between the entrance time of a pair of consecutive trains running in the same direction. It depends on the activities pair of each train in the end nodes of the edge. Table 5 provides a relevant example. Examining the eighth line below, if a train goes through PADTLL but does not stop, and then stops at ROJAOJN, then moves on, and the train behind it going also in the same direction stops at PADTLL and then stops at ROJAOJN, then there has to be at least 90 seconds between when the first train leaves PADTLL and the train behind it enters PADTLL.

Table 5: Example of MINIMUM_HEADWAY table.

LINK_START_NODE	LINK_END_NODE	START ACTIVITY TRAIN FRONT	END ACTIVITY TRAIN FRONT	START ACTIVITY TRAIN BEHIND	END ACTIVITY TRAIN BEHIND	MINIMUM HEADWAY SECONDS
PADTLL	ROJAOJN	PASS	PASS	PASS	PASS	90
PADTLL	ROJAOJN	PASS	PASS	PASS	STOP	90
PADTLL	ROJAOJN	PASS	PASS	STOP	PASS	90
PADTLL	ROJAOJN	PASS	PASS	STOP	STOP	90
PADTLL	ROJAOJN	PASS	STOP	PASS	PASS	90
PADTLL	ROJAOJN	PASS	STOP	PASS	STOP	90
PADTLL	ROJAOJN	PASS	STOP	STOP	PASS	90
PADTLL	**ROJAOJN**	**PASS**	**STOP**	**STOP**	**STOP**	**105**
PADTLL	ROJAOJN	STOP	PASS	PASS	PASS	90
PADTLL	ROJAOJN	STOP	PASS	PASS	STOP	90
PADTLL	ROJAOJN	STOP	PASS	STOP	PASS	90
PADTLL	ROJAOJN	STOP	PASS	STOP	STOP	90
PADTLL	ROJAOJN	STOP	STOP	PASS	PASS	105
PADTLL	ROJAOJN	STOP	STOP	PASS	STOP	105
PADTLL	ROJAOJN	STOP	STOP	STOP	PASS	105
PADTLL	ROJAOJN	STOP	STOP	STOP	STOP	105

3.3 Timetable and Rolling Stock Duties

Each course (i.e. a train scheduled in the planned timetable) is characterized by:

- A unique COURSE_ID;
- A nominal direction within the network, being it "Eastbound" (EB) or "Westbound" (WB);
- A category, either "OO" (passenger service) or "EE" (empty/non-revenue ride).

Table 6 provides an example from the TRAIN_HEADER table. Note that the start/end of the seconds/nodes are derived from the timetable described below.

Table 6. Example of the TRAIN_HEADER table.

TRAIN COURSE_ID	DIRECTION	CATEGORY	START SECONDS	END SECONDS	START NODE	END NODE
2C15RT#1	WB	OO	21120	22980	GIDEAPK	LIVST
2N02RW#1	WB	OO	83580	86100	PADTON	MDNHEAD
2R01RT#1	WB	OO	25200	28440	PADTON	RDNGSTN
2T01RT#1	WB	OO	18720	20400	PADTON	HTRWTM5
2W01RW#1	WB	OO	84360	86880	SHENFLD	LIVST
2W02RW#1	EB	OO	87540	90000	LIVST	SHENFLD
9U79RX#1	EB	OO	73440	74220	PADTLL	WCHAPXR

The actual train schedule – also called a 'course' – shows the nodes the train passes through and the arrival and departure times. This is found in the table SCHEDULE. Table 7 reports an example for one train that starts in PADTLL and ends at SHENFLD, travelling along some of the nodes displayed in Figure 2 (not all the nodes are displayed in the example table).

Table 7. Example of the SCHEDULE table.

TRAIN COURSE ID	SEQ	NODE	ARRIVAL SECONDS	ARRIVAL HHMMSS	DEPARTURE SECONDS	DEPARTURE HHMMSS	TRACK	ACTIVITY

9W54RN#1	1	PADTLL			60780	16:53:00	1	STOP
9W54RN#1	2	BONDST	60930	16:55:30	60960	16:56:00	2	STOP
9W54RN#1	3	TOTCTRD	61020	16:57:00	61080	16:58:00	2	STOP
9W54RN#1	4	TOTCFST	61153	16:59:13	61153	16:59:13	2	PASS
9W54RN#1	5	FRNDFST	61159	16:59:19	61159	16:59:19	2	PASS
9W54RN#1	6	FRNDXR	61230	17:00:30	61290	17:01:30	2	STOP
9W54RN#1	7	LIVSTLL	61380	17:03:00	61440	17:04:00	1	STOP
9W54RN#1	8	WCHAVRD	61539	17:05:39	61539	17:05:39	2	PASS
9W54RN#1	9	WCHAPXR	61560	17:06:00	61590	17:06:30	2	STOP
…								
9W54RN#1	29	SHENLEJ	63977	17:46:17	63977	17:46:17	1	PASS
9W54RN#1	30	SHENFLD	64020	17:47:00			5	STOP

Note this is an ordered table that shows the route of the train and gives the arrival time and departure time for each node within the route. The first node has an empty arrival time and the last node has an empty departure time.

The locations that are passed through would have arrival time = departure time. The stations that the train stops at will have a positive dwell time.

The track refers to the track at the node that the normal schedule will use. Given the direction of the train, this almost always one of the tracks listed in the NODE table. Occasionally, this track is not listed in the column of the NODE table for the train direction. Typically, this is for short empty trains that use the tracks in the opposite direction.

Note times are given two ways. One is the number of seconds from midnight. There are 86400 seconds in a day, and occasionally the train activity is early in the next day and the time will be greater than 86400. There is also a string format of the time. For those times when it goes to the next day, there is a prefix of "1d" added to the time.

The last table shows the intended set of duties for a single train set (also called rolling stock) and is called ROLLING_STOCK_DUTY.

This table shows how the train set is cycled through the network, from the first use of the train set that day to the last use. Note that every moment between the first use and last use is accounted for. Each row of the table is some type of event. There are 4 types of events:

- TRAIN: the rolling stock is operating a course (either a OO/passenger train schedule or an EE/empty train schedule),
- CHANGE_END: minimum technical time required by terminal operations. It can typically span between 60 s (without cabin turn-over) and 420 s (with cabin turn-over),
- SPARE: "free" time (can be reduced down to 0 if needed).
- RESERVE, which indicates the rolling stock is sitting idle and can be placed into use to support a timetable amendment.
    - This 'hot-reserve' duties can be used to manage duties disruptions. The START_NODE indicates the depot at which the reserve is homed.

Note that the TRAIN events feature a START_NODE different from the END_NODE, since they represent a movement of the rolling stock. The other events will always have START_NODE and

END_NODE being the same. However, in every case END_TIME_SECONDS > START_TIME_SECONDS.

Table 8 reports an example of a complete duty.

Table 8. Example from the ROLLING_STOCK_DUTY table.

DUTY_ID	SEQ	START TIME SECONDS	START TIME HHMMSS	END TIME SECONDS	END TIME HHMMSS	START NODE	END NODE	EVENT TYPE	TRAIN COURSE_ID
RSDuty_29	1	70920	19:42:00	71580	19:53:00	OLDOXRS	PADTLL	TRAIN	5U75RX#1.A1
RSDuty_29	2	71580	19:53:00	71640	19:54:00	PADTLL	PADTLL	CHANGE_END	
RSDuty_29	3	71640	19:54:00	73380	20:23:00	PADTLL	ABWDXR	TRAIN	9U75RX#1.A1
RSDuty_29	4	73380	20:23:00	73800	20:30:00	ABWDXR	ABWDXR	CHANGE_END	
RSDuty_29	5	73800	20:30:00	77760	21:36:00	ABWDXR	HTRWTM5	TRAIN	9T54RV#1.A1
RSDuty_29	6	77760	21:36:00	78180	21:43:00	HTRWTM5	HTRWTM5	CHANGE_END	
RSDuty_29	7	78180	21:43:00	78720	21:52:00	HTRWTM5	HTRWTM5	SPARE	
RSDuty_29	8	78720	21:52:00	82680	22:58:00	HTRWTM5	ABWDXR	TRAIN	9U79RV#1.A1
RSDuty_29	9	82680	22:58:00	83100	23:05:00	ABWDXR	ABWDXR	CHANGE_END	
RSDuty_29	10	83100	23:05:00	83580	23:13:00	ABWDXR	ABWDXR	SPARE	
RSDuty_29	11	83580	23:13:00	87720	1d 00:22:00	ABWDXR	MDNHEAD	TRAIN	9N92RV#1.A1
RSDuty_29	12	87720	1d 00:22:00	87840	1d 00:24:00	MDNHEAD	MDNHEAD	CHANGE_END	
RSDuty_29	13	87840	1d 00:24:00	87960	1d 00:26:00	MDNHEAD	MDNHDCS	TRAIN	5N92RV#1.A1

For your convenience, we added a computed table ALL_DUTY_START_END. This table summarizes the ROLLING_STOCK_DUTY to have one line by DUTY_ID to show the starting node, ending node of the set of duties corresponding to a single DUTY_ID. It also shows when the starting and ending time in seconds from midnight.

When you study this table, it is apparent that node-balance is not met. For example, there are four more DUTY_IDs that end in MDNHEAD by the end of the day than start there in the morning. Likewise, there are five more DUTY_ID's that start at RDNGSTN than end them. Sometime between 0100 and 0400, crews will 'ferry' these train sets to locations that need them. Most likely, the 4 extra train sets that end up at MDNHEAD will be ferried to RDNGSTN.
In the below sample of ALL_DUTY_START_END, we have proposed ferry's to bring all the train sets into balance.

Note: you should not worry about imbalances at the end of the night – it is always possible to ferry the train sets to be in the proper position the next day.

Table 9. Example from the ALL_DUTY_START_END table.

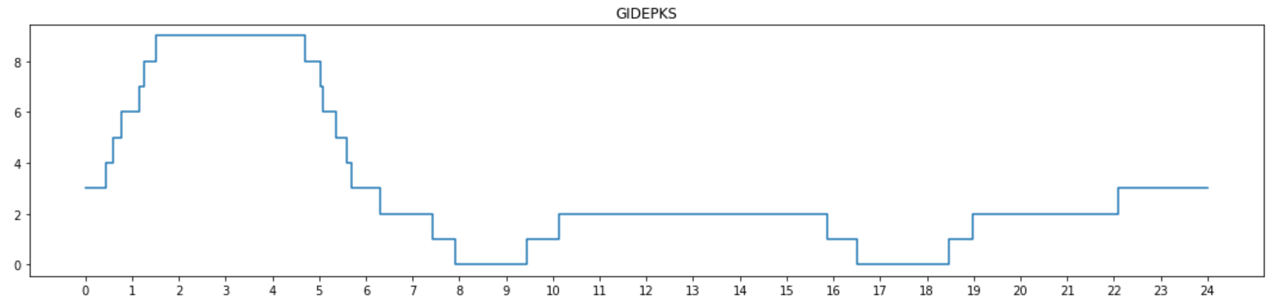
DUTY_ID	START_TIME_SECONDS	START_NODE	END_TIME_SECONDS	END_NODE
FERRY_1	7200	MDNHDCS	7245	MDNHDRS
FERRY_2	7620	MDNHEAD	7838	RDNGSTN
FERRY_3	8040	MDNHEAD	8258	RDNGSTN
FERRY_4	8460	MDNHEAD	8678	RDNGSTN
FERRY_5	8880	MDNHEAD	9098	RDNGSTN
FERRY_6	9300	HTRWTM4	11009	OLDOXRS
FERRY_7	9720	HTRWTM4	12014	RDNGSTN
FERRY_8	10140	SHENFLD	10163	SHENFMS

FERRY_9	10560	PLMSXCR	12331	WBRNPKS
RSDuty_1	26700	GIDEPKS	33060	GIDEPKS
RSDuty_10	46620	OLDOXRS	87900	SHENFLD
RSDuty_11	21000	ILFEMUD	80340	OLDOXRS
RSDuty_12	58200	RDNGSTN	82260	MDNHDCS
RSDuty_13	19320	MDNHDCS	81240	OLDOXRS
RSDuty_14	15660	OLDOXRS	72660	MDNHEAD

3.3.1 Rolling Stock Connections

Throughout the day at several nodes the rolling stock terminates its set of duties, and is stored within that node.

Below is a graph showing how many train sets are being stored at Gidea Park (GIDEPKS). We see from around 0200 to 0445 there are 9 train sets. At about 0615, there are 3 train sets. One of them pulls out to go onto a duty. We are not worried about which one of the three train sets is used. We will impose a 7 minute (420 second) minimum connection time between these train sets. As soon as one completes its set of duties at a node, it must wait at least 7 minutes before being used for another DUTY_ID.



3.3.2 Rolling Stock Duty Feasibility Requirements

When constructing timetable amendments, sometimes it would cause disruptions in the planned duties, which must be properly managed. Possible changes to the duties include:

1. Swap some components of two duties, to draw a reserve unit from a depot (if any reserve is available) or to send a unit to a depot. In any case, each time a new CHANGE_END component has to be scheduled in an amended duty, a default time of 420 s must be used.
2. In case of drawing/sending a unit from/to a depot, a new empty ride will be scheduled. The set of available depots is composed by all the locations in which planned duties originate or end. Capacity of depots is neglected, i.e. there is no limit to the number of units that can reside in same depot at the same time.

4 Problem instances

A problem instance is characterized by:

- The realized schedule until time *t*, possibly with some trains running late with regard to the planned schedule;
- A set of "known future incidents" occurring after time *t*. These incidents are causes of potentially serious delays which are already expected to occur at the time at which amendments are planned.

Problem instances are provided by means of Excel files. Different worksheets provide information about the realized timetable and the future incidents.

The worksheet REALIZED_SCHEDULE describes all the timetable events occurred before time *t*, in terms of actual arrival/departure times up to the last crossed node. Its structure is similar to that of table SCHEDULE in the input dataset, with the difference that only trains departing before or at time *t* will appear. Fields referring to events still not realized are left blank.

Table 10 provides an example for train 9W54RN#1, taken at time 17:05:00. At this time the train is still running between LIVSTLL and WCHAVRD, so the last recorded event is the departure from LIVSTLL at 17:04:00. In the example, train 9W54RN#1 is basically running on time, yet some minor deviations from the planned timetable are present.

The actual track column is not always populated if there is only one real choice for the track. For example, the last known position of the train is at LIVSTLL. This is an eastbound train, and there is only one choice of track (track 1) at LIVSTLL going eastbound, and in that case it is left blank.

Knowledge of the track maybe helpful for those trains that have not yet left the station.

Table 10. Example of the REALIZED_SCHEDULE table.

TRAIN COURSE_ID	SEQ	NODE	REAL. ARRIVAL SECONDS	REAL. ARRIVAL HHMMSS	REAL. DEPARTURE SECONDS	REAL. DEPARTURE HHMMSS	ACTUAL TRACK
9W54RN#1	1	PADTLL			60781	16:53:01	1
9W54RN#1	2	BONDST	60918	16:55:18	60968	16:56:08	
9W54RN#1	3	TOTCTRD	61056	16:57:36	61106	16:58:26	
9W54RN#1	4	TOTCFST	61158	16:59:18	61158	16:59:18	
9W54RN#1	5	FRNDFST	61161	16:59:21	61161	16:59:21	
9W54RN#1	6	FRNDXR	61236	17:00:36	61290	17:01:30	
9W54RN#1	7	LIVSTLL	61382	17:03:02	61440	17:04:00	
9W54RN#1	8	WCHAVRD					
9W54RN#1	9	WCHAPXR					
			…				
9W54RN#1.A1	30	SHENFLD					

Four types of incidents are considered. In the following, they are further described, also with the aid of examples consistent with an “amendment time” set at 17:05:00.

NOTE: In the actual database times will be given both as a number of seconds from midnight, as well as a string in the format HH:MM:SS or possibly 1d HH:MM:SS for those times past midnight.

4.1 Extended run times on an edge

This incident imposes that on edge (direction given by the start/end node) within a given time band, all trains (independently from their rolling stock) must travel with an extended running time significantly greater than the planned one.
Example: Because of planned works alongside the tracks between 17:10:00 and 18:10:00, trains will take 4 minutes to travel from TOTCTRD to BONDST, instead of the planned 1.5 minutes.
Relevant data:

- Start/end nodes;
- Start and end times;
- Extended run time

Sample table (EXTENDED_RUN_TIMES worksheet):

START NODE	END NODE	START TIME SECONDS	START TIME HHMMSS	END TIME SECONDS	END TIME HHMMSS	EXTENDED RUN TIME (s)
TOTCTRD	BONDST	61800	17:10:00	65400	18:10:00	240

4.2 Late departure from depot

This incident imposes that a course planned to leave from its initial node actually departs with a delay.

NOTE: the time when the course departs from its first node should be after the amendment time.

Example: Course *5U67RN#1* is planned to depart from OLDOXRS (Old Oak Depot) at 17:14:00. At the amendment time 17:05:00 the driver assigned to this course communicates to the dispatching center that he is late and will arrive at the depot not before 17:10:00. Then the dispatcher forecasts that course *5U67RN#1* will depart at 17:25:00, with a delay of 11 minutes.

Relevant data:

- Course id;
- Departure delay in seconds

Sample table (LATE_DEPARTURES worksheet):

COURSE_ID	DEPARTURE DELAY (s)
5U67RN#1	660

4.3 Extended dwell time for all trains stopping at a station

This incident imposes that all courses stopping at station within a time band will be subject to a dwell time significantly greater than the planned one.

Example: Due to a sport event, it is expected that all trains calling at BONDST between 18:00:00 and 18:20:00 will stop 2 minutes instead of the planned stop time.

Relevant data:

- Node;
- Start and end times;
- Extended dwell time;

Sample table (STATION_EXT_DWELL worksheet):

NODE	START TIME SECONDS	START TIME HHMMSS	END TIME SECONDS	END TIME HHMMSS	EXT DWELL TIME (s)
BONDST	64800	18:00:00	66000	18:20:00	120

4.4 Extended dwell time for a train at a station

This incident imposes that a course at a node will be subject to a dwell time significantly greater than the planned one.

Example: Course *9T58RN#1* is running on time, and is planned to arrive at LIVSTLL at 17:05:30 and stop there 1 minute. At 17:05:00, while approaching the stop, the driver communicates to the dispatching center that an ill passenger is onboard. It is then forecasted that the course will stop at the next station LIVSTLL for 6 minutes to assist the ill passenger.

Relevant data:

- Course id;
- Node;
- Extended dwell time in seconds

Sample table (TRAIN_EXT_DWELL worksheet):

COURSE ID	NODE	EXT DWELL TIME (s)
9T58RN#1	LIVSTLL	360

5 Timetable amendments

A timetable amendment is an active modification of the planned timetable. We consider the following types of basic amendments:

- **Re-timing** of courses in station *st*: planned arrival/departure (stop) times are modified within given ranges;
- **Re-platforming** of courses in station *st*: planned station track is modified, considering the set of available tracks for that course in that station specified in input data;
- **Skipped stop** in station *st*: a train passes through *st* instead of stopping as in the planned timetable;
- **Partial cancellations** in station *st*: a course is “cut” at an intermediate location.
- **Total cancellations:** a course is not operated at all.

Some timetable amendments imply the disruption of one or more rolling stock duties, which must be amended too. For instance, a train running late may miss a connection with the following course in the relevant rolling stock duties. Normally, it is desired that the following course departs on time, in order to avoid propagation of delay. Cancellations (partial or total) would in most cases produce a rolling stock duty disruption as well, which can be managed, for instance, by calling a reserve unit from a depot. In general, the following actions can be performed to amend disrupted rolling stock duties:

- **Send** a unit to a depot;
- **Draw** a unit from a depot;
- Schedule **empty rides** between different stations;
- In case of partial cancellation, **short-turning** a pair of courses: the unit of the “cut” course waits on a station tracks and “catch” the path of the following connected course in the duty. This implies a partial cancellation of the connected course as well (see Figure 5);

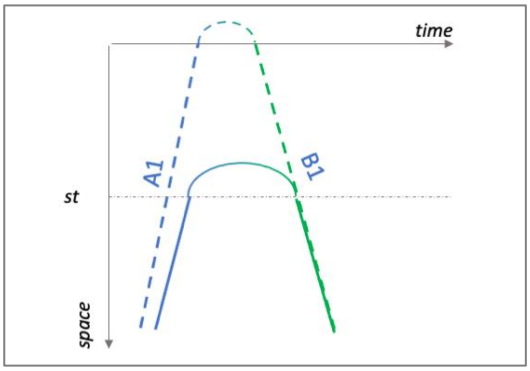


Figure 5. Short-turning at station st, resulting in partial cancellations of courses A1 and B1.

- **Adjust rolling stock circulation** at station *st*: some rolling stock duties are modified in order to avoid propagation of delays, at the price of cancelling a course. Figure 6 provides a graphical example, where planned paths are depicted by a dashed line while actual ones by a solid line. Courses A1, A2 and A3 arrive at a terminal station with certain amount of delay. In order to prevent delay propagation from the perturbed course A1 to the connected courses B1, B1 is cancelled and the rolling stock of A1 will operate course B2, which will depart on-time. Subsequently, material of course A2 will operate course B3, and finally the rolling stock of course A3 is sent to depot as a newly-created empty ride EE1 since course A4 is running on-time and there is no longer need to shift the duties. The figure also highlights the need for more than one available station track to operate this amendment. Courses can use the station tracks provided as input data.

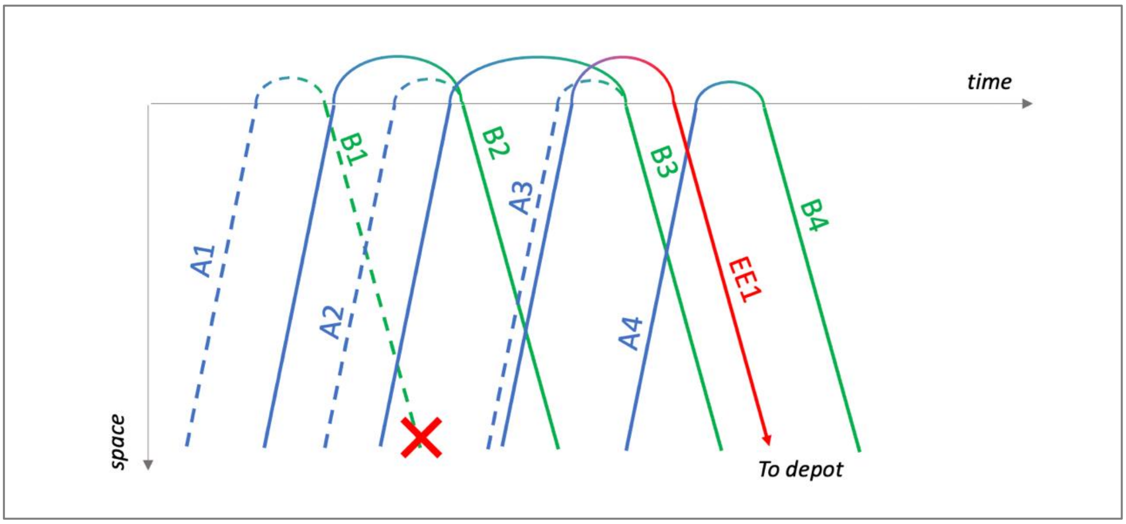


Figure 6. Graphical example of a rolling stock re-circulation at terminal.

6 Penalty computation

6.1 Skipped stops

For each course of category OO, each planned stop which is skipped in the amended timetable will involve an economic penalty, depending on the station and on the time.
Total and partial cancellations are evaluated considering the resulting set of skipped planned stops. For instance, the total cancellation of a course result in a set of skipped stops equal to the set of the planned stops for that course.
In general, let SS_c be the set of skipped stops for course c. The resulting penalty for course c called $P_{ss,c}$ is calculated as

$$P_{ss,c} = \sum_{ss \in SS_c} bsv(ss) \cdot ssf(ss)$$

$bsv(ss)$ is the Base Station Value in £ and depends on:

- The nominal direction of the course c;
- The station at which the skipped stop takes place;
- The planned arrival time for course c and the concerned station.

Base Station Values are defined by two tables (one for each nominal direction, provided in the Attachments), of which Table 11 provides a relevant example.

Table 11. Example of a Base Station Values table.

Westbound (WB)	Timebands											
Station	Start to 06.05	06.06-06.59	07.00-07.44	07.45-09.14	09.15-09.59	10.00-15.59	16.00-16.44	16.45-18.14	18.15-18.59	19.00-20.59	21.00-23.59	24.00-End
SHENFLD	96	72	120	144	120	72	90	108	90	72	72	96
BRTWOOD	128	96	160	192	160	96	120	144	120	96	96	128
HRLDWOD	96	72	120	144	120	72	90	108	90	72	72	96
GIDEAPK	96	72	120	144	120	72	90	108	90	72	72	96
…	…											

$ssf(ss)$ is the Station Stop Factor, and it is computed as follows.

- Let $\widehat{SS_c}$ the list of skipped stops $ss \in SS_c$, sorted in ascending Base Station Value order.
- The Station Stop Factor of the first element of $\widehat{SS_c}$ is 35;
- The Station Stop Factor of the second element of $\widehat{SS_c}$ (if present) is 15;
- Starting from the third element of $\widehat{SS_c}$ (if present) and for all the remaining skipped stops, the Station Stop Factor is 1.

The total penalty for skipped stops is computed as

$$P_{ss} = \sum_{c \in O} P_{ss,c}$$

O being the set of courses with category OO

A relevant example is added for clarity. Course c will skip the planned stops at SHENFLD (schedule arrival 06.57), BRTWOOD (schedule arrival 07.03) and HRLDWOD (schedule arrival 07.08). The BSVs are 72 £, 160 £, 120 £ respectively. Sorting them in ascending order, the locations are SHENFLD (BSV 18 £), HRLDWOD (BSV 30 £), BRTWOOD (BSV 40 £). So the station stop factor of SHENFLD is 35, of BRTWOOD is 1, and of HRLDWOD is 15. The resulting penalty for course c is

$$P_{ss,c} = 72 \cdot 35 + 160 \cdot 1 + 120 \cdot 15 = 4480\ £$$

6.2 Destination delays

For each course c of category OO, an arrival delay at the last station of its actual journey (also called *destination delay*, dd_c), considering possible partial cancellations, will involve an economic penalty, computed as follows:

- $P_{dd,c} = 0$, if $dd_c < 3\ min$;
- $P_{dd,c} = dd_c \cdot 125\ £/\text{min}$, if $dd_c \geq 3\ min$

The total penalty for destination delays is computed as

$P_{dd} = \sum_{c \in O} P_{dd,c}$, O being the set of courses with category OO

6.3 Passage frequency of revenue services on the central section

Passage frequency penalties are applied when the trains' passage frequency in the central section of the network is lower than a given threshold, thus resulting in a loss of service quality from the passengers' perspective

Passage frequency is evaluated by the actual headway (not to be confused with the minimum headways, which are a hard constraint to the problem) between pairs of consecutive arrivals of revenue services measured at a reference station.
Reference stations are:

- PADTLL for Westbound courses;
- WCHAPXR for Eastbound courses.

For each nominal direction d let P_d be the set of pairs $p = \{a_1, a_2\}$ of consecutive arrivals, and for each pair p, let $h = a_2 - a_1$ be the headway.
The headway penalty $P_{head,p}$ for pair p is evaluated as follows:

- $P_{head,p} = 0$ if $h \leq h_t(p)$;
- $P_{head,p} = \left(h - h_t(p)\right) \cdot 150£/min$ if $h > h_t(p)$

$h_t(p)$ is the threshold headway for pair p, and depends on the planned arrival times a_1 and a_2, defined by Table 12 for both Westbound and Eastbound services. If a_1 and a_2 belongs to two different timebands, the highest threshold headway must be considered.

Table 12. Threshold headways.

Timeband		Threshold Headway (s)
from	to	
02:00:00	06:15:00	420
06:15:00	07:45:00	252
07:45:00	09:15:00	210
09:15:00	16:45:00	252
16:45:00	18:15:00	210
18:15:00	23:00:00	252
23:00:00	23:59:00	420
23:59:00	26:00:00	630

The total headway penalty is computed as

$$P_{head} = \sum_{d \in \{WB,EB\}} \sum_{p \in P_d} P_{head,p}$$

6.4 Total penalty

The total penalty, expressed in £, combines penalties for skipped stops, destination delays and total headway, and is calculated as

$$P = P_{ss} + P_{dd} + P_{head}$$

7 Competition's objective

The problem consists in defining a method to choose a set of timetable amendments which minimizes the total resulting penalty, while satisfying all operational constraints. Rolling stock duties may have to be amended as well, in order to ensure a feasible rolling stock circulation.

A set of "training" problem instances will be provided together with the input datasets. Participants may use these instances to design, develop and validate their solution approaches. At a later stage, the "evaluation" problem instances will be provided which will serve for testing and evaluating the proposed approaches (will be published later).

The teams are required to deliver:

- An 8-10 page report, in the form of a brief scientific paper, providing a formal description of the designed method and a presentation of the relevant results;
- For each “evaluation” problem instance:
    - The amended timetable, in a tabular format consistent with the SCHEDULE table provided in the input dataset;
    - The amended rolling stock duties, in a tabular format consistent with the ROLLING_STOCK_DUTY table provided in the input dataset;
    - A summary of the applied amendments as a plain, human-readable text.
    - The description of the applied amendments in XML format. Specifications of the XML format to be used will be published at a later stage.

“Evaluation” problem instances will be published on the RAS portal at a given day and will be similar to the “training” ones in terms of possible timetable disruptions.

The evaluation process will first consider the written deliverable. Secondly, the proposed amended timetables and rolling stock duties will be checked for adherence to the various constraints such as:

1. Rolling-stock balance (the number of duty sets terminating at a node must equal to the number of duty sets originating at a node);
2. Rolling-stock count. Currently, we have 66 active train sets and 10 reserved train-sets. The solution cannot use more than 76 train sets.
3. Minimum run times;
4. Minimum line headways;
5. Ensuring that two trains do not occupy the same platform at the same.
6. Minimum time between the end of one ‘course’ and the beginning of the next ‘course’ for the same rolling stock.
7. Minimum time between the end of one duty set and the start of the next

For each problem instance, the set of calculated amendments will be evaluated by simulating the resulting amended timetables with the third-party microsimulation software Trenissimo (https://www.trenolab.com/tools/trenissimo/). Microsimulation provides an insight on how the proposed amendments would work in real world. In case any of the abovementioned constraints is violated, microsimulation may not run successfully. If a set of amendments can be successfully simulated, penalties will be computed on the simulated traffic.

The evaluation process will award solutions with the lowest number of constraint violations (hopefully 0!) and with the lowest resulting penalty.

Finally, an additional methodology to assess the computation times of the solutions will be developed and introduced at a later stage.