Track maintenance scheduling and its interactions with operations: Dedicated and mixed high-speed rail (HSR) scenarios

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Track Maintenance Scheduling and its Interactions with Operations: Dedicated and Mixed High-speed Rail (HSR) Scenarios

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ABSTRACT

HSRs are a complex system not only in terms of technical specifications, but also with respect to operations and maintenance over the track structure. Also, track structure is basically considered as the most important and costly railway asset. Its maintenance is vital to assure safety and operating practices are also of great importance to assure that a good level of service is provided.

Considering track maintenance considerations over a new HSR line, one important and critical feature is the operational regime and the question of whether the line will be operated as mixed (passenger and freight) or dedicated only to passenger traffic. This can influence the maintenance patterns: preventive maintenance planning, maintenances scheduling and assignment issues. This will be different for the dedicated and mixed HSR traffic scenarios. In this research, the main approach is focused on the interactions between track maintenance planning and operational concerns and influences in these two scenarios.

With this aim and within the current paper, a model of the preventive maintenance scheduling problem (PMSP) has been selected initially from Budai (2006) and then an upgraded revision of this model (Multi-segment assignment and scheduling of preventive maintenance problem) is introduced. Furthermore, the upgraded model of PMSP has been run over a given HSR line (Tehran-Qom HSR corridor in Iran) based on the comparison between the two scenarios of dedicated HSR and upgraded mixed HSR patterns. The main requirements, similarities and differences between these two scenarios are analyzed based on preventive maintenance scheduling and assignment requisites and interactions over the operating restrictions and considerations such as track possession patterns for maintenance activities. We conclude that decision making between these two scenarios through PMSP modeling are quite complicated and depends on the technical and operational specifications of the given HSR corridor, although some general comments on tradeoffs are possible.

Keywords: track maintenance strategy; preventive maintenance scheduling; high speed railway; mixed HSR traffic; track possession

1- INTRODUCTION

Nowadays high speed network is going to be grown with a fast rate over the world. Many countries in Asia, Europe, America and Africa are stimulated to start and develop their high speed network and create or extend the relevant high speed local and international connections between their lines especially in Europe.

On the other hand, track structure is basically considered as the most important and costly asset of railway which the track maintenance is generally accounted around 25-35 percent of operation costs. Therefore investigation and research on the track maintenance requirements, techniques, practices, management approaches, strategic modeling and its further consequences especially over high speed lines can be interesting and valuable subjects. By combining track maintenance concerns over a given new high speed line, one important and critical feature concerns about the operational regime and restrictions of the line whether the axis will be operated as mixed or dedicated traffic. This parameter can influence on the maintenance strategic patterns mainly over the preventive maintenance planning, maintenances scheduling and assignment issues which can be different on the dedicated or mixed HSR traffic scenarios.

Through the current paper, after review over definitions of dedicated HSR vs. mixed-HSR scenarios, some particular features of technical track maintenance issues with more focus on intervals and action frequencies are discussed. Then a model of preventive maintenance scheduling problem (PMSP) has been selected initially from Budai (2006) and subsequently a new upgraded edition of initial model is developed based on multi-

segment capabilities through scheduling and assignment problems. Eventually, the upgraded model of PMSP is run over the case study (Tehran-Qom HSR corridor) based on the 2 major scenarios of dedicated and upgraded mixed HSR patterns and at the end, the relevant outputs will be compared and analyzed furthermore.

2- DEDICATED VS. MIXED HSR SCENARIO

Basically high speed lines are more operated and used as passenger services to carry people as fast as possible and also most of the HSR lines and services over the world are dedicated to this purpose currently. But on the other hand there is another approach to operate a high speed line which can be called as mixed HSR traffic patterns. Thus the operation of HSR lines varies from a country to another one by following three main types: [15]

- **Type 1:** Exclusively high speed passenger traffic: dedicated HSR traffic
- **Type 2:** Exclusively passenger services, high speed services mixed only with conventional passenger trains with lower speeds
- **Type 3:** Mixed traffic types: high speed and conventional passenger services mixed with freight trains.

Of course the capability of HSR line to carry freight trains or conventional trains is different concept from real operation of mixed-share HSR lines; because in some cases, the HSR line had been designed to be able to carry freight or conventional trains over it but regularly only HSR trainsets have been operated through it.

Usually over the world, Japan's Shinkansen network can be classified totally in first type of HSR line (dedicated HSR traffic) with some short services as second type (mixed HSR-passenger service). On the other hand, in Europe similar to Japan, most of the current lines can be classified as the first type of HSR traffic, whereas some parts of the network mainly in Germany, Spain and Italy are operated as mixed traffic. Of course in future some new HSR lines will be operated as the third HSR type especially in Spain, Italy and Germany. [1] Currently in German Railway network (DB) there is no mixed traffic between HSR trains with 300 km/h and freight trains at the same line and all the trains speed are limited to maximum 250km/h. [17]

About track maintenance requirements by assuming mixed HSR scenario, because the rail weight per length must allow for the heavy freight traffic, whose high axle loads cause deterioration of the track; therefore it is very difficult and excessively costly to maintain track conditions which are adequate for running passenger trains safely and in comfort at high speeds. [14]

For instance in Barcelona-Perpignan mixed HSR line, it has been estimated that near 27% of track maintenance costs have been increased in comparison to the dedicated HSR conditions, mostly due to the increase of rail grinding and tamping needs. It may also be said that globally, for this particular line, the total (not only track) maintenance cost increase would be approximately 11% higher than the corresponding costs in the absence of freight traffic. [10]

The last point is related to the operation concerns of mixed HSR traffic. Since in mixed HSR scenario, different types of freight and passenger vehicles have different braking regimes and are operated at various maximum speeds; therefore the operation of mixed HSR traffic is more complicated than the dedicated HSR scenario. This might be the main reason why in mixed HSR regimes, e.g. DB, the main timetable of train dispatching is generated as nightly freight trains to separate them from daily HSR services as well as providing more capacity for both HSR and conventional trains. (Figure 1)

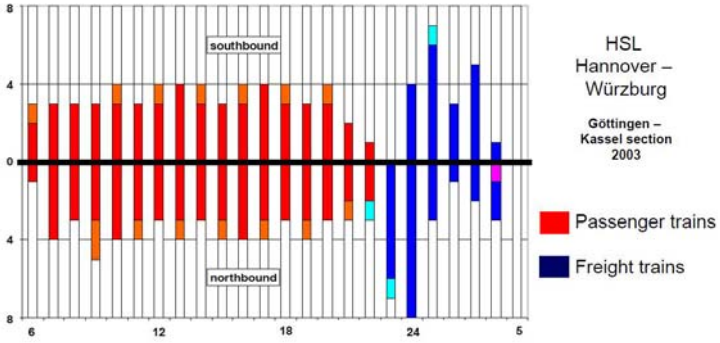

Fig. 1- Distribution of regularly scheduled trains in mixed traffic regime of Hannover-Wurzburg HSL [17]

Because of all the above reasons, operations at speeds equal or higher than 300 km/h have been restricted currently only to type1 and 2 of HSR lines and not for mixed HSR-freight lines (type3). [15]

3- MAINTENANCE-OPERATION INTERACTIONS

3-1- Bilateral Interactions

Basically maintenance activities and daily train operation (which means the running different types of the trains along the railway line during the day or even night hours) are in opposite direction of each other in terms of planning and restriction issues which may cause some further disturbances and interruption based on their relevant actions. These varied technical-operational challenges between daily operation and maintenance planning can be classified mainly as the following titles:

- Capacity and track possession

- Safety concerns
- Train scheduling interruption
- Allocation and availability

Of course in HSR lines, the maintenance-operation interactions might be more complicated based on the HSR type. For instance HSR's 3rd type can be more challengeable in terms of maintenance-operation bilateral requisites because of varied conventional and HSR trains which are operated along the line.

- ***Capacity and Track Possession Concerns***

In fact capacity shortage and track possession for maintenance activities is the main challenge between daily operational activities and maintenance concerns. In general, most of the maintenance and inspection practices need to allocate some free hours between 1 up to 6 or even 8 hours just for this purpose. This technical-operational challenge through track possession issue is grown controversially by increasing the annual traffic over the line. On one side the capacity and free slot is declined by traffic growth and on the other side the volume and maintenance application should be adapted based on the traffic loads and track degradation. It means at the same time that the capacity is decreased, the volume of maintenance and renewal activities might be increased and this challenge aggravates the planning situations for both maintenance and trains operation.

On the other hand the impact of maintenance on capacity is especially critical in shared-use HSR systems (mixed traffic lines types 2 or 3) because a key shared-use strategy is to operate freight trains at night when high speed trains are not running. Unfortunately, most track maintenance is done at night, which creates a conflict between freight movements and maintenance. [12]

- ***Safety Concerns***

This concern can be classified to three levels such as: safety provision by maintenance, safety concerns through maintenance and safety concerns after maintenance.

About first part (safety provision by maintenance) it is clear that safety is the most important aspect of railroad operations and planning. This parameter is more essential in HSR network because the faster a vehicle is traveling, the more damage will be done in an accident as well as there is less time for operators to receive and act upon train control information.

Another safety-maintenance major interaction is related to the safety problems which might be occurred through maintenance activities not only for maintenance workers and gangs but also for other trains and rolling stocks who pass through the same line or adjacent line with normal or even restricted speed. Because of this fact that during maintenance and renewal tasks, one or some failures have been occurred, the level of safety is decreased in comparison to the ordinary operation time, especially when some signaling or communication failures have been happened.

Last main feature of safety-maintenance interaction addresses further safety failures which might be occurred exactly after some maintenance practice that has not been performed functionally in right direction or might have failed some critical or noncritical tasks through the relevant application. This function-based maintenance failure usually may cause a disaster like derailment or collision with some probable injuries or fatalities.

- ***Train Scheduling Interruptions***

Although general approach of maintenance activities trends to perform relevant activities during night hours, still some of the M&R practices need to be applied within daily train's schedule. Based on this requisite, usually some serious changes might be occurred within daily trains scheduling because of upper priority by maintenance practices that imposes some interruption throughout regular train timetable.

Of course through this rescheduling, trains are classified in different categories and classes. In mixed traffic or shared-used high speed lines, the priorities between trains are more complicated and changing the schedule because of some predicted or unpredicted maintenance practices can be more challengeable. [12]

- ***Allocation and Availability Concerns***

Usually maintenance planning can be divided to two different approaches: preventative maintenance (PM) and corrective maintenance (CM). In the first class, all the maintenance and renewal practices are applied over the track based on the prescheduled maintenance plan. Thus in this case it is predictable to allocate and schedule relevant equipments and staff for the segment of track which should be maintained preventatively. In second category of M&R, the scheduling is more performed dynamically according to the daily spot failures, incidents, train accidents and other technical problems.

Thus availability of gangs and machines to be assigned for all the maintenance demand that are announced by network operator is another major challenge between maintenance planners and rail service providers. In some occasions, over-demand is requested from different spots and segments and there is not enough capacity of equipments. Therefore they have to negotiate to the rail operators and infrastructure manager to prioritize the current demand of maintenance practices.

3-2- Track's M&R Intervals and Frequencies

Generally the structure of the maintenance and renewal (M&R) actions for almost all the railway services including HSR service is not so different among each

other, which means every line needs most of the maintenance and renewal actions similar to the other tracks. But the main differences can be summarized as the quality level of treatment and supervisions based on the level of service which should be provided. Similarly M&R actions between mixed HSR and dedicated HSR scenarios are not so diverse and different, except some differences between their intervals, throughput and accessories.

As it is clear the intervals between regular preventive maintenance and inspection actions are so sensitive based on the track quality, traffic type, and level of service. Therefore in mixed HSR lines, the intervals for some preventive actions might be performed in shorter periods in comparison to the dedicated HSR lines. The shorter intervals for mixed HSR lines are derived from the fact that conventional trains usually have more negative impacts statically over the track infrastructure. Therefore the level of maintenance service over the mixed-HSR lines should be well maintained based on the more dynamic effects of high speed trains movement as well as more static effects of heavy conventional trains simultaneously. This issue is especially more important through inspection activities that some of the main differences and similarities between conventional and HSR intervals have been represented in table below.

Inspection	Inspection period (month)	
	160<V<=230 km/h	V>230 km/h
Track geometry	3	2
Dynamic behavior	6	<1
Inspection by car	3	3
Inspection by walking	3	2
Ultrasonic	4	4
Railhead profile	18	12

Table 1- Comparison between inspection's intervals [7]

Besides that the switch and crossing (S&C) equipments have usually shorter intervals of M&R actions in comparison to the plain track elements especially through HSR lines. For example in Hannover-Würzburg mixed HSL in Germany, virtually every 3 years the stabilizing and tamping application should be carried out over switches and crossing in comparison to 5 years as a interval for the main lines. Also this frequency for grinding activity over the switches is almost applied every 3 years vs. every 4 years for the main tracks in the same Hannover-Würzburg mixed HSR line. [7]

Furthermore in Netherlands rail network, the inspection of ordinary S&Cs are usually performed twice a year [4], while the inspection of HSR's S&Cs in Europe network is usually executed every 3 month which means 4 times a year [7]. Therefore it shows the high sensitivity and importance of S&C inspection in HSR networks in comparison to the conventional lines.

4- PREVENTIVE MAINTENANCE SCHEDULING MODEL

As it was mentioned before, through maintenance planning, there are 2 different approaches as corrective maintenance (CM) and preventive maintenance (PM) which the main difference between them is related to pre-scheduling and predicting capability of maintenance practices and tasks which are generally performed throughout PM. But in CM approach most of the activities are depended to the failures and defects which are happened and should be treated immediately or in short term.

On the other hand by reviewing the scientific resource and papers over track maintenance management (TMM) issue, they can be classified to two major groups. The first group concentrates mostly on track deterioration modeling defines the technical resulting work and makes some scheduling but not widespread try. The second group takes the maintenance work as input and tries to fit it in the timetable and makes a good manpower and equipment schedule. [2] Therefore second group of preventive modeling concentrates mainly on allocation, assignment and scheduling problems.

4-1- Initial Model of PMSP (Budai's model)

Following previous section, in this paper the second approach of preventive modeling namely scheduling and assignment problems is focused with more emphasizing on track possession issue through the track maintenance planning.

Among all the current and developed models and papers about track maintenance planning and scheduling, a preventive maintenance model proposed by Budai, et all [2, 3] is selected initially through this research. Then further modifications and development are suggested over it to be more efficient and useful on track preventive scheduling problem (PMSP). The following items are the main features of initial model:

- The initial model of PMSP can make a time schedule of different preventive maintenance and inspection actions in long or short term of planning,
- The main input data of this model consist of the number and set of maintenance actions, relevant intervals, average maintenance cost per actions and the operational restrictions and constraints through track possession pattern.
- Minimizing the total cost of maintenance actions in addition to the track possession cost is the object of this model.
- The track possession cost is not a real cost, but it just shows the difficulty to find free slot or capacity shortages in regard to the operational restrictions and their interactions within the preventive maintenance scheduling process.

- It has been assumed that the performance of preventive maintenance is not influenced by corrective maintenance.

4-2- Upgraded Model of PMSP (Multi-segment PMSP model)

The beauty of initial model of PMSP (Budai's model) can be summarized as the ability of considering track possession cost (or in other words operational restrictions and capacity shortages) through the preventive maintenance scheduling process. This ability is helpful to compare different operational scenarios such as mixed HSR or dedicated HSR traffic when we want to decide upon a new HSR corridor based on just preventive maintenance planning concerns.

But similar to any other model, the initial model has some shortcomings which one of them can be pointed out that it is not sensitive to the simultaneous planning of several segments. Therefore it might cause some mismatching between different segments for one maintenance action.

Based on this shortcoming, the initial model has been modified through this research in such a way that the upgraded model (multi-segment upgraded model of PMSP) is able to make a preventive maintenance plan for more than one given segment simultaneously, without any mismatching or schedule conflict between several segments. Besides that, the upgraded multi-segment modeling provides other advantages and capabilities such as:

- possibility to consider varied maintenance actions and the relevant costs through every segment independently,
- possibility to assume different maintenance intervals for every segment independently,
- possibility to consider diverse repairing projects through every segment independently,
- possibility to assume varied operational regime and track possession constraints and scenarios for every segment independently,
- possibility to consider different combination patterns between maintenance actions through every segment independently

To this aim, the relevant parameters, variables, object and constraints of promoted edition of Budai's model (Multi-segment upgraded model, developed through this research), are represented as below:

$\boldsymbol{S}$: a set of segments which are going to be planned,

$\boldsymbol{PA^s}$: a set of projects over an introduced segment $s \in S$,

$\boldsymbol{RA^s}$: a set of routine maintenance works over an introduced segment $s \in S$,

$\boldsymbol{A^s}$: $PA^s \cup RA^s$ set of all activities over an introduced segment $s \in S$,

$\boldsymbol{C^s}$: $\{(m, n) \mid$ work m is combinable with n, $\forall$ m, n ϵ $A^s\}$ set of combinable works,

$\boldsymbol{L^{as}}$: cycle length of the routine work $a \in RA^s$ over segment $s \in S$,

$\boldsymbol{G^{as}}$: number of periods elapsed since routine work $a \in RA^s$ was in the past (before the planning horizon starts) for the last time carried out over segment $s \in S$,

$\boldsymbol{LC^{as}}$: $\{t \in T | 1 + |T| - L^{as} \leq t \leq |T|\} \subseteq T$ set of time periods from the last planning cycle for routine work $a \in RA^s$ over a given segment $s \in S$,

$\boldsymbol{b_t^{as}}$: $\frac{(|T| - t)}{L^{as}}$ length of the remaining interval until the end of planning horizon over a given segment divided by the length of the planning cycle for routine work $a \in RA$ and for time period $t \in LC^{as}$,

$\boldsymbol{T_p^s \subseteq T}$: set of possible start points of project $p \in PA^s$ over a given segment,

$\boldsymbol{D_p^s}$: duration of project $p \in PA^s$ over a given segment,

$\boldsymbol{pc_t^s}$: Possession cost in period $t \in T$ over a given segment $s \in S$,

$\boldsymbol{mc_a^s}$: maintenance cost per time period for carrying out work $a \in A^s$ over a given segment,

The following binary decision variables are defined:

$\boldsymbol{x_t^{as}}$: binary variable that denotes whether activity $a \in A^s$ is assigned to period $t \in T$ over a given segment $s \in S$, $(x_t^{as} = 1)$, or not $(x_t^{as} = 0)$,

$\boldsymbol{m_t^s}$: binary variable that denotes whether the given segment $s \in S$ is used for preventive maintenance work at time $t \in T$, $(m_t^s = 1)$, or not $(m_t^s = 0)$,

$\boldsymbol{y_t^{ps}}$: binary variable that denotes whether the execution of project $p \in PA^s$ starts at time $t \in T$ over a given segment $s \in S$, $(y_t^{ps} = 1)$, or not $(y_t^{ps} = 0)$,

The object of multi-segment upgraded model of PMSP problem is:

$$\boldsymbol{Min} \sum_{s \in S} \sum_{t \in T} \boldsymbol{pc_t^s . m_t^s} + \sum_{s \in S} \sum_{a \in A^s} \sum_{t \in T} \boldsymbol{mc_a^s . x_t^{as}} + \sum_{s \in S} \sum_{a \in RA^s} \sum_{t \in LC^{as}} \boldsymbol{mc_a^s . b_t^{as} . x_t^{as}} \quad \text{(B1)}$$

Subject to:

$$\sum_{t=1}^{L^{as} - G^{as}} \boldsymbol{x_t^{as}} = \mathbf{1} \qquad \forall\, a \in RA^s, s \in S \qquad (B2)$$

$$\boldsymbol{x_t^{as}} = \boldsymbol{x_{t+q.L^{as}}^{as}} \quad \forall a \in RA^s, 1 \leq t \leq T, q \geq 1, s \in S \quad (B3)$$

$$\boldsymbol{x_t^{aq} + x_t^{ah} \leq 1} \quad \forall a \in RA^s, \forall t \in T, \{q, h \in S \mid q \neq h\} \quad (B4)$$

$$\boldsymbol{x_t^{ms} + x_t^{ns} \leq 1} \qquad \forall t \in T, s \in S, (m, n) \notin C^s \qquad (B5)$$

$$\sum_{t \in T_p^s} \boldsymbol{y_t^{ps}} = \mathbf{1} \qquad \forall p \in PA^s, s \in S \qquad (B6)$$

$$x_j^{ps} \geq y_t^{ps} \qquad \forall p \in PA^s, t \in T_p^s, s \in S, \; j = \{t, \dots, t + D_p^s - 1\} \qquad (B7)$$

$$m_t^s \geq x_t^{as} \qquad \forall a \in A^s, t \in T, s \in S \qquad (B8)$$

$$x_t^{as}, y_t^{ps}, \mathbf{m_t^s} \in \{\mathbf{0}, \mathbf{1}\} \qquad \forall a \in A^s, p \in PA^s, t \in T, s \in S \qquad (B9)$$

In order to obtain better perception about the above mathematical formulas, additional explanations are represented as the following:

- The objective (B1) minimizes the sum of possession costs (first part), the maintenance costs (second part) and the penalty cost paid if the last execution of the routine works is carried out too early in the planning horizon compared to the end of horizon (third part).
- Constraints (B2) ensure that each routine maintenance work is scheduled exactly once in the first allowed planning cycle per each segment.
- Constraints (B3) guarantee that until the end of the planning horizon the works for the other cycles will be defined as well, ensuring exactly L^a time periods between two subsequent occurrences of the same job.
- Constraints (B4) can guarantee no repetition and mismatching of one given action over 2 segments simultaneously.
- Constraints (B5) ensure that on a given segment and at the same time only combinable activities can be carried out. These combinable jobs can be either routine works or projects.
- Constraints (B6) guarantee that each project is executed once per each segment.
- Constraints (B7) ensure that each project over each segment is assigned to the right number of time periods and the starting time for performing the projects is in the interval (earliest possible starting time, latest possible starting time). Furthermore, these projects are assigned to subsequent intervals.
- Constraints (B8) ensure that time period $t \in T$ will be occupied for preventive maintenance work over each segment, if and only if for that time period on this segment at least one work is planned.
- Finally, constraints (B9) ensure that all the decision variables are binary.

5- RUNNING THE MODEL OVER CASE STUDY

Through this part, first of all, a short review of Tehran-Qom-Isfahan HSR as case study of this research is explained and then upgraded model of PMSP is evaluated and adjusted in regard to operational and technical parameters of the line. The main purpose of this analysis over the case study is to perceive the major differences and circumstances of track preventive maintenance scheduling over a given HSR axis between 2 major scenarios which are new dedicated HSR and upgraded mixed HSR-conventional traffic.

5-1- Summary of the Route Specifications

Tehran-Qom- Isfahan corridor will be the first HSR line in Iran which the first part of it, Tehran-Qom, is in operation now (175 km, double track, non-electrified, mixed passenger and freight traffic) with maximum speed of 160 km/h. There is 2 major possibilities for this section which in the first scenario the route will be remained in-operation just for conventional trains and a new dedicated HSR line will be constructed parallel to it in future. But in second scenario the current track might be upgraded as mixed HSR-conventional line. About second part of the corridor, Qom-Isfahan, it will be totally a new double track with dedicated traffic with top speed 300 km/h in future. [11]

5-2- General Assumptions over the Case Study

To run the preventive maintenance models on the case study, some assumptions, scenarios and requirements should be provided to find the proper or optimum solution over the line. These parameters are explained in details as the following.

- For computerization and running the model, a personal computer (PC-Laptop) with the following specification is used: *Pentium IV, CPU T7250- 2.00 GHz, RAM: 2GB*
- The software which is used for converting the mathematical equations and functions: *LINGO 11.0 (2008) produced by LINDO Systems Inco.*
- The first part of the corridor (Tehran-Qom section) is the sample case study of this research which might be operated later as new dedicated HSR or upgraded mixed conventional-HSR traffic. The major difference between these two major operation regimes is laid on this assumption that in first scenario, the current conventional line between Tehran-Qom will be left for existing passenger and freight trains and almost parallel to the current line, a new dedicated HSR axis should be constructed only for high speed trains. But in second operation regime, the existing line of Tehran-Qom will be upgraded in such a way that running of high speed trainsets over it can be possible technically in addition to the conventional passenger trains which they will also pass through the same upgraded line at the same time.
- For considering different segments over the line, the whole length of Tehran-Qom (175 km) has been evaluated through 3 integrated segments respectively assumed by 60km, 60km and 55km as track segments. Furthermore it has been assumed that all

the segments have similar specifications and operational regime.

- For more simplification of running the model, only maintenance actions (8 actions) have been considered through the scenarios with relevant maintenance cost per actions and intervals based on local conditions. Also it should be mentioned that the intervals of some actions for mixed-HSR scenario have been assumed rather shorter than dedicated HSR scenario.
- Both sample scenarios are performed by 8 different actins within monthly period of time through 10 years horizon time.
- Track possession parameter can evaluate the traffic characteristics and operational regime restrictions over the line that could be totally different between new dedicated HSR pattern and upgraded mixed HSR scenario. Of course this factor can be called as artificial cost (not real cost) which evaluates difficulty and restrictions of finding free slot for maintenance actins based on the traffic pattern, level of service and operational specifications of the line or track segments in different periods of time. Through the current case study and based on the local situations and operational requirements, the track possession cost has been assumed in different patterns and structures for dedicated and mixed scenarios.

5-3- First Simple Scenario (Scenario A)

In this scenario, some of the maintenance actions have been considered to be combinable to each other and not within all the actions. For instance, for combination set of "A1 to A3", it means that only plain track tamping, ballast regulating and stabilizing actions are combinable to each other and they cannot be performed simultaneously with e.g. switch maintenance actions over a given segment and vice versa.

Result status	Scenario	
	Dedicated HSR-A	Mixed HSR-A
Solution state	Global optimum	Global optimum
Total cost (thou. €)	23162	25012
Runtime	2′:31″	2′:26″
No. of variables	3240	3240
No. of constraints	451069	451177
No. of solver iterations	119939	101149

Table 2- Results status comparison between scenarios

It should be denoted that by considering no combinable action through the model, the solver found no feasible solution through this scenario, neither in new dedicated scenario, nor over upgraded mixed scenario. It means that at least some of the actions should be combinable through a given segment to find some feasible solutions by solver, of course based upon the number of actions and their relevant intervals.

About total cost comparison, as it is clear in table 2, in this scenario, the total cost difference (including maintenance cost and track possession cost) between new dedicated and upgraded mixed scenarios, has been raised up to 1850 thousands euro over 10 years or 1060 euro per km per year. Of course this saving cost through dedicated HSR scenario in comparison to the upgraded mixed HSR scenario seems to be logical based on the less track possession constraints and costs.

But it should be also noticed although the dedicated HSR scenario anticipates less expenditure, there is still one current conventional line adjacent to the dedicated HSR line scenario, which in upgraded mixed HSR scenario this track would be upgraded for both traffic patterns. Therefore this line should be also treated as conventional line in addition to the HSR line which means this saving cost of dedicated HSR scenario perhaps should be consumed for the conventional line that still is in operation. Of course conventional lines might need less expenditure cost in comparison to the HSR lines but may be not just as 1060 euro per km per year which is generally near 1/12 of a given HSR's maintenance cost (only track maintenance and inspection cost). It means this saving amount of maintenance cost for dedicated HSR scenario, probably will be spent for maintaining the adjacent conventional line, if some extra financial resource is not required for the further treatment of conventional line more than this saving amount.

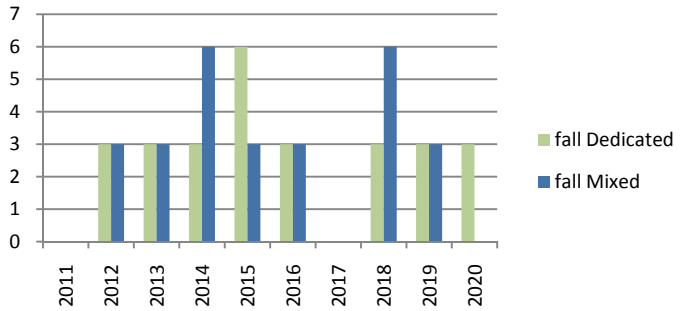

Fig.2 - The season-based diagram of number of possessed months for both dedicated and mixed scenarios (A)

About maintenance scheduling, according to the figure 2, the distribution of possessed months over the long horizon time between new dedicated and upgraded mixed scenarios are represented briefly. As it is clear, only fall months have been selected by model solver for both scenarios. The main reason is that in both scenarios there is no particular growth rate of traffic or any other operation restriction such as summer time or New Year holidays in fall months. Therefore this season has been selected by solver for further maintenance activities through whole the long horizon time of planning.

5-3- Second Scenario with Tight Operational Restrictions (Scenario B)

In previous scenarios (scenario A), both dedicated and mixed-HSR traffic patterns are evaluated with simple operational patterns and track possession constraints and the results was rather similar to each other. Through this scenario (B), the influence of some strict situations of operation restrictions in terms of capacity shortage and limitations during specific periods of time are evaluated for both new dedicated and upgraded mixed HSR patterns. Based on the previous scenario's assumptions, some extra operational restrictions are assumed through track possession cost and patterns in such a way that it seems to be as real expected conditions.

The new operational restrictions which should be applied through track possession pattern of the model are assumed as below:

- **For new dedicated HSR scenario:** assume that the conventional line adjacent to Tehran-Qom dedicated HSR corridor have to be rehabilitated and promoted in such a way that during 2014 and 2015, all the conventional trains should be run over new dedicated HSR line such as upgraded mixed traffic. Therefore in these years, some capacity shortages might be happened and in order to reduce the probability of performing any preventive maintenance actions; a remarkable amount of penalty cost as track possession cost (500 thousands euro per month) is considered in addition to the regular track possession policy (300 thousands euro monthly) throughout the rehabilitation years. This operational policy can help to avoid preventive maintenance performance through these two years as much as possible.
- **For upgraded mixed HSR scenario:** in this scenario, first of all assume that during 2014 and 2015, some ordinary freight trains should be passed along the upgraded mixed HSR corridor, because other parallel corridor should be rehabilitated temporarily. Furthermore, suppose that from the first year of HSR corridor operation start, some specific transit freight trains should be passed through the HSR line of Tehran-Qom just during fall seasons. Therefore in these years and all the fall seasons, some capacity shortages might be happened and similar to the above scenario, a significant penalty of track possession cost (every month as 500 thousands euro) is considered through these periods of tight operation conditions in addition to the regular track possession policy.

Now similar to the scenario A, the general status of running the models are reviewed briefly in table 3. Of course comparing the total cost between new dedicated and upgraded mixed patterns are not so meaningful through this scenario, because the basic assumptions of operation restrictions for upgraded mixed HSR pattern are more complex than another operational pattern. But by comparing every pattern result with previous scenario "A", it can be inferred that 1486 thousand and 1869 thousand euro are expected respectively for new dedicated and upgraded mixed patterns as extra amount of track possession cost. This share of maintenance penalty cost is inevitably imposed over the scenarios based on the new tight operational constraints that were explained in this part.

Result status	Scenario	
	Dedicated HSR-B	Mixed HSR-B
Solution state	Global optimum	Global optimum
Total cost (thou. €)	24648	26881
Runtime	2′:36″	2′:07″
No. of variables	3240	3240
No. of constraints	451069	451177
No. of solver iterations	2961	2146

Table 3- Results status comparison between scenarios (B)

Tables 4 and 5 compare number of track possessed months between the previous scenarios "A" and the new imposed operational regime restrictions through the respective pattern "B". Based on these tables, the following results can be inferred through assuming new tight operation restrictions:

- The number of possessed months through all the scenarios is similar to the previous edition without assuming new tight operation restrictions. But the distribution pattern of the possessed months has been changed over the segments because of new operational restrictions which have been imposed through track possession constraints. (figures 3,4) Because of too costly penalty which has been considered for those restricted periods of time, the model eventually preferred to avoid possessing the periods of time coincided with tight restricted months for both scenarios.

Number of Possessed months	Dedicated HSR-B	Dedicated HSR-A
1st segment (60km)	9 months	9 months
	Possessed months no. : 34,35,36,70,71, 82,96,106,107	Possessed months no. : 24,36,48,59,60,72, 96,108,119
2nd segment (60km)	9 months	9 months
	Possessed months no. : 34,35,36,70,72, 84,95,106,108	Possessed months no. : 22,35,46,58,60,71, 94,107,120
3rd segment (55km)	9 months	9 months
	Possessed months no. : 34,35,36,71,72, 83,94,107,108	Possessed months no. : 23,34,47,58,59,70, 95,106,118

Table 4- Track possession comparison between previous and new tight operation regimes for new dedicated HSR scenario

Number of Possessed months	Mixed HSR-B	Mixed HSR-A
1st segment (60km)	9 months	9 months
	Possessed months no. : 27,29,30,63,65, 77,78,99,101	Possessed months no. : 22,35,46,48,58, 71,94,96,107
2nd segment (60km)	9 months	9 months
	Possessed months no. : 29,30,33,65,66, 78,81,101,102	Possessed months no. : 24,36,47,48,60, 72,95,96,108
3rd segment (55km)	9 months	9 months
	Possessed months no. : 27,29,30,63,66, 75,77,99,102	Possessed months no. : 23,34,46,47,59, 70,94,95,106

Table 5- Track possession comparison between previous and new tight operation regimes for upgraded mixed HSR scenario

- As it is clear from the following figures, in dedicated scenario, by imposing strict and costly penalties throughout 2014 and 2015, no maintenance action has been performed during these 2 years. But in previous scenario "A" totally 9 months had been selected by model during these 2 years (figure 2). On the other hand, fall months are still the only season for dedicated HSR scenario through the whole 10 years of planning which is selected by model similar to the previous scenario even by considering new restrictions, except during 2014 and 2015.

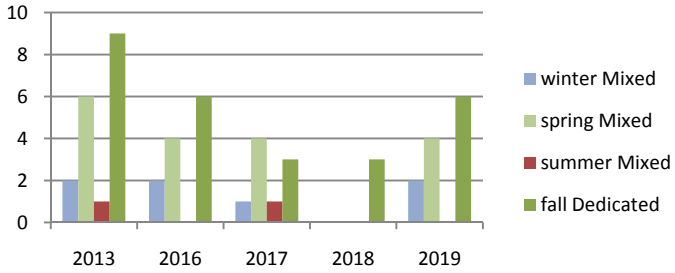

Fig.3 - The season-based diagram of number of possessed months for both dedicated and mixed scenarios (B)

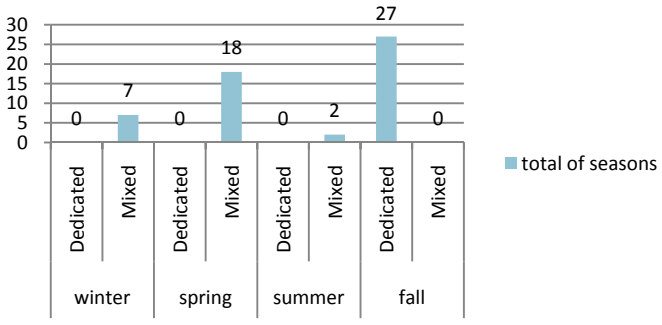

Fig.4 - Comparison between total possessed months based on different seasons through 10 years in scenario (B)

- For upgraded mixed HSR pattern, the arrangement of possessed months with new operational restrictions is totally different from both respective previous results in scenario "A" and also dedicated HSR pattern in current scenario. According to the figures 3 and 4, similar to the dedicated scenario, no preventive maintenance action has been performed through 2014 and 2015 because of considered restricted capacity during these 2 years. But on the other hand distribution of possessed months has been affected also by other restrictions through whole fall seasons which caused no action performance through fall months during whole years of planning.

5-4- Discussion

Through this model analysis, we evaluate the promoted model of preventive maintenance scheduling problem (multi-segment PMSP model) over Tehran-Qom case study. Then we applied 2 major scenarios of dedicated and mixed HSR patterns through technical and operational specifications of models to find better perception of long term planning of preventive maintenance actions based on the operational interactions and constraints. Of course we didn't consider any renewal or project activities and only regular inspection and preventive actions have been assumed. But by considering some of the renewal actions, they can change the total cost results, although the ratio weight of renewal actions would be equal for both new dedicated and upgraded mixed HSR patterns.

Also combinable and non-combinable possibilities of maintenance actions can change the results of scheduling and total cost specially when it has been interacted by some operation restrictions and even sometimes it is not possible to find feasible solutions.

On the other hand, track possession cost is assumed as penalty for capacity shortage and operational regime restrictions like level of service shortage for both passenger and freight trains when the passenger comfort or freight availability can be decreased by other purposes like maintenance actions. Therefore if some sections of the planning time like summer or New Year period are considered with more track possession cost in comparison to the other regular time, then the final results of both time schedule and total travel cost probably will be changed.

About multi-segment capability of this model, it should be mentioned that by considering different track possession policies and different operation and technical specifications over every segment, the final results of maintenance schedule can be totally different respectively.

6- CONCLUSIONS

Maintenance planning and especially preventive maintenance scheduling is an important criteria through decision making process whether a given HSR line should

be constructed as a dedicated HSR pattern or it can be operated as mixed HSR traffic regime. This evaluation is more demanded especially when there is an opportunity to upgrade an existing conventional line for HSR traffic in future.

Furthermore, deciding on a given new HSR corridor, dedicated line or mixed HSR pattern, only based on the preventive maintenance scheduling criteria is mostly depended to the operational conditions through the line as well as total cost of maintenance and track possession cost. These circumstances are different case by case based on the local conditions, opportunities and restrictions. Generally it is not easy to conclude which scenario of new dedicated or upgraded mixed HSR pattern for a new HSR line, e.g. Tehran-Qom HSR corridor, is more expensive or suitable, although the exclusive cost of a new dedicated scenario is usually less expected than upgraded mixed scenario. But the other marginal costs should be considered as well; such as conventional track adjacent to dedicated HSR line that should be still maintained. In this way, the comparison between total costs of "*current conventional line + new dedicated HSR line*" and "*upgraded mixed HSR line*" can illustrate the final conclusion in terms of financial concerns.

Finally it is emphasized again that decision making between these two scenarios through PMSP modeling are quite complicated and depends on the technical and operational specifications of the given HSR corridor. But in general it can be hypothesized that upgrading a current conventional track to a future mixed HSR line can be suggested as an acceptable solution (in terms of both maintenance disturbances and total cost of M&R performance), if the current track's quality and conditions are well maintained and proper to be operated for HSR traffic, and also the traffic pattern of conventional trains are not so widespread and divergent. However, the comparison between new dedicated and upgraded mixed HSR scenarios should take into account the consequences of operational regime interactions with preventive maintenance requisites. This research has tried to assess the possible approaches toward considering this important question.

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