# Two Comprehensive Strategies to Prioritize the Capacity Improvement Solutions in Railway Networks (Case Study: Iran)

**M. Tamannaei[1*], M. Shafiepour[2], H. Haghshenas[3], B. Tahmasebi[4]**

[1]Assistant Professor, Department of Transportation Engineering, Isfahan University of Technology, Isfahan, Iran

[2]MSc., Department of Civil Engineering, Isfahan University of Technology, Isfahan, Iran

[3]Assistant Professor, Department of Transportation Engineering, Isfahan University of Technology, Isfahan, Iran

[4]MSc., Department of Geometric Engineering, University of Isfahan, Isfahan, Iran

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| | The aim of this study is to present two comprehensive strategies for prioritizing the capacity improvement solutions in the railway networks. The solutions considered in this study include: promoting to double-track railways, block signaling system, electrification and re-opening the closed stations. The first strategy is based on a local approach, which concentrates on the critical block sections individually; whereas the second one is based on a global approach, for which the solutions are executed according to the load flow of the network and the capability of the demand absorption after removing the bottlenecks emerged in the specific corridors. For both strategies, the value of the absorbed excessive demand, the benefits, the costs, and the net present value (NPV) indicator are employed to compare the solutions. To evaluate the proposed strategies, Iranian railway network was examined. The results demonstrate the excellence of the second strategy, rather than the first one. By executing the first and the second strategies, 45.6 and 52.52 million tons per year, of the total potential demand can be absorbed to the network, respectively. The NPV values were 5.78 and 7.81 billion dollars for the first and the second strategies, respectively. In spite of more investments required, the second strategy is more efficient, rather than the first one. |

## 1. Introduction

Transportation is a substantial element in the economies of the countries. Low cost of the transportation helps a business to be competitive [1]. Railways and roadways are the two difference means of transportation systems in the world. Roads can be built in the hilly areas also whereas railway cannot be laid easily. Still, different substantial advantages, the rail transportation system is of particular importance rather than the road systems.

Some of the advantages include: the ability of the mass transport, reduction of the energy consumption, promotion of the safety, and reduction of the environmental pollution [2], [3], [4]. In recent years, governmental agencies have focused on policies to induce a demand modal shift from road to intermodal transport, in order to alleviate highway congestion and emissions. In other words, demand modal shift from road to rail is a potential means by which the negative environmental and economic impacts can be decreased [5], [6]. In spite of the mentioned

*Corresponding Author
Email Address: m.tamannaei@cc.iut.ac.ir
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benefits, the development of the rail transportation system encounters with two serious challenges: for one thing, financing rail infrastructure investment; for another, improving the productivity of rail transportation (such as eliminating the capacity bottlenecks, or reduction of the wagon cycle times) [7].

Deficiency of the capacity is one of the main problems of the railway networks. This problem may increasingly intensify, due to the growth in railway transportation demand. Solving the railway capacity deficiencies can fall into two main categories: building the new railway infrastructures, and eliminating capacity bottlenecks of the existing railways.

It is worth mentioning that allocating a high financial investment for railway infrastructures, does not necessarily lead to increase in rail demand absorption and performance. It may reasonably be doubted whether developing the new infrastructures in a specific part of the rail network will definitely recompense the capacity deficiencies of the network [8]. Hence, identification of the capacity bottlenecks and the appropriate solutions to promote them, is of a substantial importance for an advanced railway network. In this research, we have proposed two new comprehensive strategies, in order to efficiently remove the bottlenecks of a railway network.

The first strategy aims to determine an appropriate solution for the capacity improvement of the network. This strategy is based on removing the individual critical bottlenecks of the network. The second strategy tries to find a fair combination of the capacity improvement solutions, through identification of the main corridors of the network and removing their bottlenecks. The article structure is as follows: the theoretical concepts of this study (including railway capacity, solutions to improve the capacity, and assignment to the network) are presented in separate parts. In section 3, the proposed comprehensive strategies to prioritize the capacity improvement solutions in railway networks are explained. In section 4, the Iranian railway network is studied in order to evaluate the proposed strategies. Finally, the conclusions are presented.

## 2. Theoretical Concepts

### 2.1. Railway Capacity

The railway capacity analysis is a multidimensional problem. It involves several intricate systems, such as railway infrastructure, rolling stock, train schedule and crew schedule [9], [10]. Because of its convolution, railway capacity can be defined in many different ways as follows:

Railway capacity is the maximum number of trains which can be moved in each direction over a specified section of track in a specific period. This parameter is associated to the block sections of the railway corridors [11]. The capacity in the railway networks is the capability to operate the trains with an appropriate precision [12]. In other words, the capacity is a measure of the ability to move a specific amount of freight or passenger traffic over a given railway with a set of resources under a particular service schedule [13].

The UIC code has defined several parameters as the most important ones affecting the capacity and the level of service. Based on UIC definition, the capacity of railway network is a balance between the timetable stability, number of trains, average velocity and heterogeneity [14]. The above concepts of railway capacity indicate that there are great parameters in how capacity can be calculated. The reason is possibly the fact that most concepts of the railway capacity are defined nationally.

Abril et al. studied on how the railway capacity is influenced by various parameters. They also presented different methods to calculate the capacity, such as analytical, optimization and simulation methods. The results show that the analytical methods are considered as the good ones to estimate the theoretical capacity of the railway networks [15]. The analytical methods are based on the data obtained from the characteristics of the network infrastructure and the train operations [16]. One of the most popular analytical methods is called UIC 405 method, as follows:

$$C = \frac{T}{t_a + t_b + t_c} \tag{1}$$

Where C is the capacity (daily, etc.) index, T is the reference time (usually 24 hours for the daily capacity), $t_a$ is the average minimum headway, $t_b$ is an expansion margin, and $t_c$ is an extra time based on the number of the intermediate block sections on the line [17].

Pouryousef et al presented a review of different methodologies for railway according to use in Europe and the united states. The results show railway capacity analysis in Europe tends to be more timetable, e.g. application of the UIC model whereas, the United States where normally no

detailed timetable exists and conflicts are solved by improvising [18]. [19].

**2.2. Solutions to Improve the Railway Capacity:** There are various solutions, based on which the capacity of the bottlenecks can be improved. By applying all of these solutions, the average headway of the dispatching trains reduces. Some of the capacity improvement solutions are as follows:

**Promoting to Double-Track Railways**: According to Transit Capacity and Quality of Service manual [20], promoting single-track railways to double-track ones can increase the capacity for a range of 2 to 4 times. Double-track railway is capable of passing more trains, rather than the single track railway in the same period of the time, because of the independency of train movements. The restricted capacity of the single-track railways is due to need of trains to decelerate, stop, and accelerate out of sidings, in order for allowing other trains to use the same facilities [20]

**Railway Block Signaling System:** Signaling enables the railway system to avoid collisions between trains. There are two ways for vehicle control through signaling system: moving-block and fixed-block signaling. Most of the conventional signaling systems are performed based on the fixed-block principle, in which the distance between two subsequent stations is decomposed to two or more predetermined tracks. With the moving-block signaling system, a train continuously keeps a safe braking distance with its leading train [20], [21].

**Railway Electrification:** This solution is usually used for freight transportation in the mountain routes and or the railway corridors with a huge traffic. The main difference between electric and diesel locomotives is in their traction powers. The use of electric locomotive can increase the average velocity of the trains, which may lead to improve the railway capacity [22].

**Reopening the Closed Stations:** Reopening the closed stations is considered a solution for capacity improvement. This solution can shorten the block sections, which may reduce the average headway of the dispatching trains.

**2.3. Traffic Assignment to the Railway Network**

Traffic assignment is the procedure of allocating sets of trips to a defined transportation network. There are different assignment methods. Traffic assignment methods are divided into two sets. Static and dynamic traffic assignments. The static method focuses on the specified traffic loading on the network; whereas the dynamic method is in accordance with the traffic flow that illustrates how congestion levels vary with time [23]. In this study, we have used two methods: All-or-Nothing assignment (AON) and Incremental assignments. AON assignment is a method in which all the traffic flows from an origin to a destination are simply allocated to the path with lowest cost (or travel time), with no consideration of the railway capacity [24], [25]. In incremental assignment method, the OD matrix is divided into several sub-matrices. In each iteration of the incremental algorithm, one of the mentioned sub-matrices is assigned to the network, by using AON assignment. Then, the travel times of the routes are updated based on the new cumulative flows [26], [27]. The assignment process can lead to identification of the capacity bottlenecks of the network. The capacity bottlenecks are the block sections of the network, for which, the transportation exceeds the available capacity [28].

## 3. Methodology

In this section, the proposed strategies for prioritizing the capacity improvement solutions are presented. It is clear that the identification of the capacity bottlenecks of the railway network is considered as the prerequisite for application of both proposed strategies. Hence, how to identify the bottlenecks is initially explained. Then, the two strategies are presented.

### 3.1. Railway Capacity

In order to identify the capacity bottlenecks, it is necessary to assign the demand matrix to the railway network. To do this, both All-or-Nothing and incremental assignment methods are applied in this study. Note that neither AON nor incremental methods would regard the capacity of the block sections. So, we have developed a new incremental assignment method to overcome this drawback. This method is called Capacity-based Incremental

Assignment (CIA). According to this method, after allocation of each sub-matrix in incremental assignment procedure, the remained capacity of all block sections of the network are examined. If the capacity of a block section is terminated, it is removed and the network is updated. Then, the next iteration of the algorithm is executed based on the new shortest paths in the updated network. Different steps of the capacity-based incremental assignment method is presented in Figure 1.

For each of AON and CIA assignments, an indicator of volume-to-capacity ratio ($v/C$) is dedicated to each block section of the network. $(v/C)_i^{AON}$ and $(v/C)_i^{CIA}$ are the volume-to-capacity ratios for block section i through AON and CIA, respectively. Regarding these ratios, the capacity bottlenecks can be categorized in three different cases:
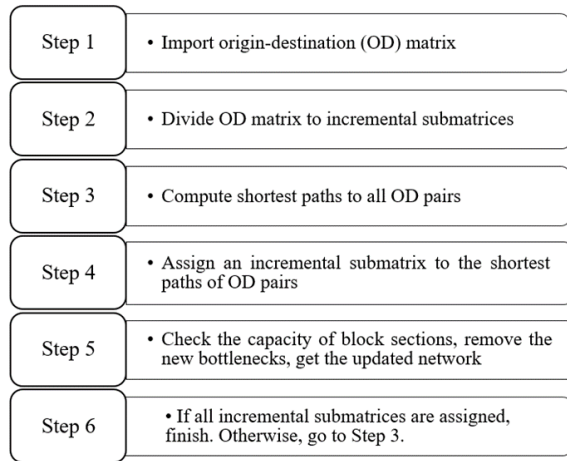


**Figure 1:** The steps of Capacity-based Incremental Assignment (CIA) method

Case 1) for capacity bottleneck i: $(v/C)_i^{AON} > 1$ and $(v/C)_i^{CIA} < 1$. In this case, the existence of some bottlenecks other than capacity bottleneck i is the main reason to prevent the demand absorption in the railway network.

Case 2) for capacity bottleneck i: $(v/C)_i^{AON} < 1$ and $(v/C)_i^{CIA} = 1$. This case implies that existence of some capacity bottlenecks would cause obstruction in parallel routes, which leads to deflect the demand flow to the route containing capacity bottleneck i.

Case 3) for capacity bottleneck i: $(v/C)_i^{AON} > 1$ and $(v/C)_i^{CIA} = 1$. In this case, capacity bottleneck i is one of the main barriers of demand absorption in the railway network. In the present study, this type of the bottlenecks are named "fundamental capacity bottlenecks". It is worthy that finding an

efficient solution to resolve these bottlenecks is an essential issue, which can lead to employ the unused capacity of the network as much as possible. The two strategies -proposed in this study for the capacity improvements of the network- present two different solutions to resolve the mentioned bottlenecks.

### 3.2. The First Proposed Strategy Solutions to Improve the Railway Capacity

The first proposed strategy is based on a local approach to the capacity problems of the railway network. In this strategy, each of the fundamental capacity bottlenecks of the network are investigated individually, so that for each one, the capacity improvement solutions are examined and the best solution is obtained. The capacity improvement solutions include: promoting to double-track railways, block signaling system, electrification and re-opening the closed stations. Each solution is executed independently on the mentioned bottleneck, and therefore the assignment process is performed to identify how much the demand absorption is increased. For each bottleneck, the best solution is the one with capability to simultaneously maximize the demand absorption, and to minimize the Net Present Value (NPV) indicator. NPV is calculated based on present value of all future costs and benefits. The present value refers to discounted value of costs and benefits (cash flows) at future dates. NPV indicator is given by:

$$NPV(i, N) = \sum_{t=0}^{N} \frac{R_t}{(1 + i)^t} \qquad (2)$$

Where $R_t$ is the net cash flow according to the difference between the benefits and the costs in period t. $i$ and N are the discount rate and the life of the investment solution, respectively [29]. In Figure 2, the flowchart associated to finding the best solution in the first strategy is illustrated.

### 3.3. The Second Proposed Strategy

The second proposed strategy is based on a global approach to the capacity problems of the railway network. In this strategy, the All-or-Nothing (AON) assignment is used to determine the load flow on the railway network. AON considers all the traffic flows from an origin, without consideration of the railway capacity. According to the AON results, the

corridors of the network, which have the capability of considerable absorption of the railway demand, are recognized. Then, a repetitive sub-algorithm is executed, in order to find the best combination of the capacity improvement solutions for each of the specific corridors. This sub-algorithm is based on finding the appropriate solutions to remove the fundamental capacity bottlenecks of the considered corridor. To do this, the Capacity-based Incremental Assignment and NPV indicator are employed. In Figure 3 the flow chart associated to achievement of the best solution for a specific corridor is illustrated. This flowchart must be performed separately for each of the corridors.

the bottlenecks emerged in the specific corridors, for which the capability of the demand absorption is considerable. An important question raised in the second strategy is: what are the quantitative criteria, based on which the railway corridors are chosen? In the present study, the railway corridor is defined according to three different criteria, as mentioned in Eq. (3) to Eq. (5):

$$Mean_b > Tr_1 \tag{3}$$

$$\frac{\sigma_b}{Mean_b} < Tr_2 \tag{4}$$
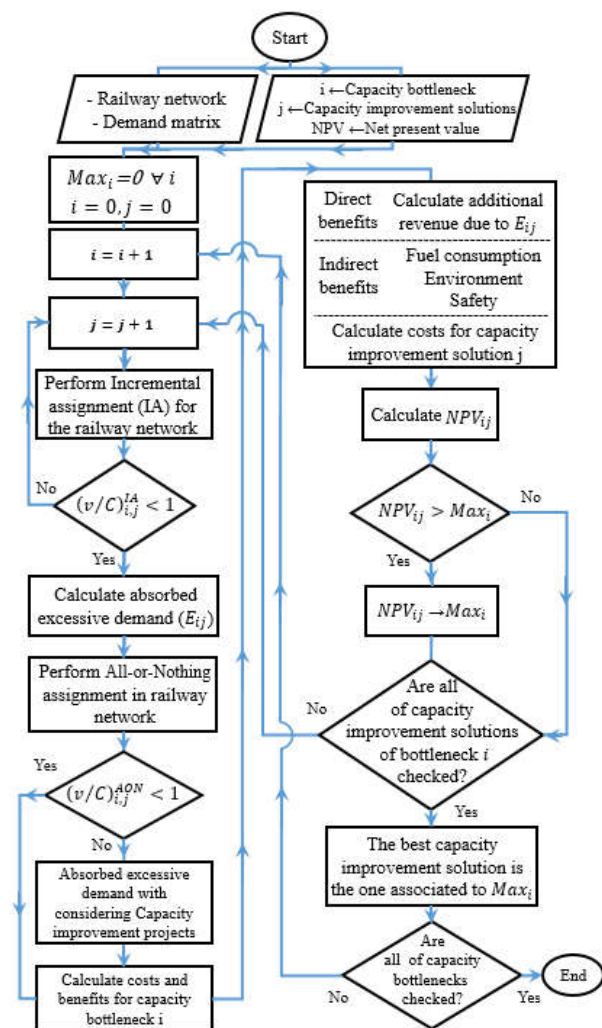
$$SE_b < Tr_3 \tag{5}$$



**Figure 2:** The first proposed strategy



**Figure 3:** The second proposed strategy, used for a specific corridor

It is noteworthy that the two proposed strategies are substantially different with each other. The first strategy concentrates on the critical block sections individually; whereas the second one is based on
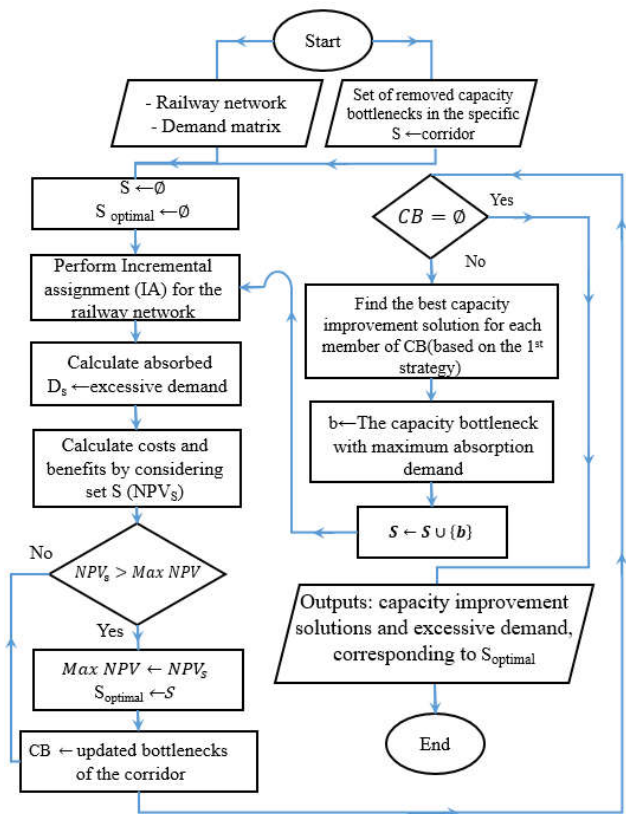
Where $Mean_b$ is the average of potential demand in specific corridor with fundamental capacity bottleneck $b$ in the considered railway corridor. $\sigma_b$ and $SE_b$ are the standard deviation and the standard error of the potential demand in specific corridor with fundamental capacity bottleneck $b$, respectively. The parameters $Tr_1$, $Tr_2$ and $Tr_3$ are considered as the threshold for the corresponding quantities. The standard deviation and standard error are formulated as follows:

$$\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - \mu)^2}, \mu = \frac{1}{N}\sum_{i=1}^{N}x_i \qquad 6)$$

$$SE = \frac{\sigma}{\sqrt{N}} \qquad (7)$$

Where $N$ and $x_i$ are the number of values $x$ and $x_i$ is one of the values from a finit data set, respectively, and $\mu$ is average data set.

### 3.4. Comparative Evaluation of the Two Proposed Strategies

The results of executing the two strategies are compared, according to NPV indicator. This indicator is calculated based on benefits and costs, associated to the capacity improvement solutions.

**Costs:** The unit costs of the capacity improvement solutions are summarized in Table 1. As shown in this table, for promoting the railways to the double-track ones, the type of terrain has the most impact to the imposed costs.

**Table 1:** The unit costs of different capacity improvement solutions [30]

| Solution | The type of terrain | Unit | Cost $ |
|---|---|---|---|
| **Promoting to double-track railways** | level | Km | 875000 |
| | rolling | Km | 1031250 |
| | mountainous | Km | 1187500 |
| **Block signaling system** | - | Km | 39063 |
| **Electrification railway** | - | Km | 239063 |
| **opening the closed stations** | - | One station | 1562500 |

**Benefits:** The benefits obtained from execution of each of the capacity improvement solutions is to be computed. In the present study, the benefits are proportional to the amount of demand (ton-kilometers), which is transferred from the road to the railway network, due to execution of the considered solution. The benefits are divided in two parts: direct and indirect. The direct benefits are calculated, merely based on the railway tariff. The indirect benefits is divided into three sections: fuel consumption saving, saving for environmental effects and saving for safety incidents. According to [30], [31], [32] and [33] and the values of indirect benefits are 14.06, 24.72 and 24.38 dollars in 1000 ton-kilometers, for fuel consumption, environmental and safety savings, respectively.

## 4. Case Study: Railway Network of Islamic Republic of Iran

In order to evaluate two proposed strategies, the Iranian railways network has been investigated. This network is divided into 404 block sections and 83 corridors. The corridor classification is based on some geographical properties like: substantial demand origins and destinations, main branches, and official network zoning of Iran Railway Association. Each corridor consists of several block sections. The OD (Origin-Destination) demand matrix predicted for year 2020, as well as the network capacity data were considered as the inputs of the study. UIC 405 method has been used to determine the capacity of each block section. The AON assignment and Capacity-based Incremental Assignment (CIA) have been performed for identification of the capacity bottlenecks of the network. The NPV indicator is calculated for 30 years duration and discount rate 10%. $i$ and N are the discount rate and the life of the investment solution

**Figure 4:** Identification of the capacity bottlenecks in Iranian railway network

## 5. Results

To prioritize the capacity improvement solutions, both proposed strategies have been performed independently for Iranian railway network.

The first strategy: In this strategy, the best solution to improve the capacity for each of the fundamental capacity bottlenecks of Iranian railway network were individually obtained. Then, they were simultaneously executed in entire network.

The best individual solutions of the fundamental capacity bottleneck of Iranian railway network are shown in Figure 5.

The execution of the first proposed strategy has led to absorption of 4.78 million tons as the excessive demand, supplemented to the absorbed demand of the Iranian railways. The total costs and benefits, obtained by execution of the first strategy is presented in Table 2.

The second strategy: In this strategy, All-or-Nothing (AON) assignment has been performed to determine the load flow, to determine the absorption capability in different corridors of Iranian railways. In Figure 6, the load flow obtained by AON assignment in Iranian railway network is illustrated.
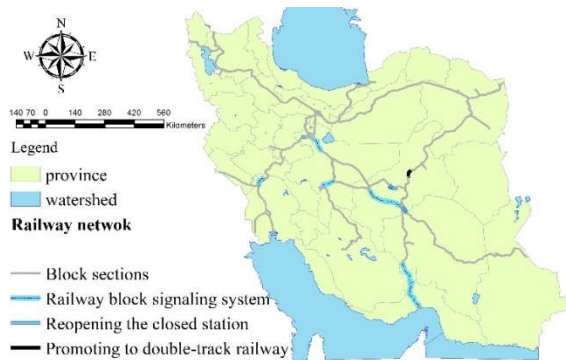


**Figure 5:** Result of the first proposed strategy in Iranian railway network

**Table 2:** The total costs and benefits, obtained by execution of the first strategy

| Results | Unit | Value |
|---|---|---|
| Excessive absorbed demand | million tons | 4.78 |
| Absorbed demand (before execution of first strategy) | ton-kilometers | 2.68E+10 |
| Absorbed demand (after execution of first strategy) | ton-kilometers | 3.47E+10 |
| Costs of solutions in different years | Dollars | 5.84E+07 |
| Costs of solutions in base year | Dollars | 7.49E+07 |
| Benefits (both direct and indirect) in different years | Dollars | 6.20E+08 |
| Benefits (both direct and indirect) in base year | Dollars | 5.84E+09 |
| NPV indicator | Dollars | 5.78E+09 |

The specific corridors of Iranian railways have been recognized, based on the criteria presented in Eq.(3) to Eq.(5). According to our intuitive cognition and knowledge from this network,

parameters $Tr_1$, $Tr_2$ and $Tr_3$ are considered 6.5 million tons, 15% and 0.5, respectively. The obtained corridors for Iranian railway network are introduced in Figure 5

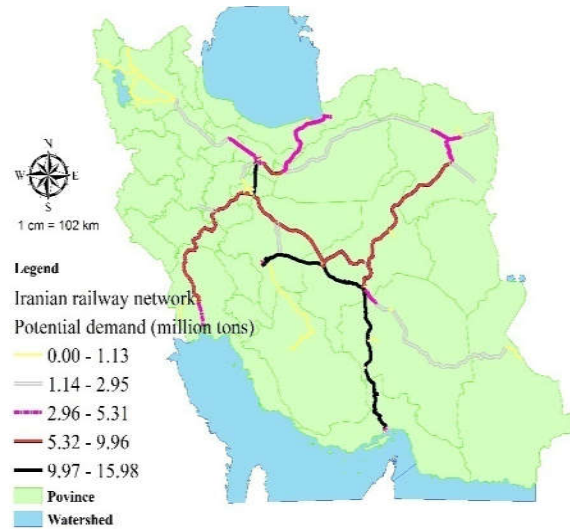The location of the obtained specific corridors of Iranian railway network is shown in Figure 7.



**Figure 6:** Load flow in Iranian railway network

**Table 3:** The corridors obtained in the second strategy in Iranian railway network

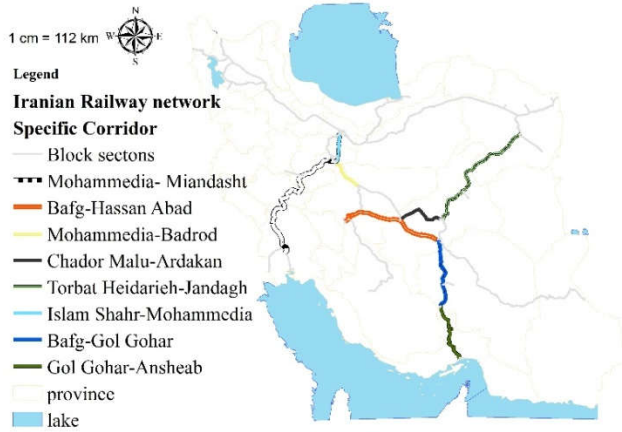| Specific corridors | $Mean_b$ | $\sigma_b$ | $\sigma_b/Mean_b$ | $SE_b$ |
|---|---|---|---|---|
| Mohammedia-Miandasht | 7.91 | 0.43 | 5.44 | 0.07 |
| Bafg-Hassan Abad | 12.86 | 1.65 | 6.00 | 0.31 |
| Mohammedia-Badrod | 8.52 | 1.26 | 14.79 | 0.43 |
| Chador Malu-Ardakan | 8.5 | 0.03 | 0.35 | 0.01 |
| Torbat Heidarieh-Jandagh | 6.68 | 0.23 | 3.44 | 0.05 |
| Islam Shahr-Mohammedia | 6.98 | 0.07 | 1.00 | 0.03 |
| Bafg-Gol Gohar | 9.2 | 0.02 | 0.22 | 0.01 |
| Gol Gohar-Ansheab | 13.94 | 0.002 | 0.01 | 0.00 |

**Figure 7:** Identification of the specific corridors in Iranian railway network

In the second proposed strategy (based on global approach), a repetitive sub-algorithm has been performed to find the best combination of the capacity improvement solutions for each of the specific corridors. As mentioned before, this sub-algorithm is based on finding the appropriate solutions to remove the fundamental capacity bottlenecks of the considered corridor. In Figure 8, the capacity improvement solutions, obtained by execution of the second strategy in Iranian railway network is shown.
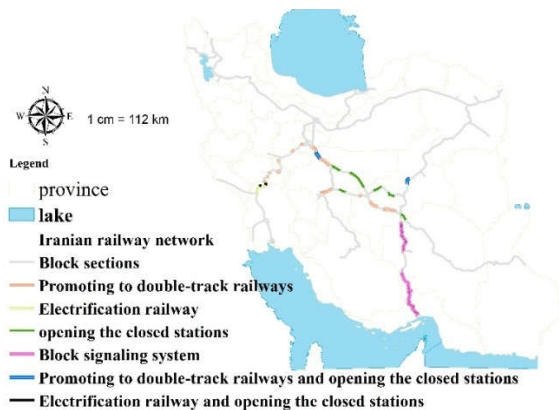


**Figure 8:** Capacity improvement solutions, obtained by execution of the second strategy in Iranian network

The execution of the second proposed strategy has led to absorption of 11.7 million tons as the excessive demand, supplemented to the absorbed demand of the Iranian railways. The total costs and benefits, obtained by execution of the second strategy is presented in Table 4.

**Table 4:** The total costs and benefits, obtained by execution of the first strategy

| Results | Unit | Value |
|---|---|---|
| Excessive absorbed demand | million tons | 11.7 |
| Absorbed demand (before execution of second strategy) | ton-kilometers | 2.68E+10 |
| Absorbed demand (after execution of second strategy) | ton-kilometers | 3.84E+10 |
| Costs of solutions in different years | Dollars | 6.11E+08 |
| Costs of solutions in base year | Dollars | 7.84E+08 |
| Benefits (both direct and indirect) in different years | Dollars | 9.13E+08 |
| Benefits (both direct and indirect) in base year | Dollars | 8.61E+09 |
| NPV indicator | Dollars | 7.81E+09 |

## 6. Discussion

The comparison of Table 2 and Table 4 demonstrates the various efficiencies of the two proposed strategies. The execution of the second strategy has led to increase of about tenfold in total costs, rather than the first strategy. However, the NPV values have been 5.78 and 7.81 billion dollars for the first and the second strategies, respectively. In other words, despite the more total cost required to execute the second strategy, much more benefits could make this strategy more justifiable.

## 7. Conclusions

The aim of this study is to present two comprehensive strategies for prioritizing the capacity improvement solutions in the railway networks. The solutions considered in this study include: promoting to double-track railways, block signaling system, electrification and re-opening the closed stations. Since the identification of the capacity bottlenecks is as the prerequisite for both proposed strategies, two assignment methods were used: All-or-Nothing assignment, as well as a novel method called Capacity-based Incremental Assignment (CIA). In the first strategy, each of the fundamental capacity bottlenecks of the network are investigated individually, so that for each one, the capacity improvement solutions are examined and the best one is obtained. In the second strategy, the All-or-Nothing assignment method is used to determine the load flow in the network. Then, by using a repetitive sub-algorithm, the best combination of the capacity improvement solutions is determined for the specific corridors of the network. The two proposed strategies are substantially different with each other. The first strategy is based on a local approach, which concentrates on the critical block sections individually; whereas the second one is based on a

global approach, for which the solutions are executed according to the load flow of the network and the capability of the demand absorption after removing the bottlenecks emerged in the specific corridors. For both strategies, the value of the absorbed excessive demand is determined. Also, on the basis of the benefits and costs related to the execution of the strategies, the net present value (NPV) indicator is used to compare the solutions. The benefits are divided in two parts: direct and indirect. The direct benefit is calculated, merely based on the railway tariff. The indirect benefit itself is divided into three sections: fuel consumption saving, saving for environmental effects and saving for safety incidents. To evaluate the proposed strategies, Iranian railway network was examined. The OD demand matrix and the network capacity data were considered as inputs. The results demonstrate the excellence of the second strategy (global approach), rather than the first one (local approach). By executing the first and the second strategies, 45.6 and 52.52 million tons per year, of the total potential demand can be absorbed to the network, respectively. The execution of the second strategy has led to about tenfold in total costs, rather than the first strategy. However, the NPV values were 5.78 and 7.81 billion dollars for the first and the second strategies, respectively. In other words, in spite of more investments required, the second strategy is more efficient, rather than the first one.

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