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TRAIN SCHEDULING ON A SINGLE - TRACK RAILWAY LINE

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ABSTRACT

Railway is known to be the best mode of land transport in terms of energy consumption and land use per passenger - km or ton - km transported; and also in terms of economic efficiency for freight transportation. It is also known to be superior to air transport in terms energy consumption per passenger - km up to some specific distance of travel. Thus, it is of crucial importance to increase the market share of rail transport for economic and environmental sustainability. Customer satisfaction through better punctuality is one of the possible strategies towards this purpose. In reality, most of the railways operate according to a timetable, within which, all trains have predetermined departure times from, arrival times at and / or passing times without stopping through all the reference points (stations, sidings) in their routes. In daily operation, some of the trains may get delayed for various reasons. This creates a knock - on effect, spreading the delay to other trains. Thus, the timetable becomes invalid, and rescheduling of the traffic becomes necessary. Efficient rescheduling helps the railway system be more punctual. In practice, rescheduling is done by human operators (called dispatchers) by manual methods. Human brain has a limited computational ability. Given additionally the computationally complex nature of the problem, this puts an upper limit on the effectiveness of rescheduling solutions produced manually by humans. Making use of the computational power of today's modern computers can provide significant improvement. In this study, an introduction for usage of mathematical models for scheduling the trains on a single - track railway line is given. Basic properties of the problem and the constraints that have to be taken into account are explained. Properties of the mathematical model which considers these constraints are mentioned. Some numerical tests performed on various sizes of problem instances are encouraging for using the proposed speed-up techniques.
Keywords: Railway transportation, train scheduling, rescheduling process, mathematical model, heuristic techniques.

BİR TEK HATLI DEMİRVOLUNDA TREN ÇİZELGELEMESİ

ÖZ

Demiryolu, kara ulaşım türleri arasında, taşınan yolcu - km veya ton - km başına enerji verimiliği en yüksek, arazi kullanımı en düşük tür olarak bilinmektedir. Ayrıca, yük taşımacılığındaki ekonomik verimliliği de karayoluna göre daha yüksektir. Yolcu taşımacılığında, belirli bir mesafeye kadar olan taşımalarda, havayoluna karşı da, enerji verimililiği bakımından üstünlük göstermektedir. Bu nedenlerle, çevresel ve ekonomik sürdürülebilirlik adına, taşımacılıkta demiryolunun pazar payının yükseltilmesi büyük önem taşımaktadır. Daha iyi bir dakiklik marifetiyle müşteri memnuniyetinin arttırılması, bu konuda geliştirilebilecek stratejilerden biridir. Gerçekte, çoğu demiryolu sisteminde, trenler, önceden belirlenmiş bir zaman çizelgesine göre hareket etmektedir. Bu çizelgede, trenlerin, rotaları üzerinde bulunan tüm referans noktalarına (istasyonlar, saydingler) varış, bu noktalardan kalkış ya da bu noktalardan durmadan geçiş zamanları kayıtlıdır. Günlük işletimde, trenlerden bazıları, çeşitli sebeplerden dolayı gecikebilir. Bu gecikmeler, bir yayılma etkisi yaratarak, diğer trenlere de sirayet etmektedir. sonuç olarak, hazırlanan zaman çizelgesi geçerliliğini yitirmekte, yeniden çizelgeleme gereksinimi ortaya çıkmaktadır. Yeniden çizelgelemeyi verimli bir şekilde yapmak, sistemin dakiklik performansının artmasını sağlayacaktır. Uygulamada, yeniden çizelgeleme, insane olan ve dispeçer adı verilen operatörler tarafından, manuel yöntemler kullanılarak yapılmaktadır. İnsan beyninin hesap yeteneği sınırlıdır. Bu durum, çizelgeleme probleminin hesap bakımından karmaşık doğasıyla birleşince, insanlar tarafından manuel yöntemle yapılan yeniden çizelgemenin kalitesi üzerine sınırlar koymaktadır. Günümüzün modern bilgisayarlarının hesap yeteneklerinden yararlanarak, bu verimliliği arttırmak mümkündür. Bu çalışmada, tek hatlı demiryollarında trenlerin yeniden çizelgelenmesi için matematiksel modellerin kullanımına ilişkin bir giriş yapılmıştır. Problemin temel özellikleri ve dikkate alınması gereken kısıtlar anlatılmıştır. Bu kısıtları dikkate alarak yapılacak matematiksel modellemenin özelliklerine değinilmiştir. Çeşitli problem örnekleri üzerinde yapılan sayısal uygulamalar, ümit verici sonuçlar üretmiştir.
Anahtar Sözcükler: Demiryolu taşımacılığı, tren çizelgeleme, yeniden çizelgeleme süreci, matematiksel model, sezgisel yöntemler.

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1. INTRODUCTION

Railway is known to be the best mode of land transport in terms of energy consumption and land use per passenger - km or ton - km transported; and also in terms of economic efficiency for freight transportation. It is also known to be superior to air transport in terms energy consumption per passenger - km up to some specific distance of travel. Thus, it is of crucial importance to increase the market share of rail transport compared to road and air transport for economic and environmental sustainability. Therefore, is a strict requirement to increase the customer satisfaction related to rail transport. This increase is only possible to improve rail transport in terms of the classical quality measures related to transportation, such as speed, safety, reliability, punctuality, service frequency and price. Developing proper strategies to achieve these improvements is very important for the future of railways. As the amount of traffic on the rail network increases and approaches to the network's capacity, problems with reliability, punctuality (which also disrupts speed by elongating the travel time) and service frequency start to arise. Moreover, these problems increase the operational costs and harm the economic edge of rail transport. When it is impossible or at least very difficult to build new infrastructure, railway infrastructure managers and train operating companies seek other solutions; such as improving the operational procedures to make better use of the existing capacity and thus improving the service quality and cost - effectiveness. Railway, just like any other transportation system, consists of three major components: The infrastructure component, the vehicles component and the operation component. The operation component includes all the rules, methods and procedures for effective, efficient and safe operation of the system. It can be said that infrastructure and vehicle components are the hardware of the system; whereas the operation component is the software. All these components are in a very close relation and a well - functioning system is possible only when all these components are well - designed and well - functioning. One of the most important parts of the operation component of a railway system is train scheduling. Train scheduling involves preparing the timetables, to which the train operations are expected to conform; and re - scheduling the traffic in case of the perturbations in real - time operations. Improving the performance of these activities would help very much to improve the service quality of rail transport. Hence this study is about train scheduling problem, and especially with the design of computer - based decision support systems for solving the train scheduling problem. The main scope of the study is rescheduling the train traffic on a single - track railway line.

2. RELATED LITERATURE

Since train scheduling problem is basically a scheduling problem, the distribution of related literature shows some similarity with the classical scheduling literature. Like any NP - Complete scheduling problem, there are three main solution approaches for train - scheduling problem. These are *exact solutions*, *metaheuristic solutions* and *problem - specific heuristic solutions*.

Exact solutions are those obtained using the integer - programming methods to generate the optimal solution. They are difficult to apply in NP - complete problem structures. Nevertheless, they have found some application in the operations research literature. Billionnet [1], Caprara et al. [2], Dessouky et al. [3] are some examples of the studies that use exact solution approaches.

Metaheuristic methods such as simulated annealing, tabu search, ant colony optimization, and genetic algorithms are widely used for train scheduling problems. These methods, for most of the time, quickly find good but not necessarily optimal solutions. Although they are generally known as effective methods, getting good results from them requires to have a high level of expertise about them. Gorman [4] applied both tabu search and genetic algorithms for solving the problem, where Ho and Yeung also added simulated annealing to the methods, but worked on a different version of the problem. Salim and Xiaogiang [5] employed a genetic algorithm model which also aims to reduce the iron dust emissions due to braking. Törnquist and Persson [6] combined tabu search and simulated annealing.

Problem - specific heuristic solutions (also called *tailor-made heuristics*) are developed exclusively for train scheduling problem. They range from simple rule - based heuristics to quite complicated branch - and - bound methods. We can further divide this category to two more sub - categories: *Greedy Heuristics* and *Heuristics with a look - ahead component.*

Greedy Heuristics: These methods focus on the problem only on the local scale. They solve the conflicts one - by - one and do not consider the effect of the current solution on the later conflicts. These methods consider only the trains involved in the immediate conflict and try to optimize the selected performance measure based on the solution of the immediate conflict. The biggest advantage of these methods is the running speed, especially for the operational scheduling problem. Since operational scheduling is indeed a real - time scheduling problem, it is very important to reach good feasible solutions in a very short time. Moreover, sometimes, these heuristics provide surprisingly good solutions. One example is the dispatcher's solution in Şahin (1999), which is based on decision behaviours of Turkish State Railways' train dispatchers. This greedy heuristic found the optimal solution in some of the cases. However, at least theoretically, a greedy heuristic is not expected to give very good results in all the instances, because of its myopic nature.

Heuristics with a Look - Ahead Component: These methods are not just local methods. They consider the consequences of the local decisions - or they try to improve the solution by choosing the alternatives of locally optimal decisions. A good example to the former approach is the heuristic developed by Şahin [7] and to the latter approach is D'Ariano et al.[8].

One problem with the non - exact solutions is that, all train scheduling problems are unique. Railway operation involves a huge number of different operational constraints, related to line topology and physics involved. Up to today, there is no pool of benchmark problems to evaluate the performance of these heuristics. So, problems are generally selected from real - world applications with real - world traffic data. They are then benchmarked with solutions of human planners. If they provide significantly better solutions than human planners, the solutions are considered to be "good enough" solutions.

Now, a wide explanation and definition of the problem will be given. Some basic insight into the railway operations and related complications is an absolute necessity to understand and employ algorithms for train scheduling.

The formal definition of scheduling is "assigning start and end times for certain tasks sharing the same resources in an efficient way", and this definition is perfectly applicable to train scheduling. However, gaining insight about what the "tasks" are can be somewhat tricky. In train scheduling, "tasks" are "train movements over railway lines." These railway lines have some different components. Therefore, before explaining the train scheduling concepts, it will help very much to provide some background information about train movements over railway lines and their elements.

3. TRAIN MOVEMENTS OVER RAILWAY LINES

The duty of a train is to travel from one point (*origin* of the train) to another (*destination* of the train); with, if necessary, some intermediate stops. This duty is called the train's itinerary. Trains perform that duty over railway lines. Railway lines have some different elements, and trains move over these elements during their travel. Because of this fact, it may be helpful to describe those elements first.

Main elements of a railway line that are relevant to train scheduling are *mainline track sections, stations* and *sidings.*

Mainline Track Sections: Mainline track sections are the sections of railway tracks between adjacent stations or sidings. Over these track sections, trains cover the bulk of the distance. Mainline tracks generally extend through stations and sidings.

Sidings: Sidings are the sections of railway lines, through which, number of parallel tracks is increased for some length of railway line, (say, 1000 - 2000 meters). Sidings are used for meeting and overtaking operations. These operations will be further explained later.

The number of tracks within the siding (including the part of mainline tracks extending through the siding) is the *capacity* of the siding, i.e. the maximum number of trains that can be present within the siding in overlapping time intervals. Sometimes, this capacity can be exceeded by means of a special operation: two or more short trains (total length of them being well below the length of the siding) bound in the same direction can be stopped on the same track. In this case, for departures from the siding, a first - in, first - out rule has to be applied. However, for avoiding overcomplicated models, this special operation to exceed the siding capacity is generally not modeled in train scheduling algorithms (More generally, siding capacity is not modeled at all, for the same purpose. This will be explained later).

Stations: Stations are similar to sidings. Within the stations, number of parallel tracks is greater than that in the mainline track sections. Meeting and overtaking operations can be done within the stations. The station capacity concept is the same as the siding capacity concept. However, stations have an additional duty: passengers board and alight the trains there. Mainline track sections, stations and sidings are depicted in Figure 1.

Train schedules are represented by time - distance diagrams called *Train Graph.* Time - distance diagrams show the movement of a train along its path with respect to time. There are two different basic orientations in railway time - distance diagrams. In the first orientation, the horizontal axis is the time axis and the vertical axis is the distance axis. In the other orientation, this scheme is reversed. Both of these orientations are widely used among different railway operating companies and infrastructure managers in the world. Neither of them has any specific advantage or disadvantage over the other one. In this study, the first orientation is adopted. In Figure 2, a sample train - graph for a section of railway line with 4 stations and 4 trains is given. In this train graph, the horizontal axis is the time axis and the vertical axis is the distance axis, which shows the stations. In this figure, stations are numbered. The general practice is writing the name of the stations there. Note that, in the graph, sometimes the paths of trains become parallel to the time axis, and this occurs only when trains are within the stations. This means, train stops at this station for some time.

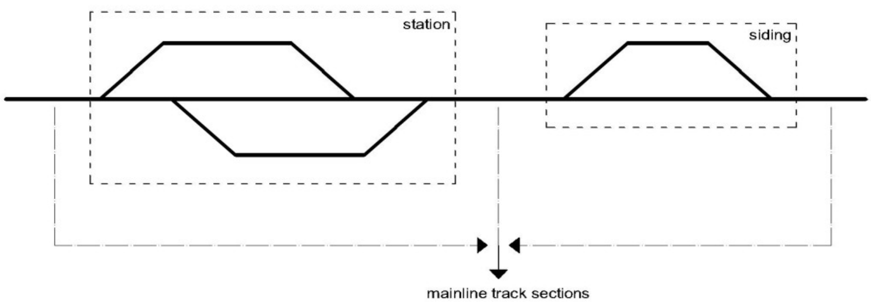


Figure 1. Station, siding and mainline track sections

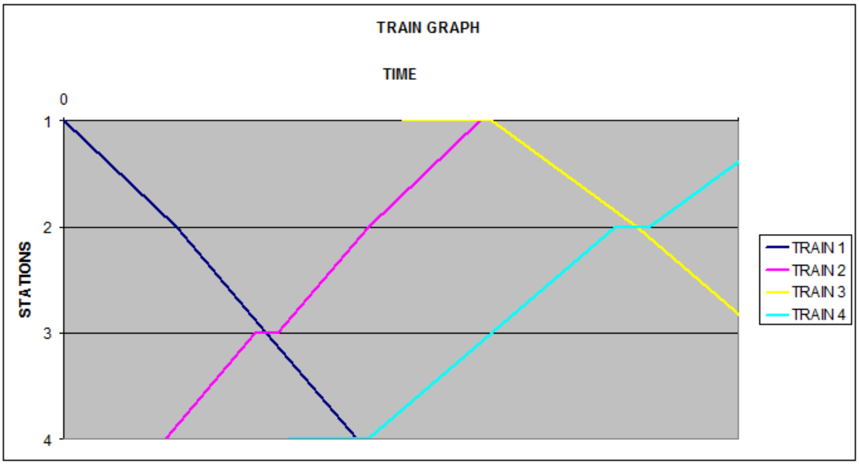


Figure 2. A sample railway time - distance graph (train - graph)

Conflict Resolution: The backbone of train scheduling is conflict resolution. When two trains try to use the same infrastructure element in overlapping time intervals, a conflict occurs. Conflict means infeasibility and has to be resolved. There are various solutions to conflicts, which will be discussed soon, shortly after defining the types of conflicts.

Conflicts Between Trains in the Same Direction: There are two basic types of conflicts between trains running in the same direction. These are *headway conflicts* and *overtaking conflicts*. In railway operations, trains in the same direction cannot depart from - arrive at a station at the same time. A minimum safety distance should be present between them, which can be assumed to translate into a minimum time, called the *minimum headway*. An example of a minimum headway constraint that is expressed verbally is as follows: "If train i will enter the mainline section s immediately after train j, it should enter the section at least h_d minutes later than this preceding train does." From now on, the word "minimum" will not be used. Only headway will be used and this will indeed refer to minimum headway. These minimum headway constraints are in action not only when entering the mainline track sections. They are in action all the way along the mainline track sections. For simplicity, it is assumed that this fact can be simulated using two different headway constraints, *depart - depart headway* and *arrive - arrive headway*. The former is the headway constraint in the entrance of the section, and the latter is the one in the exit of the section.

The verbal expression that was given in the previous paragraph was for depart - depart headway. Arrive - arrive headway version is as follows: "If train i will leave the mainline section s immediately after train j, it should enter the section at least h_d minutes later than this preceding train does." Now, we will illustrate some headway conflicts on train graphs. In Figure 3, a depart - depart headway conflict is shown. Train 1 and Train 3 are trying to depart from Station 1 (and thus enter the related mainline track section) at the same time. This is an infeasible schedule. At least the depart - depart headway of time should pass between the entrance of them.

In Figure 4, this conflict is resolved. Departure of Train 3 from Station 1 is delayed until the minimum depart - depart headway ($h_{d,d}$) amount of time passes. This schedule is feasible. It may or may not be optimal. Similar problems and solutions can be observed in arrive - arrive conflict case as well. If there is an arrive - arrive conflict, one of the trains has to be delayed to resolve the conflict.

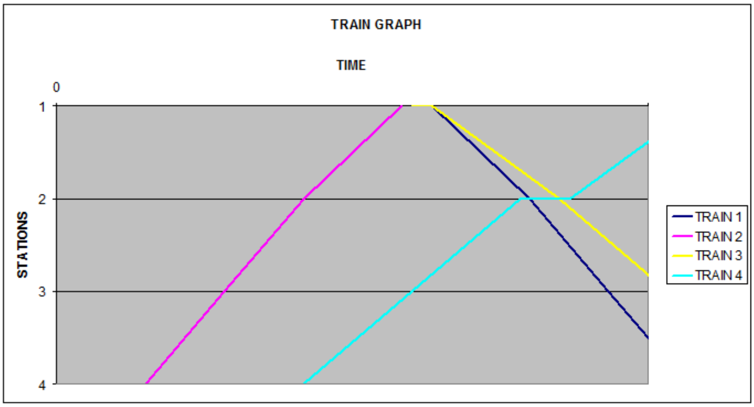


Figure 3. A depart - depart headway conflict between Train 1 and Train 3 at Station 1

Another type of conflict that can arise between two trains in the same direction is the *overtaking conflict.* Figure 5 shows an example. Here, arrive - arrive and depart - depart headway constraints are satisfied at Stations 1 - 2 and 3. However, Train 1 is faster than Train 3. As shown in the figure, Train 1 tries to overtake Train 3 within the mainline track section 2. Both trains use the same mainline track, overtaking is not possible. Overtaking can only be done at the stations / sidings. This schedule is not feasible. There are two possible solutions to this overtaking conflict. Train 1 may be allowed to overtake Train 3 at Station 2. This is depicted in Figure 6. Another solution would be to delay train 1 at station 1.

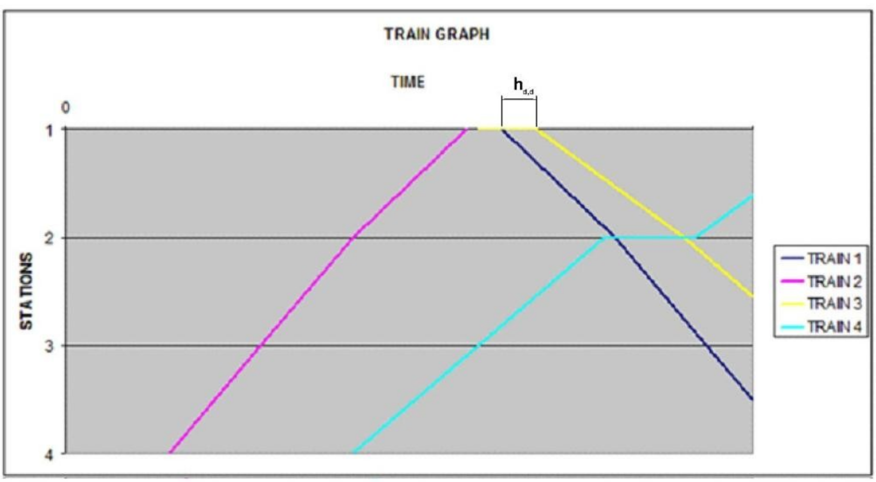


Figure 4. Depart - depart headway conflict resolved between Train 1 and Train 3 at Station 1

Conflicts Between Trains in Opposite Directions on Bidirectional Mainline Tracks: There are mainly two types of conflicts: *Meeting conflicts* and *arrive - depart headway* conflicts.

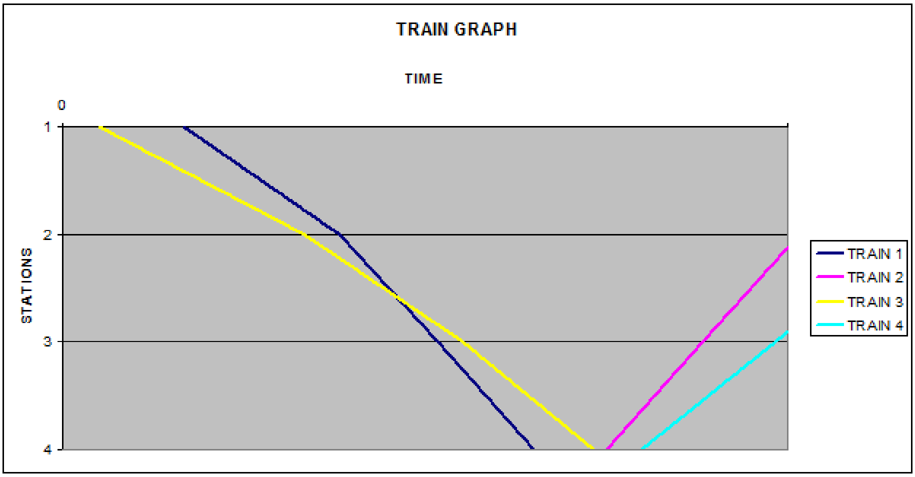


Figure 5. An overtaking conflict between Train 1 and Train 3 at mainline track section 2

Meeting Conflicts: Two trains moving in opposite directions on bidirectional tracks cannot cross each other within the mainline track sections. This crossing can only occur within stations and sidings. Figure 7 depicts a violation of this rule. We assume that the given train - graph belongs to a single - track railway. As seen in the figure, two trains try to cross each other on the mainline track section. This is an infeasible schedule. One of the trains should be given the priority and the other train has to wait in the station until the train with the priority arrives.

Arrive - Depart Headway Constraints: In Figure 8, it can be observed that waiting train does not depart as soon as the arriving train arrives. This is logical. It takes some time to arrange the mainline track section for a change of traffic direction (like throwing and locking the switches, clearing the signals, etc.). This imposes an arrive - depart headway constraint, imposed like the headway constraints between the trains travelling in the same direction.

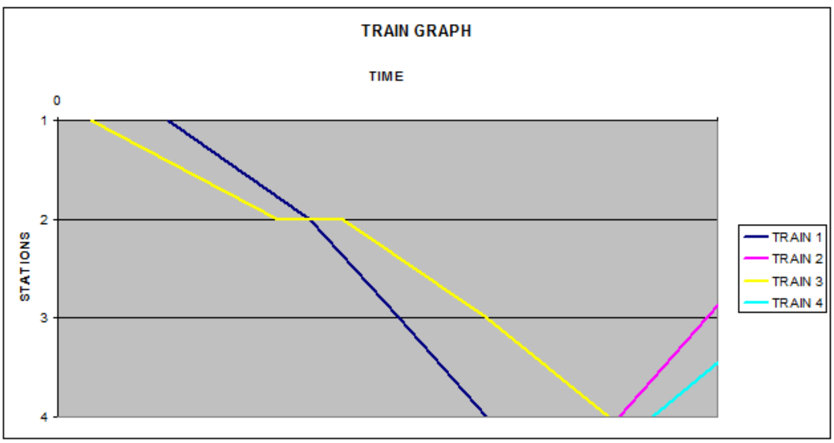


Figure 6. Overtaking Conflict Resolution by allowing Train 1 to overtake Train 3

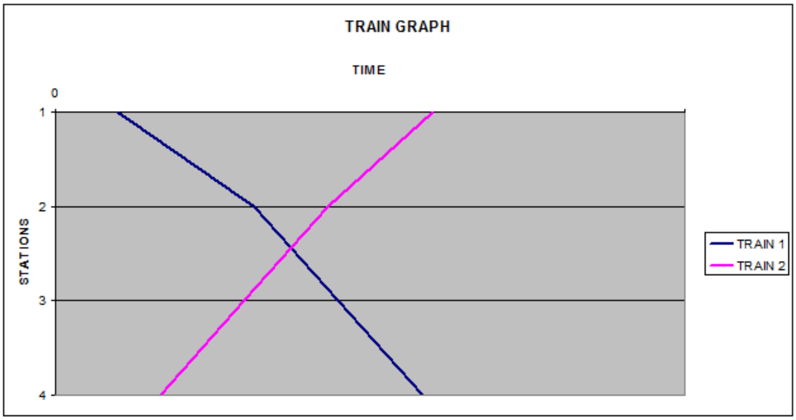


Figure 7. Meeting conflict between Train 1 and Train 2 in the mainline track section between Stations 2 and 3

Station/ siding capacity constraints: Suppose that a station has n parallel tracks. Clearly, this capacity is exceeded when n + 1 trains try to be present within the station in overlapping periods. All the cases where the number of eastbound and westbound trains add up to n + 1 should be enumerated for a complete modeling of the siding capacities. In general, siding capacity can be exceeded when there are i westbound trains (i = 0, …., n + 1) and $n+1-i$ eastbound trains. We will deal explicitly with two cases: (i = 0) and (i = 1). Note that, the problem is symmetric. The case with i westbound trains and $n+1-i$ eastbound trains is the same as the case with i eastbound trains and $n+1-i$ westbound trains, the only difference is that the number of trains in two directions are swapped, creating a case which is symmetric with the former. So, here, we include the cases where $i \leq (n + 1) / 2$ into the explanation. That is, there are more eastbound trains than westbound trains in consideration. Of course, the symmetric cases are also included when the model is coded into the solver.

Case 1: i = 0 for any n.

This means, siding capacity can be exceeded by n + 1 eastbound trains. The constraint that first comes to mind can be verbally expressed as follows: "Any eastbound train cannot overtake n trains at the same station, which has n parallel tracks." This is clearly true, because, if it tries to do so, n tracks will be occupied with n trains. The last eastbound train will need an $(n + 1)^{st}$ track to overtake all of them, which does not exist. However, although true, this is not a sufficient approach. In Table 1, an example is given. Suppose that Table 1 shows the arrival times (A_j) and departure times (D_j) of four different trains at (from) station 5, which has 3 parallel tracks (n = 3). In this case, these trains are bound for the same direction. It is clearly seen from table that, although there is no overtaking between any two of these four trains, between t = 126 and t = 128, all of the four trains are within the station during the overlapping time period. This is an infeasible movement and it must not be given as an output by the model. Feasibility can be guaranteed by the disjunctive constraint, whose verbal expression is as follows: "If any n + 1 trains in the same direction will use the same station with n parallel tracks, then, the last train into the station may enter the station only after the departure of first train to leave the station."

Case 2: i = n for any n.

This is the case that n eastbound trains and one westbound train (or vice versa) demands to pass through the same station, which has n parallel tracks. However, all of those n + 1 trains cannot be present within the station simultaneously. Furthermore, if such a meeting would occur, one of those n trains cannot be the last one to enter the station. Figure 8 illustrates this situation for n = 2. Two trains already arrived at the station and occupied all of the available tracks. Train 2 cannot enter and any of the odd - numbered trains cannot exit. This is a kind of deadlock situation.

Table 1. Sample arrival and departure times with respect to time 0

Train j	A_j (minutes)	D_j (minutes)
Train 1	120	128
Train 3	122	131
Train 5	124	134
Train 7	126	137

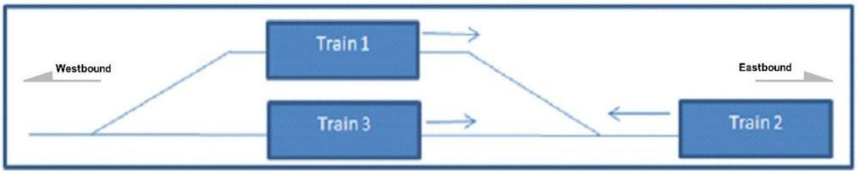


Figure 8. Train 2 cannot enter the station

Feasibility can be guaranteed by the disjunctive constraint, whose verbal expression is as follows: "If any n eastbound (westbound) trains and one westbound (eastbound) train are to meet at station s, then, the last eastbound (westbound) train into station can enter only after the departure of the first eastbound (westbound) train from the station." Figure 9 illustrates this situation for n = 2. In this figure, Train 3 is the last eastbound train moving into the station. Train 1 itself has to wait for departure until Train 2 arrives, thanks to the meeting conflict resolution constraints (which will be explained shortly). So, after Train 2 arrives, all of the tracks within the stations will be occupied. The disjunctive constraint will then keep Train 3 from entering the station until Train 1 clears the station, so there will be one empty track to accommodate Train 3.

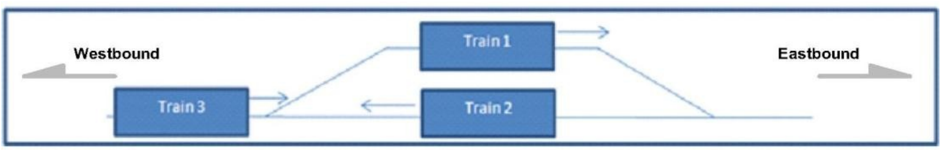


Figure 9. Feasibility will be guaranteed by forcing Train 3 to wait without entering the station until Train 1 leaves the station.

4. MATHEMATICAL MODEL

In this part, we provide some aspects of the mathematical model here. Instead of giving the mathematical model in symbolic form, we will explain it verbally. This is partly due to the tight page number limit.

Objective Function:

Objective function is a linear combination of delays of each (eastbound and westbound) train.

Minimum Departure and Arrival Time Constraints:

These constraints prevent any train from departing from the first station of its itinerary within the system before it actually enters the system (i.e. arrives at the first station).

Minimum Running Time Constraints:

These constraints enforce the minimum running times between the adjacent stations.

Minimum Dwell Time Constraints:

These constraints enforce the minimum dwell times of the trains as required by the timetable. If no dwell is required at a particular station or there is no timetable at all, these constraints are still needed. This time, they enforce the train continuities. Any train cannot depart from any station before arriving at that station. Departure times are not defined for the last stations of the respective trains' itineraries, nor dwell time constraints.

Following and Overtaking Constraints for Eastbound Trains:

These constraints guarantee that, a headway will always be maintained between any two consecutive eastbound trains. Also, they prevent overtaking on the mainline track sections and guarantee that overtakings can occur only within stations / sidings.

Following and Overtaking Constraints for Westbound Trains:

These constraints guarantee that, a headway will always be maintained between any two consecutive westbound trains. Also, they prevent overtaking on the mainline track sections and guarantee that overtakings can occur only within stations / sidings.

Forcing Meeting Constraints:

These constraints ensure that, each train couple will meet once and only once.

Meeting constraints:

These constraints dictate that, if an eastbound train and a westbound train meet at a station, arrive - depart headways will be maintained between them. These constraints also enforce that meetings can occur only within the stations/sidings.

Station / siding capacity constraints:

These constraints work as explained in Section 3.

5. NUMERICAL EXPERIMENTS

The model has been implemented on a hypothetical railway line with 18 stations. In Figure 10 an optimal solution of a problem instance with 4 eastbound and 3 westbound trains is shown.

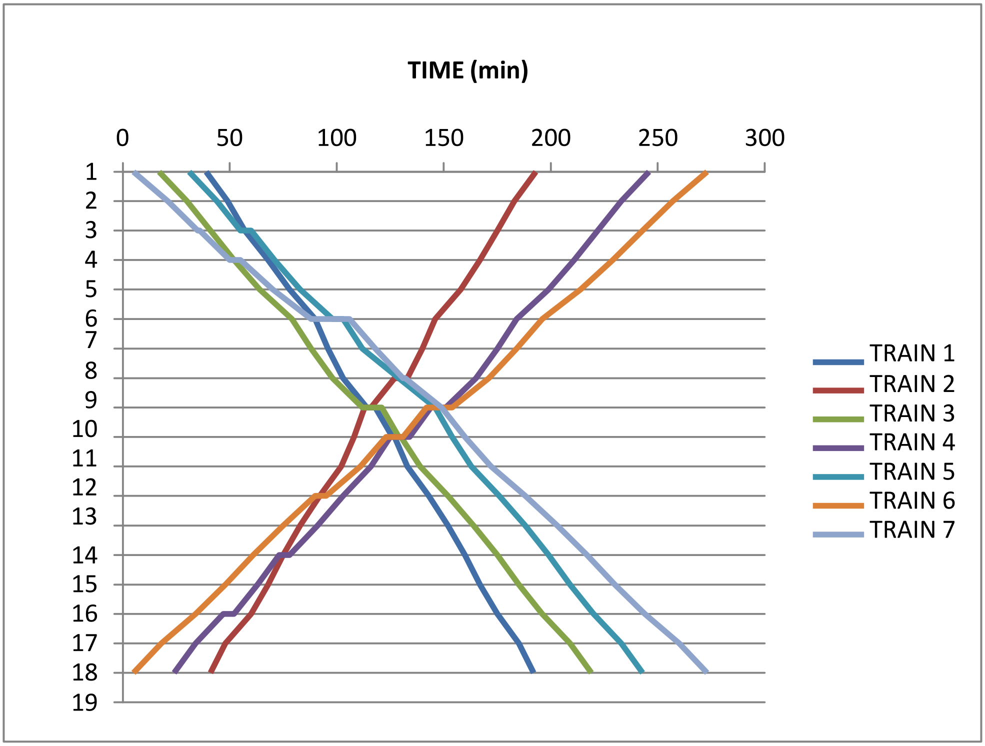
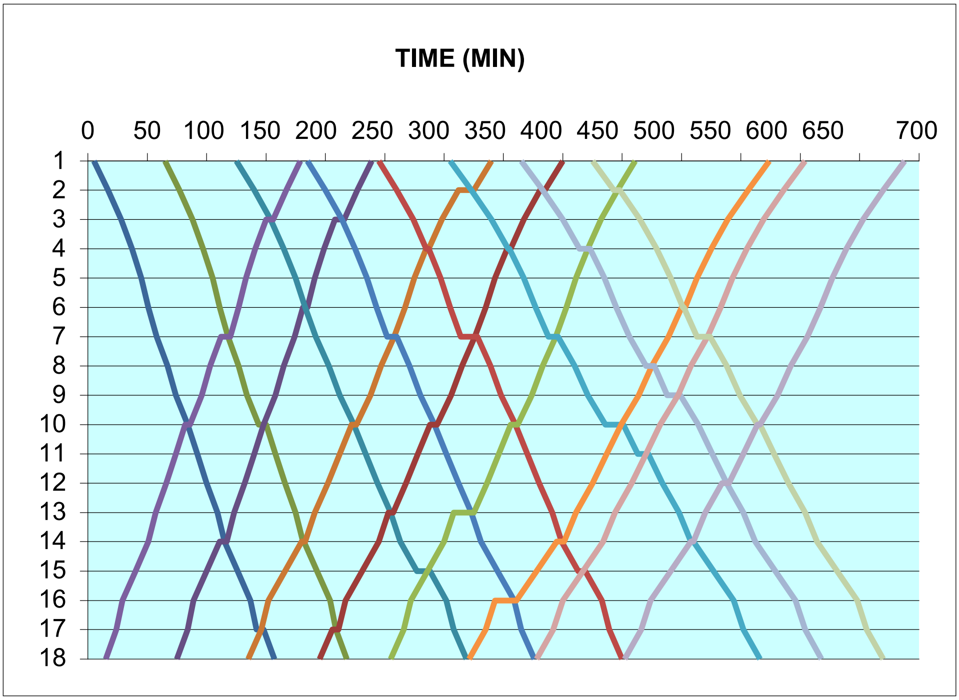


Figure 10. The optimal solution of a 4 + 3 instance

In Figure 11, an optimal solution of an 8 + 8 is given. The figures above show that, the model can solve the problem to optimality without leaving any unresolved conflicts.



6. RESULT AND DISCUSSION

In this study, the foundations of train rescheduling on a single - track railway line are given. These are strictly required to implement a mathematical model for train scheduling. Train scheduling problems are usually modeled as mixed integer linear programming problems. Explanation of the constraints showed that, precedence relations are needed between trains, like, which train will use the track segment before which. Train scheduling problem is far from being solved when it is modeled as a mixed - integer linear program. Indeed, everything starts here. Like almost all scheduling problems, this is also an NP - complete problem and needs heuristics to be solved properly in a reasonable amount of time. Some speed up heuristics are also developed to support the model, as part of this work. Future publications will include these heuristics, together with the associated results.

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