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Increasing the Safety Level in the Public Transport Sector

An Application to Support Decision Making in a Rail Network

Abstract: One of the main requisites for any public or private company operating in the transportation sector is to comply with high safety standards, besides providing to customers adequate service levels such as punctuality, comfort, reasonable prices and limited environmental impact. Those aspects are particularly critical within the public transport sector when dealing with passengers. To allow each passenger to reach its destination safely, public utility companies and/or private operators should built and maintain safe transport networks. Most of the time, to increase the overall service levels and or to comply with more stringent safety regulations, significant investments on modern technologies or infrastructure are needed. In fact, such safety investments could have significant impact in preventing accidents from happening or in reducing the consequences of such unwanted events. In this work, an optimization model is developed to support decision makers aimed at increasing the overall safety levels in a rail network. The model could be effectively used to select the optimal mix of safety measures depending on the specific features of each rail segment and given some major constraints such as a maximum budget and a strict deadline to complete the installation works. In addition, the user could use the model as a simulation tool to verify the impact on safety of different safety budgets and time horizons to support and/or influence public authorities when allocating priorities on different projects and finally make public investments more effective for citizens

1 Introduction

In this work, safety related aspects of transport networks are studied. In particular the main focus is devoted to rail networks. Nevertheless, with small adaptations the work can be easily extended to other types of transportation networks.
Rail transport is a land transport mode in which passengers and/or goods are transferred from a train station (or freight facility) to another one, by the mean of wheeled vehicles running on tracks. Rail networks represent one of the main logistics backbone for a nation economy making possible the transport of passengers and freight with limited environmental impact (on average 0.19 kg of CO_2 per passenger mile) and relatively low transportation costs.
In many countries, and especially in Europe, transportation operations are mainly carried out by public/private railway operators, while the rail infrastructure, thanks to which transport services are offered, is managed by public utility companies which are most often directly or indirectly controlled by the government. Therefore, public investments are most of the time subject to stringent budgetary and time constraints.

Most of the time, when dealing with public transport, safety is given as granted by passengers which, besides reaching their destination on time, expect comfortable journey. In general rail transport is one of the safer transportation mode. Nevertheless, accidents, despite being sporadic events, might results in major consequences [1]

For example a major rail disaster happened in Viareggio (Italy) in 2009 when a train carrying Liquefied Petroleum Gas derailed while transiting through the railway station of the city. The spill of the hazardous material triggered an explosion with subsequent fire that killed 30 people living in the nearby of the station. The accident also destroyed some buildings close to the railway station with the temporarily disruption of the rail services between Central and Northern Italy along the west coast.

An investigation is still examining the root cause that triggered the accident, even if the most likely reason is to be attributed to a structural failure of a wagon as well as damaged tracks. Another dramatic event happened in 2013 in Santiago de Compostela (Spain) as a consequence of a derailment of a passenger train. The accident caused that around 140 passengers were injured and 79 died. With high probability the cause of the accident is to be attributed to the speed of the train which was about two times higher than the limit. In February 2010, 18 people died and almost 100 people were injured by a collision of two trains in Brussels (Belgium). Also, in Belgium in May 2013, an explosion of toxic chemical goods carried in a train that derailed killed one person with almost 50 injured. More recently, in 2016, in Southern Italy a head-on collision between two trains travelling on the same single-track line caused dozens of injured with 25 people dead. It seems that the root cause of such accidents is due to a human error as well as possible failures in the rail network infrastructure.

Those examples are quite emblematic since a more effective rail infrastructure could have significantly mitigated the consequences of such episodes or even prevented those events from happening. Public and private companies which are responsible of the rail network are often accountable for the safety conditions of the rail network. Therefore they should maintain and improve the efficiency and effectiveness of rail operations subject to limited budgets as well as investing in safer infrastructure by adopting more effective safety measures such as train inspection systems, signaling systems and so on.

In many cases safety budgets are constrained and significant prioritization efforts are needed focusing on the most impacting projects aimed at increasing the overall safety levels in a rail network. In addition, due to safety regulations, installation works are to be completed by a certain time horizon. In many cases, due to the strict deadline on the utilization of public funds, budget expenditures are not allowed if deadlines are passed. Moreover, when dealing with complex and quite extended rail networks, especially if several stakeholders are involved, decision making might be really challenging [2]

For those reasons, methods and models from operations research are borrowed to deal with the inner complexity of the safety-related problem, such as also illustrated in Vromans et al [5]. More specifically an optimization model is developed in this paper to support decision making, while selecting appropriate safety investments for each network segment. Those investments are represented by a single or a combination of safety measures which are compatible with the rail segments on which they are installed. The goal is to increase the overall safety level of a whole transportation network.

In the next Section the problem is described in more detail, while in Section 2 a specific application of the model to a rail network is described. Section 3 concludes the work and proposes some interesting paths for future research.

2 Problem description

The research question that is addressed in this work is mainly related to the risk reduction in a railway network. A railway network has been modelled by using a Set of railway segments or tracks denoted by letter N. For each segment $i \in N$ some features are available such as r_i which represents the initial risk level associated to rail segment i; s_i which denotes the maximum number of signals allowed on rail segment i and l_i which represents the length of the segment i. The risk index is pre-defined for each rail segment and assessed by risk experts depending on the specific features of the associated tracks such as maximum allowable speed, length, number of passengers, number of trains per km, and so on.

Moreover, a set of safety measures denoted by letter M is available. Each safety measure j is characterized by a cost c_j expressed by euro per Km depending on the rail segment on which it will be installed; e_j which denotes the risk reduction capability associated to safety measure j; w_j which represents the amount of time in weeks needed to install safety system j. fs_j which is the minimum number of signals needed by safety measure j to operate. Moreover, A represents a compatibility matrix with element $a_{ij} \in A$ equal to 1 if safety measure j is compatible with rail segment i, 0 otherwise $\forall i \in N, j \in M$. The compatibility matrix A is pre-defined based on the available information about the rail segments in the network and their features. Finally, B represents the safety budget, while T is the maximum time limit expressed in weeks. Those latter represent inputs of the problem that should be provided by the user. By changing these parameters, decision makers can generate different investment scenarios. The decision variable x_{ij} $\forall i \in N, j \in M$ is a binary variable equal to 1 if safety system j is installed on rail segment i, 0 otherwise.

The objective of the problem (1) is to minimize the overall network risk. A factor a_{ij} is used to take into account the compatibility of the selected safety system with the rail network.

$$\min \sum_{i=1}^{N} r_i \cdot \left(1 - \sum_{j=1}^{M} e_j \cdot a_{ij} \cdot x_{ij}\right) \tag{1}$$

The problem is subject to the following constraints:

$$\sum_{i=1}^{N} \sum_{j=1}^{M} c_j \cdot l_i \cdot x_{ij} \le B \tag{2}$$

$$\sum_{i=1}^{N} \sum_{j=1}^{M} w_j \cdot x_{ij} \le T \tag{3}$$

$$\sum_{j=1}^{M} fs_j \cdot x_{ij} \le s_i \cdot \sum_{j=1}^{M} x_{ij} \qquad \forall i \in N \tag{4}$$

$$\sum_{j=1}^{M} x_{ij} \le 1 \qquad \forall i \in N \tag{5}$$

$$x_{ij} \in \{0,1\} \qquad \forall i \in N, j \in M \tag{6}$$

Constraint (2) represents the so called budget constraint forcing that the total investment in safety systems is not greater than the maximum available budget. Constraint (3) imposes that the total number of weeks needed to install the selected safety systems in the whole rail network cannot be greater than a total time limit. Constraint (4) denotes a set of technical constraints. In particular, safety measures should be compliant with the rail segment in which they are installed. This compatibility is based on the maximum number of signals that the rail segment can transmit. The number of signals of a safety measure cannot be greater than the number of functioning signals for the associated rail segment. According to Constraint (5) on each rail segment at maximum one safety measure can be installed. Constraint (6) defines the domain of the decision variable.

3 Simulation

The problem stated in the previous section has many features in common with the well-known category of knapsack problems. The latter are general combinatorial optimisation problems in the operations research field. A comprehensive survey on all aspects of the knapsack problem was given by Kellerer et al [4]. In a classical knapsack problem a set of objects is available, each item presents a given weight and a value. Decision maker has to select the objects to include in the knapsack itself, which presents a fixed-size, in order to maximize the total value and make sure that the total weight is not greater than the limit of the knapsack.
The problem studied in this article is therefore a variant of the knapsack problem in which the effective safety systems which are able to produce the highest risk reduction effects are to be selected given some technical constraints, a fixed safety budget and a strict deadline.

The mathematical model has been coded in JAVA language and IBM CPLEX solver [3] has been used to find optimal solutions. Several simulations have been run by testing the effects on the solutions of different values of the maximum budget B, and the time limit T and assuming different levels of compatibilities between rail segment and safety systems by adjusting matrix A. Moreover, two instances have been tested with a different number of safety measures and number of rail segment (*case 1 with* $|N| = 412$ and $|M| = 7$; case *2 with* $|N| = 992$ and $|M| = 4$). As expected the higher the number of rail segments and safety measures, the higher the complexity of the problem and thus the computation time.

For each solution the model provides for each rail segment, the selected safety measure and the resulting risk associated to the rail segment is expected to be equal or lower than the initial risk value.

Assuming levels of compatibilities equal to 100% compatibility between rail segments and safety measures, the relationship between the overall impact on the safety levels are shown in Figure 1 considering the larger instance (case 1). On the vertical axis it is shown the risk reduction capability expressed as percentage reduction versus the initial network risk level which has been measured by summing all risks index associated to the rail segments in the network ($\sum_{i\in N} r_i$). As it can be seen, the higher the max time limit and the max budget, the higher the risk reduction potential. However, it can be observed that the marginal effect on the risk reduction are decreasing when the budget and or the time limit is doubled.

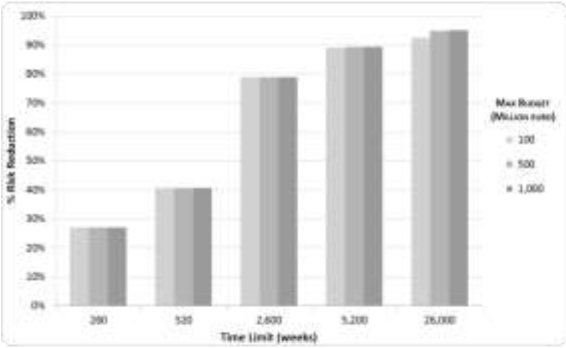

Fig. 1: Impact on solutions of different budgets and time limits.

4 Conclusions

The optimization model developed in this work can be effectively used to support decision-makers from railways infrastructure companies to deal with safety investment decisions. To this end, the model produces an optimized scenario based on specific constraints such as time horizon of the investment, safety budget and compatibility levels. The goal is to select for each rail segment the most appropriate safety measures maximizing the resulting overall safety levels within complex railway networks. The model can be used as a simulation tool testing how the outcome varies depending on the input variables.

Further research could be aimed at incorporating additional features into the model such as the impact of rolling stocks on the safety decision by measuring all interdependencies between trains that can roll over the network and each rail segment. In addition, different measures of risk could be used and their effects on solutions could be compared.

Finally, the model can be adjusted and extended to other transportation networks capturing all specific features of each transport mode.

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