Minimising economic losses due to inefficient rescheduling*

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Abstract

This article sets out a procedure that enables a monetary rating of conflict-resolution scenarios for train services to be conducted by coupling simulation procedures from railway operations research with mode-choice models. Such an approach has only previously been adopted for strategic network planning. Forms of conflict resolution have hitherto had no account to the implications for end-customers.

Forming the basis for monetary ratings are the delays suffered by resolved train-running conflicts. These delays are established for given train priorities using the LUKS-S software tool and serve as input variables for mode-choice models.

Delays suffered by trains influence the mode of transport selected by the end-customer. The modal split thus computed reflects demand for the rail mode and is called upon to determine revenues. Revenues are set against variable costs to form a contribution margin per train run. Changes in the contribution margin are extrapolated by comparison with delay-free timetable conditions.

How trains are prioritised impacts on the decisions taken to resolve a conflict and hence also on the ensuing delays. Forms of conflict resolution can be rated monetarily. A conflict can thus be resolved most effectively, where the change in contribution margin is minimised.

Keywords

Mode-choice model · Monetary rating · Operation simulation · Railway Operations · Rescheduling
1 Introduction and Project Remit

The railway system is such as to allow a train move to be portrayed by means of a distance-time curve. Located along the curve are blocking-time segments that together form a stepped blocking-time series. This model is adopted to compute levels of track occupation on railway infrastructure. Each blocking-time segment represents occupation by a train run of an infrastructure element. Infrastructure can only be occupied by one train run at any one time, meaning that any other simultaneous train runs have to be prevented [1], [2]. Duplicate track occupation may occur during timetabling, however, where there is simultaneous demand for paths. The same applies during running as a result of possible delays. The ensuing track-occupation conflicts then have to be resolved.

The present paper sets out a procedure for conducting a monetary rating of conflict-resolution scenarios in railway operations. Measures of this kind have only been rated for operational purposes hitherto. The emphasis here is on viable, smooth-running rail services as well as on a robust timetable. Priorities for train runs are frequently awarded in a conflict-resolution algorithm. They are mapped with the aid of ranking numbers that cause high-ranking trains to be given precedence over lower-ranking services [3], [4], [5]. This is a course of action that can be adopted at both the scheduling and operating stages. Further approaches exist besides this ranking-based form of conflict resolution that apply different decisional criteria to the prioritisation of trains. They are summarised by [6].

In the procedure set out here, conflicts are to continue to be resolved on the basis of train priorities. Both at the scheduling and operating stages, conflict-resolution measures generally give rise to waiting times for the lower-ranking train. These waiting times can be determined with the aid of railway operations research methods and are a key variable in the dimensioning of railway infrastructure and gauging of quality. Waiting-time totals are confined to a route section or node where the application of quality benchmarks is concerned.

No account has hitherto been had to end-customers when rating the waiting times computed. This is remedied under the present approach by coupling railway operations research methods with mode-choice models. Existing approaches with this kind of coupling are only adopted in the sphere of strategic network planning for long-term planning horizons. Use is made there of analytical methods to establish waiting-time totals on the basis of macroscopic infrastructure and train data, which is applied by Deutsche Bahn, for example (totals that likewise serve as input variables for determining the modal split for rail in macroscopic mode-choice models). It is possible in this way to map long-term end-customer responses, which has been used by London Underground’s network as long ago as the early 1990s. Many works with regard to the impact of delays on demand for rail transport relate mostly to the use of elasticities based on different time periods [7], [8], [9], [10], [11].

The present approach considers a railway-operations procedure that analyses individual conflict-resolution scenarios and their impact on the end-customer. The aim continues to be to couple this with mode-choice models. In shifting the focus to individual conflict-resolution scenarios, however, use is made of a simulation procedure that functions at the microscopic level and hence delivers delay characteristics exactly determinable in space and time. There is thus no longer any direct scope for coupling with mode-choice models. Adjustments accordingly have to be made to the methods and influencing parameters adopted.

2 General Procedure

The conflict-resolution algorithm continues to be based on the application of priorities. Whereas the allocation of train priorities has hitherto depended on the trains’ urgency, type or travelling speed, however, the responses of end-customers are additionally to be addressed under this method. This is done by establishing contribution margins
comprising the revenues and variable costs of train operating companies (TOCs). The approach subdivides into the three modules “traffic simulation”, “mode-choice model” and “contribution costing” (cf. Fig. 1), which are run in several loops.

Accurate predictions of anticipated conflicts can only be made on the basis of microscopic infrastructure and train data. Assessments of end-customer flows over specific point-to-point routes in the railway network are similarly necessary. A single train run is likely to incorporate a multiplicity of such point-to-point routes. They each display distinct properties and need, therefore, to be considered separately. It is essential that this greater volume of data be readily comprehensible, clearly structured and manageable.

The repercussions of conflict-resolution measures in the form of delays to the trains involved serve as input variables for the macroscopic mode-choice model. Competing modes of transport are considered with a view to establishing the mode passengers choose on the point-to-point routes under review (cf. Section 4). The modal split thus arrived at serves as an input variable for computing TOC revenues along with further train class-specific values. The variable costs of train runs are additionally established as a function of distance travelled in a given time.

Contribution margins are computed for each train and conflict arising under this method as well as overarching for diverse awards of train priorities. Computations are conducted both under non-conflicting timetable conditions and for a delay scenario necessitating conflict-resolution measures. It is subsequently possible to call upon the contribution margin for the purpose of effecting monetary ratings of train-move delay minutes, conflict-resolution scenarios and modified train priorities. An illustrative application of the method is detailed at the end of this paper.

3 Simulating Railway Operations

The repercussions of conflict-resolution measures are expressed for monetary rating purposes in the form of delays. Conflict-resolution measures can generally take a variety of forms that give rise to waiting times of differing duration. The trains involved in a conflict can be accurately determined and thus it is also possible to precisely allocate said conflict’s repercussions. Underpinning the process are microscopic infrastructure and train data.
3.1 The LUKS-S simulation tool

The LUKS® railway operations research tool (the German title translates as Analysis of Nodes and Lines) is adopted as a means of quantifying delays for specific trains. LUKS® is used as a standard tool for capacity issues by DB Netz AG, Germany’s Federal Railway Authority and others. It is made up of several modules. In addition to conducting investigations on a simulation basis with LUKS-S, it is likewise possible to adopt compilatory (LUKS-K) and analytical (LUKS-A) methods [12]. LUKS-S allows the two process levels of the scheduling and railway operations to be simulated on the basis of microscopic conflict-resolution scenarios. The infrastructure utilised in this paper draws on a generic mixed-traffic line with uniform block, station and passing-track distances as well as on a predefined utilisation level and line speed.

It is a simple example to develop and introduce the new method of the monetary evaluation. It can be assigned to a real model area, for which the amount of database as well as the whole procedure get larger and more complicated. This applies to the simulation of railway operations as well as the mode choice calculation. The revenues are estimated for each single route of end-customers and also get more complicated, especially with regard to the amount of database.

Fig. 2 illustrates part of the standard line modelled. The maximum line speed is 230 km/h. There are a total of four larger stations at which passengers can board and alight. The interchange stations are 40 kilometres (25 miles) apart. Passing stations are positioned at ten-kilometre intervals between these nodes that can facilitate potential passing events for conflict resolution purposes. Both the infrastructure and aspects of the various train types such as their design series, number of coaches, ride dynamics, delay properties and ranking number are considered.

The input data upon which traffic simulation is founded are a non-conflicting timetable and the delay characteristics for specific train types. The level of delay is the sum of the probability of a delay arising and average delay per train type. This is used to pinpoint what are known as initiating delays that disrupt the non-conflicting timetable for each individual train run with the aid of an attendant probability distribution function [20]. Initiating delays can be of differing levels, breaking down into “imported” and “initial” types. Imported delays whereby trains enter a network section at a different time than that originally scheduled are suffered significantly more frequently. Their origins lie outside the network section under review but are causally linked to it. Initial delays, by contrast, are less frequent, arising within the network section under review as a result of damage or disruption to systems, crews or vehicles [2].

Delays can be introduced so as to trigger conflicts between different trains. LUKS-S simulates the rescheduling process by first detecting and subsequently resolving conflicts. Various means of resolution are available to this end (cf. Section 3.2).

Modified awards of train priorities can lead to different means of resolution being adopted. They are only ever sought for the one disruption scenario into which given delays have been introduced, however.

LUKS-S facilitates the rating both of individual simulation exercises and several simulation runs together [12]. This is necessary, since the coupling with macroscopic mode-choice models envisaged here involves simultaneous use being made of individual delays arising from individual conflict-resolution scenarios and of empirical values from average delay totals. Overall, the simulation tool yields a large amount of output data containing microscopic details of infrastructure, itineraries, train characteristics, disruptions and conflict-resolution scenarios. These serve as input.
parameters for mode-choice models and contribution costing exercises.

3.2 Approaches to resolving conflicts in railway operations

The simulation tool deployed adopts a variety of approaches to resolving conflicts between two train runs. Conflict resolution is fundamentally on a priority basis, thus allowing the repercussions of measures to be channelled. With conflicts being resolved down to the level of single trains, there is scope for directly comparing the priorities of the two train runs affected and for deciding which train is to have delays imposed upon it. Delay types of this kind that arise on account of interactions between trains are referred to as knock-on delays. A variety of conflict-resolution measures can be adopted in concert with the infrastructure under review.

Conflict-resolution measures can give rise to changes in either the itinerary or timing of the scheduled train journey or, indeed, to both. There are four common means of returning as closely as possible to the normal condition, to wit: modulation by means of recovery allowances, parallel displacement of the time-slot, dwelling time extensions and passing stops [21].

The conflict-resolution output file explicitly details the kilometric position at which a given change of timing occurs for the train run. It is thus possible to assign any requisite delays regardless of the route section or node at which they arise. Table 1 contains a sample extract from the output file listing conflict-resolution scenarios from a simulation run. The train numbers and node names are wholly fictitious.

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Extract from output file</th>
</tr>
</thead>
<tbody>
<tr>
<td>Train number</td>
<td>Time</td>
</tr>
<tr>
<td>IC 200/4</td>
<td>07:57:18</td>
</tr>
<tr>
<td>IC 200/4</td>
<td>08:19:02</td>
</tr>
<tr>
<td>IC 200/4</td>
<td>08:19:02</td>
</tr>
<tr>
<td>IC 200/4</td>
<td>08:19:02</td>
</tr>
<tr>
<td>IC 200/4</td>
<td>08:59:42</td>
</tr>
<tr>
<td>IC 200/6</td>
<td>08:59:42</td>
</tr>
</tbody>
</table>

The ensuing knock-on delays have differing implications for end-customers depending on where they occur. The method presented continues to operate with train priorities. In the event of a conflict, the lower-ranking train usually suffers an enforced delay. The trains’ ranking numbers are, however, varied in subsequent simulation runs so as to enable different means of resolving the conflict to be found for the same disruption scenarios and trains.

4 Modal Choice Models

Mode-choice models allow pronouncements to be made regarding the percentage distribution of passengers or goods amongst various modes of transport. The outcome is what is known as the “modal split”, which serves to map patterns of demand in the transport market. If the quality of service provided by a mode of transport rises, demand for it will likewise rise. Shorter running or waiting times have a crucial impact upon quality of service. The modal split is able to take account of the interaction between competing modes of transport with differing qualities of service.

The influencing parameters and models for establishing the modal split and modes of transport available divide for choice-of-mode purposes into local passenger, long-distance passenger and freight services. Use is accordingly made of
a variety of mode-choice models within the framework of the project.

4.1 Models adopted for passenger train services

Usually elasticities are applied to map long-term end-customer responses in public transport. They describe the change of demand depending on different influencing variables, for example costs, delays, carriage time. To describe macroscopic and strategic approaches long-term elasticities are applied, whereas effects on smaller timescales are modelled using short-term elasticities, for example conflict resolutions. They differ in a significant level [12], [13], [14], [15], [16], [17], [18].

Whilst the mode-choice model for freight traffic is based on elasticities, the demand of passengers is calculated by means of transport resistances, which represents a new kind of mode-choice model [22], [23], [24]. Resistance-driven mode-choice models are used to establish a modal split in passenger services for specific point-to-point routes. Different service features of competing transport modes as well as the passenger’s journey for each mode are considered separately. At their heart is a travel resistance comprising objectively gaugeable service features and the passenger’s attendant subjective time ratings. It is measured in units of resistance.

\[
r = t \cdot TRF(t)[UoR]
\]  

where
- \( r \): resistance [UoR]
- \( t \): time [min]
- TRF (t): time rating function (as a function of t) [-]

The overall course of a passenger’s journey is seen as being a chain of resistances embracing pre-carriage to point of departure, main leg of journey and post-carriage to final destination. The long-distance transport model [22], [23] is more complex than its local transport counterpart [24]. The travel chain for a long-distance train journey is illustrated in Fig. 3. Alongside straightforward time-elements, consideration is additionally given to resistances deriving from cost, obtaining travel information and any overnight accommodation required.

![Fig. 3 Traffic-resistance chain of long-distance transport](image)

The subjective time ratings are verified by different projects for German cities and councils (not published) as well as for long distance travel [22]. The TRF have general validity and have not to be generated for each single route. The combination with objective time and cost data provides an easy access to data without required surveys.

Operating with resistances enables individual service features to be reviewed separately. Each competing mode of transport has its own chain of resistances. The present method confines itself to reviewing rail traffic and private motoring. The overall resistances for the various modes of transport are compared and contrasted to this end to establish the respective modal split.

All single resistances are summarised to the overall resistance for each various mode of transport. They are compared
and contrasted to establish the respective modal split by using Eq. (2).

\[
MS_i = \frac{1}{r_{ov,i}} \sum_{j=1}^{r_{ov,j}}
\]

(2)

where
MS: modal split [-]
r: overall resistance for each single transport mode [UoR]
i: transport mode

Key service features from a rail viewpoint are carriage time as per the timetable, intervals and any waiting time involved. Both models operate with average values for specific point-to-point routes. The attendant time rating displays an underlying tendency to develop exponentially as a function of time. Thus, higher time values are given a significantly more negative rating than low values. Each resistance reveals differing time-rating functions. Waiting time, for instance, is rated as being more negative than carriage time. Differing travel purposes are similarly accorded a variety of time ratings.

Business, commuter, leisure and holiday purposes are considered. As a consequence each resistance of the travel chain has four different time rating functions. It is also valid for waiting times at the platform which include delays at beginning of the journey. The correlations involved can be gleaned from Fig. 4.

![Fig. 4 Time rating function of average waiting time](image)

The waiting time is self-chosen by the passenger depending on the travel purpose. Passengers orientate themselves to the offered frequency of the train. The delay at the beginning of the journey is added to these waiting times and rated by
the passengers. By using the TRF and their exponential curves it is crucial at which level of the waiting times an additional delay occurs. Thus there is not only a rating of the delay but of the increase of waiting times, as well.

Delays that arise when resolving conflicts equate to changes in service features. Locating where they arise in space is of prime importance when transferring them from the simulation tool to mode-choice models. A distinction is made between whether the passenger suffers the delay on the platform or on the train. The two delay types are rated differently by the passenger, since in the one case they are moving towards their destination whilst in the other they are required to wait at one point. The different time ratings are ensured by matching the two delay types to the related resistance. This is established separately for each travel purpose and each possible point-to-point route.

Deviations in service parameters cause individual resistances to alter. Hence, the modal split for the mode of transport under review varies too. The impact of delays arising from resolution of a conflict under traffic simulation conditions can accordingly be quantified via the modal split. They cause the attendant resistance to rise and rail’s share of the modal split to fall. Demand for services drops on this point-to-point route, and this is reflected in a future loss of passengers.

The method does not rate delays for their own. Instead they are matched to the related resistance and are rated together either with the waiting time at the platform or with the carriage time, depending on where the delays occur. In regard to the exponential curve it is crucial at which level of the related times the delays occur. In this way a delay of five minutes is not always rated the same. If the carriage time accounts for e. g. ten minutes, a delay of five minutes will get a worse rating than if the carriage time has a value of five minutes.

In Fig. 5 and Fig. 6 two developments of modal split for a single example of long-distance travel are shown. It deals with the route from node A to D with regard to the model area in Fig. 8 and assumes only one type of occurring delay (at the platform or inside the train).

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**Fig. 5** Modal split depending on delays at the platform [own diagram]
Other examples including their route-specific features would have their own development, especially for short-distance travel. The final calculation of modal split combines the different level of both resistance types, depending on the location where the delay occur.

### 4.2 Model adopted in railfreight traffic

No resistance-driven model exists for freight traffic. It is not therefore possible to conduct a detailed review of various service parameters as for passenger services. The model approach selected operates on an elasticity basis. A correlation is produced between percentage changes in haulage time and rail’s share of the modal split. Sequences are in place for establishing the modal split as a function of freight category, cargo size and haulage distance [25]. They draw on the unpublished results of a survey conducted in 1988. Resort is had to this approach owing to the dearth of data available and to the resultant difficulty of adopting mode-choice models in freight traffic. By analogy with passenger services and the various travel purposes, freight traffic is likewise divided into different freight categories as a means of factoring in variations in sensitivity to delays. The elasticity functions in place (cf. Fig. 7) can be applied to a variety of statistics from the freight traffic sphere so as to extrapolate a representative modal split covering all available freight categories, cargo sizes and haulage distances. The change in haulage time brought about by the delay imposed is established to this end.
There are of course newer models to describe the demand in railfreight traffic depending on delays [26], [27], [28]. Their use in practice is mostly restricted by the lack of available survey data and a gauging of estimated parameters.

5 Coupling Microscopic and Macroscopic Model Types

Coupling microscopic and macroscopic model types necessitates making adjustments to the parameters to be transferred. The key variable takes the form of the ensuing knock-on delays engendered by forms of conflict resolution generated by the simulation tool. With the modal split being computed on the basis of average values as well as of service parameters of a general nature in the macroscopic model, the delays established only have a very limited influence as individual events. Under this method, however, it is the rating of individual conflict-resolution scenarios that is considered, rendering it necessary to quantify the influence of an individual delay more precisely. This is done by combining individual and average delays of differing weightings. Weighting is performed adopting one coupling parameter per delay element (cf. Eq. (3)).

\[
t_{mcmm} = \alpha \cdot \bar{t}_d + (1 - \alpha) \cdot t_{id}
\]

where
- \( t_{mcmm} \): input parameter for mode-choice model [min]
- \( \alpha \): combined parameter for average delay [-]
- \( \bar{t}_d \): average delay [min]
- \( t_{id} \): individual delay arising from conflict resolution [min]

Average delays can be established either on the basis of an acceptably high number of simulation runs or with direct reference to statistical delay data for the network section under review. Use is made of the former under the present method, with 100 simulation runs being conducted. This allows end-customers’ own experiences to be factored in. If
past experience reveals specific trains to be frequently delayed on selected point-to-point routes, then the choice of mode will already have been influenced. Average delays are thus included as additional service parameters in the mode-choice model, serving as a means of defining end-customers’ underlying transit behaviour on a given point-to-point route. The output level of the modal split is thus established taking account of average delays.

Any individual delay arising when a conflict is resolved constitutes an additional delay for which the end-customer is not prepared. It alters the general average level of delay and hence also the underlying choice of mode. Of crucial importance at this juncture is the size of the additional delay relative to that already in place. The impact of any additional individual delay is determined by the nature of the initial average delay. The mode-choice models used for passenger services here take account of this differential by means of exponential time-rating functions. The conflict resolutions and the ensuing delays can be exactly matched to train, time and location of occurrence. Passengers recognise this either at the platform or aboard the train. The single event of one conflict resolution will be mixed with an average delay to adjust the two different levels of time rating (cf. Fig. 4).

In a supplementary step, the two delay characteristics are not transferred to the mode-choice model in toto but are varied in accordance with their weightings. This is performed via the coupling parameters, which can be custom-adapted to various attendant factors such as time of day, train class, travel purpose etc.

The passengers themselves are not necessarily cognisant of the decisions being made by the dispatcher. They only recognise the perceived outcomes in the form of delays. The delays can be matched to the caused conflict resolution without the direct knowledge of passengers.

6 Economic Repercussions of Resolving Conflicts in Railway Operations

The monetary rating is evaluated for each set of rankings awarded with the aid of a tool developed in-house. Modifying the ranking numbers in the simulation tool whilst leaving the disruption parameters unchanged gives rise to differing conflict-resolution scenarios that yield differences in knock-on delays, revenues, variable costs and, hence, contribution margins. The ideal economic solution is subsequently arrived at by comparing changes in the contribution margin for all ranking awards under review.

It is thus a question of finding the conflict-resolution scenario and attendant rankings awarded that displays the least change in contribution margin relative to timetable conditions. This rating objective is achieved by adding up the changes in contribution margin for all trains involved in the conflict. It is, however, similarly possible by raising the degree of detail to produce monetary ratings for delays to specific trains.

It is possible via the sum of changes in contribution margin for all conflicts arising within the period and sections under review to produce monetary ratings for all rankings awarded. How trains are prioritised impacts on the decisions taken to resolve a conflict and can now be re-examined bearing end-customers in mind.

6.1 Contribution costing

Monetary ratings of conflict-resolution scenarios are produced with reference to the contribution margin, which is taken to be the differential between revenues (cf. Section 6.2) and variable costs (cf. Section 6.3) for a train. Fixed costs do not figure in the equation. Both trains involved in the conflict are rated in this way. The sum of the totals thus arrived at yields the monetary rating of the conflict-resolution scenario in question. The correlation is illustrated in Eq. (4) and (5).
\[ CM_i = R_i - \text{var } C_i \]  \hspace{1cm} (4)

\[ CM_{cr} = \sum_i (CM_{cr,i}) \]  \hspace{1cm} (5)

where
CM: contribution margin
R: revenues [EUR]
var C: variable costs [EUR]
cr: conflict-resolution scenario
i: trains involved

Reference scenarios are reviewed for the purpose of explicitly applying the contribution margin to a conflict-resolution scenario. Railway operations with their potential delays are juxtaposed with non-conflicting timetable conditions. Thus, in a further step, any change in contribution margin brought about by a given conflict-resolution scenario is established. The potential for forgoing the superfluous task of establishing fixed cost constituents considerably reduces the workload involved in providing input variables.

\[ \Delta CM_c = CM_{tt} - CM_{cr} = (R_{tt} - \text{var } C_{tt}) - (R_{cr} - \text{var } C_{cr}) \]  \hspace{1cm} (6)

where
\( \Delta CM \): change in contribution margin
c: case of conflict
tt: timetable
R: revenues [EUR]
var C: variable costs [EUR]

Conflicts also prevent time slot requests being met at the scheduling stage. Here, though, the reference scenario takes the form of TOCs’ requested orders, data that, together with their implications for revenues or variable costs, are very difficult to establish.

### 6.2 Revenues in passenger rail and railfreight traffic

TOC revenues affected by delays relate exclusively to fare receipts and can be derived from the number of passengers or goods and what these yield individually. The volume of end-customers correlates with the quality of service of the competing modes of transport under review. The modal split accordingly forms part of the revenue calculation process at this point. Use is made to this end of what is known as a “demand factor” (cf Eq. (7)), which compares two patterns of demand through a process of quotient formation [25], [26].

\[ f_D = \frac{MS_{cr}}{MS_{tt}} \]  \hspace{1cm} (7)

where
f: demand factor
MS: modal split
cr: case of conflict resolution
tt: timetable
The demand factor is arrived at by correlating the pattern of demand obtaining upon implementation of a given conflict-resolution scenario with that under timetable conditions. The pattern of demand is articulated by the modal split. Delays have a negative influence on the quality of service, causing the overall quotient to assume a value of less than one. Revenues fall as a result. Knowledge of revenues under timetable conditions is required for the drop to be quantified.

A train’s itinerary incorporates a multiplicity of point-to-point routes. How many depends in passenger services on the number of scheduled stops at which passengers can board or alight. Total revenue for a train run can be computed by adding up the revenues for each point-to-point route. In freight traffic, it is posited that no goods are handled within the network section under review. Hence, a freight train’s overall itinerary comprises a single point-to-point route with the attendant revenue.

With point-to-point routes being the unit of review, use is explicitly made of ticket sales per point-to-point route in passenger services. Different types of tickets are posited for the four purpose-of-travel categories (Business, Commuting, Holiday or Leisure) to reflect differing travel frequencies, income brackets, and hence time ratings and response to delays. Based on a single train run, business travellers are accordingly the highest-yield and commuters the lowest-yield grouping. Thus, total revenue for a point-to-point route actually breaks down into revenues for four specific travel purposes. Like ticket type, the demand factor is travel purpose-specific.

The various proportional revenues for specific point-to-point routes and travel purposes are added up and, in combination with costs that do not relate to specific point-to-point routes, collated to form a contribution margin per train.

No detailed data on end-customer flows over individual point-to-point routes were available in the form of passenger counts, hence these have been estimated. This was done by breaking ridership for the move as a whole up into proportionate fractions for the individual point-to-point routes, which may by reciprocal comparison have low, normal or high loadings. The sum of all fractions equals one, meaning no passenger features twice or, indeed, not at all.

In passenger services, the average number of passengers is first formed by multiplying possible seats on the train by the average load factor. For the purposes of the latter, the published network-wide average value is adapted to the respective individual train run under review with the aid of annual, weekly and daily traffic distribution curves. Review of utilisation for the line as a whole may lead to individual point-to-point routes lying either below or above the average load factor. These values are substituted parameters for the exact knowledge of origin-destination data for each train. It is crucial to consider the different time slices to get the variable train values. Individual revenues for passenger services are established by running the following equation for each train and route.
\[ R_{j,tp}(cr) = n \cdot \mu \cdot a \cdot \gamma_d \cdot T \cdot f_D \] (8)

where
- \( R \): revenues
- \( j \): point-to-point route
- \( tp \): travel purpose
- \( t \): time
- \( n \): number of seats
- \( \mu \): load factor for train
- \( a \): proportion of end-customers on point-to-point route
- \( \gamma \): purpose-of-travel fraction on train
- \( T \): ticket price
- \( f_D \): demand factor

Revenues in freight traffic relate to lines as opposed to point-to-point routes in the network section under review. Revenue-earning capacities are not documented for individual lines, however. Resort is accordingly had at this juncture to network-wide specific revenues per tonne-kilometre multiplied by length of line (route mileage) \[26\]. By analogy with the various travel purposes in passenger services, four different freight categories with differing revenue-earning capacities are reviewed in freight traffic (Farming, Metals, Bulk Goods and Capital Goods). A freight train is formed by apportioning the freight categories under review on a percentage basis to yield an average composition. Haulage flows per principal category in freight traffic are difficult to establish. The procedure opted for here, therefore, is to convert freight train mass into cargo weight with the aid of network-wide average values \[26\].

6.3 Costs in rail passenger and railfreight traffic

Variable costs are established for an entire train run in the section under review. They can only be caused by additional delays or possible extensions of itinerary. In contrast to the total revenue earned by a train run, constituting the sum of sub-revenues from point-to-point routes, variable costs are dependent not on point-to-point routes but only on the overall working. The TOC may incur added costs on account of disrupted vehicle and staff turnrounds. Account is given to the cost of servicing loans and of maintenance for an older vehicle as well as to staff costs \[26\]. These vary as a function of the traction selected and the number of coaches or wagons.

Conflict-resolution measures result in train runs deviating in time and space, thus giving rise to higher power costs. Consideration is given to extended dwelling times as well as to additional passing events. Auxiliaries such as the heating or air-conditioning systems continue to require power, notably on passenger trains, when dwelling times are extended. The case of an unscheduled stop is used to additionally establish, adopting the delta-\( v \) step method, the power consumed when re-accelerating to line speed \[30\]. Separate calculations are run for electric and diesel propulsion. To summarise, therefore, time and itinerary-dependent costs are determined individually for each train, as each cost component involves values for specific trains. Power costs, moreover, are to be computed explicitly for a given conflict resolution measure. The sum of part-costs forms the total costs for a train.

\[ C_i = C_{cap} + C_{main} + C_{staff} + C_{power} \] (9)
where
\[ C_i \]: costs for train involved [EUR]
\[ C_{cap} \]: cost of servicing loans [EUR]
\[ C_{main} \]: maintenance costs [EUR]
\[ C_{staff} \]: staff costs [EUR]
\[ C_{power} \]: power costs [EUR]

Refunds to passengers by the TOC additionally impact on costs. They vary depending on the extent of the delay and can only usually be claimed for delays of at least an hour. The nature of the refund depends on the ticket type. Where such extensive delays do occur, this may lead to sizeable revenue losses. They may actually result from a conflict having been resolved and be explicitly assignable to a conflict scenario. They are factored in as TOC outgoings.

7 Illustrative Application

Set out here is an illustrative computation to show how the method operates. To this end, a transport schedule is drawn up for the illustrative line detailed in Subsection 3.1. The timetable covers 20 individual train runs over a four-hour time slice in the morning peak period that fall into five different train classes. The classes involved are two long-distance passenger trains (ICE, IC), two local passenger trains (RE, M) and one freight train (IKS).

Trains enter the section under review ahead of node A and leave it having negotiated node D. Passengers can be conveyed on six different point-to-point routes along this line owing to stops being possible at all nodes. No consideration is given to passengers on a train when it enters the section under review and still on it when it leaves the section. There are similarly road links between all nodes, thus also allowing attention to be paid to the competing private motoring mode. Freight workings run through the section under review without stops being foreseen.

![Modal area for illustrative application](image)

Fig. 8 Modal area for illustrative application

A non-conflicting timetable is in place for the following review of operations. Possible delays are established for all individual trains on the basis of levels of delay for specific train types. These are divided into imported and initial delays (cf. Subsection 3.2).

Taken from the multiplicity of individual trains and conflicts arising, this illustrative example portrays in depth the conflict between a passenger train (IC) and a freight train (IKS) for two different sets of rankings awarded. In the first variant, the IC with a Number 4 ranking is given precedence and the IKS with a Number 5 ranking suffers delays arising from resolution of the conflict. In the second variant, the roles are reversed. The same initiating delays from the
Instead of being awarded different rankings, the trains involved may alternatively be of equal rank. It is then no long possible to deduce a specific preference from the ranking number and hence to allocate delays conclusively. Two solution variants are run for this scenario whereby preference is accorded the first and second trains in turn. The preferred solution yields the same results in this illustrative example as the rankings awarded in the first variant. Tables 2 and 3 show the adjusted files output by the simulation tool detailing the forms of conflict resolution adopted as well as their repercussions in the form of delays and where precisely these occur.

**Table 2** Conflict resolution based on ranking award 1

<table>
<thead>
<tr>
<th>Train number/priority</th>
<th>Priority</th>
<th>Conflict resolution: measure / location / knock-on delay</th>
<th>Reason for conflict: train / location / priority</th>
</tr>
</thead>
<tbody>
<tr>
<td>IKS 1000/2</td>
<td>5</td>
<td>change of train itinerary in O-St5</td>
<td>IC 200/2 at O-St6 / 4</td>
</tr>
<tr>
<td>IKS 1000/2</td>
<td>5</td>
<td>longer dwell time in O-St5 for 00:02:10</td>
<td>IC 200/2 at O-St6 / 4</td>
</tr>
</tbody>
</table>

**Table 3** Conflict resolution based on ranking award 2

<table>
<thead>
<tr>
<th>Train number</th>
<th>Priority</th>
<th>Conflict resolution: measure / location / knock-on delay</th>
<th>Reason for conflict: train / location</th>
</tr>
</thead>
<tbody>
<tr>
<td>IC 200/2</td>
<td>5</td>
<td>change of train itinerary in A-City</td>
<td>IKS 1000/2 at A-City / 4</td>
</tr>
<tr>
<td>IC 200/2</td>
<td>5</td>
<td>longer dwell time in A-City for 00:21:38</td>
<td>IKS 1000/2 at O-St1 / 4</td>
</tr>
</tbody>
</table>

Delays alter the quality of service of the two train runs in comparison with private motoring. This finds expression in a change in the modal split obtaining. Resolving conflicts gives rise to individual delays that need to be adapted using the average levels of delay for specific train types for further use. For the purposes of this illustrative example, the two combination parameters $\alpha$ and $\beta$ are each set at one. With revenues being established for specific point-to-point routes and travel purposes (cf. Subsection 6.2), a separate modal split is established for each differentiating feature. It is essential in the process that the ensuing delays be allocated to the correct point-to-point route.

The shares of the modal split enjoyed over specific point-to-point routes either once the conflict has been resolved or given a non-conflicting, delay-free timetable are established for each train run involved. Dividing one modal split figure by the other yields the demand factor (cf. Eq. (7)). This serves as an input variable along with further train-specific input data (cf. Eq. (8)) for calculating the revenues earned by a train run. The demand factor is used to determine the potential loss of passengers to the competing mode of transport on account of delays. In a further step the time and itinerary-related costs for each train run are computed both for timetable and delay conditions (cf. Eq. (8) and (9)). Contribution margins are likewise established as the differential between revenues and costs (cf. Eq. (6)). Finally, a change in contribution margin for the two trains affected is established by comparative assessment. The findings for the two ranking awards are set out in the following Tables.

**Table 4** Change in contribution margin (CM) given ranking award 1

<table>
<thead>
<tr>
<th>Train number</th>
<th>Revenues (tt)</th>
<th>Costs (tt)</th>
<th>Revenues (cr)</th>
<th>Costs (cr)</th>
<th>CM (tt)</th>
<th>CM (cr)</th>
<th>$\Delta$CM</th>
</tr>
</thead>
<tbody>
<tr>
<td>IKS 1000/2</td>
<td>1,386 EUR</td>
<td>621 EUR</td>
<td>1,292 EUR</td>
<td>621 EUR</td>
<td>765 EUR</td>
<td>671 EUR</td>
<td>95 EUR</td>
</tr>
<tr>
<td>IC 200/2</td>
<td>16,471 EUR</td>
<td>1,122 EUR</td>
<td>16,353 EUR</td>
<td>1,122 EUR</td>
<td>15,349 EUR</td>
<td>15,231 EUR</td>
<td>118 EUR</td>
</tr>
</tbody>
</table>

sum $\Delta$CM 213EUR
Table 5 Change in contribution margin (CM) given ranking award 2

<table>
<thead>
<tr>
<th>Train number</th>
<th>Revenues (tt)</th>
<th>Costs (tt)</th>
<th>Revenues (cr)</th>
<th>Costs (cr)</th>
<th>CM (tt)</th>
<th>CM (cr)</th>
<th>ΔCM</th>
</tr>
</thead>
<tbody>
<tr>
<td>IC 200/2</td>
<td>16,471 EUR</td>
<td>1,122 EUR</td>
<td>14,435 EUR</td>
<td>1,494 EUR</td>
<td>12,940 EUR</td>
<td>2,409 EUR</td>
<td></td>
</tr>
<tr>
<td>IKS 1000/2</td>
<td>1,386 EUR</td>
<td>621 EUR</td>
<td>1,386 EUR</td>
<td>621 EUR</td>
<td>765 EUR</td>
<td>765 EUR</td>
<td>0 EUR</td>
</tr>
<tr>
<td>sum</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2,409 EUR</td>
</tr>
</tbody>
</table>

The ultimate objective is a monetary rating of the resolution to a conflict equating to the change in contribution margin relative to that for the non-conflicting timetable. It is possible to establish the monetary value of a specific conflict by adding together the amount of change for the two trains involved. Owing to delays generally resulting in reduced revenues and increased costs, the contribution margin for any conflict-resolution scenario will always be lower than under timetable conditions. The differential between the two amounts cannot, therefore, fall below zero. The optimum means of resolving a conflict, the one giving rise to the lowest monetary loss, will accordingly involve the smallest change in contribution margin. That is achieved by Ranking Award 1 (Table 4) in this illustrative example.

8 Summary & Conclusion

The method presented here allows conflict-resolution scenarios in train services to be rated in monetary terms. It is a form of valuation that is no longer confined to strictly operational factors but, instead, takes account of repercussions in the form of delays for the end-customer. Railway operations research methods are coupled with mode-choice models for this purpose. The monetary rating is arrived at on the basis of changes in the contribution margin for individual conflict-resolution scenarios. This involves comparing non-conflicting timetable conditions with a delay scenario.

The rating process weighs train operating companies’ revenues up against their variable costs. Whereas variable costs are itinerary and time-dependent, demand for services by end-customers additionally plays a role when establishing revenues. Use can be made of mode-choice models to map potential migrations by end-customers from or to competing modes as a result of a transport service being impaired.

The contribution margin is computed per train run, conflict-resolution scenario and train-priority award and is called upon whenever a monetary rating of delay minutes is performed. How trains are prioritised impacts on the decisions taken to resolve a conflict and hence also on the ensuing delays. Forms of conflict resolution can be rated monetarily and compared citing the change in contribution margin arising. A conflict can thus be deemed to have been resolved most effectively, notably due to the ranking numbers awarded, where the change in contribution margin is minimised.

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9 Bibliography


