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Keywords: cost-effective routing, train flows, KTZ main railway network, distance-based cost allocation, infrastructure usage fees, fuel consumption, algorithmic costs

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AN ECONOMICAL APPROACH TO TRAIN ROUTING ON KAZAKHSTAN'S PRIMARY RAILWAY NETWORK: AN ALGORITHMIC COST ESTIMATION METHOD

Summary. Optimizing the operations of Kazakhstan Railways Company's (KTZ) main railway network depends significantly on efficient train routing. Accurate computation of train operation costs is crucial for this optimization. This article presents a comprehensive and customized methodology for economically routing train flows within KTZ's main railway network. The proposed methodology considers various cost factors, including fuel consumption, infrastructure wear and tear, labor expenses, locomotive maintenance, and other operational costs. It also introduces a novel approach for assessing the cost-effectiveness of different routing options. By algorithmically comparing costs for various routing scenarios, transportation planners and decision-makers can identify the most cost-efficient routes for train flows on KTZ's main railway network. This strategy streamlines resource allocation and enhances operational efficiency, leading to significant cost savings for KTZ. The methodology outlined in this article offers KTZ railway operators a systematic framework for finding cost-effective routing solutions, improving decision-making processes, operational efficiency, and profitability in managing train flows on Kazakhstan's primary railway networks.

1. INTRODUCTION

The optimization of transportation networks plays a pivotal role in guaranteeing the efficient and economical movement of goods and passengers. Within the domain of railway systems, the effective routing of train flows stands as a crucial element in reducing operational costs while upholding elevated service standards. A significant transport infrastructure, the main railway network of Kazakhstani Railways (KTZ), interconnects diverse regions, facilitating the conveyance of commodities and travelers across the nation. To enhance the operational efficiency of train services on this network, the development of a comprehensive methodology for cost computation becomes imperative. This methodology would serve as a guide for decision-making processes, enabling the selection of cost-effective routing strategies.

The present article expounds upon the methodology depicted in Fig. 1. It delves into the phase of cost estimation for pre-calculated train flow routing options. In other words, this article's focus centers on scenarios where the input already encompasses forecasts of freight traffic demand, categorized on a monthly basis for a year ahead, including all cargo types and messaging classifications (export, import, transit, domestic). Accurate demand forecasts are essential for organizational planning in finance, marketing, and distribution, ensuring effective decision-making [1]. Demand forecasting involves predicting future product demand by analyzing past data and environmental factors [2]. In the transportation industry, this is crucial for planning operations, marketing, and finance.

KTZ, a major rail transport company in Kazakhstan, is key to freight and passenger transportation with a vast network over 21,000 km and more than 115,000 employees. Its primary revenue comes from freight transportation [3], making demand forecasting vital for optimizing operations and revenue.

Demand forecasting methods include qualitative approaches, based on opinions or judgments, and quantitative methods, which use past data or causal relationships. While many studies focus on urban rail demand [4-7], fewer address national railway networks [8-9]. KTZ's successful application of the study's recommendations highlights the importance of advanced models and software tools in transportation demand forecasting [10].

The next step is to calculate the variable costs for these routes. Once these costs are determined, the planning process moves to the final phase, which involves selecting train flow routes across the KTZ primary network while accounting for capacity constraints. This article focuses on the fifth of six stages in planning and routing train flows within the KTZ network. This stage involves computing algorithmic variable costs for each routing option identified in previous planning stages, allowing for quick comparisons.

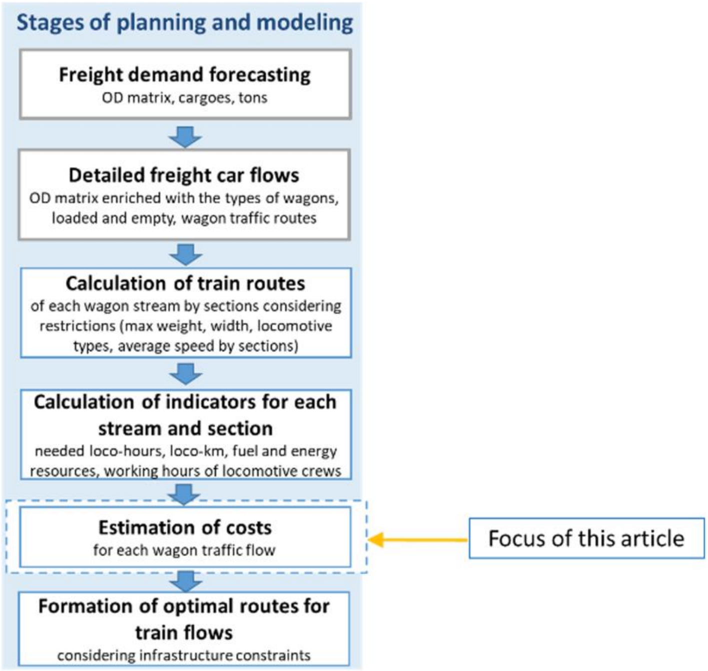

Fig. 1. Focus of the Article

The rationale behind the development of the methodology described in this article, in contrast with the prevailing planning methodology at KTZ, can be delineated as follows:

1. In the current manual planning process executed by KTZ staff, the guiding principle is to direct car flows along the shortest path. However, considering the existence of two locomotive traction types on the KTZ network, namely diesel and electric, the shortest distances might not always equate to cost-effectiveness.
2. With the introduction of the new methodology and model, the ability to expeditiously evaluate and contrast various routing alternatives on the network becomes feasible. This model facilitates the rapid generation of routing options to achieve diverse objectives, such as cost minimization or revenue maximization. Such flexibility is nearly unattainable within the existing KTZ planning process.
3. The application of this methodology using modern software tools substantially accelerates the computation of optimal routes. It further allows the visualization of outcomes, enabling visual comparisons of different forecast car flow routing options across the KTZ network from a financial perspective. These visualizations aid subsequent managerial decisions.

The algorithmic cost calculation methodology delineated in this article constitutes a component of a long-term resource and economic planning framework, distinct from a budgetary planning tool. Consequently, the cost estimates for wagon flow routing, as outlined in this methodology, may not necessarily align with analogous cost items in KTZ's planned budget. The core objective of this methodology is to construct a visual tool for KTZ's operational planning services. This tool would foster the linkage between technical and operational parameters frequently employed by operational planners, and economic parameters. This amalgamation permits decisions regarding flow redirection within the KTZ network to be guided not solely by the shortest distance and requirements such as car-hours and locomotive-hours, but also by cost metrics. Ultimately, this approach opens avenues for cost savings and highlights potential lost profits when cost-efficiency isn't the primary concern in routing flows within the network.

To differentiate between costs in KTZ's budget and costs employed for operational decision visualizations, the costs referenced in this article are denoted as algorithmic costs. These are the costs applied within the framework of the Traffic Route Optimization (TRO) algorithm developed by KTZ. The article does not delve into altering the methodology, algorithms, or models for traffic route optimization. Instead, it focuses on the methodology for transforming and utilizing available data from various KTZ internal systems and external sources. This facilitates the integration of algorithmic cost data into traffic route optimization algorithms for the purpose of long-term resource planning (spanning 12 months or more).

The article encompasses concrete tables and data structures sourced from multiple existing KTZ systems used by operational planners. Examples of these systems encompass the IOMM system (an automated system for integrated processing of locomotive driver itineraries) and MultiRail Enterprise Edition (MREE - a system housing regulatory and reference information for KTZ network stations, points, hauls, and segments, including distances between them). The article's structure encompasses an introduction, literature review, methodology description (comprising data preparation and table transformation segments, alongside the algorithmic cost computation methodology based on transformed data), results of test calculations employing the methodology, discussion, conclusion, and funding information for the study.

2. LITERATURE REVIEW

In scientific literature, when optimizing train flow routes, the primary cost categories commonly utilized include shunting cost, routing cost, and holding cost, as discussed by [11]. Shunting cost pertains to the expenses incurred during the handling of freight cars at shunting yards. These costs vary based on yard size, with smaller yards generally incurring higher expenses compared to larger ones. This distinction arises from the more resource-efficient handling of a greater number of cars simultaneously, a practice more feasible in larger yards.

The routing cost encompasses all operational expenses of a train, including factors like energy consumption, train weight, locomotive charges, and train driver costs. This study assumes a cost rate per kilometer, factoring in weight-based track use, energy consumption, locomotive, and driver utilization, referred to as the cost per train kilometer. Routing costs typically constitute the largest portion among the three cost classifications considered.

The holding cost for freight cars covers the total time freight cars spend within the railway network, including rail travel time and shunting yard duration. Shunting yard time is divided into the time required for the shunting process and the waiting time until a freight car's train departs.

The challenge of guiding vehicles through a railway network with intermediate classification operations emerged in Operations Research (OR) literature during the 1960s. [12] developed a comprehensive model surpassing existing models and influencing subsequent approaches. Their model considers the objective function comprising transportation costs per arc, classification costs per yard, and delay-associated expenses. The model was tested using data from a U.S. railroad company.

[13] introduced a model considering two cost aspects within the objective function: transportation cost per train and cost per yard. [14] proposed a mix of personal, energy, locomotive, and delay costs

for transportation, and a blend of classification and waiting costs for the yard. [15] presented a model for a service network incorporating terms for trains and classification costs of cars. This model accommodates different train types with varying costs, demonstrating nonlinearity due to delay costs dependent on train count.

[16] examined a route-based model incorporating train, waiting, and delay costs. Computational results were presented for a 26-node, 333-commodity instance with a maximum train length constraint. [17] developed a primal heuristic and employed Lagrange relaxation to compute lower bounds. [18] designed a model for a broader network budget design problem (BDP) incorporating route costs per car. [19] proposed a solution method using Lagrangean relaxation for minimizing handling costs and car mileage.

[20] introduced an arc-based model accounting for linearly related transportation costs per car and classification costs. [21] presented a model focusing on train costs and determining the minimum required train kilometers for demand, considering maximum train lengths and weights.

However, none of the mentioned works addressed scenarios involving two locomotive traction types for cargo operations. This article introduces a Kazakhstan-applicable approach considering main railway network characteristics.

3. METHODOLOGY

In the process of optimizing traffic routing decisions, algorithmic variable costs will be involved. These costs encompass:

- The expense of fuel or electricity utilized for traction.
- The expenditure on locomotive crews deployed.
- The outlay on maintenance, repair, and overhaul tasks (MRO).
- The cost of renting rolling stock and furnishing security services for cargo.

These expenses will be integrated into the traffic route optimization (TRO) algorithm. Consequently, once the routing is finalized, these costs will be associated with each traffic record and potential alternate route. This arrangement empowers users to effectively compare diverse routes.

After evaluating various methodologies for assessing variable costs and examining normative KTZ documents related to cost prediction, the method of statistically calculating estimated unit productivity parameters was adopted across all cost categories. Essentially, this involves creating a reference table for each cost category, outlining unit productivity parameters derived from past data concerning expended resources and completed work. This delineates the quantity of resources used per unit of work. This reference table undergoes a semi-automatic calibration process and manual adjustments for updates. These refined tables are then employed to estimate costs for projected traffic records.

The undertaking involves maintaining and populating four key tables:

- Table encompassing velocity, average train weight, and average consist.
- Reference tables detailing work distribution based on locomotive traction type and locomotive series.
- Reference table for unit productivity parameters.
- Pricing reference tables.

The forthcoming sections elucidate these tables and detail the automated (or refreshed) population process through past data.

3.1. Processing past data in preparation to automatic population of reference tables

Processing past data for automatic reference table population involves calculating past unit productivity parameters. These parameters are essential for populating reference tables automatically. To compute these parameters, a connection between crew run-based data (THO1 report) in the IOMM system and segment-based data (TsO4 report) in the same system must be established.

The THO1 report, a standard form in the IOMM system used by KTZ, focuses on comparing planned and actual fuel consumption. It provides information on crew runs and locomotive series, including locomotive-kilometers, locomotive-hours, fuel consumption, and ton-kilometers.

However, crew run modeling for traffic route optimization is challenging due to intersections and uneven distribution of train work. In contrast, the TsO4 report (section 3) in the IOMM system outlines past metrics for train and wagon work, categorized by segments and traction types. This form presents locomotive-kilometers leading trains, locomotive-hours on segments, ton-kilometers, and wagon-kilometers.

Notably, the TsO4 report lacks locomotive series-specific details and data about locomotive work on non-mainline tracks, as it does not allocate dwells, fuel consumption, and shunting work among segments based on crew runs. Despite potential IT system changes, THO1 and TsO4 forms will persist in use for locomotive data collection, familiar to KTZ specialists. These forms rely on "individual route lists of the locomotive driver," offering detailed post-run information on trains, locomotives, and crew activities.

Another vital data source is the "Report on the work of locomotive crews," a standard monthly collection in the IOMM system. This report provides crew run-based data, detailing work duration, types, and professions. It serves as the basis for determining the actual time spent by locomotive crews.

3.1.1. Collection of work for locomotives, trains and crews

The THO1 report is a monthly IOMM system report that stores multiple data entries, each containing various variables for data classification or locomotive/train work metrics representation. This section provides a detailed description of the final data format extracted from the THO-1 report.

Certain preliminary data adjustments are necessary to appropriately handle THO-1 data:

- Only data related to freight operations should be utilized at this stage. THO1 includes a flag distinguishing the type of operation for each data entry (the numerical values of this flag can be interpreted using the "Operations type" reference table).
- To process THO-1 data correctly, it must be linked to a specific crew run. This requires parsing the "Crew run" parameter. Typically, this parameter consists of a combination of a crew run name and a 3-digit numeric code. These numeric digits need to be separated into an independent variable for subsequent usage.
- However, some entries only provide a crew run name in the crew run field. These entries belong to "unnormed crew runs" and necessitate processing through a distinct reference table. This process eventually yields a numeric code for the crew run.
- After parsing the Crew Run field, the outcome is the creation of a new Crew Run ID field for the majority of records within the THO-1 report. Entries in THO-1 lacking a valid pairing of Locomotive Depot ID and Crew Run number are discarded.

Furthermore, the 28th variable in the THO-1 report, termed "Gross ton kilometers," is stored in THO1 using units of 10,000 ton-km. To enhance clarity for subsequent calculations, this parameter needs to be recalibrated into ton-km.

Based on the aforementioned transformations, the subsequent data structure is to be extracted from the THO1 database (refer to Table 1). The process of collecting data from TsO-4 is quite analogous: initial application of filters followed by the selection of pertinent variables. Analogous to the THO1 report, the TsO-4 report (provided as monthly reports within the IOMM system database) lacks explicit labels for individual variables. Inference of these labels relies on documentation outlining the database structure (included as the TsO4 structure reference table) and the sequence of variables in each data entry (refer to Table 1).

When collecting data from the THO-1 report, it's crucial to ensure that none of the three train operational parameters (train-km, train-h, and GTKM) holds a value of zero. This precaution is necessary to prevent potential calculation errors arising from division by zero. Similarly, during data collection from the TsO-4 report, it's imperative to confirm that none of the four train operational parameters (train-km, train-h, wagon-km, or GTKM) is at a value of zero. Such precautions are in place to avoid introducing "division by zero" errors that could disrupt subsequent calculations. The most recent report containing the essential data for generating reference tables is titled "Report on the work of locomotive crews." This report is generated on a monthly basis and stored within the data repository of the IOMM system. The process of data filtration within this report follows the same approach as the previous two reports. The outcome of this filtration process transforms the "Report on the work of locomotive crews" into a table, as illustrated in Table 2.

Table 1

The final format of data extracted from THO-1 and TsO-4 reports

Parameters	Description	Comment
NU_CODE	Crew run code parsed from Crew run name field in THO1	As described above, this is a 3-digit code of crew run, pulled from the 5th variable of THO1 database
LOCOMOTIVE_DEPO_ID	Locomotive Depot id code	A Locomotive depot code needed to identify crew run ID
NU_ID	Crew run ID	This ID has to be looked up in IOMM_N_NU reference table based on the combination of variables NU_Code and LOCOMOTIVE_DEPO_ID for each data entry
TRACTION_TYPE	Traction type code	Traction type code. In THO1 database traction type of “1” corresponds to electric and traction type of “2” to diesel
LOCO_SERIES_ID	Locomotive series ID code	ID code of specific locomotive series. A specific reference table is used to identify names of locomotive series corresponding to each code
L_KM	Total locomotive kilometers	Total locomotive kilometers in kilometers (including dwells)
L_KM_LINE	Line locomotive kilometers	Total locomotive kilometers (excluding dwells)
L_H	Total locomotive hours	Total locomotive hours in hours
FUEL	Total fuel consumed	Total fuel consumed (in kilos or kWh)
Tr_KM	Train kilometers	Train kilometers
GTKM	Gross ton kilometers	Gross ton-kilometers, freight operations, in thousands
ID_PU	Segment code	Segment code, as per network mapping of segments in IOMM
Tr_H	Train-hours (total)	Train-hours, including both time spent on segments and dwelling on intermediate stations
Tr_H_seg	Train-hours (segment)	Train-hours, including only time spent on segments
W_km	Wagon-kilometers	Wagon-kilometers
NTKM	Net ton-kilometers	Net ton-kilometers, freight operations, in thousands

3.1.2. Automatic population of velocity, average train weight and consist reference tables for segments

As stated in section 1, the objective of this phase is to create and auto-fill a reference table with velocity details, average train weight, and average train consist. The table would possess the structure outlined in Table 3.

Since Route Optimization modeling is performed on a monthly basis, table 3 must be populated for each individual month separately. The reference table's population can be automated by employing past data from the IOMM system database, particularly from the THO-1 and TsO-4 reports. This process involves assigning THO-1 data to TsO-4 data, which is specific to segments. Subsequently, the TsO-4 segments need to be correlated with traffic route optimization segments using the TRO to IOMM segment relation table.

Table 2

Report on work of locomotive crews

Parameter	Description	Comments
LOCOMOTIVE_DEPO_ID	Locomotive depot ID	ID of the locomotive depot, that in conjunction with the NU_CODE allows to identify specific crew run ID of the entry
TIME_IN_HOURS_LOCOMOTIVE DRIVER	Actual work time in hours for locomotive drivers	Time spent by locomotive drivers for specific crew run (year total)
TIME_IN_HOURS_CONDUCTOR	Actual work time in hours for conductors	Time spent by conductors for specific crew run (year total)

Table 3

Structure table for velocity, average train weight and average train consist

Parameter	Description	Comments
ID_PU	TRO segment code	Code of a TRO segment. The reference table should cover all TRO segments – full list of which can be found in the network data
MONTH	Specific month of the year	A month of the year in numeric format
DIRECTION	Direction flag for the segment	Reference data is direction specific - so for each Segment this flag will have values of “1” (reversed) or “0” (not reversed)
TRACTION_TYPE	Traction type code	Traction type code (2 for diesel locomotives and 1 for electric locomotives)
SEGMENT_VELOCITY	Segment velocity	Segment velocity, which is average velocity of all trains including time spent on dwells at intermediate station (in km/h)
TECH_VELOCITY	Technical velocity	Technical velocity, which is average velocity of all trains excluding time spent on dwells at intermediate station (in km/h)
AVERAGE_WEIGHT_PER_RUN	Average train weight	Average weight of the train (in gross tons)
AVERAGE_TRAIN_CONSIST	Average train consist	Average consist of the train (in wagons)

The allocation of THO-1 data to TsO-4 necessitates further elucidation: although THO-1 and TsO-4 reports are founded on distinct network demarcation methodologies, an underlying element exists that facilitates the allocation of crew-run data to segments, namely railway links. Each link within the IOMM system (representing a network segment bounded by two stations) is associated with one exclusive segment, thereby establishing a "many-to-one" relationship between the link database and the segment database. This connection is elaborated in the IOMM system's reference table named POLYGON.PU. Moreover, a single link can belong to multiple crew runs, resulting in a "many-to-many" relationship between the link database and the crew run database. This relationship is detailed in the IOMM system's reference table known as IOMM_N.NU.

In order to allocate crew run-related data to segments, a reference table of link parameters, derived from the segment parameters reference table, becomes indispensable (as depicted in Fig. 2).

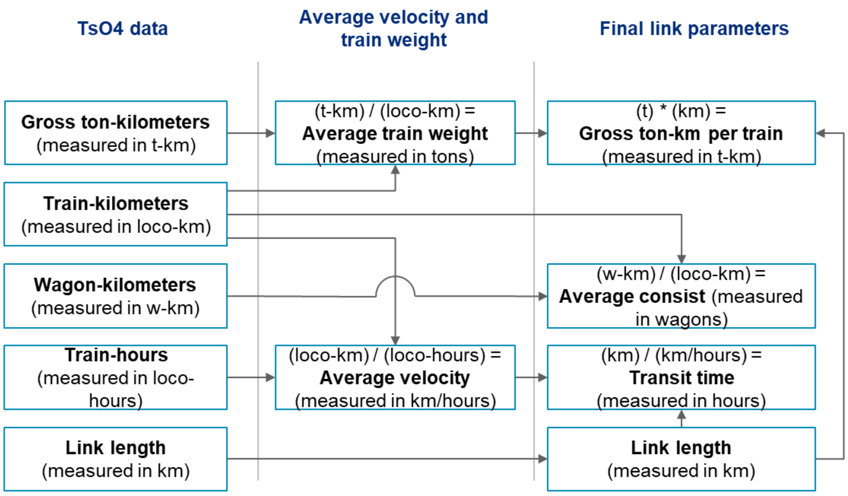

Fig. 2. Reference table of link parameters

TsO-4 data serves the purpose of populating a reference table for segment parameters with automatic input of velocity, average train weight, and average train consist data for each segment based on the specific traction type. The information extracted from TsO-4 is tailored to each pairing of "segment" and "traction type." Consequently, the subsequent calculations are carried out for each pairing as outlined below:

1. Average Train Weight: Gross ton-kilometers are divided by Train-kilometers.
2. Segment Velocity: Train-kilometers are divided by Train-hours on the segment.
3. Technical Velocity: Train-kilometers are divided by Train-hours on the link.
4. Average Train Consist: Wagon-kilometers are divided by Train-kilometers.

These computed values are subsequently employed in the allocation of crew run-based data to the segments' next stages. To facilitate easy reference, this particular table is further denoted as the "Historic Information on Velocities, Train Weights, and Consists" table. The historic velocities are employed for populating a reference table of link parameters. It is assumed that all links connected to a specific segment share the same Average train weight, Segment velocity, Technical velocity, and Average train consist for that segment (specific to the traction type).

Furthermore, the Table of Historic Velocities is also instrumental in automatically completing the "Velocity, Train Weight, and Train Consist" reference table of the TRO (Transportation and Routing Optimization) system. As the Historic velocities are computed for IOMM (Integrated Operations Management and Monitoring) system segments, while the TRO reference tables are aligned with TRO segments, the automated population of the TRO reference table requires a matching process that associates Historic velocities with TRO segments through the intermediary TRO to IOMM system segment relation table (as indicated in Table 4).

Given that the link parameters of segment velocity and train weight are already filled in, additional link parameters can be calculated using the following formulas:

*Gross ton-km per train = (Average train weight * Length of the link)* (1)

Transit time = (Length of the link / Segment velocity) (2)

Link parameters described above have the advantage of being cumulative – e.g. Sum of Transit time of several adjacent links equals to the Transit time needed to cover all of these links in sequence. This allows calculation of Transit time, Gross ton-km per train and Length for segments and crew runs, based on the reference tables relating links to segments and links to crew runs (see Fig. 3).

Relationship between PU1 to NU and PU2 to NU are calculated for each of the 3 parameters of links for each traction type. Relationships of PUs to NUs for each of the 3 parameters and for each traction type, are calculated the following way:

Share of PU1 in NU$_{(by\ Ton\text{-}km\ per\ run)}$ *= (Ton-km per run of link X1 + Ton-km per run of link X2) / (Ton-km per run of link X1 + Ton-km per run of link X2 + Ton-km per run of link Y1)* (3)

Table 4

Structure table for TRO to IOMM system segment relation table

Parameter	Description	Comments
ID_PU	Segment code (for IOMM segments)	6-digit code of an IOMM segment. The list of segments, which the reference table has to cover, are taken from the Relation table between MREE segments and TsO4 segments
ID_PEREGON	Link code (for IOMM links)	Link code. List of links needs to be taken from the Relation table between IOMM segments and IOMM links
TRACTION_TYPE	Traction type code	Traction type code (2 for diesel locomotives and 1 for electric locomotives)
RUN_TIME	Run time	Average time, that this specific link can be crossed by a freight train (in hours). Calculated as described above
T_KM_PER_RUN	Tonnage per train	Average tonnage carried by a single freight train over this link (in gross ton-kilometers) Calculated as described above
PEREGON_LENGTH	Length of the link	Length of the link (in km). That value has to be taken from the IOMM link table reference table.

Fig. 3. Example of IOMM system links and their association with segments and crew runs

This ratio signifies that within the total Gross ton-km in crew run NU, only this specific portion of PU1 in NU is attributed to PU1. The resulting reference table will appear as follows (refer to Table 5).

Upon computing the proportions of PUs in NUs, the subsequent stage involves allocating statistical data regarding locomotive and train work to the segments. The reference table "PU in NU share" presents three distinct shares for every viable combination of segment and crew run:

- Proportion of segment-related work in the overall work of the crew run, measured by Gross ton-kilometer work per train.
- Proportion of segment-related work in the overall work of the crew run, measured by Length.
- Proportion of segment-related work in the overall work of the crew run, measured by Transit time.

The allocation of past volumes to segment A is executed as follows:

Train-kilometer and locomotive-kilometer volumes for all crew runs in which segment A holds a non-zero share by Length are multiplied by the Length-based share of segment A in those crew runs.

- Train-hour volumes for segment-locomotive series combinations are computed by dividing corresponding train-kilometers (following allocation) by the SEGMENT_VELOCITY derived from the "Historic velocities, train weights, and lengths" table.
- Locomotive-hour volumes for all crew runs where segment A possesses a non-zero share by Transit time are multiplied by the Transit time-based share of segment A in those crew runs.
- Gross ton-kilometer and fuel consumption volumes for all crew runs in which segment A holds a non-zero share by Gross ton-kilometers per train are multiplied by the Gross ton-kilometers per train-based share of segment A in those crew runs.

Table 5

Reference table for relationship between PU1 to NU and PU2

Parameter	Description	Comments
NU_PU_SHARE_RUN_TIME	Run time	Average time that this specific link can be crossed by a freight train (in hours). Calculated as described above
NU_PU_SHARE_T_KM_PER_RUN	Tonnage per train	Average tonnage carried by a single freight train over this link (in gross ton-kilometers) Calculated as described above
NU_PU_SHARE__LENGTH	Length of the link	Length of the link (in km). That value has to be taken from the IOMM link table reference table.

As data from THO-1 is saved individually for crew run and locomotive series pairings, this action will assign train and locomotive tasks to segment and locomotive series combinations. The resultant past locomotive work table, detailing the interaction of segments and crew runs, will adopt the format outlined in Table 6.

Table 6

Format of the resulting table of past locomotive work

Parameter	Description	Comments
ID_NU	Crew run ID	This ID has to be looked up in IOMM_N_NU reference table based on the combination of variables NU_Code and LOCOMOTIVE_DEPO_ID for each data entry
LOCO_SERIES_ID	Locomotive series ID code	ID code of specific locomotive series. A specific reference table is used to identify names of locomotive series corresponding to each code
L_KM	Locomotive kilometers	Volume of historic locomotive kilometers accumulated for each combination of Crew run – Segment – Traction type – Locomotive series
L_KM_LINE	Line locomotive kilometers	Volume of historic line locomotive kilometers accumulated for each combination of Crew run – Segment – Traction type – Locomotive series
L_H	Locomotive hours	Volume of historic locomotive hours accumulated for each combination of Crew run – Segment – Traction type – Locomotive series
FUEL	Volume of fuel (or energy) consumed	Volume of historic consumption of fuel (or energy) accumulated for each combination of Crew run – Segment – Traction type – Locomotive series
Tr_KM	Train kilometers	Volume of historic train kilometers accumulated for each combination of Crew run – Segment – Traction type – Locomotive series

Table 7 isn't a report form or adjustable reference table, but it's crucial for auto-populating various reference tables. Thus, its detailed description is essential. Each crew run is associated with a single locomotive depot. The past locomotive work in Table 6 can be summarized (via GroupBy or similar operation in a relational database) into the past locomotive work table. This table includes locomotive kilometers, line locomotive kilometers, locomotive hours, gross ton-kilometers, fuel consumption, and train kilometers. It's organized for every combination of Segment, Locomotive depot, Traction type, and Locomotive series.

When values in the first table are divided by corresponding values in the second table, a Segment in Depot Work Share Reference Table is generated. This table shows the proportion of work from each segment that can be allocated among all depots. This reference table follows the format shown in Table 7.

Table 7

Segment in depot work share reference table

Parameter	Description	Comments
ID_DPL	Locomotive depot ID	Locomotive depot ID, that is used in the IOMM data base
LOCO_SERIES_ID	Locomotive series ID code	ID code of specific locomotive series. A specific reference table is used to identify names of locomotive series corresponding to each code
PU_DPL_L_KM_SHARE	Locomotive kilometer share	Share of total work (locomotive kilometers only) of this segment, that belongs to this depot
PU_DPL_L_KM_LINE_SHARE	Line locomotive kilometer share	Share of total work (line locomotive kilometers only) of this segment, that belongs to this depot
PU_DPL_L_H_SHARE	Locomotive hour share	Share of total work (locomotive hours only) of this segment, that belongs to this depot
PU_DPL_FUEL_SHARE	Fuel consumption share	Share of total work (fuel consumption only) of this segment, that belongs to this depot
PU_DPL_Tr_KM_SHARE	Train kilometer share	Share of total work (train kilometers only) of this segment, that belongs to this depot
PU_DPL_GTKM_SHARE	Gross ton-kilometer share	Share of total work (gross ton-kilometers only) of this segment, that belongs to this depot

This reference table, labeled as Table 7, finds its application in crafting reporting forms categorized by locomotive depots. This action occurs subsequent to the completion of the segment-based forecast. The distribution of crew work details to the segments is accomplished using a distinct reference table known as the "Depot in segment work share reference table." The method of populating this reference table mirrors that of Segment in Depot Work Share Reference Table 7: initially, the first Table 7 is utilized to construct an intermediate table that contains past locomotive work parameters for each combination of Segment, Depot, Traction Type, and Locomotive Series. Subsequently, the same Table 8 contributes to the development of another intermediate table which captures past work parameters for each locomotive depot (omitting divisions by Segments, Traction Types, or Locomotive Series).

When the values in the initial intermediate table are divided by corresponding values in the second intermediate table, the outcome yields a "Depot in Segment Work Share Reference Table." This table retains information regarding the proportional allocation of work from each locomotive depot to specific segments. The structure of the table itself adheres to the format outlined in Table 8.

Table 8

Reference table for depot in segment work share

Parameter	Description	Comments
DPL PU_TT L_H_SHARE	Locomotive hour share	Share of total work (locomotive hours only) of this depot, that belongs to this combination of segment – traction type – locomotive series
DPL_PU_TT FUEL_SHARE	Fuel consumption share	Share of total work (in consumed fuel and electricity only) of this depot, that belongs to this combination of segment – traction type – locomotive series
DPL_PU_TT Tr_KM_SHARE	Train kilometers share	Share of total work (train kilometers only) of this depot, that belongs to this combination of segment – traction type – locomotive series

Table 8 is useful for applying to the locomotive crew work database (refer to Table 2). This application helps distribute work assignments for segments, traction types, and locomotive series in line with the division of locomotive-hours. This division aligns with the method used to later calculate unit productivity of locomotive crew work in this document. Consequently, past data assigned to segments and locomotive series will form the subsequent table (see Table 9).

Table 9

Historic information allocated to segments and locomotive series

Parameter	Description	Comments
L_KM	Total locomotive kilometers	Total locomotive kilometers in kilometers (including dwells)
L_KM_LINE	Line locomotive kilometers	Total locomotive kilometers (excluding dwells)
L_H	Total locomotive hours	Total locomotive hours in hours
Tr_H	Train hours	Train hours in hours
FUEL	Total fuel consumed	Total fuel consumed (in kilos or kWh)
Tr_KM	Train kilometers	Train kilometers
GTKM	Gross ton kilometers	Gross ton kilometers
ENG_H	Actual work time in hours for locomotive drivers	Time spent by locomotive drivers for specific crew run (year total)
CON_H	Actual work time in hours for conductors	Time spent by conductors for specific crew run (year total)

3.1.3. Automatic population of reference tables for work shares and unit productivity parameters

As discussed above, three reference tables must be developed and maintained. First, a reference table for work shares among Traction types within each Segment (see Table 10).

Table 10

Reference table for work shares among traction types within each segment

Parameter	Description	Comments
ID_PU_ISP	ISP segment code	Code of an ISP segment. The reference table should cover all ISP segments – full list of which can be found in the network data
DIRECTION	Direction flag for the segment	Reference data is direction specific - so for each Segment this flag will have values of “1” (reversed) or “0” (not reversed)
TT_SHARE_GTKM	Work share by gross ton kilometers	Share of the work conducted by a specific traction type within the total work done on this segment (by gross ton kilometers)
TT_SHARE_Wag_KM	Work share by wagon kilometers	Share of the work conducted by a specific traction type within the total work done on this segment (by wagon kilometers)
TT_SHARE_NTKM	Work share by net ton-kilometers	Share of the work conducted by a specific traction type within the total work done on this segment (by net ton-kilometers)

Second, a reference table for work shares among Locomotive series within each Traction type of each Segment (see Table 11).

Table 11

Reference table for work shares among locomotive series within each traction type of each segment

Parameter	Description	Comments
SERIES_SHARE_GTKM	Work share by gross ton kilometers	Share of the work done by a specific locomotive series within all work done by a specific traction type in a specific segment (by gross ton kilometers)
SERIES_SHARE_Tr_H	Work share by train hours	Share of the work done by a specific locomotive series within all work done by a specific traction type in a specific segment (by train hours)
SERIES_SHARE_Tr_KM	Work share by train kilometers	Share of the work done by a specific locomotive series within all work done by a specific traction type in a specific segment (by train kilometers)

Third, a reference table for unit productivity parameters specific for Locomotive series, Traction type and Segment (see Table 12).

Table 12

Reference table for unit productivity parameters specific for locomotive series, traction type and segment

Parameter	Description	Comments
UNIT_PRODUCTIVITY_L_H_by_deriv_Tr_H	Unit productivity parameters of locomotive hours per one train hour	A ratio of how many locomotive hours are “spent” per each train hour
UNIT_PRODUCTIVITY _L_KM_by_Tr_KM	Unit productivity parameters of locomotive kilometers per one train kilometer	A ratio of how many locomotive kilometers are “spent” per each train kilometer
UNIT_PRODUCTIVITY _FUEL_by_GTKM	Unit productivity parameters of fuel (in kilograms or kWh) per one gross ton kilometer	A ratio of how many kilos of fuel or kWh of energy are “spent” per each train hour
UNIT_PRODUCTIVITY _ENG_H_by_Tr_H	Unit productivity parameters of locomotive driver hours per one train hour	A ratio of how many work hours of an locomotive driver are “spent” per one train-hour
UNIT_PRODUCTIVITY _CON_H_by_Tr_H	Unit productivity parameters of conductor hours per one train hour	A ratio of how many work hours of a conductor are “spent” per one train-hour
UNIT_PRODUCTIVITY _LINE_L_KM_by_Tr_KM	Unit productivity parameters of line locomotive kilometers per one train kilometer	A ratio of how many line locomotive kilometers are “spent” per each train kilometer

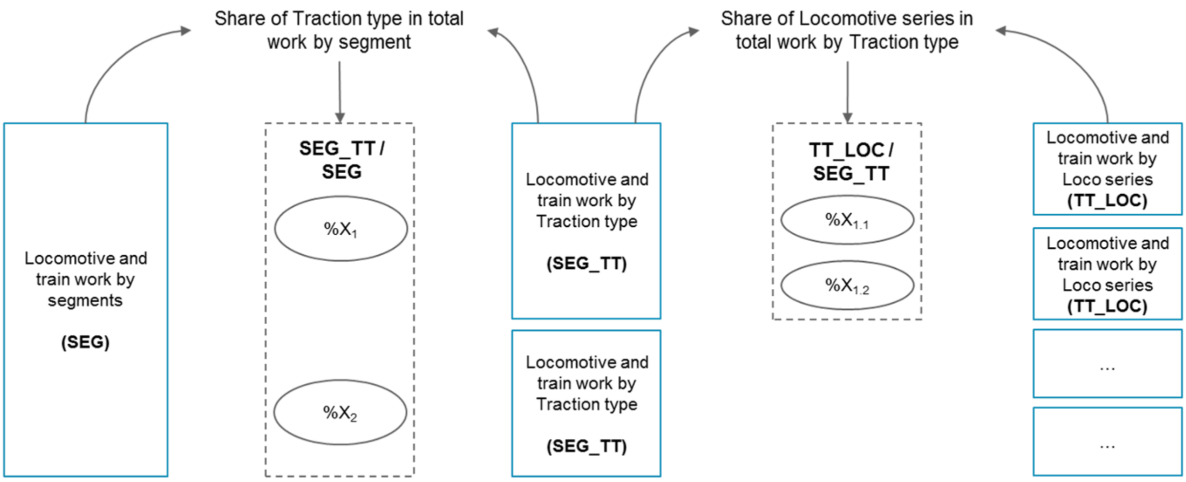

Fig. 4. Calculation of work shares for traction types and locomotive series

The Table 10 traction type work share reference is populated automatically by utilizing past data from the TsO-4 section 3 database regarding train work parameters. The work share reference tables are also automatically populated by past locomotive and train work data, which are already assigned to segments. This process is detailed in Fig. 4.

If segment PU1 contains 95% of its tasks handled by electric locomotives (mainline freight work), and 5% conducted by diesel locomotives (local and yard work), this data will be recorded in the "Historic share of Traction type in total work by segment" table. Regarding electric locomotive tasks, 80% are performed by VL80 locomotives, while locomotives KZ8A handle the remaining 20% - these details will be stored in the "Historic share of Locomotive series in total work by Traction type" reference table.

The information stored in the past work share tables serves two primary purposes: first, it's used to allocate locomotive and train work data to specific segments, and second, it automatically populates the TRO work share reference tables. It's important to note that the alignment of IOMM segment data to TRO segments relies on the TRO to IOMM segment relation table. TRO work share reference tables play a vital role in accurately accounting for various traction types and locomotive series. By calculating work shares, TRO becomes capable of aggregating unit productivity parameters for different Traction types and Locomotive series, resulting in a unified algorithmic cost for each segment.

The automatic population of the unit productivity parameters reference table involves assigning locomotive and train work data to corresponding segments and locomotive series, while considering the necessity to match IOMM segment data with TRO segments through the TRO to IOMM segment relation table. Following the aforementioned steps, past information about locomotive and train work is situated within Table 13.

Table 13

Historic data on locomotive and train work

#	Name	Unit of measurement
C_1	ID_PU	Segment code (for IOMM segments)
C_2	TRACTION_TYPE	Traction type code
C_3	LOCO_SERIES_ID	Locomotive series ID code
1	L_KM	Total locomotive kilometers
2	L_KM_LINE	Line locomotive kilometers
3	L_H	Total locomotive hours
4	deriv_Tr_H	Derivative train hours
5	FUEL	Total fuel consumed
6	Tr_KM	Train kilometers
7	GTKM	Gross ton kilometers
8	ENG_H	Actual work time in hours for locomotive drivers
9	CON_H	Actual work time in hours for conductors

While determining unit productivity parameters for locomotive-hours, locomotive driver-hours, and conductor-hours, the initial step involves computing derivative train-hours for segments. These derivative train-hours for each segment are obtained by dividing train-kilometers per segment by the segment velocity. This stems from the fact that the past train-hours in the THO-1 report incorporate non-freight activities, leading to an inflation of train-hour values in the report.

To facilitate the automatic population of the reference table for unit productivity parameters, past unit productivity parameters are calculated. This calculation is performed by dividing locomotive work data by train work data for each entry (refer to Table 14).

The following article section offers extra clarifications for various unit productivity parameters and the essential changes and data required to shift from unit productivity parameters to costs.

Table 14

Historic unit productivity parameters calculation

Name	Calculation on the basis of historic data
UNIT_COST_L_H_by_deriv_Tr_H	[2 / 3]
UNIT_COST_L_KM_by_Tr_KM	[1 / 5]
UNIT_COST_FUEL_by_GTKM	[4 / 6]
UNIT_COST_ENG_H_by_deriv_Tr_H	[7 / 3]
UNIT_COST_CON_H_by_deriv_Tr_H	[8 / 3]
UNIT_COST_LINE_L_KM_by_Tr_KM	[1 / 5]

3.2. Developing price reference tables and providing further clarifications

As previously mentioned, the primary objective of TRO is to determine operational parameters by utilizing routing algorithms on projected traffic. Consequently, unit productivity metrics must be transformed into algorithmic costs, reflecting specific conditions governing cost considerations. This transformation is necessary to derive projected costs, which differ from the estimates generated by certain specialized divisions within KTZ for variable operational expenses. The distinctions can be summarized as follows:

The costs calculated within the TRO model serve as approximations for routing and certain strategic decision-making scenarios. Specialized departments utilize variable operational cost forecasts as a foundation for formal budgetary processes.

In essence, diverse goals are attained through distinct methodologies, yielding disparate outcomes. An assessment of the gap between the outcomes from these two methodologies, and the deviation from the intended forecasting purpose, can be performed post-TRO implementation. However, this requires two prerequisites: a) a clear rationale for the usefulness of such analysis, and b) a commitment to adjusting both methodologies to bridge the identified gap.

This section delineates the techniques employed to incorporate variable operational costs as part of TRO's costs, while highlighting key discrepancies from the methodologies employed by specialized departments within KTZ.

3.2.1. Fuel and Energy Consumption Calculation for Traction

Section 3.1.3 outlines the automated generation of fuel consumption norms, facilitating the creation of reference tables for fuel consumption (measured in kilograms or kWh) per gross ton-kilometer in freight operations, specific to each locomotive series on every segment. To convert these unit productivity metrics into algorithmic costs per segment, they must be matched with fuel or energy prices. Additionally, locomotive series and traction type shares are integrated to consolidate individual unit productivities into an algorithmic value. The costs of fuel and electricity are managed separately and updated by KTZ specialists. The unit fuel productivity table contains approximately 24,000 entries, representing unique combinations of Segment, Locomotive series, and Month parameters. These reference tables are relatively easy to maintain due to their three-dimensional nature, allowing swift manual adjustments in response to operational changes (e.g., introduction of a new locomotive series on a specific segment). Presently, KTZ's forecasting and norming processes rely on established fuel consumption norms stored in the IOMM system. These norms are calculated for individual crew runs (not segments), considering eight parameters. However, using crew-run-based calculations poses challenges as discussed earlier.

3.2.2. Prediction of Locomotive Crew Costs

To incorporate variable locomotive crew costs into TRO's framework, a labor productivity unit parameter is employed. The calculation process, outlined in section 3.1.3, converts this parameter, established for each segment, traction type, and locomotive series, into an algorithmic cost. This involves applying Traction type shares (Table 12) and Locomotive series shares (Table 13) to aggregate unit productivities. Additionally, individual costs per hour for locomotive drivers and conductors are factored in. KTZ's current forecasting and planning methods rely on crew run norms to estimate required locomotive crews based on forecasted line mileage and trip times. As previously discussed, parameters based on crew runs cannot be used for algorithmic cost calculations due to inherent limitations. Moreover, the lack of centralized storage for the critical "Trip time (including return trip) in hours" parameter impedes TRO's integration with KTZ's forecasting approach.

Comparing the existing TRO approach and KTZ's approach, it's evident that forecasted locomotive crew counts and costs would not align. As stated earlier:

TRO's forecasts are preliminary and constrained by specific TRO costs used for routing.

Analyzing and minimizing the discrepancy between TRO and KTZ forecasts is feasible post-TRO implementation, contingent upon the practicality of such analysis and the resources available to adjust both methodologies.

3.2.3. Maintenance, Repair, and Overhaul Costs (MRO costs)

Incorporating maintenance costs into algorithmic costs is accomplished through service fees allocated to locomotive kilometer or hour of work. While service fees for all locomotive series enable a straightforward transition to algorithmic segment costs, actual maintenance costs vary based on repair events or service contracts. Service agreements facilitate the conversion of service fees from locomotive hours to inventory locomotive hours through technical availability coefficients, specific to each locomotive series. Integrating unavailability coefficients, usually part of service agreements, into TRO ensures consistency with actual maintenance arrangements.

*Fee per 1 locomotive-hour = (Fee per 1 calendar day / 24 hours) * (1+*
+Unavailability coefficient) . (4)

The process of converting service fees (both existing and virtual) into algorithmic costs is explained further in section 3.3.

To incorporate individual maintenance expenses into algorithmic costs for locomotive series that aren't governed by service agreements (and hence follow time or mileage-based servicing schedules), it's necessary to transform these time or mileage intervals into a "virtual service fee" per locomotive-kilometer or locomotive-hour. This involves initially determining the proportion of each maintenance task attributed to one locomotive kilometer (or hour), then multiplying this proportion by the corresponding maintenance event's cost.

As an illustration, let's consider the 2TE10M series locomotives with the subsequent approved maintenance intervals for various events:

A TO-2 event is scheduled every 72 hours.

A TO-3 event is scheduled every 8500 kilometers.

A TO-5 event is scheduled every 55000 kilometers.

A TO-7 event is scheduled every 110000 kilometers.

A TO-8 event is scheduled every 220000 kilometers.

Here, TO-2, TO-3, TO-5, TO-7, and TO-8 denote distinct locomotive maintenance procedures encompassing a series of activities aimed at preserving the locomotive's functionality and operational status. These maintenance categories are periodic in nature and intended to oversee the locomotive's component and system health, thereby minimizing operational breakdowns. There are additional maintenance categories that are non-periodic and can be implemented as required.

In essence, this approach entails breaking down the virtual fee for each locomotive within the 2TE10M series into two separate values:

*Per 1 loco-kilometers = 1/8500 * cost of a TO3 event + 1/55000 * cost of a TO-5 events +*
*+1/110000 * cost of a TO-7 event + 1/220000 * cost of a TO-8 event.* (5)

As well as,

*Per 1 loco-hour = 1/72 * cost of a TO-2 event* . (6)

Additional points need to be highlighted regarding this example:

- 2TE10 locomotive series consists of paired locomotives, and repair costs for this locomotive series are provided for each unit. Therefore, algorithmic costs for a complete locomotive should be doubled.
- When reevaluating costs in the maintenance price list and distances in the maintenance interval list for TO-2 events, it's imprudent to use the full duration of the TO-2 maintenance interval. This is because these intervals serve as absolute maximum allowed durations, and locomotives never reach the full interval length in practice (as trips exceeding the remaining TO-2 interval length are not allowed).
- Overhauls and major maintenance events (like TO-8U maintenance events every 10 years) aren't factored into the virtual fee calculation. The decision to include them depends on KTZ experts, considering whether these events will occur before the locomotives are decommissioned.

After calculating virtual service fees for non-service agreement locomotive series, their maintenance costs can be added to algorithmic costs.

Currently, locomotive maintenance cost forecasts rely on standardized monthly turnover norms. Experts determine maintenance event counts and types for the upcoming year based on these norms. This approach differs from forecasting maintenance algorithmic costs using TRO methodology. TRO uses specific forecasts of locomotive kilometers for different segments and series, rather than a standardized turnover rate.

As discussed earlier, the gap between forecasts from these methodologies can be reconciled if there's a clear rationale and willingness to adjust both approaches. The specifics of calculating virtual service fees for each locomotive series are determined by KTZ specialists. The crucial aspect for this methodology is the resulting fee's core characteristics, which represent the specific maintenance cost per locomotive hour or kilometer.

3.2.4. Rolling stock rental costs per segments

KTZ, as a freight railway operator, doesn't pay for rolling stock rental, avoiding direct costs tied to wagon fleet operation. However, ignoring wagon operating costs can hinder optimal routing by incentivizing the model to overlook time increases. This discrepancy can be resolved by introducing an algorithmic cost per wagon hour, acting as a rental fee (denominated in Kazakhstani tenge per hour). This fee ranges from 0 to X tenge, where X represents the daily market rental fee per wagon (distinct by wagon type). Opting for the fee X makes the model account for all extra rolling stock rental costs, while a fee of 0 results in their disregard. Once the desired fee is selected, it becomes an algorithmic cost per wagon-hour, a fundamental metric for segments, needing no further unit productivity factors for recalculation. The fee, regardless of size, is documented in reference tables and external sources. Determining wagon rental fees and future forecasts is the responsibility of KTZ planning experts.

3.2.5. Algorithmic Costs for Cargo Security Services

Calculating security service costs for cargo involves multiplying the number of security objects by a standard fee. Security objects include most cargo-bearing wagons (except bulk cargo like coal) and containerized cargo in structured transit container trains. Security fees are part of wagon-hour algorithmic costs. These costs are applied to wagon-hours in a train, calculated by dividing wagon-kilometers by the segment velocity, without considering intermediate station dwell times. To forecast security costs, the secured operating fleet is divided by division, and corresponding security fees are calculated. KTZ experts maintain and update the security fees reference table. Algorithmic costs are applied to train wagon-hours, and total security fees are computed for the operating wagon fleet. However, the sum of these algorithmic costs won't necessarily match the projected security costs due to operational nuances. Identification of eligible traffic records for security fees is based on traffic categories fit for security. This entails using five key parameters of a traffic record to define its traffic category: communication type, shipping type, loaded/empty status, cargo group, and wagon type. Currently, eligibility for security is established by belonging to a particular loaded cargo group for wagons and a specific combination of communication type and cargo group for containers.

3.2.6. Algorithmic Costs of Station Passage

Algorithmic station passage costs are derived from two sources:

1. Actual variable costs linked to wagon and train handling in yards.

2. "Artificial" unit costs for station passage designed to encourage the model to select paths with fewer intermediate station dwells, promoting lower overall dwell time.

3.2.6.1. Actual Algorithmic Costs of Station Passage

The current KTZ operations planning and cost accounting lacks explicit variable costs tied to yard operations, specifically allocated to wagon traffic managed by yards. Station resources mainly remain fixed due to limited traffic intensity variability across years, making them constant. The only resource truly variable in yard operation is the fuel and energy used by shunting locomotives. This resource correlates (though not linearly) with the number of wagons handled. However, shunting operations' resource consumption is tracked by locomotive depot in KTZ and can't be directly allocated to stations without analyzing crew logs. As a result, no concrete algorithmic costs for station passage based on actual costs are suggested in this methodology. Potential changes in operations accounting might enable such estimates in the future.

3.2.6.2. Artificial Algorithmic Costs of Station Passage

Creating "artificial costs" for station passage is suitable when minimizing on-line wagon fleet value is vital or when certain traffic categories must follow the "fastest" route for high service velocity. However, this approach isn't recommended within KTZ operations technology, as detailed train formation plans and station capacities are omitted. Trying to reroute for a "faster" path might slow other flows in the network. In most cases, the "Least path" routing aligns with higher service velocity, and optimization for this in TRO isn't necessary.

Given the above, auto-populating algorithmic costs for station passage isn't advisable. In specific analyses, "artificial" algorithmic costs for station passage could be set based on average dwell times with or without handling. For major sorting yards, a weighted-average of dwell times with and without switching is suggested. Station passage cost could be established by multiplying the algorithmic wagon-hour cost by the average wagon dwell time at the station.

3.3. Final Algorithmic Costs Calculation

Algorithmic costs (AC) represent penalty coefficients for algorithms in Kazakhstan's national currency, tenge, utilized in TRO. These ACs are employed for computed route elements, facilitating the comparison of distinct calculated traffic routes (consisting of sequences of segments and/or districts and stations traversed by each traffic record) for the same traffic record. The computation involves establishing unit productivity parameters and procuring price reference tables, as elaborated in the preceding sections. The unit productivity parameter reference tables are organized to encompass specific entries for every pairing of "segment" and "locomotive series." Conversely, algorithmic costs need to be computed on a per-segment basis, constituting a solitary cost for each parameter within the computed traffic routes (CTP). Consequently, the ultimate stage in determining algorithmic costs entails aggregating all individual unit productivity parameters into a singular cost per parameter, which can be applied to any CTP traversing a segment.

3.3.1. Algorithmic Costs Per Unit of Turnover

Algorithmic costs per unit of turnover are determined using reference tables of unit fuel productivity for various locomotive series and segments, outlined in section 3.1.3. The calculation formula for these algorithmic costs is as follows:

$$\text{AC per 1 ton-km gross} = \sum_i (Sh_{GTKM} * F_{GTKM} * P_{FUEL}) \quad (7)$$

where

i – is the locomotive series operating on a specific segment,

Sh_{GTKM} – is a work share (calculated for turnover specifically) of this series in total turnover over this segment,

F_{GTKM} – is unit fuel productivity of this specific locomotive series in kilos of fuel or KWT-hours per one gross ton-km,

P_{FUEL} – is cost of one kilo of fuel or 1 KWT-hour for this specific segment.

3.3.2. Algorithmic Costs of Train-Kilometers

Algorithmic expenses of l-km symbolize charges for locomotive upkeep. They're computed using a reference table of locomotive-kilometers per train-kilometer productivity and maintenance service fees (derived from service agreements and maintenance intervals). The calculation formula for this AC is as follows:

$$AC\ per\ 1\ train\text{-}km = \sum_i (ShTrKM * F_{TrKM} * P_{MRO}) \quad (8)$$

where, i – is the locomotive series operating on a specific segment,

Sh_{TrKM} – is a work share (calculated for train-kilometers specifically) of this series in total train-kilometer work done in this segment,

F_{TrKM} – unit productivity of this locomotive series calculated as number of loco-kilometers per one train-kilometer of work,

P_{MRO} – service fee for this locomotive series per one locomotive-kilometer (either factual or calculated)

3.3.3. Algorithmic Costs of Train-Hours

Algorithmic expenses related to locomotive hours encompass both crew expenditures and locomotive maintenance costs for trains. These costs are computed based on distinct sets of unit productivity parameters. These parameters encompass the efficiency of locomotive-hours per train-hour, the efficiency of locomotive driver-hours per train-hour, and the efficiency of conductor-hours per train-hour. The initial parameter is evaluated for each combination of locomotive series and segments, while the latter two are calculated solely for segments, irrespective of the series. Additionally, this computation takes into account service charges derived from service agreements, as well as those determined from maintenance intervals. Moreover, it considers labor charges for every hour of locomotive driver labor and conductor labor.

The formula for calculation of this AC is as follows:

$$AC\ of\ 1\ train\text{-}hour = \sum_i Sh_{TrH} * (F_{TrH} P_{MRO} + F_{EnH} * P_{EnH} + F_{ConH} * P_{ConH}) \quad (9)$$

where, i – is the locomotive series operating on a specific segment,

Sh_{TrH} – is a work share (calculated for train-hours specifically) of this series in total train-hour work done in this segment,

F_{TrH} – unit productivity of this locomotive series calculated as number of loco-hours per one train-hour of work,

P_{MRO} – service fee for this locomotive series per one locomotive-hour (either factual or calculated)

F_{EnH} – unit productivity of this locomotive series calculated as number of locomotive driver-hours per one train-hour of work,

P_{EnH} – the labor fee of one hour of locomotive driver work

F_{ConH} – unit productivity of this locomotive series calculated as number of conductor-hours per one train-hour of work,

P_{ConH} – the labour fee of one hour of conductor work.

3.3.4. Algorithmic Costs of Wagon-Hours

The algorithmic cost of a wagon-hour encompasses two main components: expenses related to leasing rolling stock and security charges. As information about containers is stored in TRO as the

"Containers per wagon" ratio, the algorithmic expenses tied to container-hours can be included within the framework of wagon-hour costs.

Formula for calculation of this algorithmic cost is the following:

$$AC\ per\ 1\ wagon\text{-}hour\ = PriceWag_i + cost_{wag} + k_j * cost_{cont} \tag{10}$$

where

$PriceWag_i$ – cost of renting one wagon-hour for the specific traffic category of this traffic record,

$cost_{wag}$ – security fee per one wagon-hour for wagon-load traffic for the specific traffic category of this traffic record. Is set to 0 if traffic category of this traffic record is not eligible for security fee,

$cost_{cont}$ – security fee per one container-hour for containerized traffic for the specific traffic category of this traffic record. Is set to 0 if traffic category of this traffic record is not eligible for security fee,

k_j – ratio of number of containers to a wagon for this particular traffic record.

3.3.5. Algorithmic Costs of Station Traversal

Algorithmic station traversal costs are not automatically computed using this approach (refer to section 3.2.6). In certain analysis scenarios, unique "artificial" station traversal expenses can be manually set for specific stations by directly modifying the TRO input table of algorithmic costs (see section 3.2.6.2).

4. RESULTS

After completing the preparatory steps outlined earlier and calculating algorithmic costs for each potential route of the car flow, you should generate the subsequent tables containing the computed algorithmic cost values. These values are available in Tables 15-17. Additionally, you have the option to visualize this data as shown in Fig. 5. Compiled by the authors based on data on past traffic volumes obtained from KTZ internal information systems.

Table 15

An example of calculating the algorithmic costs of a car flow with three different routing options

RouteID	Flow (from to)	Route (Via)	Total costs	Fuel costs	Crew costs	MRO costs
13_24	Iletsk I - Dostyk	Arys I, Almaty I	2 664 913 713	1 854 165 882	212 477 038	598 270 793
13_25	Iletsk I - Dostyk	Sekseul, Moiynty	2 390 648 069	1 708 137 986	156 296 491	526 213 592
13_26	Iletsk I - Dostyk	Tobol, Moiynty	1 958 522 356	1 338 231 729	159 286 643	461 003 985

Table 16

Example of calculating parameters used as an input for algorithmic costs calculation

Flow (from to)	Route (via)	GTKM	Loco-hrs	Loco fleet use	Loco-km	Total Distance	Train-hr	Train-km
Iletsk I - Dostyk	Arys I, Almaty I	4 309 986 500	67 050	7,65	1 873 847	3 647	37 655	1 629 132
Iletsk I - Dostyk	Sekseul, Moiynty	3 563 230 067	49 250	5,62	1 306 374	2 428	28 634	1 136 722
Iletsk I - Dostyk	Tobol, Moiynty	3 887 049 893	50 099	5,72	1 240 943	3 083	26 563	1 125 733

Table 17

An example of calculating the parameters of wagons for algorithmic costs calculation

RouteID	Flow (From to)	Route (via)	Wagons per day	Wagon-km	Wagon fleet in trains
13_24	Iletsk I - Dostyk	Arys I, Almaty I	76	278 327	268
13_25	Iletsk I - Dostyk	Sekseul, Moiynty	76	185 265	194
13_26	Iletsk I - Dostyk	Tobol, Moiynty	76	235 223	231

Indicators	Route 1	Route 2 (shortest)	Route 3
Proceeding stations	Arys, Almaty	Sekseul, Moiynty	Tobol, Moiynty
Range **(in km)**	3317	2742 km	2991 km
Locomotive hours (**in locomotive hours per year**)	67 050	49 250	50 100
Kilometers traveled by cars. **(in cars)**	268	195	231
Cost Estimation (in a year)	2.6 billion KZT	2.4 billion KZT	2.0 billion KZT
of which, F&E resources (in a year)	1.8 billion KZT	1.7 billion KZT	1.3 billion KZT

Fig. 5. An example of visualization of three alternative routes for the movement of car flows in the direction of Iletsk - Dostyk with the selection of the lowest indicators

5. DISCUSSION

Efficient transportation systems are crucial for economic growth and development, and railways play a key role in ensuring smooth movement of goods and passengers. In Kazakhstan, the primary railway network managed by Kazakhstan Temir Zholy (KTZ) is vital for the nation's logistics and trade. To enhance the effectiveness and profitability of this vital transportation infrastructure, it's essential to create methods that optimize train routing, considering economic and operational factors.

Efficient train routing involves evaluating variables like distance, fuel consumption, maintenance, and labor costs. However, an important factor in assessing routing plans is accurately estimating costs for different routes. A dependable and comprehensive methodology for cost calculation is the main focus of this article.

As shown in Figure 4, although the Sekseul and Moiynty route is shorter and requires fewer locomotive hours, its total costs exceed those of the Tobol and Moiynty route. This is due to route 3 primarily using cost-effective electric traction compared to diesel traction on route 2. Thus, choosing route 3 over route 2 could potentially save KTZ around 400 million tenge ($0.8 million) annually. The Tobol-Kandyagash line in Figure 4 is displayed as a dotted line due to capacity limitations that restrict all projected traffic. However, analyzing constraints and their impact on network routing is beyond this article's scope.

Quick evaluation and comparison of optimization options on the network are impossible without the cost allocation methodology explained here, which is based on KTZ's existing cost allocation systems and methods. This methodology enables swift cost estimation based on car flow routing options on the KTZ network, utilizing standard reporting forms and existing information systems without altering KTZ's accounting policy or systems. What sets this methodology apart is its consideration of diverse locomotive traction types used by KTZ. In contrast to the United States and European Union, where a single traction type prevails—electric in Europe and diesel in the United States.

6. CONCLUSIONS

The article's objective was to explore and suggest a more effective approach for evaluating expenses linked with various routing choices on the KTZ main railway system. Through a systematic method, this approach will allow KTZ railway operators and planners to make well-informed choices, ultimately leading to economical train flow routing and improved overall network performance.

By using a mix of data analysis, mathematical modeling, and practical insights, this article introduced a comprehensive structure for assessing algorithmic expenses based on different measures. These factors encompass elements like fuel/energy usage, locomotive maintenance prerequisites, crew expenditures, and other operational outlays. The proposed approach takes into consideration the distinctive features of the KTZ main railway network, assuring its suitability and pertinence to the local environment.

The application of this technique enables KTZ railway authorities to enhance train flow routing, curbing expenses while upholding safety and operational efficiency. The potential upsides comprise of better resource allocation, decreased fuel consumption, and heightened competitiveness within the transportation domain. Furthermore, this strategy is in line with worldwide trends in railway administration, underscoring the significance of cost-effectiveness and sustainability.

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References

1. Merkuryeva, G. & Valberga, A. & Smirnov, A. Demand forecasting in pharmaceutical supply chains: A case study. *Procedia Computer Science*. 2019. Vol. 149. P. 3-10. DOI: https://doi.org/10.1016/j.procs.2019.01.100.
2. Milenković, M. & Švadlenka, L. & Melichar, V. & Bojović, N. & Avramović, Z. SARIMA modelling approach for railway passenger flow forecasting. *Transport*. 2015. Vol. 33. No. 2. P. 1-8. DOI: https://doi:10.3846/16484142.2016.1139623.
3. Roos, J. & Gavin, G. & Bonnevay, S. A dynamic Bayesian network approach to forecast short-term urban rail passenger flows with incomplete data. *Transportation Research Procedia*. 2017. No. 26. P. 53-61. DOI: https://doi.org/10.1016/j.trpro.2017.07.008.
4. Zhang, J. & Chen, F. & Shen, Q. Cluster-based LSTM network for short-term passenger flow forecasting in urban rail transit. *IEEE*. 2019. Vol. 7. P. 147653-147671. DOI: https://doi.org/10.1109/ACCESS.2019.2941987
5. Tang, Q. & Cheng, P. & Li, N. **基于GSO-BPNN方法的城市**轨道交通客流短时预测[J]. 2017. **通信**领域的技术与经济(1): 1-4. [In Chinese: Tang, Q. & Cheng, P. & Li, N. Short time forecasting of passenger flow in urban railway using GSO-BPNN method. *Technology & Economy in Areas of Communications*. 2017. T. 19(1). P. 1-4].
6. Намиот, Д.Е. & Покусаев, О.Н. & Лазуткина, В.С. О моделях пассажирского потока для городских железных дорог. *International Journal of Open Information Technologies*. 2018. Vol. 6. No. 3. P. 9-14. [In Russian: Namiot, D.E. & Pokusaev, O.N. & Lazutkina, V.S. On passenger flow models for urban railways. *International Journal of Open Information Technologies*].
7. Andersson, M. & Brundell-Freij, K. & Eliasson, J. Validation of aggregate reference forecasts for passenger transport. *Transportation Research Part A: Policy and Practice*. 2017. Vol. 96. P. 101-118. DOI: https://doi.org/10.1016/j.tra.2016.12.008.
8. Prakaulya, V. & Sharma, R. & Singh, U. & Itare, R. Railway passenger forecasting using time series decomposition model. In: *2017 International conference of Electronics, Communication and Aerospace Technology (ICECA)*. 20-22 April 2017. Coimbatore, India. P. 554-558.
9. Markovits-Somogyi, R. Measuring efficiency in transport: the state of the art of applying data envelopment analysis. *Transport*. 2011. Vol. 26. No. 1. P. 11-19. DOI: https://doi.org/10.3846/16484142.2011.555500.
10. Sultanbek, M. & Adilova, N. & Sładkowski, A. & Karibayev, A. Forecasting the demand for railway freight transportation in Kazakhstan: A case study. *Transportation Research Interdisciplinary Perspectives*. 2024. Vol. 23. No 101028. ISSN: 2590-1982. DOI: https://doi.org/10.1016/j.trip.2024.101028.

11. Frisch, S., Hungerländer, P., Jellen, A. & et al. Integrated freight car routing and train scheduling. *Cent Eur J Oper Res*. 2023. Vol. 31. P. 417-443. DOI: https://doi.org/10.1007/s10100-022-00815-3.
12. Bodin, L.D. & Golden, B.L. & Schuster, A.D. A model for the blocking of trains. *Transportation Res. Part B*. 1980. Vol. 14(1-2). P. 115-120.
13. Assad, A.A. Analytical models in rail transportation: An annotated bibliography. *INFOR*. 1981. Vol. 19(1). P. 59-80.
14. Assad, A.A. Analysis of rail classification policies. *INFOR*. 1983. Vol. 21(4). P. 293-314.
15. Crainic, T. & Rousseau, J.M. Multicommodity, multimode freight transportation: A general modeling and algorithmic framework for the service network design problem. *Transportation Res. Part B*. 1986. Vol. 20(3). P. 225-242.
16. Keaton, M.H. Designing optimal railroad operating plans: Lagrangian relaxation and heuristic approaches. *Transportation Res. Part B*. 1989. Vol. 23(6). P. 415-431.
17. Keaton, M.H. Designing railroad operating plans: A dual adjustment method for implementing Lagrangian relaxation. *Transportation Sci*. 1992. Vol. 26(4). P. 263-279.
18. Newton, H. Network design under budget constraints with application to the railroad blocking problem. Ph.D. thesis, Auburn University, Auburn, AL. 1997.
19. Barnhart, C. & Jin, H. & Vance, P.H. Railroad blocking: A network design application. *Oper. Res*. 2000. Vol. 48(4). P. 603-614.
20. Ahuja, R.K. & Jha, K.C. & Liu, J. Solving real-life railroad blocking problems. *Interfaces*. 2007. Vol. 37(5). P. 404-419.
21. Fügenschuh, A. & Martin, A. Computational integer programming and cutting planes. Aardal, K. & Nemhauser, G. & Weismantel, R. (eds.). *Handbooks in Operations Research and Management Science*. 2005. Vol. 12. Elsevier, Amsterdam. P. 69-122.