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Urban Mobility Modeling in PTV Visum with Various Options for Bus Fare Structure

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Abstract

The study focused on applying linear and non-additive fare structure models to simulate flat fares with a set of constraints for each fare model that can be used on public transport in real-world conditions. To this end, a method for modeling flat fares using PTV Visum software, specifically the origin-destination fare model, has been developed. The impedance function, which is used in the public transport headway-based assignment, is determined to minimize deviations between actual and calculated passenger volumes for bus routes using SQV statistics. The case study aims to develop a method for modeling flat fares within PTV Visum to predict and analyze passenger traffic on municipal bus routes in the Ukrainian city of Kryvyi Rih in the case of implementing flat fares for these routes. Two options were modeled: the current situation with a flat fare of UAH 15 (EUR 0.35) for bus routes run by private operators and fare-free public transit for municipal bus routes, and an anticipated scenario with a flat fare of UAH 15 (EUR 0.35) for bus routes operated by private companies and a flat fare of 8 UAH (0.18 EUR) for municipal bus routes. These evaluations provide insight into passenger flows on municipal bus routes under the existing fare option and in the case of implementing a charge for municipal transport in Kryvyi Rih. Obtaining results of passenger volumes and devising an approach to fare modeling is crucial for transportation sector decision-makers, aiding in the development of effective fare strategies within the city.

Keywords

public transport, transport modeling, PTV VISUM, survey, fare modeling, flat fare, free-fare transit

1 Introduction

Implementing public transport (PuT) fares helps control passenger costs and ensures a steady income for PuT operators. It is also important to tackle the financing and day-to-day expenses of public transportation, like drivers' wages, bus maintenance, and infrastructure improvements (Hörcher and Tirachini, 2021). Additionally, implementing fares can help manage the demand for transportation services and ensure efficient use of PuT (Thurmann-Moe et al., 2024).

The paper discusses recent developments in altering the fee systems of major urban areas (Schmöcker et al., 2016). One common trend is the implementation of larger, integrated fare systems in cities, emphasizing revenue management and cost balancing. Another trend focuses on simplifying fare structures, as seen in Oslo's reform reducing fare zones from 88 to 8. Various cities demonstrate a dilemma between favoring simplicity and exploring new possibilities for a more complex fare structure using electronic ticketing. Berlin, for example, aims to switch from an open to a closed access system alongside electronic ticketing to potentially increase revenue. Similarly, cities and regions like Barcelona, East Austria, Madrid, Montreal, and Philadelphia are also looking into leveraging advanced ticketing options.

Schmöcker et al. (2016) examine two fare structure concepts. Firstly, the concept of "flexible zones", seen in Seoul, involves flat fares within a defined radius from the traveler's initial morning boarding point, complemented by distance-based fares for longer journeys. The authors propose that adopting "price-capping", like London's model, appeals to both users and operators due to its potential revenue enhancement. This mechanism could foster user acceptance of fare structure intricacies by establishing a maximum price threshold.

Recently, many researchers have been dealing with the issues of modeling fares for urban PuT and regional transport.

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Weibel et al. (2024) employ conjoint analysis and market simulations to evaluate the potential attractiveness of a hypothetical three-part far structure named the bonus fare. Initially, the researchers investigated customer fare selection to discern biases towards pay-per-use or flat-rate options. Borndörfer et al. (2012) demonstrate that fare setting profoundly influences passenger behavior, especially travel choices and travel demand. Therefore, evaluating passenger behavior and corresponding passenger volumes in PuT necessitates careful consideration of the fare structure. Haase and Muller (2015) compute the expected revenue for each origin-destination pair and the number of fare zones crossed. They conduct numerical investigations using the GAMS/CPLEX solver and artificial data to demonstrate the applicability of their approach. Pfetsch (2007) proposes a fare planning approach assuming passenger behavior in response to fares can be modeled using demand functions. Gattuso and Musolino (2004) introduce a method employing simulation models to estimate the impacts of implementing an integrated fare system in regional transport services. The practice of application of flat fares for different regions is described in detail in the paper (Gokasar et al., 2023). It was noted that a flat fare system is well-suited for small cities and short travel distances. Otto and Boysen (2017); Müller et al. (2022) examine how the specific layout of fare zones and pricing structures for transportation services impact the user's willingness to pay. Schöbel and Urban (2022) tackle the challenge of determining the most cost-effective ticket, which entails identifying the cheapest fare across different distance- and zone-based fare structures. The idea behind the study (Czerliński and Bańka, 2021) was to convert flat and differentiated fares into mathematical functions such as linear, power, logarithmic, polynomial (max. of 4^{th} degree), and exponential by using regression analysis. Ali et al. (2021) focus on optimizing the bus operator's fares while considering bus frequency and minimizing commuters' travel expenses using a sub-assignment traffic model conducting simulations with flat fares and various bus fare ranges. The study by Šipuš et al. (2022) aims to establish fair criteria for defining fare zones in integrated passenger transport systems. Cats et al. (2016) present one of the few studies that examine changes in user behavior following the implementation of free PuT in Tallinn.

Before enacting any alterations to the PuT fare policy, it is crucial to evaluate the potential assignment of passenger volumes resulting from this decision.

Predicting changes in PuT demand under these circumstances can be done by using modern transportation planning and modeling software such as SYSTRA (Strategic Transport Modelling and Simulation, online) or PTV Visum (PTV Planung Transport Verkehr GmbH, online).

PTV Visum provides various fare structures, including distance-based, zone-based, from-to-zone-based fare, short-distance fare, and time-based fares (PTV Planung Transport Verkehr GmbH (b), online; PTV Planung Transport Verkehr GmbH (d), online). In cases where a fixed price must be established for a PuT trip, PTV Visum currently lacks a specific flat fare option.

Thus, despite numerous studies of PuT fare structures, there is a gap in the studies exploring the potential for modeling a flat rate within the specialized software for transport modeling such as PTV Visum.

A pressing scientific priority is to devise a methodology for modeling PuT flat fares utilizing linear specifications and non-additive fare structures, which can be tailored for transport planning objectives. The methodology's application will be demonstrated through an assessment of shifts in passenger volumes on municipal bus routes in the city of Kryvyi Rih (Ukraine) following modifications to the fare structure. Additionally, it aims to establish the correlation between fare value and travel demand within the PuT system.

Expanding the given details, the study aims to:

- Developing a methodology of applying linear and non-additive fare structure models to simulate flat fares with a set of constraints for each fare model.
- Implement the methodology developed within the specialized transportation modeling software PTV Visum.
- Modeling the demand for PuT under both the existing PuT fare structure and in the scenario of implementing flat fares in municipal bus routes.
- Analyzing the passenger volumes derived from the modeling outcomes of the mentioned scenarios.
- Establishing the relationship between fare value and travel demand in the system of PuT by buses.

Thus, conducting a relevant study using transportation modeling emerges as a crucial task for making informed decisions in smart urban transportation.

2 Methodology

2.1 General procedure of the study

The study's general procedure is depicted in Fig. 1. The preparatory phase involves conducting field surveys to assess traffic data (volumes of vehicles) in the city's street and road network, administering sociological surveys to

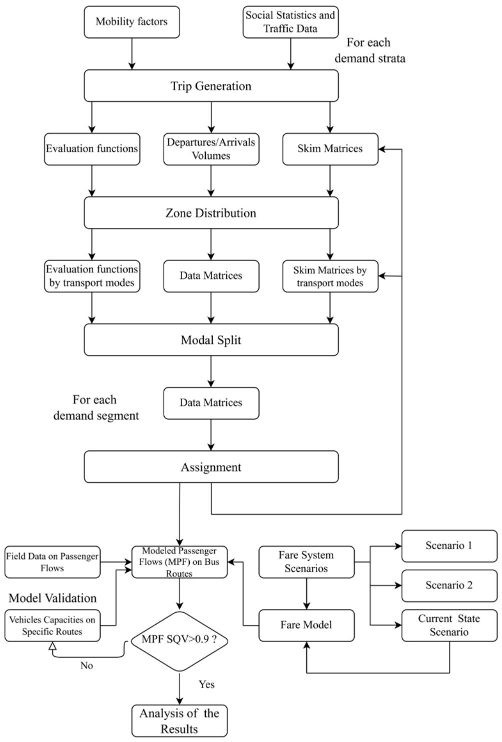

Fig. 1 The study's general procedure

gather key mobility indicators from respondents (mode of transport, modal split, demand strata, travel time, start and end points for origin-destination pairs, start/end time of the trip), obtaining social and economic statistics (list of institutions of industry and construction, small business, healthcare, education, sports, culture and tourism, social protection, transport and communications, as well as a list of institutions engaged in legal, law enforcement and financial activities, number of jobs by type of activity, population in each district of the city), analyzing actual passenger flows on public transport routes, and developing a passenger transport model using dedicated software tools.

One outcome of transport modeling is the assignment of PuT services. In the context of implementing various fare policies on municipal bus routes, the modeling outputs include daily passenger volumes on respective routes resulting from such assignments. The transport model is validated against the baseline (current) fare structure scenario. The criterion for convergence between actual and modeled passenger flows on bus routes is determined using the scalable quality value, defined by the following equation (Friedrich et al., 2019):

$$g_{SQV} = \frac{1}{1+\sqrt{\left(m-c\right)^2 / f \cdot c}} \quad (1)$$

where
g_{SQV} – scalable quality value;
m – modeled value of daily passenger flow;
c – real-world value of daily passenger flow;
f – scaling factor (for the number of person trips per day $f = 1$).

The validation process continues until the condition is satisfied.

A more detailed description of the demand model, the specifics of the assignment procedures, the fare model, and the model validation procedure are presented in the following sub-sections and sections of this paper.

2.2 Network model

Road facilities are represented using a network model structured as a topological graph. This model integrates various transportation modes into a unified network, incorporating specific elements such as links, nodes, turns, zones, connectors, origin-destination pairs, stops, stop areas, zone areas, and line routes. Each element within the network possesses its own set of attributes. For instance, links are characterized by parameters including length, free-flow speed, current speed of the private transport (PrT) system within the operational network, PrT system-specific impedance, the volume of PuT in terms of passenger numbers, and others. The spatial trajectory of a PuT line route in one direction is defined as a sequence of route points. Route points encompass selected locations along the line routes, primarily including all stops and potentially traversed nodes.

2.3 Demand model

The transport demand model includes data such as trip origins and destinations, transport modes employed, and other relevant mobility information.

In this study, to replicate the outcomes resulting from the adoption of a fare system, explicit simulations of mode and PuT route selections were conducted.

At the trip generation stage, the traffic volumes from origins to destinations are calculated for all transport zones, categorized by demand strata. The proportion of trips generated from each transport zone is determined using the ratio of movement distribution across demand strata and specific trip purposes obtained from surveys and socio-economic statistics.

At the stage of traffic distribution by zones, traffic flows between all transport zones are calculated, detailed by demand strata, but without detailing by transport mode.

During the modal split stage, data matrices are calculated, each conforming to trips allocated to specific modes of transport.

The distribution of correspondences across demand strata and the mode choice were conducted utilizing the Kirchhoff function.

The assignment calculation, differentiated by transport mode, enables the derivation of model values for daily traffic volumes. The assignment was carried out using the Bi-conjugate Frank Wolfe procedure for modeling PrT and the headway-based procedure for modeling PuT.

The assignment procedure for PrT demand uses the shortest path algorithm to identify generalized paths with minimal impedance, depending on the load and the resistance factors of the network. The vehicle delay function (VDF) formula articulates travel time as the product of the free-flow time (t_0) and a normalized capacity-restraint function (CR), which delineates the correlation between the current traffic load and the maximum capacity. Various CR functions are calibrated and tailored for specific network elements within the transportation model. The Lohse function is applied to links, while TModel Nodes is utilized for nodes and turns.

2.4 Public transport assignment model

The PuT assignment resolves around analyzing the mean headway, which encompasses the sequence of PuT stops, the duration of travel between these stops, and the intervals between successive vehicles along the route of the line route.

The PuT assignment process based on headway comprises three operational phases:

- Determination of the headway for the transportation line.
- Identification and selection of the specific line route.
- Loading of the chosen line route.

The computation of the line's headway can be executed through various methods:

1. Utilizing the user-defined temporal attributes along the line route.
2. Deriving from the average headway values stipulated in the schedule for the line route.
3. Estimation of the average waiting duration according to the schedule of the line route.

In the third instance, as utilized in this paper, the headway is calculated based on the equation (PTV Planung Transport Verkehr GmbH (a), online):

$$h^{a,b} = \frac{1}{b-a}\sum_{i=0}^{n} \Delta_i \qquad (2)$$

where
a, b – start and end of the time interval;
n – number of departures in the time interval [a, b];
i – index;
$\Delta_i = (y_{i+1} - y_i)^2$ for all $i \epsilon \{1, ..., n-1\}$;
y – departure.

The process of selecting a route (line) in the headway-based procedure involves two key stages:

- Evaluation of routes based on their impedance, which encompasses the total cost associated.
- Utilization of a choice model employing logistic regression to make the selection.

Configuring the impedance function represents a fundamental step in headway-based PuT assignment.

This function delineates the factors directly influencing the selection of transport mode (Headway-based assignment: Impedance tab). To achieve this, within the procedure for headway-based PuT assignment, it is essential to define the relationship between travel time and ticket price.

Impedance is determined as follows:

$$IMP = \infty \cdot PJT + \beta \cdot FARE \qquad (3)$$

Perceived journey time (PJT) is the travel time perceived by the user, *FARE* is the ticket price, α, and β are calibration coefficients. The coefficient α is set at 1, and the coefficient β corresponds to the quantity of transfers undertaken throughout the journey (Zhuk et al., 2024). The calibration coefficients of the impedance function should be chosen to align the importance or utility of the ticket price with that of travel distance for a PuT user.

The travel time, in turn, is defined as a function of the components of the trip time $PJT = f\,(ACT, EGT, OWT, TWT, NTR, IVT, WKT, XZ)$. Each of these components is described in the PTV Visum User Guide (PTV Planung Transport Verkehr GmbH (c), online).

- *In-vehicle time* (*IVT*) is the duration spent in PuT vehicles, encompassing any idle time experienced at stops.
- *Ride time* (*RIT*) is the time between departure from the initial stop and arrival at the final stop:

$$RIT = \sum IVT + \sum TWT + \sum WKT \qquad (4)$$

- *Access time* (*AT*) is the time required to pass the initial connection point.

- *Egress time* (*ET*) refers to the time needed to reach the destination from the current location.
- *Walk time* (*WKT*) is necessary for transferring between two stop points within the same area or between different stop areas and on links.
- *Origin wait time adopted* (*OWTA*) is waiting time at the origin (only applicable for the headway-based assignment).
- *Transfer wait time* (*TWT*) is the duration one spends waiting between the arrival of one vehicle and the departure of another at the transfer stop point.
- *Number of transfers* (*NTR*) is the number of transfers between the point of origin and the point of destination (per connection).

In the context of headway-based assignment, the decision model, governing passengers' choice to board a vehicle, presumes that their behavior is affected by the available information accessible to them.

2.5 Fare models

This study explores fare models characterized by linear specifications and non-additive fare structure (Gattuso and Musolino, 2004).

The flat fare system can be represented mathematically as follows:

$$f_{ij} = f_0 \tag{5}$$

where

$f_{i,j}$ – base fare which represents the total cost of the journey;
f_0 – initial fare, serving as the baseline value of the journey that can be construed as an access fee to utilize the network supply;
i – index of transport system for which appropriate fare system is utilized
j – index of path leg for which the suitable fare system is employed.

The linear fare system example is also a distance-based model that can be expressed by as follows:

$$\begin{cases} f_{ij} = f_0 + \sum_{i=1}^{n}\sum_{j=1}^{m}\left(f_{vij}\left(p\right) + f_{tij}\right), \\ p > 0, f_{ij} \geq 0, f_{tij} = 0 \end{cases} \tag{6}$$

where

n – number of transport systems;
m – number of path legs within the journey;
$f_{vij}(p)$ – variable fare that depends on the number of fare points within the transport system i and on the path leg j;
p – number of traversed fare points;
f_{tij} – fare applicable for the transfer between appropriate transport systems.

To adopt any linear or additive fare structure model to simulate flat fare, a set of constraints for each fare model was formulated.

The constraints for implementing the distance-based fare model are outlined as follows Eq. (2):

- The count of traversed fare points must exceed zero.
- The resultant fare must equal or exceed zero.
- Transfer fares are to be ignored, as they are not encompassed within the existing fare system.

In the short-distance fare model, fares are applied to tickets where the length, travel time, and number of stops do not surpass the predetermined thresholds (Ticket types).

The equations delineating the short-distance fare model are as follows:

$$\begin{cases} f_{ij} = f_0 + \sum_{i=1}^{n}\sum_{j=1}^{m}\left(f_{vij}\left(d\right) + f_{tij}\right) \\ f_{ij} = f_0 + \sum_{i=1}^{n}\sum_{j=1}^{m}\left(f_{vij}\left(t\right) + f_{tij}\right) \\ v_d \geq d_{\max} \geq d, v_t \geq t_{\max} \geq t, v_s \geq s_{\max} \geq s_n \\ p_{ij} \geq 0, p_{tij} = 0 \end{cases} \tag{7}$$

where

$f_{vij}(d)$ – variable fare that depends on the distance within the transport system i and on the path leg j;
$f_{vij}(t)$ – variable fare that depends on the travel time within the transport system i and on the path leg j;
d – traversed distance;
t – travel time;
s_n – number of stops;
d_{max}; t_{max}; s_{max} – pre-defined threshold values of traversed distance, travel time, and number of stops respectively;
v_d, v_t, v_s – large numerical values have been adopted for the parameters of traversed distance, travel time, and number of stops, respectively.

In order to simulate flat fare through the short-distance fare model, the maximum values of travel time, traversed distance, and the maximum number of stops must exceed any large numerical value assigned to these indicators.

The origin-destination fare model relies on the concept of OD connections. An example of such a model is the from-to zone-based non-additive fare system. In this model, the total fare accumulated during the journey is calculated based on the combination of the initial fare derived from the origin fare zone and the destination fare zone, linked through the fare matrix (Ticket types).

To simulate a flat fare using the from-to-zone-based fare model, the following equations must be satisfied:

$$\begin{cases} f_{il} = \sum_{i=1}^{n}\sum_{l=1}^{k}\left(f_{od} + f_{tij}\right), \\ f_{od} \int F_{od}, F_{od} = \left(e_{ij}\right), e_{ij} = 1 \\ k = 1, f_{ij} \geq 0, f_{tij} = 0 \end{cases} \tag{8}$$

where
f_{od} – from-to-zone-based fare item;
F_{od} – fare matrix comprising elements representing the fare associated with each pair of initial and target fare zones;
l, k – parameters associated with the number of fare zones;
e_{ij} – rank-one fare matrix element.

3 Application to the city of Kryvyi Rih

3.1 Problem definition

Kryvyi Rih, home to more than 600 000 residents, is a significant industrial center in central Ukraine's Dnipro region, particularly for the mining and metallurgical industries. Also, there are various enterprises involved in machine building and engineering, supporting the metallurgical and mining industries. The location of mining enterprises (underground iron-ore mining and iron ore open pits) shaped the city's planning structure, resulting in a layout that extends over 60 km and influencing the topology of the transportation network. This also influences the average route length in the passenger transport network, which is notably 18.6 km.

The PuT network in Kryvyi Rih includes a combination of municipal and private buses, a rapid transit light rail system, trams, and trolleybuses.

Based on the survey results gathered for this study, PuT makes up 59% of all trips in the city, while 24% of residents walk, and 13% use cars. Other modes of transport, such as bicycles, taxis, and motorcycles, account for 1-2% of trips.

In the urban passenger transport network in Kryvyi Rih, a flat fare is applied for passenger travel, independent of distance, travel duration, or the number of fare zones traversed. On bus routes managed by private operators, a single passenger aged 6 or older, not eligible for discounted fares, incurs a charge of UAH 15 (EUR 0.35) per trip. Since 2021, a fare-free PuT has been operational, encompassing municipal city buses, trolleybuses, trams, and light rail. The eruption of a large-scale war against Ukraine in 2022 has brought about considerable financial shifts in the frontline city of Kryvyi Rih, sparking discussions about potential alterations to PuT subsidies. Simultaneously, the city administration intends to introduce a fare of UAH 8 (EUR 0.18) per trip for municipal bus routes.

Thus, two fare model options can be outlined, allowing for a comparison of the operational efficiency of PuT:

- the current state, featuring flat fare of UAH 15 (EUR 0.35) for bus routes run by private operators and fare-free transit for municipal bus routes;
- the expected situation that also includes a flat fare of UAH 15 (EUR 0.35) for bus routes operated by private companies plus implemented a flat fare of UAH 8 (EUR 0.18) for municipal bus routes.

To evaluate the proposed methods – Eqs. (6)–(8) – in determining a flat fare for PuT, the Kryvyi Rih transportation model (KRTM) was developed and validated in PTV Visum.

3.2 Data collection

To ascertain transportation behavior regarding trip purposes, a survey was conducted among city residents. The survey yielded a total of 9665 trips per day across all demand strata. Specifically, 4364 trips were attributed to work-related purposes, 292 trips were for education, and 5109 trips were categorized under other trip purposes. These survey findings serve as foundational data for determining attraction and production trips, along with their respective coefficients, in the initial stage of the 4-step demand model.

Automated traffic video analysis software with artificial intelligence technology was used to determine the traffic volumes in the network for the PrT model. The paper details the method for conducting traffic volume surveys and specifies the locations surveyed (Sistuk et al., 2023).

The field data on passenger flows for bus routes was determined from the daily transaction reports from the Kryvyi Rih Card system (Center for electronic services, municipal enterprise of the Krivorihzhka city Council, online) for each day of operation on the route. The reports cover the period from November 6, 2023, to November 12, 2023. Comprehensive passenger flow data for PuT systems, including electric vehicles, throughout December 2023 has been acquired. This data pertains to urban transportation systems such as buses, rapid transit light rail, trams, trolleybuses, and minibuses.

3.3 Supply model attributes

The transport network in the model comprises 13 transport systems, 7 modes, 10097 nodes, 27598 links, 83270 turns, 238 zones, 1748 connectors for private transport, 3013 connections for PuT, 534 stops, 1165 stop areas, 1190 stop points, and 130 lines and 218 line routes.

3.4 Demand model adjustment

The demand model includes both a freight transport model and a passenger transport model, encompassing 7 demand segments. Specifically, the passenger transport model comprises 14 demand strata. The coding of the demand strata is shown in Table 1.

3.5 Public transport assignment validation

In the KRTM, the PJT parameter of impedance in headway-based PuT assignment is described as follows:

$$PJT = IVT + RIT + 1.1 \cdot AT + 1.1 \cdot MAZ \\ + 1.5 \cdot WKT + 1.5 \cdot OWTA + 1.5 \cdot TWT + 20 \cdot NT \quad (9)$$

Ultimately, the version of the impedance formula was considered, where the weight (utility) of user travel time and ticket price are equal, implying calibration coefficients equal to one were used.

To determine the most suitable method for calculating the flat fare for the KRTM among the three proposed options Eqs. (6)–(8), the results of the PuT assignment for the current state scenario were analyzed, employing the following PuT line attributes.

Three attributes are used for the PuT lines: *Passenger Flow*, *PTripsUnlinked(AP)*, *VolDev*.

Passenger Flow is a user-defined attribute where actual daily passenger volume data obtained from surveys is inputted.

Table 1 Coding of the demand strata in the KRTM

Number	Code	Name
1	001_HW_KrR	Home – Work
2	002_WH_KrR	Work – Home
3	003_HS_KrR	Home – Study
4	004_SH_KrR	Study – Home
5	005_HO_KrR	Home – Other
6	006_OH_KrR	Other – Home
7	007_WO_KrR	Work – Other
8	008_OW_KrR	Other – Work
9	009_WW_KrR	Work - Work
10	010_OO_KrR	Other – Other
11	011_HHE_KrR	Home – Higher education
12	012_HEH_KrR	Higher education – Home
13	013_HD_KrR	Home – Dacha
14	014_DH_KrR	Dacha – Home

PTripsUnlinked(AP) represents the calculated transport demand per day on the PuT line.

VolDev is also a user-defined attribute, it is calculated using the formula [*PTripsUnlinked(AP)*] - [*Passenger Flow*]. Essentially, it represents the difference between the calculated passenger volume and the passenger volume obtained from surveys.

SQV is a user-defined attribute to calculate scalable quality value using *Passenger Flow* and *PTripsUnlinked(AP)* attribute values.

The Passenger Flow attribute for bus routes utilizes field passenger volume data.

In each iteration of the PuT assignment calculation procedure, initial adjustments were made to the coefficients to accommodate the capacity of vehicles on specific routes. This consideration is reflected in the model through the *PutComfort* attribute. The goal was to minimize discrepancies between the actual passenger volumes on the bus routes and the calculated passenger volumes for the same routes using SQV statistics (Friedrich et al., 2019).

With the modeling of PuT assignment for predicted passenger volumes following the implementation of flat fares, the impedance formula for travel time and ticket price also utilized calibration coefficients of 1.

3.6 Fare model selection and implementation

This paper shows that creating a flat fare in PTV Visum can be achieved through several methods in accordance with constrains which are described in Eqs. (6)–(8). For all of them, since PuT system typically lacks transfer fare, a Fare System in PTV Visum must be chosen when setting it up: Each path leg separately: *A ticket has to be bought for each path leg of the fare system (PuT fare model, Ticket types).*

3.6.1 Distance-based fare solution

The proposed solution entails implementing a distance-based fare system. Distance-based fares are determined not by the actual distance traveled but by the number of designated fare points. These fare points are assigned to:

- *links* (segments, separately for different transportation systems);
- *time profile items* (time profiles on PuT routes).

The total distance covered by a passenger is computed as the aggregate of fare points associated with both types of network objects. One straightforward approach involves calculating the number of fare points for each time profile item based on the distance traveled.

Configuring the *Ticket type* is essential, regardless of the *«distance»* measured in fare points, as there is no need for calculation.

This setup can be accomplished in Tickets *(Network - PuT fares - Ticket types)*, where intervals of *«distances»* can be defined. For each interval, a flat fare or interpolation can be set. For the current task, only one interval with a flat fare is required.

Since the *«distance»* value must be greater than 0, it is essential to allocate some non-zero value for the fare points. The simplest approach to achieve this is by setting, for instance, 1 fare point for each time profile element, with a fixed value, using multi-edit (Fig. 2). This ensures that every trip will have a non-zero *«distance»* value.

Following this, the fare system can be linked to bus routes (in the *Fare Systems* tab), and the customized ticket type can be specified in the *Demand Segments* tab (Fig. 3).

3.6.2 Short distance fare solution

This approach involves creating a ticket for short distances, setting unrealistic travel times and maximum distances, and a flat fare (Fig. 4).

3.6.3 From-to-zone matrix solution

The first step is to create 1 fare zone, which is used to mark all stops (using the corresponding attribute). The final step is to generate a fare matrix consisting of only one element (Figs. 5 and 6).

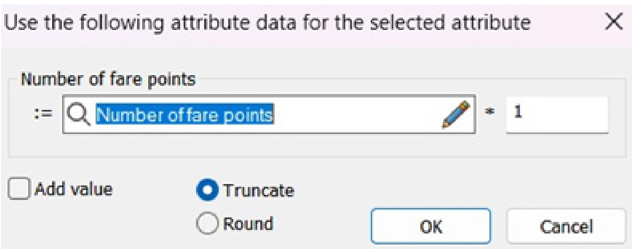

Fig. 2 Number of fare points in the line route time profile items

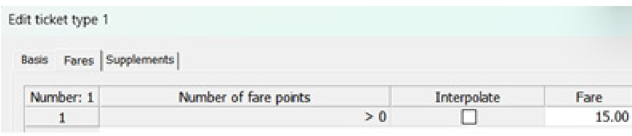

Fig. 3 Configuring the ticket type

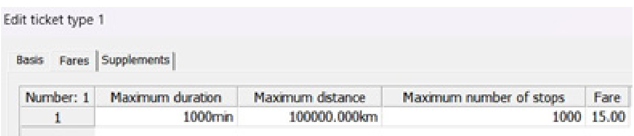

Fig. 4 Creating a short distance ticket and considering restrictions

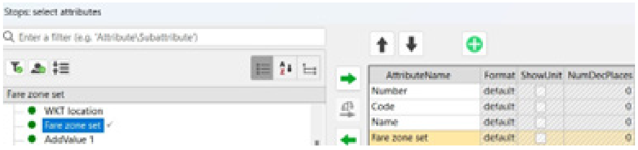

Fig. 5 Selecting a stop attribute

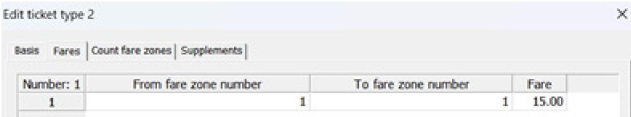

Fig. 6 Configuring the ticket type

This approach was selected for modeling fare structures in the KRTM after comparing the outcomes of base scenario modeling based on the outlined procedure (Fig. 1) using the three methods described.

The analysis of the modeling results of these two options is outlined in the subsequent section.

4 Results and discussion

The results of the PTV Visum modeling for the city of Kryvyi Rih enabled the determination PuT demand assignment for the two options considered, namely, the current state, when municipal bus routes are free of charge, and in the case of the implementation of a flat fare for the same routes.

Fig. 7 shows the graphical interpretation of the results obtained.

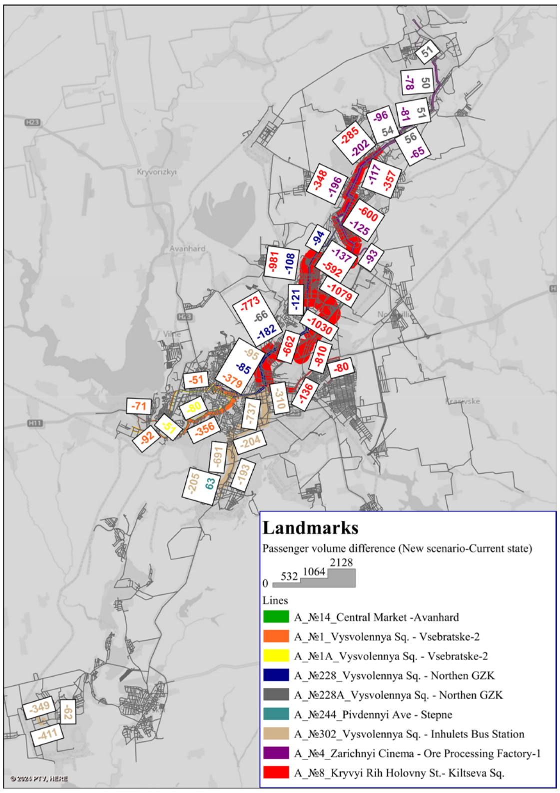

Fig. 7 Passenger volumes differences for the bus routes

The line bars illustrate the disparities in daily passenger volumes on nine bus routes that could occur upon implementing flat fares for these routes. These line bars facilitate a comprehensive evaluation of the contrast in daily passenger flows between the new and existing conditions across various sections of the urban road network.

In the case of implementation of the flat fare for municipal PuT, the most substantial decrease in demand for passenger volumes is anticipated on bus route A8, estimated at approximately 37%. Routes A1 and A302 are expected to experience a decrease in passenger volumes by 29%, while route A1a is projected to decline by 25%, route A4 is predicted to witness a reduction of 23% and route A228 is expected to decrease by 17%. Conversely, routes A228a, A244, and A14 are anticipated to maintain passenger volumes unchanged compared to the current situation. On average, a decrease in passenger flows of around 29% is projected.

According to the weekday schedule, route A1 operates 24 one-way vehicle journeys per day, route A1a has 25 vehicle journeys per day, and route A302 runs 31 vehicle journeys daily. Currently, the average weekday passenger volumes are 3515 for route A1, 3025 for route A1a, and 7618 for route A302. It is important to note that implementing fares on these bus routes is expected to lead to the decline in passenger traffic, with a projected decrease up to 29%, which cannot be compensated for by using alternative PuT routes without requiring transfers. These routes cannot be substituted by micro-mobility options like bicycles or scooters because of the long route lengths (up to 43 km). Apart from PuT with transfers, the only practical alternatives are private cars or taxis.

Thus, a negative consequence of the introduction of fixed fares in the network of municipal bus routes will be the fact that even for those routes that cannot be compensated by other PuT routes, there will still be a decrease in demand.

The most substantial decrease in passenger flow (approximately 1000 passengers per day in one direction) is expected for the road network section between such locations as the 95th Quarter and Kres PuT stop.

Changes in fare policy will undoubtedly impact the choice of PuT modes. Simulation results indicate that a decrease in passengers on municipal bus routes following a fare change will lead to an increase in demand for other PuT options.

Specifically, passenger flows on private bus routes could rise by 6%, while the trolleybus system may see a 1.3% increase, and trams might experience a 1.6% increase. The most significant rise in passenger traffic is projected for the rapid transit light rail system, with an increase of 9.7% compared to the current situation.

One limitation of the proposed method for modeling PuT fare is the complexity involved in the current state mobility model calibration. This process is time-consuming requiring numerous iterations with adjusting the settings of specific coefficients (the *PutComfort* attribute) to ensure that the calculated passenger flow values for all routes in the network align with actual field data, as assessed by the SQV statistics criterion. Moreover, this method can be employed regardless of the chosen fare model or even when no fare model is in place.

This study primarily aims to develop a universal method for modeling a flat fare using PTV VISUM software. The passenger flow indicators for PuT in Kryvyi Rih, generated through this modeling, enable decision-makers to establish a balanced fare policy while considering potential risks. If the new fare is implemented, there will be an opportunity to further verify the modeled passenger flow indicators, allowing for an additional evaluation of the adequacy of the proposed approach in subsequent research.

5 Conclusion

The author's new scientific contribution involves the creation of mathematical models that enable the adoption of linear or non-additive fare structures to simulate flat fares, incorporating specific constraints for each fare model. These fare models were integrated into PTV Visum using a newly developed approach, which was tested through the urban mobility model of Kryvyi Rih, analyzing passenger volumes on PuT bus routes with various fare strategies.

PTV Visum features an advanced fare system and structure, yet it lacks the capability to directly model PuT demand using a flat fare structure. In this regard, the paper proposes and tests three approaches to modeling flat fares in PTV Visum based on distance, from-to zone matrix and short distance fare. The cost of fare in PTV Visum serves as a factor influencing the impedance during the process of the PuT assignment. The coefficients of the impedance function in PuT assignment procedure are chosen to minimize discrepancies between the actual passenger flows observed on municipal bus routes in November 2023 and the passenger flows calculated for these routes in PTV Visum.

Following a series of executions of appropriate procedures in PTV Visum for the current state option, utilizing the three proposed methods, it was determined that the most suitable approach for modeling a flat fare within the Kryvyi Rih transport model is the From-to-Zone Matrix solution.

The fare model developed in PTV Visum enabled the modeling of two options: the current scenario features a flat fare of UAH 15 (EUR 0.35) for private bus routes and free-fare system for municipal bus routes and the projected scenario incorporating a flat fare of UAH 15 (EUR 0.35) for private bus routes and UAH 8 (EUR 0.18) for municipal bus routes.

Implementing a flat fare for municipal PuT in Kryvyi Rih is expected to result in the most substantial decline in passenger volumes on bus route A8, approximately 37%. Routes A1 and A302 may see a decrease of around 29%, while A1a is projected to drop by 25%. A4 and A228 are estimated to decline by 23% and 17%, respectively.

The suggested method for modeling flat fares applies to mobility models in other cities with similar fare structures.

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