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Passenger-Weighted Route Deviation Ratio (PWRDR) as a Parameter of Public Transport Quality

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ABSTRACT: Abstract: Designing efficient and competitive public transport services in urban areas requires a balance between service quality, accessibility, and operational efficiency. While tra- ditional planning methods primarily optimize for travel time and coverage, this paper introduces the Passenger-Weighted Route Deviation Ratio (PWRDR) as a novel parameter to evaluate the quality of transit routes. The PWRDR quantifies the extent to which a public transport line deviates from its direct path to serve additional areas, balancing accessibility and efficiency. This parameter considers the relationship between deviation length, travel time impact, population served, and the functional purpose of the route. We present a mathematical formulation and a methodological framework for integrating PWRDR into public transport planning. By incorporating this metric, planners can better assess the trade-off between directness and service coverage, leading to more effective and user-centered transit network designs.

KEYWORDS: Public transport, Public transport Quality, Travel Time, Transport planning, Route Deviation

I. INTRODUCTION

Public transport is a significant part of the intermodal transport system that serves both regions and individual set- tlements. However, public transport parameters must be set competitively to ensure its attractiveness compared directly to individual vehicle transport. In this regard, some solutions fail, and public transport's competitiveness against car transport remains insufficient. Currently, public transport plays a crucial role in serving areas in the Czech Republic and is regulated by Act No. 194/2010 Coll., on Public Services in Passenger Transport and on Amendments to Other Acts. The service of these areas relies on standard methods and algorithms, such as location models (e.g., p-median or p-center models) (1) and shortest-path algorithms (like Dijkstra's or A* algorithms) (2), (3), which aim to optimize route planning by minimizing travel time or distance while ensuring coverage of key points of interest. However, these sometimes fail or do not provide sufficient service quality. These approaches sometimes fail or do not provide adequate service quality (4).

The quality of service in a given area is a crucial factor for both passengers and the overall efficiency of the transport system (5), (6), (7). To better assess this quality, we introduce the concept of route deviation (also referred to as route me- andering) (8), (9), which describes how transit routes deviate from the most direct path to serve additional areas. Proper classification and evaluation of these deviations are essential to understand their impact on service quality and efficiency (10).

The primary objective of this study is to define the deviation from the route as a new quality parameter and establish a framework for its evaluation. Beyond its definition, our objective is to clarify its purpose and practical application, particularly in relation to different types of public transport routes and the areas they serve. This classification allows for a structured evaluation of how deviations from the route influence service quality both for passengers in affected areas and for those who already travel the route (11). By quantifying these impacts, we contribute to a more informed approach to public transport planning, balancing accessibility with effi- ciency.

To determine the value of the deviation from a direct route, which directly affects transport quality, it is essential to define various types of route deviation (10). These deviations differ in their nature, length, and purpose, thus influencing service quality both in terms of travel time and from the psychological perspective of passengers, who perceive extended time spent in the vehicle as inefficient.

In public transport planning, the concept of route configuration plays a crucial role in determining service efficiency and passenger satisfaction. Various terms have been used to describe the indirectness of a transit route, including *route tortuosity* (8), *route meandering* (9), and *route deviation* (11). Each of these terms captures different aspects of how transit services deviate from the most direct path to accommodate passenger demand.

Route tortuosity is a well-established metric that mathemat- ically quantifies the indirectness of a route, typically expressed as the ratio between the actual route length and the shortest possible path between its end points. Although precise, this definition focuses primarily on geometric inefficiency and does not directly account for passenger-related trade-offs, such as accessibility versus travel time.

Route meandering, on the other hand, is a more descriptive term that emphasizes how routes deviate from their main corridor to serve additional areas. It better captures the passen- ger experience, highlighting perceived inefficiencies caused by unnecessary detours. Although this term is widely understood in discussions about transport planning, it lacks a formal definition in the academic literature.

To bridge the gap between quantitative precision and practi- cal applicability, we introduce the term *Route Deviation Ratio (RDR)* in our research. RDR extends the concept of tortuosity by incorporating both the deviation from the direct route and its impact on service accessibility. In doing so, it provides a balanced metric that is analytically rigorous and intuitive for planners and policy makers, facilitating improved decision making in the design of public transport networks.

Given the focus of this study on the practical implications of route design and passenger perception, the term "route deviation ratio" will be used throughout this paper. This choice aligns with the goal of not only analyzing route configurations mathematically but also considering their real-world impact on public transport quality and user experience.

II. STATE OF THE ART

A functional public transport system is based on a proper planning approach, which includes high-quality infrastructure, adequate transport service offerings, and knowledge of the area both in the present and in the future. The current trend in transport planning relies on understanding travel behavior based on preferences for transport mode choice, points of interest, and trip relations, including the modal split. This theoretical foundation is mapped, described and used for the real design of public transport services (12), (13).

In connection with the design of public transport services, fare systems play a crucial role. A significant approach is the integrated fare system, which supports the concepts of intermodality and sustainable transport. By sharing transport modes and, most importantly, fare systems, traveling becomes more convenient, accessible, and therefore more competitive. However, this does not always hold, leading to problems with public transport services.

When implementing standard approaches to area service, using location models such as the p-median and p-center models, and shortest path algorithms like Dijkstra's algorithm and A* algorithm (2), (3), or Genetic Algorithm (14), which are employed due to their ability to handle complex optimization problems by simulating evolutionary processes, is a need to search for complete origin and destination points. These methods aim to optimize service by minimizing travel time and distance, while ensuring comprehensive area coverage. Using location models or shortest path algorithms, there is a need to search for complete origin and destination points. The goal is to serve the entire area and all designated points of interest. In such cases, even an integrated system can fail, as a robust transport network may serve less significant points using standard routes. Due to low demand and consequently longer service intervals, as seen in the case of certain suburban areas e.g. within the Prague Integrated Transport system (PID), where low-frequency routes serve distant points of interest, resulting in extended waiting times and fragmented schedules for such points, exceptions in standard route service arise, leading to inconsistency and undesired service.

Situations occur where fully occupied vehicles detour into areas with minimal demand during their route, artificially extending travel times. This negatively impacts transport quality, and therefore competitiveness. A similar issue arises with the last-mile problem, where high-capacity vehicles travel to low-demand areas, often without effective utilization. These phenomena have received attention, yet they highlight the need to define Transport Quality (6). The definition and implementation of Transport Quality are crucial parameters. However, transport quality is not only related to passengers, but also to the transport system, which designs and ensures public transport service.

III. PUBLIC TRANSPORT QUALITY

As described above, even a well-designed integrated tariff system fails in certain served areas, particularly in small, remote regions or municipalities. Therefore, the concept of Public Transport Quality is introduced as an auxiliary indicator for optimal transport service. (6) This quality is often related to the needs of the passengers. To create competitiveness, this quality becomes a crucial parameter.

The key qualitative parameters include:

- **Infrastructure quality:** A parameter associated with the possibility of deploying vehicles or travel speed
- **Travel time:** One of the most important parameters for passengers, often determining their choice of transport mode
- **Reliability:** Similar to travel time, reliability significantly influences passengers' decisions regarding their mode of transport
- **Service frequency:** This parameter relates not only to the ability to catch the desired connection but also to the psychological influence on potential passengers for future or irregular trips
- **Comfort:** A parameter that may describe the vehicles used, their capacity, or the quality of onboard equipment

This quality of public transport affects passengers, but it also impacts the transport system itself. The establishment of public transport services must logically aim to attract passengers, ensure competitiveness, and consequently maintain the financial sustainability of the transport system.

A. Proposal of the Route Deviation Ratio Parameter

For the transport system (and ultimately for the passenger), a crucial parameter is the ability to serve a given area. The method of serving an area follows certain rules, and defined methods are applied, as described. However, these methods do not always have clear guidelines, and there is often an effort to serve an area "at any cost," even at the expense of travel speed and passenger comfort. To describe the detour into specific areas, the term *Route Deviation Ratio* is defined.

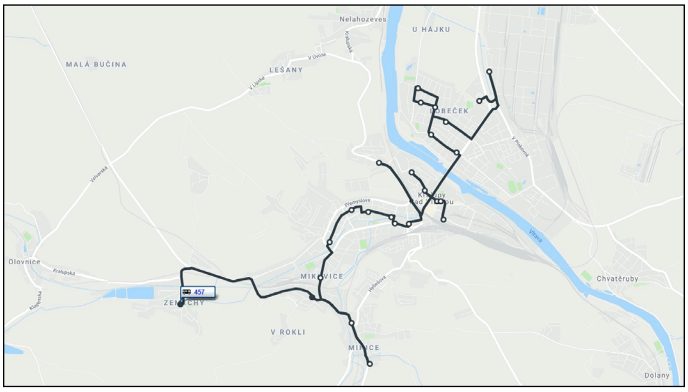

Fig. 1. Route deviation example

An example of significant route deviations and departures from a direct route can be observed in the case of line 457 within the PID system. Fig. 1 illustrates the irregularity of the route and the substantial deviations, which considerably reduce the travel speed. If passengers travel between terminal stops of the route, the line becomes completely uncompetitive. Therefore, the parameter of RDR is highly significant.

To properly express the RDR parameter, it is necessary to define the types of public transport routes according to the purpose of transport service so that this parameter can be meaningful for transport planning (15), (16). At the same time, it is crucial to understand which parameters are associated with the served area, as the type of route and the area it serves are directly related.

- **Main Lines (Express Lines):** Routes that serve important areas, with direct paths and minimized travel time. These routes typically have connections to Local Lines
- **Local Lines:** Public transport routes that serve areas outside the main routes, often involving certain levels of Route Deviation Ratio

- **Lower-Level Local Lines:** Routes for more remote areas that cannot be effectively served by standard routes. These may include on-demand transport or special last- mile services, where a higher degree of Route Meander- ing can often be observed.

This classification allows for a more precise evaluation of route deviation, as different types of route inherently exhibit varying levels of deviation from direct paths. Main lines aim to minimize meandering, while service and supplementary routes often show more pronounced route deviations because of their focus on covering less accessible areas.

B. Line Deviation Type

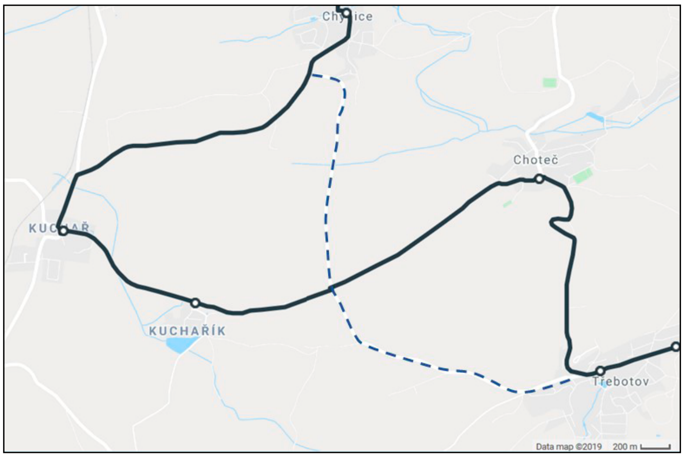

Fig. 2. Line Deviation Type - Diversion from main route

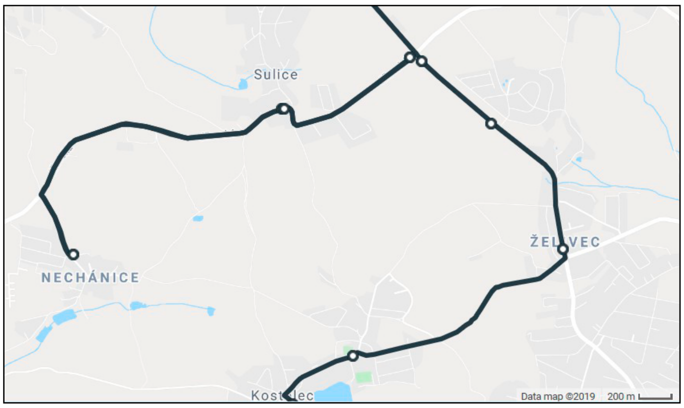

Fig. 3. Line Deviation Type - Same return route

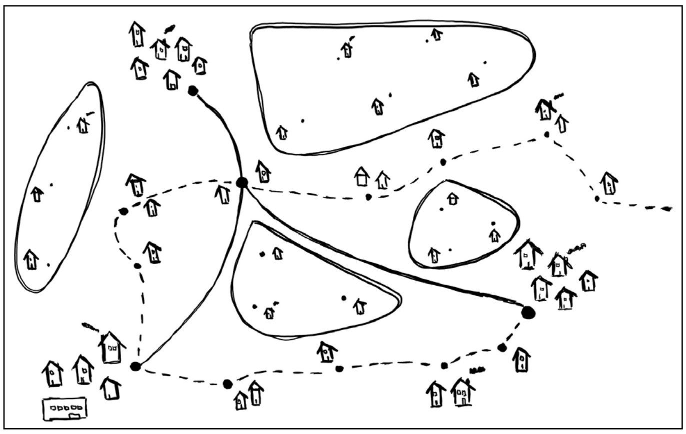

Fig. 4. Areas and lines division

One of the additional parts and another essential element to determine the RDR are the line deviations. The RDR is a complete route description, the Line deviation element describes and classifies only part of it. These elements clarify and logically explain the purpose and significance of the deviation of the line, not only from a transportation perspective, but also from the psychological approach of passengers. It is crucial to distinguish whether a line deviation involves detours into areas off the main route and direction Fig. 2, or whether the service of a given area requires a significant detour followed by a return along the same path. Fig. 3. Although line deviations can be categorized into various levels, a simple representation is sufficient to convey the core concept.

IV. METHODS

While the proposed improvement works with various approaches, including the above mentioned genetic algorithm based approaches, we present our improvement to the traditional Dijkstra's algorithm only.

A. Traditional Shortest Path Algorithm

Dijkstra's algorithm (3) is one of the most widely used methods for finding the shortest path in a graph. Given a weighted graph $G = (V, E)$, where V represents the set of nodes and E the set of edges, the goal is to determine the shortest path from a source node s to all other nodes.

Each edge $(u, v) \in E$ has an associated weight $d(u, v)$, typically representing distance or travel time. The algorithm iteratively expands the shortest known path from the source node, updating the distance estimates for its neighbors until all reachable nodes have been processed.

Algorithm 1 Dijkstra's Shortest Path Algorithm

Initialize: Set $d(s) = 0$, $d(v) = \infty$ for all $v \neq s$, and insert s into priority queue Q.
while Q is not empty **do**
  Extract node u with the smallest cost $d(u)$.
  for each neighbor v of u **do**
    if $d(u) + d(u, v) < d(v)$ **then**
      Update $d(v) = d(u) + d(u, v)$.
      Insert v into Q.
    end if
  end for
end while=0

While Dijkstra's algorithm efficiently minimizes travel dis- tance or time, it does not account for deviations that improve service coverage, particularly in public transport and demand- responsive mobility.

B. Definition of Passenger-Weighted Route Deviation Ratio (PWRDR)

To extend the shortest path problem beyond mere distance minimization, we introduce the concept of curvature , which represents deviations from the most direct route. Instead of solely penalizing geometric curvature, we focus on a more transport-relevant measure: the Passenger-Weighted Route De- viation Ratio (PWRDR) .

Definition: The PWRDR quantifies how much a route deviates from the shortest possible path while considering the number of passengers benefiting from the deviation. It is defined as:

$$\text{(1)}\quad \text{PWRDR} = \sum_{i \in S} \left(\frac{\text{Detour Length}_i}{\text{Direct Distance}_i} \times \frac{\text{Passengers Served}_i}{\text{Total Passengers}} \right)$$

where:

- S is the set of segments i where a deviation occurs.

- Detour Length$_i$ is the extra distance traveled due to the deviation.
- Direct Distance$_i$ is the shortest path distance for the same segment.
- Passengers Served$_i$ is the number of passengers benefiting from the deviation.
- Total Passengers is the total passenger demand on the route.

This metric effectively balances route efficiency and passenger accessibility:

- If a detour serves many passengers , its penalty is lower.
- If a detour adds excessive extra distance for few passengers, it is discouraged.

C. Modified Dijkstra's Algorithm with PWRDR

We incorporate PWRDR into Dijkstra's algorithm by modifying the cost function to account for deviations from the direct route:

$$(2)\ \min \sum_{e \in P} \left(d(e) + \lambda \cdot \mathrm{PWRDR}(e)\right),$$

where:

- $d(e)$ is the standard edge weight (distance or time).
- λ is a weighting factor balancing distance minimization and deviation penalties.
- PWRDR(e) is the passenger-weighted deviation for edge e.

Algorithm 2 Modified Dijkstra's Algorithm with PWRDR

0: **Initialize:** Set $d(s) = 0$, $d(v) = \infty$ for all $v \neq s$, and insert s into priority queue Q.
0: **while** Q is not empty **do**
0: Extract node u with the smallest cost $d(u)$.
0: **for** each neighbor v of u **do**
0: Compute modified weight:
(3) $w(u, v) = d(u, v) + \lambda \cdot \mathrm{PWRDR}(u, v)$.
0: **if** $d(u) + w(u, v) < d(v)$ **then**
0: Update $d(v) = d(u) + w(u, v)$.
0: Insert v into Q.
0: **end if**
0: **end for**
0: **end while**=0

V. DISCUSSION

Public transport route planning has traditionally relied on *shortest path algorithms*, such as *Dijkstra's algorithm* and *A**, as well as *location models*, including the *p-median* and *p- center models*. These methods optimize routes based primarily on travel time and distance, while ensuring coverage of key points of interest. However, they present certain limitations when applied to public transport networks. The *Passenger- Weighted Route Deviation Ratio (PWRDR)* introduced in this paper addresses these challenges by integrating route deviation with passenger demand weighting.

A. Addressing the Limitations of Traditional Methods with PWRDR

- **Accessibility Considerations:** Traditional shortest path algorithms minimize travel distance or time but neglect accessibility for passengers outside primary transit corridors (17). PWRDR explicitly incorporates deviations that improve service accessibility while ensuring they are justified by passenger demand.
- **Demand-Driven Detours:** Existing models assume fixed demand distributions, leading to inefficient service in areas with fluctuating demand (18). PWRDR dynamically weights route deviations based on passenger volume, ensuring deviations provide meaningful service improvements.
- **Route Optimization Approach:** Location models like p-median and p-center focus solely on geometric distance minimization, ignoring critical factors like service frequency, reliability, and perceived passenger convenience (7). PWRDR introduces a trade-off metric that balances directness with practical service considerations.
- **Balancing Directness and Coverage:** Traditional methods do not explicitly measure the trade-off between directness and service coverage, often leading to inefficient deviations (15). PWRDR quantifies this trade-off, allowing for more balanced route planning decisions.

Several studies have attempted to modify shortest path algorithms to account for alternative constraints. (19) introduces curvature-based constraints for car-like robots but does not consider passenger service trade-offs. (20) incorporates a probability cost matrix to allow alternative routing but does not explicitly measure route deviations.

Unlike these approaches, PWRDR directly quantifies the deviation-benefit ratio, making it a practical metric for optimizing public transport routes.

VI. CONCLUSIONS

This paper introduced the *Passenger-Weighted Route Deviation Ratio (PWRDR)* as a novel metric for evaluating public transport route quality. By integrating route directness and pas- senger demand weighting, this parameter enhances traditional transport planning models, providing a more comprehensive approach to assessing the efficiency of service deviations.

Our analysis highlights key benefits of incorporating PWRDR into public transport planning:

- **More Balanced Route Optimization:** Unlike shortest path algorithms that focus solely on travel time minimization, PWRDR ensures that deviations are justified by the number of passengers benefiting from them.
- **Improved Passenger Experience:** By penalizing unnecessary detours while maintaining accessibility, transit agencies can design routes that remain competitive with personal transport options.
- **Potential for Demand-Responsive Transit (DRT) Integration:** PWRDR can be extended to support dynamic routing in flexible transport services, bridging the gap between fixed-route and on-demand transport solutions.

A. Future Research Directions

Further research is needed to refine the *weighting factors in PWRDR*, particularly in multimodal networks where connections between transport modes (e.g., buses and rail) impact route deviation evaluations. Among the parameters that will be further tested are not only the connectivity between traffic modes, but also, for example, the type of road, the type and importance of the municipality served, or a specific time of day or day of the year. Furthermore, real-world implementation studies will be conducted to validate the effectiveness of PWRDR in actual transit networks and assess its influence on passenger behavior and riding patterns.

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