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INTELLIGENT MODEL FOR FINDING THE OPTIMAL ROUTE TO COVER ALL STREETS WITH MOVEMENT CONSTRAINTS

D. Yedilkhan, N. Khaimuldin*, D. Ospanova, B. Amirgaliyev
Astana IT University, Astana, Kazakhstan.
E-mail: n.khaimuldin@astanait.edu.kz

Didar Y. — PhD, professor, Head of the Smart City research center, Astana IT University, Astana, Kazakhstan
E-mail: d.yedilkhan@astanait.edu.kz, https://orcid.org/0000-0002-6343-5277;
Khaimuldin N. — MSc, senior-lecturer, «The Department of Computer Engineering», Astana IT University, Astana, Kazakhstan
E-mail: n.khaimuldin@astanait.edu.kz, https://orcid.org/0000-0002-3767-4418;
Ospanova D. — Master's student in Applied Data Analytics, «the Department of Computing and Data Science», Astana IT University, Astana, Kazakhstan
E-mail: 242982@astanait.edu.kz, https://orcid.org/0009-0003-2405-2374;
Amirgaliyev B. — PhD, professor, «the Department of Computer Engineering», Astana IT University, Astana, Kazakhstan
E-mail: beibut.amirgaliyev@astanait.edu.kz, https://orcid.org/0000-0003-0355-5856.

Abstract. This study presents the development of an intelligent routing model tailored for municipal service optimization, with a particular emphasis on snowplow deployment within the urban environment of Astana. The model integrates advanced Python libraries for data processing and visualization, alongside a mapping API selected through rigorous comparative analysis. The city's street network was reconstructed using topological and statistical attributes–such as segment lengths and intersection density–that are critical for efficient route optimization. The central routing challenge was framed as a variation of the Chinese Postman Problem and addressed through the implementation of key algorithms, including those of Dijkstra, Edmonds, and Hierholzer. This approach yielded an optimized traversal path that ensures full street coverage within the designated area while minimizing redundancy. The proposed solution demonstrably enhances route efficiency, thereby reducing superfluous

travel and contributing to improved municipal service planning. Prospective research will extend the model's capabilities to accommodate real-time dynamic routing and multi-vehicle coordination, supporting broader smart city applications.

Keywords: intelligent systems, GIS technologies, smart city, urban optimization, Chinese postman problem

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БАРЛЫҚ КӨШЕЛЕРДІ ҚОЗҒАЛЫС ШЕКТЕУЛЕРІМЕН ҚАМТУҒА АРНАЛҒАНОҢТАЙЛЫМАРШРУТТЫТАБУДЫҢИНТЕЛЛЕКТУАЛДЫ МОДЕЛІ

Д. Еділхан, Н. Хаймульдин*, Д. Оспанова, Б. Амиргалиев

Astana IT University, Астана, Казахстан.

E-mail: n.khaimuldin@astanait.edu.kz

Дидар Е. — PhD, профессор, Smart City ғылыми-зерттеу орталығының жетекшісі, Astana IT University, Астана, Казахстан
E-mail: d.yedilkhan@astanait.edu.kz, https://orcid.org/0000-0002-6343-5277;
Хаимульдин Н. — магистр, «Компьютерлік инженерия» департаментінің аға оқытушысы, Astana IT University, Астана, Казахстан
E-mail: n.khaimuldin@astanait.edu.kz, https://orcid.org/0000-0002-3767-4418;
Оспанова Д. — «Деректерді қолданбалы талдау» бағдарламасының магистранты, «Есептеу және деректер ғылымы» департаменті, Astana IT University, Астана, Казахстан
E-mail: 242982@astanait.edu.kz, https://orcid.org/0009-0003-2405-2374;
Амиргалиев Б. — PhD, «Компьютерлік инженерия» департаментінің профессоры, Astana IT University, Астана, Казахстан
E-mail: beibut.amirgaliyev@astanait.edu.kz, https://orcid.org/0000-0003-0355-5856.

Аннотация. Қазіргі заманғы қалаларда көлік жүйесін оңтайландыру – коммуналдық қызметтердің тиімділігі мен тұрақтылығын арттырудың маңызды факторы. Бұл зерттеудің мақсаты – Астана қаласында қар тазалау көліктеріне арналған интеллектуалды бағыттау моделін әзірлеу. Модель Python тіліндегі талдау және визуализация құралдарын, сондай-ақ картографиялау API-сын пайдаланады. Қаланың көше желісі жолдардың ұзындығы мен қиылыстардың тығыздығы сияқты топологиялық және статистикалық сипаттамаларды ескере отырып құрылған. Бағытты оңтайландыру мәселесі қытай пошташысы есебіне негізделіп, Дейкстра, Эдмондс және Хайрхольцер алгоритмдері арқылы шешілді. Нәтижесінде көшелерді толық қамтитын және артық қозғалысты азайтатын тиімді маршрут құрылды. Бұл тәсіл қалалық қызметтердің жұмысын жетілдіруге мүмкіндік береді. Болашақта модельді нақты уақыттағы деректерді ескере отырып кеңейту және бірнеше көлік пен мақсаттар үшін бейімдеу жоспарлануда.

Түйін сөздер: Зияткерлік Жүйелер, ГАЖ Технологиялары, Ақылды Қала, Қалалық Оңтайландыру, Қытай Пошташы Есебі

Дәйексөздер үшін: Д. Еділхан, Н. Хаймульдин, Д. Оспанова, Б. Амиргалиев. Бейне барлық көшелерді қозғалыс шектеулерімен қамтуға арналған оңтайлы маршрутты табудың интеллектуалды моделі//Халықаралық ақпараттық және коммуникалық технологиялар журналы. 2025. Т. 6. No. 22. 57–74 бет. (ағылшын тілінде). https://doi.org/10.54309/IJICT.2025.22.2.004.

Мүдделер қақтығысы: Авторлар осы мақалада мүдделер қақтығысы жоқ деп мәлімдейді.

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ИНТЕЛЛЕКТУАЛЬНАЯ МОДЕЛЬ ПОИСКА ОПТИМАЛЬНОГО МАРШРУТА ПОКРЫТИЯ ВСЕХ УЛИЦ С ОГРАНИЧЕНИЯМИ ПО ПЕРЕМЕЩЕНИЯМ

Д. Едилхан, Н. Хаймульдин*, Д. Оспанова, Б. Амиргалиев

Astana IT University, Астана, Казахстан.

E-mail: n.khaimuldin@astanait.edu.kz

Едилхан Д. — PhD, профессор, руководитель НИЦ Smart City, Astana IT University, Астана, Казахстан
E-mail: d.yedilkhan@astanait.edu.kz, https://orcid.org/0000-0002-6343-5277;

Хаимульдин Н. — магистр, старший преподаватель департамента «Компьютерной инженерии», Astana

IT University, Астана, Казахстан
E-mail: n.khaimuldin@astanait.edu.kz, https://orcid.org/0000-0002-3767-4418;
Оспанова Д. — магистр образовательной программы «Прикладная аналитика данных», департамент вычислений и науки о данных, Astana IT University, Астана, Казахстан
E-mail: 242982@astanait.edu.kz, https://orcid.org/0009-0003-2405-2374;
Амиргалиев Б. — PhD, профессор, департамент «Компьютерной инженерии», Astana IT University, Астана, Казахстан
E-mail: beibut.amirgaliyev@astanait.edu.kz, https://orcid.org/0000-0003-0355-5856.

Аннотация. В условиях современных городов оптимизация транспортных систем играет ключевую роль в повышении эффективности и устойчивости муниципальных служб. Цель данного исследования - разработка интеллектуальной модели маршрутизации для городских служб, с акцентом на применение для снегоуборочной техники в городе Астана. Модель интегрирует библиотеки Python для анализа и визуализации данных, а также картографическое API, выбранное после сравнительного анализа. Уличная сеть города была воссоздана с учетом топологических и статистических характеристик, таких как длина дорог и плотность перекрёстков. Задача маршрутизации была сформулирована как задача китайского почтальона и решена с применением алгоритмов Дейкстры, Эдмондса и Хайрхольцера. В результате был построен оптимизированный маршрут, обеспечивающий полное покрытие улиц с минимальными повторами. Решение позволяет сократить избыточные перемещения и повысить эффективность работы коммунальных служб. В дальнейшем планируется расширение модели для учёта динамических данных и масштабирования на многомашинные и многокритериальные задачи в контексте умных городов.

Ключевые слова: интеллектуальные системы, гис-технологии, умный город, оптимизация городской среды, задача китайского почтальона

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Introduction

Modern cities face significant challenges in efficiently managing the movement of municipal and service vehicles tasked with covering large and complex urban areas. Traditional route planning methods often result in redundant travel, wasted resources, and delayed services due to their inability to adapt to dynamic constraints such as time windows, traffic, and partial accessibility. This leads to increased operational costs, inefficient use of manpower, and environmental impact.

The idea of the research is to develop a model that allows for covering all streets and key points in the city of Astana with minimal travel. Using the developed method, the system enables significant cost and time savings when applied to practical tasks such as planning the routes for snowplows, dynamically measuring air quality indicators, watering city plants, and many others.

The main goal is to develop an intelligent system for finding the optimal route to cover multiple points in the city of Astana, considering time constraints and possible movement limitations. This research is part of the broader Smart City initiative, which includes tasks related to intelligent systems, optimal route search problems, work with GIS technologies, and data analysis.

In this research, the focus is on creating optimal transport routes across the city of Astana. This will allow for the actualization and integration of data from different systems in one place, helping to solve optimization tasks that are crucial for practical applications. These applications include, but are not limited to, determining snowplow routes, dynamically monitoring air quality, optimizing plant watering schedules, and many more.

The novelty of this work lies in the development of an efficient system for solving smart city problems, such as determining optimal routes for covering a single region of the city, with demonstrated practical impact.

Literature Review

Urbanization is rapidly transforming global demographics. According to the United Nations' report, more than half of the world's population now lives in urban areas, and this figure is expected to rise to 70 percent by 2050 (United Nations, 2023: 34). This trend calls for sustainable urban management using modern information and communication technologies.

One strategic response is the Smart City concept, which integrates information and communication technologies to address these challenges. Many challenges in smart cities can be framed as classical mathematical problems solvable with modern technologies, such as artificial intelligence (AI) and optimization methods used in mathematics, computer science, and economics. Optimization helps solve complex problems by identifying the best solution from a range of alternatives while considering urban constraints. One of the most important applications of AI and optimiza-

tion in urban environments is the transportation problem - a classical linear programming problem that seeks the most efficient distribution of resources while minimizing transportation costs. As automated systems become more common and more data is constantly being produced, these classic problems have become useful and relevant again in real-world situations. A key area where optimization plays a crucial role in smart cities is transportation management.

In the transportation problem, mathematical models are used to determine routes with minimal cost and maximal safety by accounting for transportation expenses, time constraints, and other limitations between sources and destinations. In simple terms, these models aim to improve safety and reduce costs by controlling key influencing factors. Multi-objective decision-making in transportation tasks can be achieved using AI, mathematical modeling, and heuristic search algorithms such as genetic algorithms. For example, AI techniques enable models to adapt route planning in the presence of dynamic disruptions, such as weather conditions and accidents (Prakash et al., 2024: 172094).

In most cases, the goal of transportation optimization is to minimize overall transportation costs (Prifti et al., 2020: 5; Malacký & Madleňák, 2023: 323–329). The origins of the transportation problem can be traced back to the work of Newton, Leibniz, and Lagrange in the 18th and 19th centuries, with the foundations of modern linear programming laid by French mathematicians such as Jean-Baptiste and Joseph Fourier. Numerous researchers have since contributed to advancing transportation optimization through real-world applications and simulation tools. Kukharchyk, for example, applied mathematical models to cost optimization in transportation tasks, underlining the importance of constraints when shipment volumes are predetermined (Cao, 2022: 2). Mojtahedi et al. proposed a coordinated vehicle routing framework for solid waste management that optimizes financial, environmental, and social objectives (Mojtahedi et al., 2021: 100220). However, these studies do not provide a concrete case study based on real-world data. Yao et al. address the scheduling problem of electric buses with multiple vehicle types, considering range, charging time, and energy use, and present a case study on a real-world transit network in Beijing (Yao et al., 2019: 101862). Also, Gunawan et al. studied the optimization of shipping routes for container ships operating between Indonesia and the Asia-Pacific region (Gunawan et al., 2023: 1360). They used and compared different heuristic algorithms to solve a route optimization problem where fuel costs were minimized.

While traditional methods have provided valuable insights, modern urban logistics have increasingly shifted towards machine learning techniques such as reinforcement learning. (RL). This is a type of machine learning where an agent learns to make decisions by interacting with an environment. The goal is to maximize a reward signal over time. For instance, Khaidem et al. use human mobility data to train and evaluate policies in a realistic simulation environment, where their RL algorithm approximates the system dynamics and finds optimal traffic policies (Khaidem et al., 2020: 171528–171541). Another study shows that deep reinforcement learning can effectively reduce delivery time by optimizing delivery routes (Xing & Cai, 2020:

334–338). Phiboonbanakit et al. combine a reinforcement learning model with a tree-based regression model to evaluate route feasibility based on the current state and action, enabling the RL agent to adjust its decisions for optimal vehicle routing (Phiboonbanakit et al., 2021: 163325–163347). However, the proposed methodology is limited by its reliance on stored experiences, which may be ineffective for unfamiliar event patterns and insufficient for handling uncertainties such as demand, vehicle utility, and productivity.

One of the fundamental challenges in urban route planning involves covering multiple locations while accounting for operational constraints such as travel efficiency and resource limitations. This challenge is formally recognized in mathematics as the Chinese Postman Problem, or Route Inspection Problem, which focuses on determining a traversal of all edges in a network with minimal repetition and cost. Solving the CPP in real-world conditions is complex, requiring consideration of various factors that affect optimal route design and operating costs. Examples include the number of vehicles needed, the presence of dead-end streets, fuel consumption, road conditions, and time-dependent constraints (Rao et al., 2011: 2785–2790). To address this combinatorial optimization challenge, mathematical techniques can serve as powerful tools for generating effective and efficient routes. Matsuura and Takazawa introduced a heuristic algorithm for the Maximum Benefit CPP that reflects practical needs by prioritizing streets with higher service value, even if they must be traversed more than once (Matsuura & Takazawa, 2022: 1283–1291). Another study by Li et al. addressed the complex challenge of delivering emergency supplies when multiple disasters occur simultaneously (Li et al., 2024). It proposed a vehicle routing system that prioritizes deliveries based on the urgency of demand, ensuring that items with higher urgency are distributed first. Such prioritization is especially valuable in scenarios where both urgency and resource optimization are significant.

One of the most practical urban applications of the Chinese Postman Problem is snow removal, where the objective is to cover all streets with the fewest possible passes. Previous studies, such as Sullivan et al. combined network clustering and vehicle routing with capacity limits to improve coverage during snow and ice events (Sullivan et al., 2019: 18–31). Another approach is using the tabu search algorithm to optimize snowplow routing (Xu et al., 2022: 199–211). While effective in certain scenarios, these methods often fail to fully reflect real-world constraints. Additional factors such as one-way streets, turn restrictions, and varying traffic conditions also significantly influence the structure and efficiency of route planning.

This research project seeks to propose a more advanced and practical route optimization strategy tailored to municipal operations in Astana, with a focus on snow removal. The methodology incorporates the Chinese Postman Problem and applies a linear algorithm to generate initial routes and shortest paths (Siloi et al., 2021). By integrating operational constraints, the goal is to identify cost-effective routing solutions that address the limitations of existing methods.

Data Collection

As a first step in this research project, it was essential to gather up-to-date and detailed information on the street network of Astana. This data is crucial for building, analyzing, and visualizing the city's street layout accurately. To achieve this, various mapping APIs were reviewed and compared to select the most suitable one for the project. The selection of the most appropriate mapping API was based on several criteria, including data completeness and accuracy, ease of use and integration with other tools, and overall cost-effectiveness—especially since many services require paid access.

Among the most widely used APIs are Google Maps, Yandex Maps, 2GIS, Mapbox, OpenStreetMap (OSM), Bing Maps, and ArcGIS. Each of these APIs comes with its own strengths and limitations in terms of data accessibility, accuracy, and pricing.

The main drawback of using the 2GIS API for the project's research tasks was the limitation on the number of requests (no more than 3,000) and the short duration of the free version (3 months), which necessitated payment to increase the request quota and ensure continuous access. Additionally, 2GIS is primarily focused on providing data about businesses and reviews, whereas the research required more detailed routing information, along with the ability to develop and integrate custom algorithms with maps for the city of Astana. Similarly, the Mapbox API presented challenges due to the complexity of working with its interface components. Despite its capabilities, the difficulty in navigating and utilizing the various components made it less ideal for the project's specific needs. Given these limitations, OpenStreetMap API emerged as the preferred solution for the project. It offers a powerful, flexible, and open-source tool for geographic data, which aligns with the research objectives. Its ease of use and ability to provide the necessary data in a convenient format made it the most suitable choice for the project's requirements.

For visualizing the road network of Astana, the OSMnx Python library (v1.6.0) was used for spatial analysis and visualization. The NetworkX library was also employed to analyze network structure through metrics such as centrality, connectivity, and shortest paths. Together with OSMnx, NetworkX enhances the analytical capacity for complex urban networks. Astana's street network was visualized in two different color schemes using graph_from_place () for the entire city.

For detailed statistical analysis, the graph was first converted into a geospatial dataset using the osmnx.graph_to_gdfs() function. This function allows extraction of either nodes, edges, or both as GeoDataFrames, enabling comprehensive analysis of intersections and street segments. The resulting dataset contains numerous columns, most of which correspond to OpenStreetMap tags. For instance, the columns u and v represent the start and end nodes of each edge, reflecting the network's topology. Additional attributes include bridge presence, number of lanes, edge length, speed limits, street names, directionality, and more.

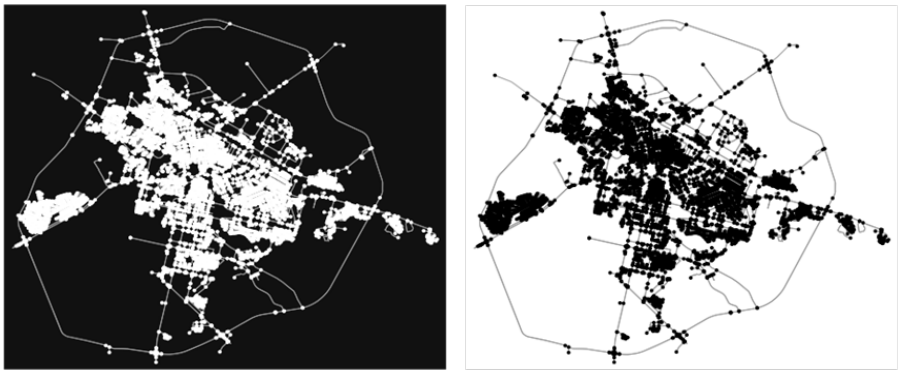


Fig. 1. Graph of the City of Astana in Different Color Palettes

The graph_from_bbox function is used to generate street network data within a specified bounding box, while the graph_from_point function allows for visualizing a street network graph centered on a specific geographic point within a defined distance in meters. An example of filtering the city graph to display only the Expo district of Astana is shown below. To make the visualization more intuitive, various color elements can be applied to the graph's nodes and edges.

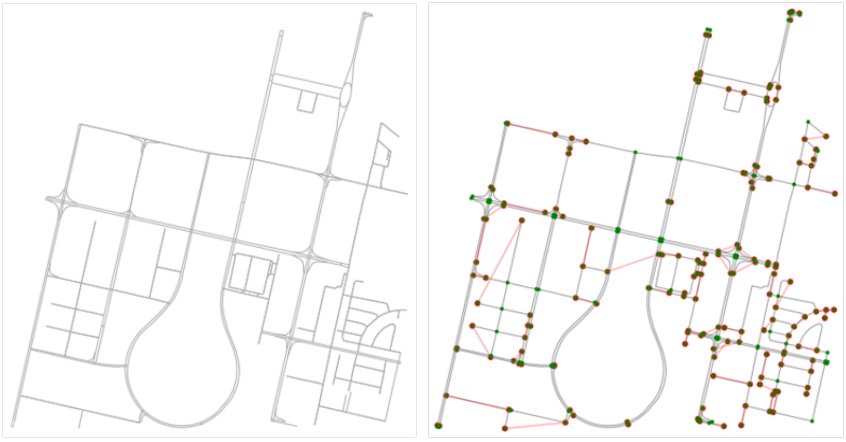


Fig. 2. A filtered Graph of Astana from the Point 51.0975, 71.4176 with a Distance of 1,250 meters

In the extracted street network graph of the entire city of Astana, there are a total of 18,091 edges, all of which are tagged. The distribution of edge types is presented in Table 2. The raw data is complex, so it needs preprocessing before we can fully understand or analyze it.

A total of 7,445 nodes are present in the Astana street network. Of these, 595 are marked as specific features: 581 as traffic_signals or city intersections, 10 as motorway_junctions, 3 as crossings, and 1 as a milestone.

Table 1. Distribution of Edges (Streets) by Type in Astana

Edge Type (Original OSM Name)	Count
Residential	11,931
secondary	1,984
tertiary	1,728
unclassified	1,301
primary	453
secondary_link	240
tertiary_link	128
trunk	125
primary_link	112
trunk_link	60
[unclassified, residential]	8
[tertiary, residential]	8
living_street	2
[tertiary, secondary]	2
[secondary, residential]	2
[residential, living_street]	2
[motorway, trunk]	2
road	2
motorway	1

Methodology

The problem of finding a route that covers all streets originates from graph theory, specifically the famous Seven Bridges of Königsberg problem, where the objective is to find a route that traverses every edge exactly once (Susitha, 2023). However, in most real-world scenarios, the graph is not Eulerian, meaning it is impossible to visit each street just once without repetition. A Eulerian graph is a graph containing a closed walk that includes every edge exactly once (Deo, 2016). Therefore, finding an optimal route can be reframed as the more general and well-known Chinese Postman Problem with the goal is to visit every street in a certain district or across an entire city at least once. An algorithm is needed to accomplish this efficiently and avoid unnecessary detours or multiple traversals of the same street. The desired solution is an optimal route that covers every edge at least once while minimizing the total length of the journey. To solve this, the research project employed a method based on minimum matching, as proposed by Edmonds and Johnson (Edmonds & Johnson, 1973: 88–124). Their work leverages matching theory to identify an optimal graph structure that supports a Eulerian tour.

In most real-world urban networks, such as Astana's street map, the corresponding graph is not Eulerian, meaning that not all vertices have an even degree. This makes a direct traversal without edge duplication impossible. The key idea behind this solution is to transform the graph into a Eulerian multigraph by duplicating

certain edges. The goal is to identify the minimum set of additional edges required to ensure that all vertex degrees become even, thus making it possible to compute a Eulerian circuit. The algorithm is visualized below:

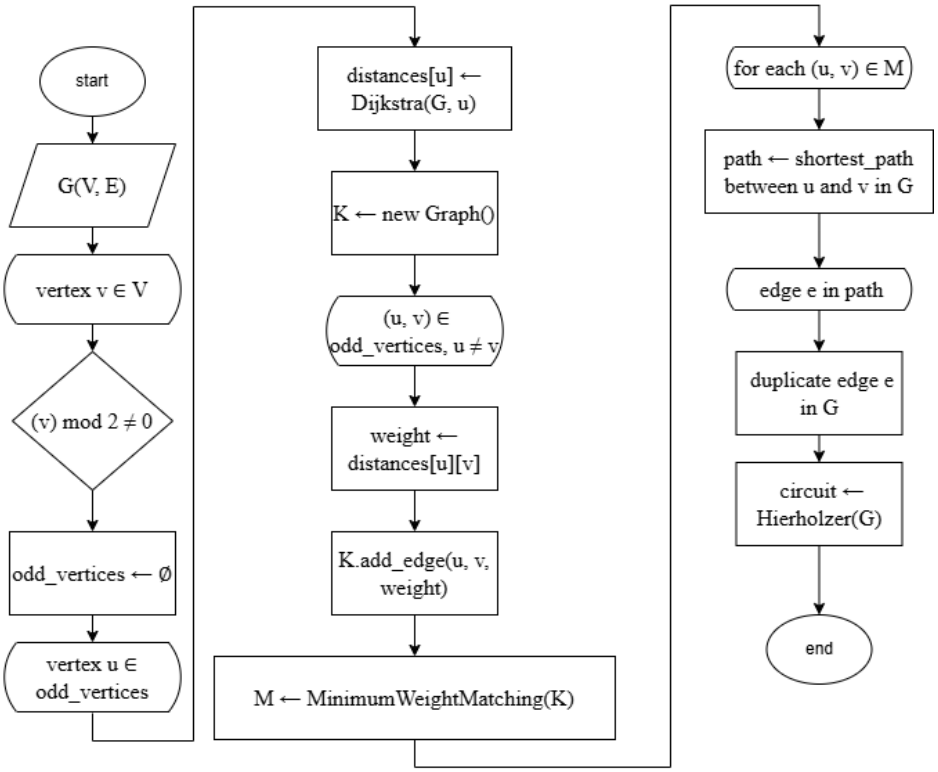


Fig. 3. Block Diagram of the Chinese Postman Problem

The process begins by identifying all vertices with an odd degree (Step 1). Since a Eulerian circuit can only exist if all vertex degrees are even, these odd-degree vertices must be paired in a way that balances the graph. In Step 2, the shortest paths between all pairs of odd-degree vertices are computed using Dijkstra's algorithm, which is suitable for real road networks with non-negative edge weights. These shortest paths are then used to construct a complete weighted graph (Step 3), where each vertex corresponds to an odd-degree vertex from the original graph, and edge weights represent the distance of the shortest path between them. In Step 4, we apply Edmonds' algorithm to find a minimum-weight perfect matching on this complete graph. The result is a set of disjoint pairs of odd-degree vertices such that the total weight of the added paths is minimized. For each matched pair, the corresponding shortest path is duplicated in the original graph (Step 5). This ensures that all vertices now have even degrees, resulting in a Eulerian multigraph. Finally, Hierholzer's algorithm was applied (Step 6) to generate the Eulerian circuit. The Hierholzer algorithm requires certain conditions to be met – specifically, the graph must be connected, and all nodes must have even degrees. It proceeds as follows:

1. Select any vertex as the current node to start the traversal
2. While the current vertex has unused edges:
a. Select one of the unused edges
b. Traverse to the adjacent vertex
c. Remove the traversed edge from the graph
3. If the current vertex has no unused edges, push it onto a stack
4. If the stack is not empty, pop a vertex from the stack and make it the current vertex.
5. Repeat steps 2–4 while there are vertices in the stack.

The algorithm starts at any vertex and moves along unused edges to connected vertices, removing each edge after it is used. When there are no unused edges left at the current vertex, it is saved on a stack, and the algorithm backtracks by returning to previous vertices from the stack. This process continues until all edges have been visited exactly once. It produces a path sequence that ensures every edge (including the added duplicates) is traversed exactly once.

Algorithm 1. Chinese Postman Problem

Input: G(V, E) – an undirected graph representing the street network

Output: circuit – a minimal-cost Eulerian tour covering all original edges of G

Procedure:

1. Identify all vertices with odd degree:
odd_vertices ← ∅
for each vertex v ∈ V:
if degree(v) mod 2 ≠ 0:
add v to odd_vertices
2. Compute shortest paths between all pairs of odd-degree vertices (Cormen et al., 2022):
distances ← ∈
for each vertex u ∈ odd_vertices:
distances[u] ← Dijkstra(G, u)
3. Construct a completely weighted graph K over odd_vertices:
K ← new Graph()
for each pair (u, v) ∈ odd_vertices, u ≠ v:
weight ← distances[u][v]
K.add_edge(u, v, weight)
4. Find a minimum-weight perfect matching M in graph K (using Edmonds' algorithm) (Galil, 1986: 23–38):
M ← MinimumWeightMatching(K)
5. Duplicate the shortest paths corresponding to matched pairs in G:
for each (u, v) ∈ M:
path ← shortest_path between u and v in G
for each edge e in path:
duplicate edge e in G
6. Apply Hierholzer's algorithm to construct a Eulerian circuit (Kronegger, 2016):
circuit ← Hierholzer(G)

To validate the proposed algorithm, we applied it to a selected region of the city of Astana, focusing on a 750-meter radius around the "Triumphal Arch" area on the left bank. The original street graph was derived from OpenStreetMap data using the OSMnx library and converted into an undirected format to allow bidirectional traversal. This conversion is particularly important in real-world networks where one-way streets could disrupt Eulerian traversal.

In the initial stage, 62 vertices with odd degrees were identified in the subgraph. This set of vertices defined the scope for the matching problem. Using the NetworkX implementation of Dijkstra's algorithm, shortest paths were computed between every pair of these odd-degree nodes. The results were then used to construct a complete auxiliary graph, where the weight of each edge represented the length of the corresponding shortest path in the original network.

To determine the optimal set of edge duplications, a custom implementation of Edmonds' algorithm was employed to find the minimum-weight perfect matching. Each matched pair represented a pair of odd-degree nodes to be connected via duplicated paths. These paths were then traced and added back to the original graph, transforming it into a valid Eulerian multigraph.

This methodology is highly adaptable and can be applied to various municipal services such as snow removal, street cleaning, or delivery routing, where complete street coverage with minimal redundancy is essential. For example, in snow plowing activities, it ensures all streets are plowed without unnecessarily repeating any of them, which saves time and gasoline. Similarly, for street sweeping, the approach helps in optimizing sweeping routes for covering all the roads systematically while minimizing overlap. In delivery routing, the method helps in designing routes that cover all the required locations with minimal backtracking, improving the speed of service and reducing the expense of operations. Overall, by eliminating duplicated travel, the method improves the utilization of resources, lowers emissions, and increases the efficiency of public service operations in smart cities.

Results

The algorithm of solving Chinese Postman Problem is demonstrated on a selected area of the left bank of Astana, centered around the "Triumphal Arch" (51.10415184350422, 71.42986881334336), including all nearby streets and crossroads within a 750-meter radius. For simplicity, the original directed multigraph was converted into an undirected graph, allowing bidirectional traversal on one-way streets.

As the first step in the algorithm outlined earlier, we begin by identifying all nodes with an odd degree using the graph.degree() function to automate this process. As a result, we found 62 nodes in the graph that have an odd degree.

The next step involved calculating the shortest distances between each pair of these odd-degree nodes. For this, we used Dijkstra's algorithm — a well-known and widely applied method, particularly effective for computing shortest paths in road networks. Specifically, we employed the nx.dijkstra_path_length() function from the NetworkX library, feeding in all possible combinations of the odd-degree nodes. The

output provided the shortest path lengths for each unique pair of nodes, which we will refer to in the following steps.

Next, using the previously obtained list of weighted edges a complete graph is constructed, and a minimum weight matching is found. To achieve this, a custom function was developed. It takes the list of weighted node pairs as input and returns a matched list of edges with their corresponding weights. The output of this function is a set of optimal pairings that minimizes the total added distance.

To provide a more intuitive visualization of the resulting graph, the matched nodes are displayed on a plot, with different colors used to distinguish the pairs in the matched graph.

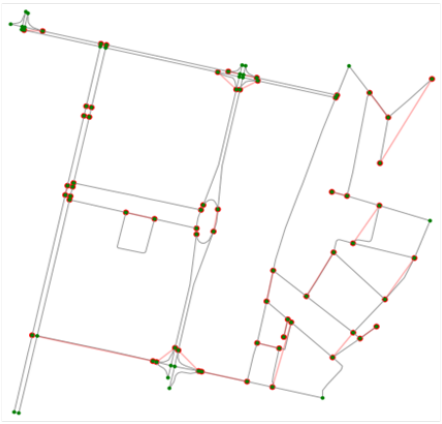


Fig. 4. Graph Within a 750-Meter Radius Around the "Triumphal Arch" Point

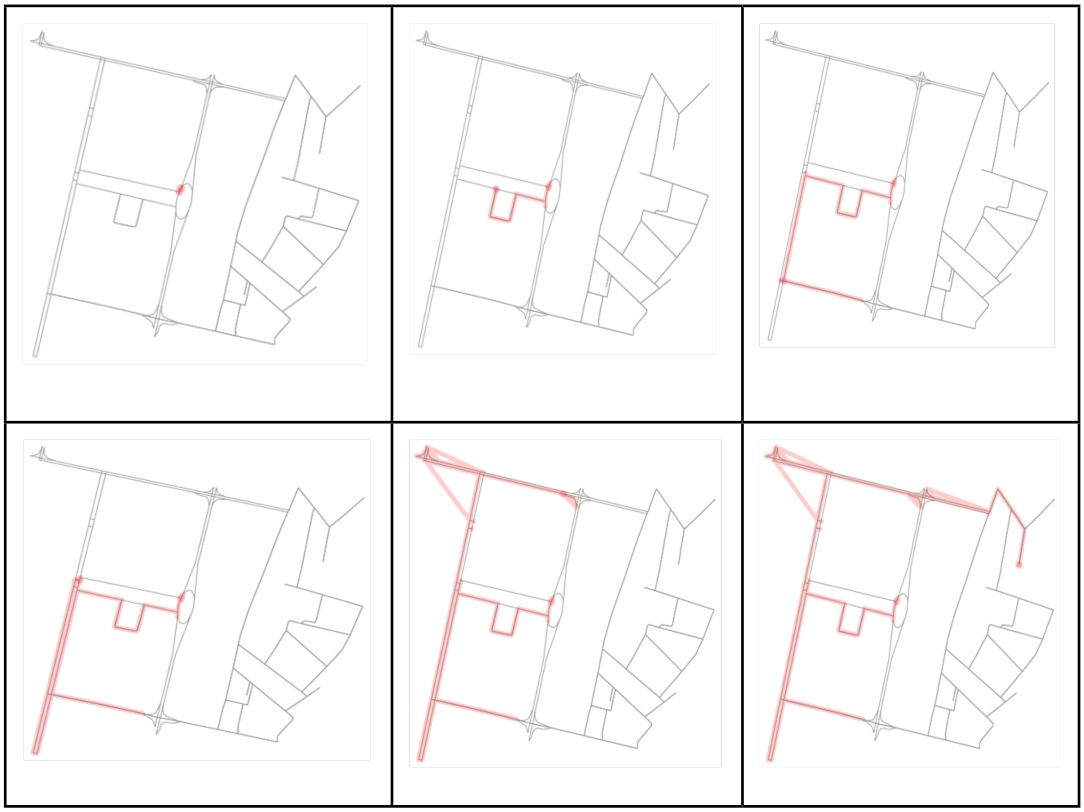
Next, it is necessary to list all edges of the augmented graph, including both the original edges and those added during the minimum matching step. In other words, the nodes from both graphs are represented as edges using OSMnx identifiers, which are expressed as integers ranging from zero to the total number of nodes. The result is a list of node pairs, such as (0, 43), (0, 20), (0, 2), (1, 3), (1, 4), (1, 66), and so on.

After this step, the Eulerian path is computed using the Hierholzer algorithm (also known as Eulerian circuit traversal). This algorithm constructs a path that visits every edge in the graph exactly once. The output of the Hierholzer algorithm is a sequence of integers, where each number represents a vertex in the graph—for example: 0, 43, 74, 77, 42, 41, 51, 52, 34, 51, 34, 35, 25, 24, and so on. This resulting sequence is then converted back into the OSMnx node ID format and can be visualized on the map. An excerpt of the final traversed path through the graph is shown in Table 2 as a set of node pairs.

To provide a more dynamic visualization, 14 intermediate steps of the graph traversal are shown below, as the full traversal involves many steps.

Table 2. Final Graph Traversal Path

From	To
1773441975	1773441979
1773441979	1773441975
1773441975	2639882499
2639882499	1773441998
1773441998	2639882499
2639882499	5263395275
5263395275	5263395273
5263395273	5263395275
5263395275	5263395272



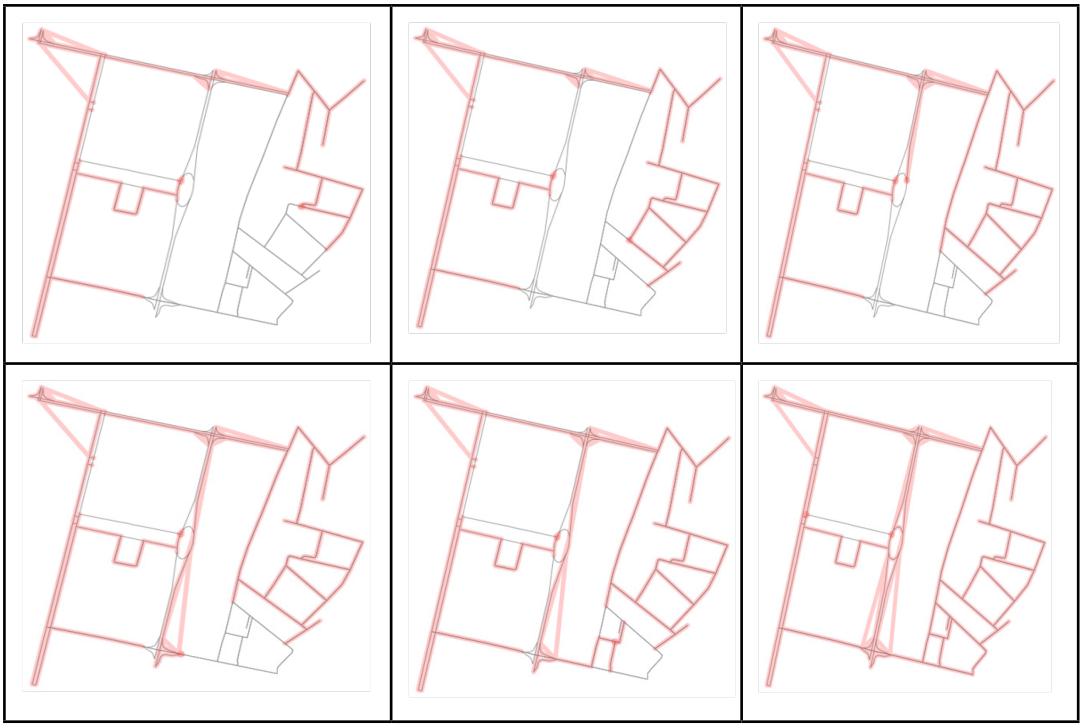


Fig. 5. Step-By-Step Traversal of the Graph

The implemented algorithm successfully generated an optimal route that efficiently covers all streets in the target city area with minimal total travel distance. By framing the problem as a Chinese Postman Problem and applying the Edmonds and Johnson solution, the method effectively constructed a Eulerian multigraph that accounts for necessary edge duplications. This allowed the identification of a Eulerian trail representing the most efficient traversal sequence. The resulting route ensures full coverage of the street network while minimizing redundant travel, demonstrating the practical effectiveness of the proposed approach in urban route optimization.

Conclusion

The study contributes to the field of route optimization under constraints by developing an intelligent model for identifying an optimal route that covers all streets in the city of Astana, while accounting for real-world movement limitations. The algorithm, tested on real geospatial data, showed promising results and holds potential for improving urban transport planning, logistics, and infrastructure maintenance.

This model has several impactful applications. In the public sector, it can assist city planners and municipal services in optimizing street cleaning, snow removal, garbage collection, and road inspection operations, especially in cities facing extreme climates or rapid urban development like Astana.

However, the model has certain limitations. It assumes static conditions and does not yet incorporate dynamic factors such as real-time traffic, weather conditions, or road closures. Additionally, it does not currently account for resource constraints like vehicle fuel consumption, driver working hours, or the number of available ve-

hicles.

Future research could focus on extending the model to dynamic routing scenarios, integrating real-time data streams, and developing multi-vehicle or multi-objective optimization versions. Furthermore, future research could explore the scalability of the proposed approach to other cities with different urban structures and transportation needs.

With further development, the model has the potential to grow into a powerful tool for supporting smart city operations by helping cities deliver services more efficiently, lessen their environmental footprint, and make everyday urban life more comfortable and sustainable for residents.

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ХАЛЫҚАРАЛЫҚ АҚПАРАТТЫҚ ЖӘНЕ КОММУНИКАЦИЯЛЫҚ ТЕХНОЛОГИЯЛАР ЖУРНАЛЫ

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