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## NAVIGATION ALGORITHM FOR OPTIMAL CHOICE OF THE CITY VEHICLE ROUTE

### НАВІГАЦІЙНИЙ АЛГОРИТМ ДЛЯ ОПТИМАЛЬНОГО ВИБОРУ АВТОМОБІЛЬНОГО МІСЬКОГО МАРШРУТУ

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**Abstract.** *The study is a fundamentally new approach to solving an extremely important nowadays problem – the problem of congestion in any large city. The navigation task of the vehicle time-optimal routes choice has been solved. The research is based on the use of mechanisms for modeling and working with various networks – graph theory and A-star algorithm. The latter traces the route in the graph (transport network) between two selected positions of the vehicle – origin and destination ones. To navigate the route the problem of registering the traffic load of the city's transport network is solved. Traffic data from the real transport network is reproduced on the electronic map of the city. Each vehicle receives a unique marker consisting of an origin-destination pair. Each such pair is tracked on an electronic map of the city. Since each vehicle is under control of the Traffic Management Center (TMC), it is possible to accompany it on the optimal route, taking into account the urban traffic dynamics. Support is provided via the General Packet Radio Service (GPRS) channel, which allows each driver to receive instructions as to an optimal travel path.*

**Key words:** *weighted oriented graph, A-star algorithm, city traffic, traffic jams, congestion.*

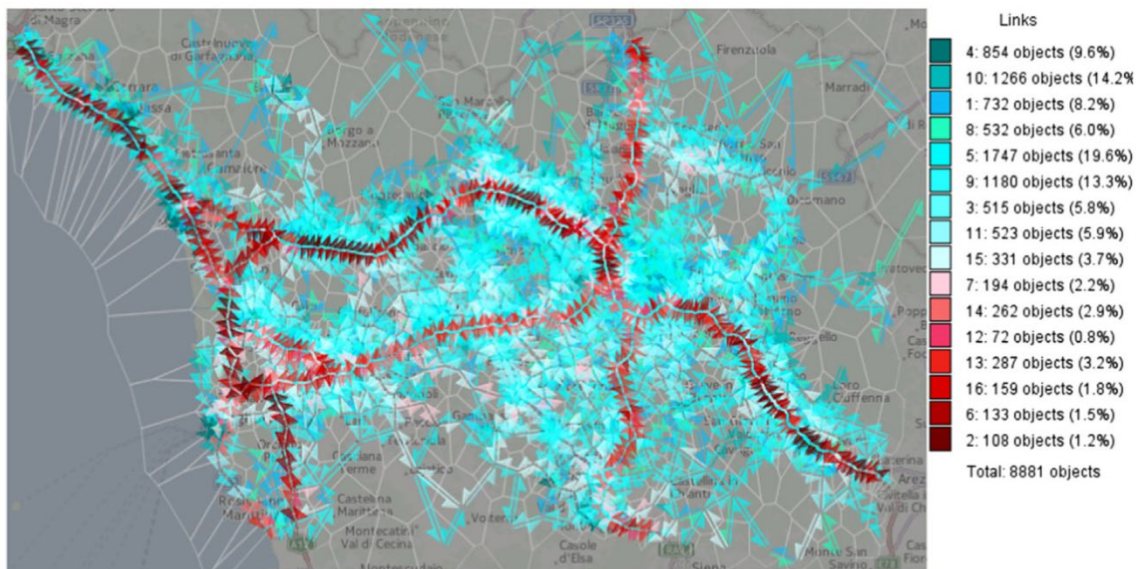
**Introduction** The research is based on a use of mechanisms for modeling and working with various networks – graph theory and A-star algorithm. The latter navigates the optimal route in graph (or in transport network of city) between two selected positions of the vehicle – origin and destination ones. To navigate the optimal route, it is need to know a load by vehicles of city transport network. The load of traffic lanes corresponds to the arcs weights of the graph that simulates the transport network of city. This kind of comparison allows to use an oriented weighted multigraph to model the city's transport network. In turn, graph theory has a raw of algorithms that allow to lay the optimal routes. In this study we are talking about the optimal routes, namely those that take a minimum of time.

The result of this investigation is: i) support of an optimal route of each guided vehicle, that minimizes a travel time between a start and end (ordered) positions; ii) synchronization of traffic flows; iii) optimal use of transport arteries throughout the city; (iv) significant reduction in the duration and frequency of congestion.



## Analytical review of literature

A fundamental issue in the regulation of urban traffic is the transfer (bijective reflection) of real urban traffic on the electronic map of city [1-3]. The real picture of visualization of traffic flows in a big city can look like, for example, shown in Fig.1



**Fig.1. Visualization of traffic flows. Green is not congested transport arteries, and red is congested ones [4]**

Knowledge of city streets' congestion level is a starting point in solving the problem of traffic regulation. If have place redirection vehicles from the central congested streets (in Fig. 1 the corresponding roads are highlighted in red), on uninhabited ones the traffic will go to a state that will approach equilibrium.

The question of the equilibrium state of any system is a fundamental point in game theory [5, 6]. The state of equilibrium is especially relevant for dynamic systems, where deviations from this state are quite common. One of the highly dynamic systems is transport network of a large modern city. Therefore, the main issue is to create an algorithm for bringing the mentioned system to a state of Nash equilibrium [5], which means an absence of congestion in the transport network.

The study of networks of different nature, including neural, allows to make predictions as to urban transport networks [7 - 9].

Monitoring the city's transport arteries is relevant due to the possibility of a certain



periodicity (during the day, week, season) in city traffic. This circumstance allows forecasting traffic processes.

Particular attention is paid to choice of optimal routes in the urban transport network, as this issue is key in terms of urban traffic strategy. In particular, the study [10] to solve this problem uses a macroscopic mathematical model to control the dynamic factors of traffic – speed, intensity and congestion of vehicles.

It is expedient to study the transport networks principles functioning in different modes. Particular attention in this regard should be paid to the overloaded mode, which causes congestion. Investigation [11] is devoted to the dynamics of the transition between different phases of traffic.

The authors of [12] proposed a real algorithm that allows to navigate time-optimal route for travel. It is important that there is a constant correction of the route taking into account the dynamics of changes in the transport traffic of city. Each intersection is equipped with special sensors that allow to monitor the load of lanes at any given time and respond in a timely manner to such changes. The transport network is modeled in the form of a weighted planar oriented multigraph. The weight of each arc of such graph corresponds to the load of the real city lane. Drivers who interact with the TMC via GPRS channel have an opportunity to receive constantly updated data as to the optimal route. The procedure of plotting a route in the graph that simulates the transport network of the city is performed by a computer program that implements an A-star algorithm.

At the heart of urban traffic processes optimization is a separate urban intersection. This facility is one of the main causes of congestion on urban transport networks. The main task in this sense is to maximize the throughput at each intersection. Many researchers pay attention to this problem. Let's focus on the analysis of the results of [13] which analyzes Connected Vehicles Technology (CVT). This work proposed an algorithm to optimize travel through a controlled intersection. The algorithm allows to record location and speed of connected and identified unconnected vehicles within an area of interest around the intersection. As a result of the algorithm, we obtain the optimal sequence of switching phases of the intersection traffic lights



and their length: the algorithm gives the minimum delay time of vehicles at the intersection. Works [14-19] are also devoted to a similar problem.

The investigation [20] is devoted to the prospects of using automated cars not driven by drivers. The advantages of such innovative approach and real prospects for use are described. This problem has recently received special attention from researchers around the world and number of publications has increased dramatically in recent years.

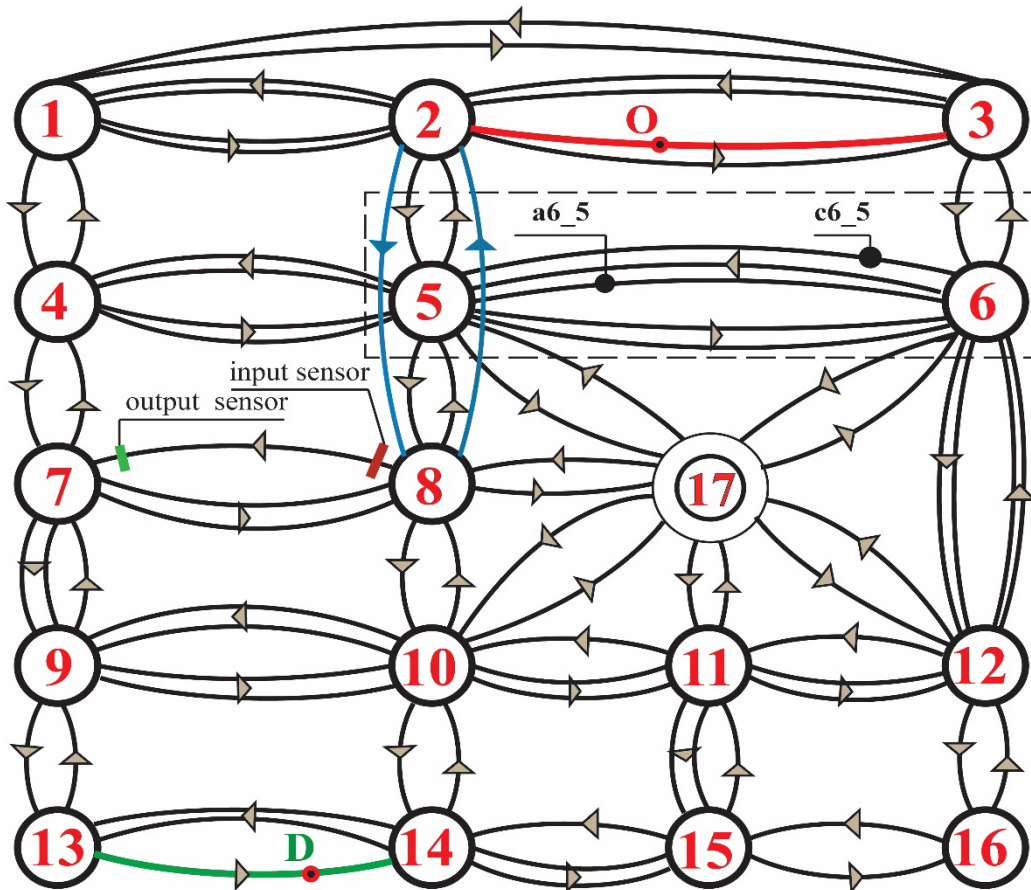
### **Results of the work**

It is time to formulate the stages of solving a problem of optimal mode of urban traffic management. The first step in this regard is modeling of a city's transport network using a weighted oriented non-planar multigraph (Fig. 2). The fundamental point is that in such graph each arc is compared in accordance with the dynamic value – the weight, the value of which is compared with the actual load of cars in each urban lane. In graph theory this graph is a bijective (maximum objective) reflection of a distribution of vehicles on a transport artery of city. The second important point is the use of the A-star algorithm, which is used to plot optimal routes in graphs between pointed two vertices.

The next stage is a software algorithm that implements the navigation of specific routes, taking into account all features of transport network dynamics. Such features include high mobility and different levels of congestion as separate lanes on the same section of road and individual streets – the central highways are usually congested, while the secondary ones – underloaded (Fig. 1). Therefore, one of the tasks of the proposed algorithm is to organize a uniform distribution of vehicles on the city's arteries. In this sense, if analyzed the data on the distribution of cars presented in Fig. 1, the task of the study is to achieve uniform color over the entire area, which will mean a uniform distribution of vehicles on urban transport arteries. And, finally, the main – the fourth – point is the technical organization of registration of the rolling stock of vehicles using special sensors located on the electronic map of the city near the intersection. Data from these sensors act as input values of the software module that implements the A-star algorithm. As a result of the implementation of above steps,



there will be a complete synchronization of traffic flows, which leads to a fundamentally new quality and, consequently, to the disappearance of congestion (or a sharp reduction) in the transport network. This will allow each driver to arrive at their destination in a minimum short time. Thus, urban traffic is transformed into a fundamentally new state – the state of Nash equilibrium [5,6].



**Fig.2. Weighted oriented non-planar multigraph modeling a fragment of the city's transport network.**

*Vertex 17 is a special case of the intersection, where a circular motion is organized and therefore intersections 5, 6, 8, 10, 11 and 12 are connected by means of 17. The symbol "O" symbolizes the starting position of vehicle, and the symbol "D" – his final position. Between vertices 5 and 6 there are lane designations (for example, the designation c6\_5 means the third lane from the axial dividing line, directed from intersection 6 to intersection 5). Intersections 2 and form a transport interchange (the road connecting these intersections, runs over the intersection 5).*



Graph (Fig. 2) simulates not just a road between intersections, but reproduces individual lanes, which is a fundamentally important point, because the load of different lanes, as a rule, differ significantly. Therefore, it is necessary to record the load of each lane separately. Full program code of our investigation is available on a GitHub service at the link [21]. The code navigating route of vehicle from the starting position  $O$  to the finishing position  $D$  (Fig. 2) is presented. The fundamental question is to navigate an optimal (as to minimum time) route for each vehicle. To do this, it is needed to introduce the basic concepts which are formulated as follows.

*Definition 1. Resistance  $R_j(h, t)$  of any intersection  $J$  from the side of the lane  $h$  at time  $t$  is essentially a virtual path that car would travel at an average speed  $V_{ij}$  during the time it was delayed at the intersection. Such resistance of the intersection is defined as*

$$R_j(h, t) = S_j(h, t) \cdot V_{ij} \cdot T_j, \quad (1)$$

where  $V_{ij}$  – the average speed of vehicles flow on a road directed from the intersection  $i$  to intersection  $j$ ;  $T_j = t_j^{red}(h) + t_j^{green}(h)$  – duration of traffic light switching cycle at the intersection  $J$ ;  $S_j(h, t)$  – the value specified as follows

$$S_j(h, t) = \begin{cases} \delta \\ t_j(h) / T_j + \delta \\ t_j^{red}(h) / T_j + C_j(h) + \delta \\ t_j^{green}(h) / T_j + C_j(h) + \delta \end{cases}, \quad (2)$$

where value  $\delta \ll 1$  corresponds to the ratio = time of travel by vehicle at intersection / duration of a switching cycle of traffic lights  $T_j$ ; that is, in the case of the first term, vehicle crosses the intersection without delay; value in the second term is obtained when the vehicle approaches the intersection at a time of red light, delayed for a while  $t_j(h) \leq t_j^{red}(h)$  and passes this intersection immediately after the inclusion of the green phase; the value  $t_j^{red}(h) / T_j + C_j(h)$  in the third term consists of a fraction



$t_j^{red}(h) / T_j$  plus the number of traffic light switching cycles ( $C_j(h) \geq 1$ ), during which the car is delayed at an intersection;  $t_j^{green}(h) / T_j + C_j(h)$  – the part of the fourth term value consisting of a fraction  $T_j$  in sum with an integer number of traffic light switching cycles ( $C_j(h)$ ).

Delay time of car at an intersection

$$t_j^{delay}(h) = \begin{cases} \delta \cdot T_j \\ t_j(h) + \delta \cdot T_j \\ t_j^{red}(h) + C_j(h) \cdot T_j + \delta \cdot T_j \\ t_j^{green}(h) + C_j(h) \cdot T_j + \delta \cdot T_j \end{cases} \quad (3)$$

The weight  $W(n_{ij})$  of each arc of the graph (Fig. 2) is a sum of the resistance  $R_j(h, t)$  of an intersection  $j$  on the side of the lane  $h$  and the own length  $L_{ij}$  of the lane, i.e.

$$W^h(n_{ij}) = S_j(h, t) V_{ij} T_j + L_{ij} \quad (4)$$

Here  $n_{ij}$  means the lane directed from the intersection  $i$  to the intersection  $j$ ; the symbol  $n$  indicates name of lanes (a, b, c, d, ...).

The strategic task set in this paper is as follows

$$\sum_{h=1}^I (S_j(h, t) \cdot V_{ij} \cdot T_j(h) + L_{ij}) \rightarrow \min \quad (5)$$

Here  $I$  is the set of all city intersections. Expression (5) consists of variable (first term) and constant components (second term). The variable component is a function of time because traffic in city is a highly dynamic entity. To synchronize between actual traffic in city and work of the program, the latter performs a constant recalculation of a route for each vehicle. Thus, the problem of navigating an optimal route in the graph/city network, synchronized in time with the real situation with the traffic on the city transport network, solves an A-star algorithm by constantly correcting a calculation of an optimal route between selected vertices of the graph. Technically, the route adjustment process is shown in Listing 1.



### Listing 1

Course-1: [b1\_2-Liberty avenue, **a2\_5-Heroes street**, a5\_8-Victory street, a8\_10-Lincoln street, a10\_14-Candy street, a14\_13-Cherry street, a13\_14-Cherry street]

Course-2: [*a2\_5-Heroes street*, **a5\_8-Victory street**, a8\_10-Lincoln street, a10\_14-Candy street, a14\_13-Cherry street, a13\_14-Cherry street]

Course-3: [*a5\_8-Victory street*, **a8\_10-Lincoln street**, a10\_14-Candy street, a14\_13-Cherry street, a13\_14-Cherry street]

Course-4: [*a8\_10-Lincoln street*, **a10\_14-Candy street**, a14\_13-Cherry street, a13\_14-Cherry street]

Course-5: [*a10\_14-Candy street*, **a14\_13-Cherry street**, a13\_14-Cherry street]

Course-6: [*a14\_13-Cherry street*, **a13\_14-Cherry street**]

Course-7: [**a13\_14-Cherry street**]

Expression (5) can be represented as a record

$$\sum_h W^h(n_{ij}) \rightarrow \min, \quad (6)$$

which is an objective function of the problem: *the total weight of all consecutively located along the route lanes should be minimal*. The minimization of function (6) is performed by an A-star algorithm, the main code result of which for the graph in Fig. 2 is shown in Listing 2 [21].

*Definition 2. The weight of a route (6) is a minimum virtual path traveled by the vehicle from the starting position to the final one. The passage of such route takes a minimum of time (taking into account the same average speed  $V_{ij}$  ( $i, j \in A$ ) car movement in the city).*

Expression (6) is equivalent to the following

$$t^{trip} = \sum_{j=1}^I (t_j^{delay} + L_{ij} / V_{ij}) \rightarrow \min, \quad (7)$$

where  $t^{trip}$  – travel time of vehicle from its starting position to the destination one.



*Definition 3. Equivalence of expressions (6) and (7) gives grounds to talk about the optimization of vehicle travel on selected route just in time. Accordingly, the total time spent by all vehicles involved in traffic will also be optimal (minimal).*

Thus, the algorithm proposed in the study minimizes an actual travel time of the vehicle on the selected route.

### **Conclusions**

1. A multigraph model that reproduces the transport network of a city district, simulates all an actual existing lane. Each arc of the graph receives a weight that changes synchronously according to changes in traffic.

2. The use of sensors, which are located on an electronic map in an area of each intersection, allows a registration of traffic flows. This means that entire transport network of the city is under control of TMC. This circumstance makes it possible to track all changes in traffic and calculate the dynamic optimal routes for each vehicle, relevant for each time. This circumstance avoids congestion.

3. The study developed a working software module [21] that navigates an optimal time route in graph, and hence in the real transport network. The investigation uses a heuristic A-star algorithm – a powerful computational method of graph theory. This makes it possible to synchronize vehicles' flows and therefore urban traffic takes a qualitatively new level.

4. The study proposes operation only with electronic services. This allows to implement proposed technology organically and without significant costs.

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**Анотація.** Дослідження є принципово новим підходом до вирішення надзвичайно важливої сьогодення проблеми – проблеми заторів у будь-якому великому місті. Вирішено задачу навігації транспортних засобів для вибору оптимальних за часом маршрутів. Дослідження базується на використанні механізмів моделювання та роботи з різними мережами – теорії графів та алгоритму A-star. Останній прокладає маршрут у графі (транспортній мережі) між двома вибраними позиціями транспортного засобу – початковою та кінцевою. Для навігації по маршруту вирішується задача реєстрації транспортного навантаження транспортної мережі міста. Дані про дорожній рух з реальної транспортної мережі відтворюються на електронній карті міста. Кожен транспортний засіб отримує унікальний маркер, що складається з пари початкова-кінцева. Кожна така пара відстежується на електронній карті міста. Оскільки кожен транспортний засіб знаходиться під управлінням центру керування трафіком (ЦКТ), є можливість супроводжувати його оптимальним маршрутом з урахуванням динаміки міського руху. Підтримка здійснюється через канал GPRS (General Packet Radio Service), що дозволяє кожному водієві отримувати інструкції щодо оптимального маршруту руху.

**Ключові слова:** зважений орієнтований граф, алгоритм A-star, міський трафік, затори, перевантаження