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TOSHKENT DAVLAT TRANSPORT UNIVERSITETI

Tashkent state transport university

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Mathematical modeling of the urban public transport system in Termiz city based on passenger flows and simulation-based timetable improvement

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Abstract: This paper presents a simulation-based approach for analyzing and optimizing urban bus transport systems and their timetables using the city of Termiz as a case study. Rapid urbanization, population growth, and the expansion of residential and public service areas have increased the demand for efficient public transport services. However, the existing bus route network and operating timetables do not fully correspond to current passenger demand, resulting in uneven vehicle loading, longer passenger waiting times, and inefficient utilization of transport resources.

A mathematical model based on graph theory and simulation is developed to evaluate the performance of the urban bus network. The model considers passenger flows, route characteristics, bus stops, service headways, and overlapping route sections to improve timetable coordination and resource allocation. Based on the simulation results, recommendations are proposed for route reorganization, timetable optimization, and service frequency adjustment.

The findings demonstrate that the proposed methodology improves the operational efficiency and reliability of the urban bus transport system, reduces passenger waiting time, and supports more rational use of transport resources. The proposed approach can serve as a practical decision-support tool for planning and managing public transport systems in medium-sized cities.

Keywords: urban public transport, bus transport system, bus route network, timetable optimization, simulation modeling, graph theory, passenger flow analysis, timetable synchronization, overlapping routes, transport network optimization

Termiz shahri jamoat transporti tizimini yo‘lovchi oqimlari asosida matematik modellashtirish va simulyatsiya orqali harakat jadvalini takomillashtirish

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Annotatsiya: Mazkur maqolada Termiz shahri misolida shahar avtobus transporti tizimi va uning harakat jadvalini simulyatsion modellashtirish asosida tahlil qilish hamda optimallashtirish usuli taklif etilgan. Urbanizatsiya jarayonlarining jadallashuvi, aholi sonining ortishi hamda yangi turar joy massivlari va ijtimoiy infratuzilma obyektlarining kengayishi samarali jamoat transporti xizmatlariga bo‘lgan talabni sezilarli darajada oshirmoqda. Biroq, mavjud avtobus yo‘nalishlari tarmog‘i va harakat jadvallari amaldagi yo‘lovchi talabiga to‘liq mos kelmaydi. Natijada transport vositalarining notekis yuklanishi, yo‘lovchilarning kutish vaqtining ortishi va transport resurslaridan samarasiz foydalanish holatlari yuzaga kelmoqda.

Tadqiqotda graf nazariyasi va simulyatsion modellashtirish usullariga asoslangan matematik model ishlab chiqilgan. Mazkur modelda yo‘lovchi oqimlari, avtobus yo‘nalishlarining tavsiflari, bekatlar soni, harakat oralig‘i (headway) hamda ustma-ust tushadigan marshrut uchastkalari hisobga olinib, harakat jadvallarini muvofiqlashtirish va transport resurslarini oqilona taqsimlash masalalari tahlil qilingan. Simulyatsiya natijalari asosida avtobus yo‘nalishlarini qayta tashkil etish, harakat jadvallarini optimallashtirish va qatnovlar chastotasini takomillashtirish bo‘yicha ilmiy asoslangan tavsiyalar ishlab chiqilgan.

Tadqiqot natijalari taklif etilgan metodologiya shahar avtobus transporti tizimining ekspluatatsion samaradorligi va ishonchliligini oshirish, yo‘lovchilarning kutish vaqtini qisqartirish hamda transport resurslaridan yanada oqilona foydalanishni ta’minlashini ko‘rsatdi. Taklif etilgan yondashuv o‘rta hajmdagi shaharlar jamoat transporti tizimini rejalashtirish va boshqarishda qaror qabul qilishni qo‘llab-quvvatlovchi samarali amaliy vosita sifatida qo‘llanilishi mumkin.

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Kalit so‘zlar: shahar jamoat transporti, avtobus transporti tizimi, avtobus yo‘nalishlari tarmog‘i, harakat jadvalini optimallashtirish, simulyatsion modellashtirish, graf nazariyasi, yo‘lovchi oqimini tahlil qilish, harakat jadvalini sinxronlashtirish, ustma-ust tushadigan yo‘nalishlar, transport tarmog‘ini optimallashtirish

1. Kirish

Jamoat transporti tizimining samaradorligi yo‘lovchilarga ko‘rsatilayotgan xizmat sifati, avtobus yo‘nalishlari tarmog‘ining oqilona tashkil etilishi hamda harakat jadvallarining yo‘lovchi talabiga mosligi bilan belgilanadi. Transport xizmatlari sifatini oshirishda yo‘nalishlarning qulayligi, harakat oralig‘ining me’yoriy darajada saqlanishi, bekatlar infratuzilmasining rivojlanganligi va qatnovlarning muntazamligi muhim omillar hisoblanadi. Ushbu ko‘rsatkichlarni optimallashtirish yo‘lovchilarning jamoat transportidan foydalanish darajasini oshirish, shaxsiy avtomobillardan foydalanish ulushini kamaytirish hamda yo‘l-transport tarmog‘idagi tirbandlik, transport vositalarining notekis yuklanishi, bekatlarda ortiqcha kutish vaqti va atmosfera havosiga chiqarilayotgan zararli moddalarning kamayishiga xizmat qiladi.Surxondaryo viloyati Transport boshqarmasi ma’lumotlariga ko‘ra, 2023-yilda Termiz shahrida bir nafar fuqaro yil davomida o‘rtacha 316 marta jamoat transporti xizmatidan foydalangan. Shundan 60–65 % qismi ish joylari va ta’lim muassasalariga qatnovlar hissasiga to‘g‘ri kelgan. Mazkur holat shahar avtobus transporti tizimida yo‘lovchi oqimlarini simulyatsion modellashtirish, harakat jadvallarini optimallashtirish hamda yo‘nalishlararo muvofiqlashtirish masalalarining dolzarbligini tasdiqlaydi.

2. Tadqiqot metodologiyasi

Transport tizimini rejalashtirish va boshqarishda yo‘lovchi oqimlari, harakat jadvallari hamda yo‘nalishlar tarmog‘ini matematik va simulyatsion modellashtirish asosida baholash transport xizmatlari sifatini oshirishning muhim omillaridan biri hisoblanadi. Bunday yondashuv yo‘lovchilar ehtiyojini aniq baholash, resurslardan oqilona foydalanish va harakat jadvalini optimallashtirish imkonini beradi [7]

Ties Brands, Eric de Romph, Tim Veitch va Jamie Cook tadqiqotlarida yo‘lovchilarning jamoat transportidan foydalanish jarayonida yo‘nalish tanloviga ta’sir etuvchi omillar tahlil qilingan. Mualliflar transport tizimini modellashtirishda yo‘lovchining bekatgacha yetib borishi (access), asosiy qatnovni amalga oshirishi va manzilgacha harakatlanishi (egress) jarayonlarini yagona tizim sifatida hisobga olish zarurligini ta’kidlaydilar. Mazkur yondashuv yo‘lovchi oqimlarini aniq prognozlash va harakat jadvallarini optimallashtirish imkonini beradi [1].

J. Gerlach va H. Voss agentlarga asoslangan simulyatsion modellashtirish (Agent-Based Simulation, ABS) yordamida jamoat transporti yo‘nalishlari tarmog‘ini optimallashtirish metodikasini taklif etgan. Tadqiqot natijalari qayta tashkil etilgan yo‘nalishlar tarmog‘i transport qamrovini 12–18 % ga oshirish va yo‘lovchilarning safar vaqtini 10 % gacha qisqartirish imkonini berishini ko‘rsatgan [2].

Rose J.M. va Francisco Martínez tomonidan ishlab chiqilgan Land Use and Transport Interaction (LUTI) modeli shahar hududlaridan foydalanish va transport infratuzilmasi o‘rtasidagi o‘zaro bog‘liqlikni baholashga xizmat qiladi. Ushbu modelda diskret tanlov (Logit va Nested Logit) usullari orqali yo‘lovchilarning manzil tanlovi, bekatlargacha bo‘lgan masofa, safar vaqti va transport xarajatlari hisobga olinadi. Mazkur yondashuv yo‘lovchi oqimlarini prognozlash, avtobus yo‘nalishlari tarmog‘ini shakllantirish hamda harakat jadvallarini simulyatsiya asosida takomillashtirishda samarali ilmiy vosita hisoblanadi [3, 4].

Matematik model orqali tahlil etiladi. Umumiy tashish vaqtini **minimallashtirish** va tashish samaradorligini **maksimallashtirish.buyerda,** L – umumiy marshrut uzunligi (km); V – o‘rtacha tezlik (km/soat); N – bekatlar soni; T_f –bir bekatda o‘rtacha to‘xtash vaqti (min); Q– yo‘lovchilar oqimi (kishi/soat); C – transport vositasining sig‘imi (kishi); n – transport vositalari soni; t_{ij} – i-bekatdan j-bekatgacha vaqt (soat).

Maqsad funksiyasi: umumiy xizmat ko‘rsatish vaqtini minimallashtirish

$$minT_{um} = \sum_{i=1}^{N-1} t_{i,i+1} + N \cdot \frac{T_f}{60} \quad (1.1)$$

bunda N – oraliq bekatlar soni; L – umumiy marshrut uzunligi (km); V – transport vositasining o‘rtacha tezligi (km/soat); T_f – bir bekatda to‘xtash vaqti (minut); T_{um}– umumiy harakat vaqti (soat); D – yo‘lovchilarning kutilgan kutish vaqti (minut).

Talabga ko‘ra to‘xtash modelida har bir qo‘shimcha to‘xtash o‘rtacha ΔN marta sodir bo‘ladi, va harakat yo‘nalishi bo‘yicha umumiy bekatlar soni oshadi:

$$T_{um} = \frac{L+\Delta L}{V} + (\Delta N) \cdot \frac{T_f}{60} \quad (1.2)$$

buyerda ΔL – talabga ko‘ra marshrutning ortiqcha yurilgan masofasi.

Qat’iy bekatlar bilan modelida marshrutning harakat vaqti doimiy, yo‘lovchilar uchun kutish vaqti minimallashadi

$$T_{um} = \frac{L}{V} + N \cdot \frac{T_f}{60} \quad (2.3)$$

Bunda $\Delta N > N$ bo‘ladi, demak umumiy harakat vaqti, marshrutdagi o‘rtacha harakat vaqti va yoqilg‘i sarfi, yo‘lovchilar uchun kutish vaqti oshadi.

Yo‘lovchi tashish samaradorligini oshirish

$$max\ \eta = \frac{Q \cdot L}{n \cdot T_{um}} \quad (1.4)$$

bunda η– transport samaradorligi ko‘rsatkichi (kishi·km/soat). Bu funksiya - har bir avtobusning bir soatda qancha yo‘lovchi·km ishlab chiqarganini ko‘rsatadi. Shu qiymat **maksimallashtiriladi.**

Yo‘lovchi oqimi oshgan holatlardagi yondashuvlarda biri yo‘lovchi oqimi oshgan holatlarda transport tizimi quyidagicha moslashuvchanlikni talab qiladi, ya’ni adaptiv bekat tizimi. Bunda yo‘lovchi oqimi yuqori bo‘lgan bekatlarda bekatdagi avtobus to‘xtash vaqti T_f ortadi. Bunday holatda qo‘shimcha vositalar ajratish yoki marshrutni qismlarga bo‘lish samarali bo‘ladi.

Ikkinchisi esa yo‘nalishni zichlashtirish. Agar $Q > n \cdot C$, ya’ni har bir transport vositasining maksimal sig‘imi yetmay qolsa, transport vositalari soni n oshiriladi yoki “express” (kam bekatli) yo‘nalishlar tashkil qilinadi.

Yo‘lovchi talabi va oqimi vaqt bo‘yicha o‘zgarib turgan sharoitlarda (masalan, ertalab va kechki tig‘iz soatlar) “pik” davrlarda avtobuslar harakat oralig‘i qisqartirilib, qatnovlar

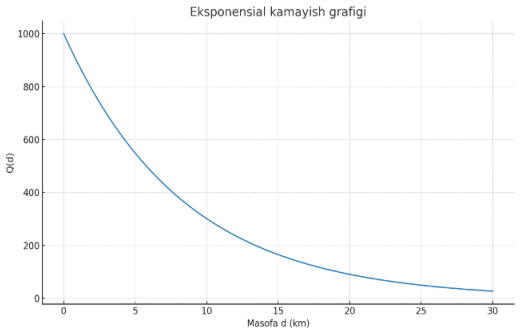
soni ko‘paytiriladi, kam yuklama kuzatiladigan vaqtlarda esa harakat jadvali siyraklashtiriladi.

Bekatlar orasidagi o‘rtacha masofa d, va yo‘lovchi oqimi Q orasida bog‘liqlik mavjud bo‘lib, yo‘lovchi oqimi masofaga qarab eksponentsial kamayadi va quyidagi (1.5) formula bilan ifodalanadi [5].

$$Q(d) = Q_{max} \cdot e^{-\alpha d}, \quad (1.5)$$

bunda $Q(d)$– oraliq masofa d bo‘lgan ikki bekat orasidagi yo‘lovchi oqimi, α – pasayish koeffitsiyenti (hududga bog‘liq).

Gravitatsion model asosida ishlab chiqilgan transport oqimi modellarida foydalaniladigan bu model orqali bekatlar soni va joylashuvi yo‘lovchi oqimiga qarab optimallashtiriladi (1-rasm).



1-rasm. Eksponensial kamayish grafigi.

Qat’iy belgilangan bekatlar bilan tashishni maqsad funksiyasi orqali optimallashtirish mumkin. Yo‘lovchi oqimi oshgan holatlarda tizim adaptiv yondashuv talab qiladi. Samaradorlik uchun yo‘nalish zichligi, express tarmoq, vaqtga bog‘liq jadval, bekat zichligi singari parametrlar optimallashtiriladi [5].

To‘xtash bekatlari (oraliq punktlar) orasidagi **optimal masofani aniqlash** - shahar jamoat transporti tizimidagi **asosiy samaradorlik ko‘rsatkichlaridan biri** hisoblanadi. Optimal masofa shunday tanlanishi kerakki, **yo‘lovchilarga qulaylik, tashish vaqti xarajatlar,** va **yo‘lovchi oqimi** o‘rtasida **muvozanatni ta’minlasin**.

O‘rganilayotgan hududda oraliq to‘xtash bekatlari ratsional masofa $d$ni aniqlash uchun (1-jadvalda keltirilgan asosiy mezonlardan foydalanildi).

1-jadval

Oraliq to‘xtash bekatlari ratsional masofasini aniqlash mezonlari

№	Mezoni nomi	Izoh
1	Yo‘lovchi oqimi $Q(d)$	Masofa ortgani sari kamayadi $Q(d) = Q_{max} \cdot e^{-\alpha d}$,
2	Tashish vaqti T_{um}	Bekatlar soni ko‘p bo‘lsa – ko‘p vaqt ketadi $T_{um} = \frac{L}{V} + N \cdot \frac{T_f}{60}$
3	Xarajatlar $C(d)$	Ko‘p bekat – ko‘p to‘xtash, ortiqcha energiya, vaqt va ekspluatatsiya xarajati
4	Yo‘lovchilarga qulaylik	Masofa juda katta bo‘lsa – odamlar piyoda yurishni istamaydi, bekatlar uzoq

Ma’lum qiymatlarni asos qilib, **optimal masofani** aniqlovchi **maqsad funksiyasi** tuzamiz:

$$min\ Z(d) = w_1 \cdot T_{um}(d) + w_2 \cdot C(d) - w_3 \cdot Q(d) \quad (1.6)$$

yoki

$$maxZ(d) = w_3 \cdot Q(d) - w_1 \cdot T_{um}(d) - w_2 \cdot C(d) \quad (1.7)$$

bunda $Z(d)$ –umumiy xarajat, $T_{um}(d)$ – harakatga sarflanadigan **vaqt** (odatda oraliq bekatlar soni ko‘payganda ortadi), $C(d)$ – **ekspluatatsion xarajatlar** (yoqilg‘i, texnik xizmat, tormoz-tezlik yuklamalari), $Q(d)$ – **yo‘lovchilar soni** (masofa ortgan sari kamayadi, ammo ijobiy holat sifatida qaraladi), w_1, w_2, w_3 –vazn koeffisientlari. Bu modelda $Z(d)$ minimalga erishganda d optimal qiymat hisoblanadi.

Hisoblash uchun parametrlar: (2-jadval)

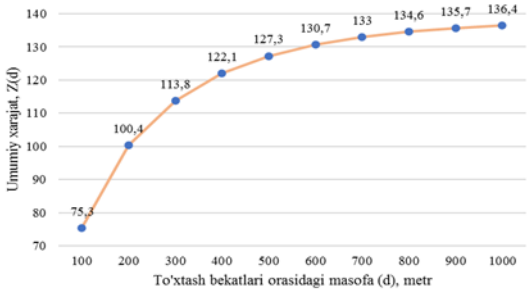
$$L = 6000\ m, \propto = 0{,}5, Q_{max} = 358\ yo'lovchi,$$
$$w_1 = 0{,}4, \quad w_2 = 0{,}2, \quad w_3 = 0{,}4.$$

2-jadval

Optimal bekatlar oralig‘ini aniqlash uchun maqsad funksiyasini hisoblashda foydalanilgan parametrlar

d, m	N = L	Q(d)	$T_{um}(d$	$C(d)$	$maxZ(d)$
100	60	218.25	0.010	60	87.3−0.004 −12=75.296
200	30	265.95	0.005	30	106.38−0.002−6=100.378
300	20	294.67	0.0033	20	117.87−0.0013−4=113.8687
400	15	312.86	0.0025	15	125.14−0.001−3=122.139
500	12	324.21	0.002	12	129.68−0.0008−2.4=127.279
600	10	331.89	0.0016	10	132.76−0.0006−2=130.759
700	8.57	336.82	0.0014	8.57	134.73−0.0006−1.714=133.0
800	7.5	340.48	0.00125	7.5	136.19−0.0005−1.5=134.69
900	6.67	343.22	0.0011	6.67	137.3−0.0004−1.34=135.96
1000	6	345.32	0.001	6	138.13−0.0004−1.2=136.93

Misolar natijasiga ko‘ra Z(d) qiymati ortib bormoqda, bu bekatlar oralig‘i oshgan sari foyda ortishini bildiradi. Ammo bu nazoratsiz to‘xtashlarni kamaytirish hisobiga bo‘ladi, bu esa xizmat sifati va transport qulayligini pasaytiradi [8]. Bunda oraliq masofa optimal *d=600-700 metr* atrofida keskin o‘sishdan keyin barqarorlashadi. Agar ekologik zarar, ortiqcha yoqilg‘i sarfi va real vaqt xarajati ham qo‘shilsa, **optimal oraliq** yana **300-400 metr** oralig‘iga tushadi (2-rasm).



2-rasm. Bekatlar orasidagi masofa bo‘yicha foyda funksiyasi

Hisoblash natijalariga ko‘ra bekatlar oralig‘i ortishi bilan avtobusning harakat vaqti qisqaradi, ekspluatatsiya xarajatlari kamayadi. Biroq 700–800 m dan keyin

yo‘lovchilarning bekatgacha piyoda yurish masofasi ortishi hisobiga transportdan foydalanish darajasi pasaya boshlaydi. Kompleks baholash natijalariga asosan Termiz shahri sharoiti uchun avtobus bekatlari oralig‘ining ratsional masofasi 500–700 m ekanligi aniqlandi. Mazkur masofa transport vositalarining harakat samaradorligi, yo‘lovchilar uchun qulaylik va ekspluatatsiya xarajatlari o‘rtasidagi optimal muvozanatni ta’minlaydi (3-rasm).

Avtobuslar harakatini simulyatsion nazorat qilish quyidagilarni nazorat qilishga imkon yaratadi:

-yo‘nalishlar va harakat jadvalini optimallashtirish imkonini beradi;

-yo‘lovchi oqimlarini hisobga olgan holda transport resurslarini samarali taqsimlaydi;

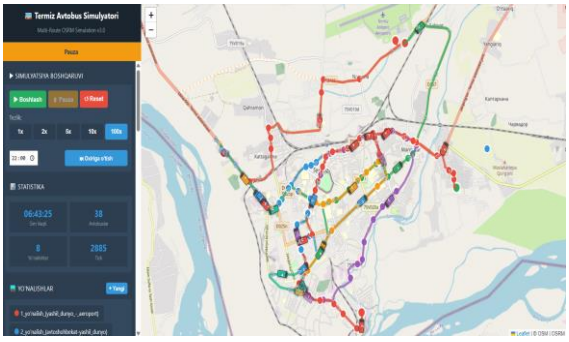
-avtobuslar orasidagi interval va kutish vaqtini kamaytiradi;

-tirbandlik va avtobuslarning bir joyga to‘planishini (bus bunching) oldini oladi;

-yoqilg‘i sarfi va ekspluatatsiya xarajatlarini kamaytiradi;

-turli ssenariylarni real sharoitga yaqin muhitda sinovdan o‘tkazishga imkon yaratadi;

-transport tizimining samaradorligi va xizmat sifatini oshirish bo‘yicha ilmiy asoslangan qarorlar qabul qilishga xizmat qiladi.



3-rasm Avtobuslar harakatining smulyatsiya jarayoni

3. Xulosa

Taklif etilgan simulyatsiya modeli Termiz shahri jamoat transporti tizimining ishlashini real sharoitlarga yaqin muhitda tahlil qilish imkonini beradi. Model yordamida avtobuslar harakati, yo‘lovchi oqimlari, harakat oralig‘i hamda yo‘nalishlarning o‘zaro ta'siri kompleks baholanadi. Simulyatsiya natijalari Termiz shahri avtobus yo‘nalishlari tarmog‘ida transport resurslaridan oqilona foydalanish, harakat jadvalini optimallashtirish, yo‘lovchilar kutish vaqtini kamaytirish hamda transport tizimining iqtisodiy va ekspluatatsion samaradorligini oshirish bo‘yicha ilmiy asoslangan qarorlar qabul qilish imkonini beradi.

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