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TRANSPORT UNIVERSITETI**
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**Post-Kvant kriptografiya algoritmlarining matematik asoslari va zamonaviy
yondashuvlar tahlili**

D.T.Muhamediyeva¹, F.A.Tagayev¹, Yu.Sh.Yuldoshev²

¹«Toshkent irrigatsiya va qishloq xo'jaligini mexanizatsiyalash muhandislari instituti» milliy
tadqiqot universiteti

² Ma'mun universiteti

Annotatsiya. Ushbu maqolada post-kvant kriptografiyaning asosiy algoritmlari va ularning matematik asoslari tahlil qilinadi. Kvant kompyuterlarning rivojlanishi natijasida an'anaviy kriptografik tizimlarning zaiflashuvi yangi, kvantga chidamli algoritmlarni ishlab chiqishni talab etmoqda. Tadqiqotda panjara asosli, kodga asoslangan, ko'p o'zgaruvchili va hash-funksiyaga asoslangan kriptografik yondashuvlar chuqur o'rganiladi. Har bir algoritmning ishlash prinsipi, matematik modeli hamda xavfsizlik darajasi solishtirma tarzda baholanadi. Shuningdek, ushbu algoritmlarning afzalliklari va kamchiliklari aniqlanib, ularning amaliy qo'llanish istiqbollari muhokama qilinadi. Olingan natijalar post-kvant kriptografiya sohasida optimal yondashuvlarni tanlashda muhim ahamiyat kasb etadi.

Kalit so'zlar. Post-kvant kriptografiya, kvant kompyuterlar, panjara asosli algoritmlar, LWE, kodga asoslangan kriptografiya, multivariate tizimlar, hash-funksiyalar, kriptografik xavfsizlik

1. Kirish.

Axborot xavfsizligini ta'minlash zamonaviy raqamli jamiyatning eng muhim masalalaridan biri hisoblanadi. Hozirgi kunda keng qo'llanilayotgan kriptografik algoritmlar, jumladan RSA, Diffie–Hellman va elliptik egri chiziqlarga asoslangan tizimlar matematik jihatdan murakkab muammolarga tayanadi. Biroq kvant kompyuterlarning rivojlanishi ushbu muammolarni samarali yechish imkonini berishi sababli, mavjud kriptotizimlar o'z ahamiyatini yo'qotishi mumkin. Shu munosabat bilan post-kvant kriptografiya yangi ilmiy yo'nalish sifatida shakllanmoqda. Ushbu yo'nalish kvant kompyuterlar sharoitida ham xavfsiz bo'lib qoladigan kriptografik algoritmlarni ishlab chiqishga qaratilgan. Post-kvant kriptografiyaning asosini klassik kompyuterlar uchun murakkab bo'lgan, ammo kvant kompyuterlar uchun ham samarali yechimi topilmagan matematik muammolar tashkil etadi. Hozirgi vaqtda post-kvant kriptografiyada bir nechta asosiy yondashuvlar mavjud. Ular orasida panjara asosli kriptografiya, kodga asoslangan tizimlar, ko'p o'zgaruvchili kvadratik tenglamalar hamda hash-funksiyalarga asoslangan imzo tizimlari alohida o'rin tutadi. Har bir yondashuv o'ziga xos matematik modelga ega bo'lib, ularning xavfsizlik darajasi va amaliy samaradorligi turlicha [1-4].



Mazkur maqolada post-kvant kriptografiyaning asosiy algoritmlari, ularning matematik asoslari va ishlash prinsiplari tizimli ravishda tahlil qilinadi. Shuningdek, turli yondashuvlarning afzallik va kamchiliklari solishtirilib, ularning amaliy qo'llanish istiqbollari yoritiladi. Bu esa kelajakda xavfsiz kriptografik tizimlarni tanlash va ishlab chiqishda muhim ilmiy asos bo'lib xizmat qiladi. Post-kvant kriptografiya sohasidagi ilmiy tadqiqotlar kvant kompyuterlarning rivojlanishi bilan keskin faollashdi. Klassik kriptotizimlar xavfsizligi asosan faktorizatsiya va diskret logarifm muammolariga asoslangan bo'lib, ular kvant algoritmlari yordamida samarali yechilishi mumkin. Shu sababli, yangi kriptografik yondashuvlar murakkab matematik muammolarga asoslanmoqda. Adabiyotlar tahlili shuni ko'rsatadiki, post-kvant kriptografiya bir nechta asosiy yo'nalishlarga bo'linadi va har bir yo'nalish o'ziga xos matematik modelga ega [5-8].

Panjara asosli kriptografiya eng ko'p o'rganilgan va amaliy jihatdan istiqbolli yo'nalishlardan biri hisoblanadi. Ushbu yondashuv panjara nazariyasiga asoslanadi va unda asosiy murakkab masala sifatida eng qisqa vektor muammosi qaraladi [9-12]:

$$\lambda_1(L) = \min_{v \in L, \{0\}} \|v\|.$$

Bu yerda L panjara bo'lib, nolga teng bo'lmagan eng kichik uzunlikdagi vektor topilishi talab etiladi. Ushbu muammo yuqori o'lchamli fazolarda hisoblash jihatidan juda murakkab bo'lib, kvant kompyuterlar uchun ham samarali algoritmlar mavjud emas [13-15].

Amaliy kriptografik tizimlarda panjara asosli yondashuvning keng qo'llaniladigan varianti — Learning With Errors (LWE) muammosidir. U quyidagi matematik model orqali ifodalanadi [16-18]:

$$b = As + e \pmod{q},$$

bu yerda A tasodifiy matritsa, s maxfiy vektor, e esa kichik xatolikni ifodalovchi vektordir. Tadqiqotlar shuni ko'rsatadiki, xatolik komponentining mavjudligi tizimni kriptotahlilga nisbatan sezilarli darajada mustahkamlaydi. Kodga asoslangan kriptografiya ham post-kvant xavfsizlikni ta'minlashda muhim o'rin egallaydi. Ushbu yondashuv xatolarni tuzatish nazariyasiga asoslanadi va quyidagi ko'rinishda ifodalanadi [19-21]:

$$c = mG + e,$$

bu yerda G generator matritsa, m ochiq matn, e esa xatolik vektori hisoblanadi. Adabiyotlarda McEliece kriptotizimi yuqori xavfsizlik darajasi bilan ajralib turishi ta'kidlanadi, biroq uning asosiy kamchiligi sifatida kalit hajmining katta bo'lishi ko'rsatiladi. Ko'p o'zgaruvchili kvadratik tenglamalarga asoslangan kriptografiya ham keng o'rganilgan yo'nalishlardan biridir. Ushbu



yondashuvda shifrlash yoki imzo yaratish quyidagi umumiy ko'rinishdagi tenglamalar tizimiga asoslanadi:

$$P_i(x_1, x_2, \dots, x_n) = \sum_{j,k} a_{jk}^{(i)} x_j x_k + \sum_j b_j^{(i)} x_j + c_i.$$

Bu yerda asosiy muammo — ko'p o'zgaruvchili kvadratik tenglamalar tizimini yechish bo'lib, bu NP-qiyin masala hisoblanadi. Tadqiqotlar shuni ko'rsatadiki, ushbu tizimlar yuqori tezlikka ega bo'lsa-da, ayrim parametr tanlovlarida xavfsizlik zaiflashishi mumkin. Hash-funksiyaga asoslangan kriptografik tizimlar esa eng ishonchli yondashuvlardan biri sifatida qaraladi. Ularning matematik asosi quyidagi ifoda bilan belgilanadi:

$$h = H(m),$$

bu yerda H — kriptografik hash funksiya, m — kiruvchi xabar. Ushbu yondashuvning xavfsizligi hash funksiyaning kolliziyaga chidamliligi va bir yo'nalishliligiga bog'liq.

Adabiyotlar tahlili shuni ko'rsatadiki, har bir post-kvant kriptografik yondashuv ma'lum afzallik va kamchiliklarga ega. Panjara asosli algoritmlar yaxshi muvozanatni ta'minlasa, kodga asoslangan tizimlar yuqori ishonchlilikni beradi. Ko'p o'zgaruvchili tizimlar tezkorligi bilan ajralib tursa, hash asosli yondashuvlar maksimal xavfsizlikni ta'minlaydi. Barcha tadqiqotlarda umumiy xulosa sifatida quyidagi muammolar qayd etiladi: hisoblash murakkabligi, kalit hajmining kattaligi, implementatsiya murakkabligi va uzoq muddatli xavfsizlikni isbotlashdagi cheklovlar. Aynan shu omillar post-kvant kriptografiya sohasida hali ham faol ilmiy izlanishlar olib borilayotganini ko'rsatadi.

2. Metodologiya.

Mazkur tadqiqotda post-kvant kriptografik algoritmlarni tahlil qilish va baholash uchun formal matematik model, ehtimollik nazariyasi hamda hisoblash murakkabligi nazariyasiga asoslangan kompleks metodologik yondashuv qo'llanildi. Tadqiqotning asosiy maqsadi turli post-kvant kriptotizimlarning xavfsizlik darajasi, samaradorligi va amaliy qo'llanish imkoniyatlarini qat'iy matematik asosda solishtirishdan iborat.

Kriptotizim umumiy holda quyidagi formal model orqali ifodalanadi:

$$\Pi = (\text{KeyGen}, \text{Enc}, \text{Dec}),$$

bu yerda kalit generatsiyasi ehtimollik xarakteriga ega bo'lib,

$$(pk, sk) \leftarrow \text{KeyGen}(1^\lambda)$$

ko'rinishida aniqlanadi. Bu yerda λ — xavfsizlik parametri. Shifrlash jarayoni ehtimollik algoritmi sifatida quyidagicha ifodalanadi:

$$c \leftarrow \text{Enc}(pk, m; r),$$



bu yerda r — tasodifiylik manbai. Deshifrlash esa deterministik yoki ehtimollik funksiyasi sifatida:

$$m = \text{Dec}(sk, c)$$

ko'rinishida amalga oshiriladi.

Tadqiqotda asosiy e'tibor panjara asosli LWE modeliga qaratildi. Ushbu modelda maxfiy kalit $s \in \mathbb{Z}_q^n$ bo'lib, ochiq kalit quyidagi taqsimotdan olinadi:

$$(A, b) \in \mathbb{Z}_q^{m \times n} \times \mathbb{Z}_q^m, \quad b = As + e \pmod{q},$$

bu yerda $e \sim \chi^m$ — diskret Gauss taqsimotiga ega xatolik vektori. Diskret Gauss taqsimoti quyidagicha aniqlanadi:

$$\Pr[e = x] = \frac{e^{-\pi \|x\|^2 / \sigma^2}}{\sum_{y \in \mathbb{Z}^m} e^{-\pi \|y\|^2 / \sigma^2}},$$

bu yerda σ dispersiyani ifodalaydi.

Shifrlash jarayoni quyidagi tenglamalar orqali amalga oshiriladi:

$$c_1 = \mathbf{A}^T \mathbf{r},$$

$$c_2 = \mathbf{b}^T \mathbf{r} + \left\lceil \frac{q}{2} \right\rceil \cdot m,$$

bu yerda $\mathbf{r} \in \{0,1\}^m$ tasodifiy vektor. Deshifrlash jarayoni esa quyidagicha:

$$m = \left\lfloor \frac{c_2 - \mathbf{s}^T c_1}{q/2} \right\rfloor$$

ko'rinishida amalga oshiriladi.

Xavfsizlikni formal baholash uchun IND-CPA modeli qo'llanildi. Bu modelda hujumchining ustunligi quyidagicha aniqlanadi:

$$\text{Adv}_A^{\text{IND-CPA}}(\lambda) = \left| \Pr[A(c) = b] - \frac{1}{2} \right|,$$

bu yerda $b \in \{0,1\}$ — tanlangan xabar indeksi. Tizim xavfsiz hisoblanadi, agar:

$$\text{Adv}_A^{\text{IND-CPA}}(\lambda) \leq \text{negl}(\lambda),$$

bu yerda $\text{negl}(\lambda)$ — nolga tez yaqinlashuvchi funksiya.

Hisoblash murakkabligi nazariyasi asosida algoritmlar samaradorligi quyidagi ko'rinishda baholandi:

$$T_{\text{Enc}}(n) = O(n^2), \quad T_{\text{Dec}}(n) = O(n^2).$$

Bunda asosiy hisoblash xarajatlari matritsa-vektor ko'paytmasiga bog'liq:



$$\mathbf{A}_s = \sum_{i=1}^n s_i a_i.$$

Shuningdek, xotira murakkabligi ham hisobga olindi:

$$S(n) = O(n^2 \log q),$$

bu yerda $\log q$ har bir elementni saqlash uchun zarur bitlar sonini bildiradi.

Ko'p o'zgaruvchili kriptotizimlar uchun metodologiya quyidagi algebraik modelga asoslandi. Berilgan polinomlar tizimi:

$$P = \{P_1, P_2, \dots, P_m\}, \quad P_i \in \mathbb{F}_q[x_1, \dots, x_n]$$

bo'lib, yechim topish murakkabligi Gröbner bazislar orqali baholanadi:

$$\text{Complexity} \sim O\left(\binom{n+d}{d}\right)^\omega,$$

bu yerda d — polinom darajasi, ω — matritsa ko'paytirish eksponenti.

Kodga asoslangan kriptotizimlarda esa sindrom dekodlash muammosi asosiy rol o'ynaydi:

$$\mathbf{s} = \mathbf{H}\mathbf{e}^T,$$

bu yerda $\mathbf{H}$ — paritet tekshiruv matritsasi. Ushbu muammoning murakkabligi eksponensial bo'lib:

$$T(n) \approx O(2^{\alpha n})$$

ko'rinishida baholanadi.

Metodologiya nazariy tahlil, matematik modellashtirish va hisoblash murakkabligini baholashni birlashtirgan holda ishlab chiqildi. Ushbu yondashuv turli post-kvant kriptografik algoritmlarni chuqur va obyektiv solishtirish imkonini berdi.

Post-kvant kriptografik algoritmlar kvant kompyuterlar sharoitida ham hisoblash jihatdan murakkab bo'lib qoladigan matematik muammolarga asoslanadi. Ushbu bo'limda asosiy algoritmlar chuqur matematik formalizm asosida bayon etiladi.

1. Panjara asosli kriptografiya (Lattice-based, LWE/RLWE).

LWE muammosi quyidagi ehtimollik taqsimotiga asoslanadi:

$$(A, b) \sim U(\mathbb{Z}_q^{m \times n}) \times \mathbb{Z}_q^m, \quad b = As + e \pmod{q},$$

bu yerda:

$$s \leftarrow \mathbb{Z}_q^n \text{ — maxfiy kalit,}$$

$$e \leftarrow \chi^m \text{ — diskret Gauss taqsimoti.}$$

$$\chi(x) = \frac{1}{Z} \exp\left(-\frac{\pi \|x\|^2}{\sigma^2}\right).$$



RLWE (Ring-LWE) umumlashmasi esa polinom halqalarida aniqlanadi:

$$b(x) = a(x)s(x) + e(x) \pmod{(x^n + 1, q)},$$

bu yerda:

$$a(x), s(x), e(x) \in R_q = \mathbb{Z}_q[x] / (x^n + 1).$$

Shifrlash:

$$c_1(x) = a(x)r(x) + e_1(x),$$

$$c_2(x) = b(x)r(x) + e_2(x) + \left\lfloor \frac{q}{2} \right\rfloor m(x).$$

Deshifrlash:

$$m(x) = \left\lfloor \frac{c_2(x) - s(x)c_1(x)}{q/2} \right\rfloor.$$

2. Kodga asoslangan kriptografiya (McEliece tipi).

Kodga asoslangan kriptotizimlar chiziqli kodlar nazariyasiga asoslanadi. Ochiq kalit quyidagicha hosil qilinadi:

$$G' = SG P,$$

bu yerda:

G — generator matritsa.

S — invertible matritsa.

P — permutatsiya matritsasi.

Shifrlash:

$$c = mG' + e.$$

Deshifrlash:

$$c' = cP^{-1} = mSG + eP^{-1},$$

$$m = (mS)S^{-1},$$

bu yerda xatolik vektori dekodlash algoritmi yordamida olib tashlanadi.

Sindrom dekodlash muammosi:

$$s = He^T,$$

bu yerda H — paritet tekshiruv matritsasi.

3. Ko'p o'zgaruvchili kvadratik tizimlar (Multivariate Quadratic, MQ).

MQ kriptotizimlar quyidagi polinomlar tizimiga asoslanadi:

$$P: \mathbb{F}_q^n \rightarrow \mathbb{F}_q^m.$$



$$P_i(x_1, \dots, x_n) = \sum_{j=1}^n \sum_{k=j}^n a_{jk}^{(i)} x_j x_k + \sum_{j=1}^n b_j^{(i)} x_j + c_i.$$

Yashirin transformatsiyalar orqali ochiq kalit shakllantiriladi:

$$P_{\text{pub}} = T \circ P \circ S,$$

bu yerda:

S, T — invertible affin transformatsiyalar.

Imzo yaratish:

$$P_{\text{pub}}(x) = y.$$

Deshifrlash yoki imzo tekshirish:

$$y \stackrel{?}{=} P_{\text{pub}}(x).$$

Ushbu tizimning xavfsizligi NP-qiyin bo‘lgan MQ muammosiga asoslanadi.

4. Hash-funksiyaga asoslangan imzo algoritmlari.

Hash asosli tizimlar Merkle daraxtlari va bir martalik imzolar asosida ishlaydi.

Bir martalik imzo:

$$\sigma = (sk_i, H(sk_i)).$$

Merkle daraxt ildizi:

$$\text{root} = H(H(\dots H(h_1 \parallel h_2) \parallel h_3) \dots).$$

Imzo:

$$\sigma = (\sigma_i, \text{auth path}).$$

Tekshirish:

$$\text{root} \stackrel{?}{=} H_{\text{path}}(H(m)),$$

bu yerda H_{path} autentifikatsiya yo‘li bo‘yicha hisoblanadi.

5. Izogeniyaga asoslangan kriptografiya.

Izogeniyaga asoslangan tizimlar elliptik egri chiziqlar orasidagi izogeniyalarga asoslanadi.

Elliptik egri chiziq:

$$E: y^2 = x^3 + ax + b.$$

Izogeniya:

$$\phi: E_1 \rightarrow E_2,$$

bu yerda ϕ guruh homomorfizmi hisoblanadi.

Kalit almashish:



$$j(E_{AB}) = j(\phi_A(\phi_B(E))),$$

bu yerda $j(E)$ — j – invariant.

Post-kvant algoritmlarning umumiy murakkabligi quyidagi sinflarga ajratiladi:

$$\text{LWE} \sim O(n^2), \quad \text{MQ} \sim O(2^n), \quad \text{Code-based} \sim O(2^{an}).$$

Xavfsizlik darajasi esa ehtimollik asosida baholanadi:

$$\text{Pr}[\text{break}] \leq 2^{-\lambda}.$$

Post-kvant kriptografik algoritmlar murakkab algebraik va ehtimollik modellariga asoslanadi. Ularning xavfsizligi klassik kriptografiyaga nisbatan chuqurroq matematik muammolar bilan ta'minlanadi. Shu bilan birga, har bir algoritmi turi o'ziga xos hisoblash murakkabligi va amaliy cheklovlarga ega bo'lib, ularni kompleks tahlil qilish muhim ilmiy vazifa hisoblanadi.

3. Natijalar

Mazkur tadqiqot doirasida post-kvant kriptografik algoritmlar — panjara asosli (LWE/RLWE), kodga asoslangan, ko'p o'zgaruvchili kvadratik (MQ) hamda hash-funksiyaga asoslangan tizimlar kompleks matematik va hisoblash mezonlari asosida baholandi. Olingan natijalar algoritmlarning samaradorligi, xavfsizlik darajasi, hisoblash va xotira murakkabligi hamda amaliy qo'llanish imkoniyatlarini aniqlashga qaratildi.

Quyida keltirilgan jadvalda post-kvant kriptografik algoritmlar bo'yicha olingan natijalar ilmiy mezonlar asosida umumlashtirildi (1-jadval):

1-jadval

Post-kvant kriptografik algoritmlar natijalari

Algoritmi turi	Matematik asos	Hisoblash murakkabligi $T(n)$	Xotira murakkabligi $S(n)$	Xavfsizlik darajasi	Afzalliklari	Kamchiliklari
Panjara asosli (LWE)	$b = As + e \bmod q$	$O(n^2 \log q)$	$O(n^2 \log q)$	Yuqori $2^{-\lambda}$	Kvantga chidamli, barqaror	Kalit hajmi katta
Panjara asosli (RLWE)	$b(x) = a(x)s(x) + e(x)$	$O(n \log n)$	$O(n \log q)$	Yuqori	Tezkor, optimallashtirilgan	Parametr tanlash murakkab
Kodga asoslangan	$c = mG' + e$	$O(nk)$	$O(n^2)$	Juda yuqori	Sinovdan o'tgan, ishonchli	Juda katta kalit hajmi
Multivariante (MQ)	$Pi(x_1, \dots, x_n)$	$O(n^2)$	$O(n^2)$	O'rta–yuqori	Juda tez ishlaydi	Ba'zi hujumlarga zaif
Hash asosli	$h = H(m)$	$O(n)$	$O(n \log n)$	Juda yuqori	Eng ishonchli	Imzo hajmi



						<i>katta</i>
<i>Izogeniy a asosli</i>	$\phi: E1 \rightarrow E2$	$O(n^2)$	$O(n)$	<i>Yuqori</i>	<i>Kalit kichik</i>	<i>Hisoblash sekin</i>

2-jadval

Umumiy solishtirma tahlil

<i>Mezoni</i>	<i>Eng yaxshi algoritm</i>	<i>Izoh</i>
<i>Tezlik</i>	<i>MQ, RLWE</i>	<i>Eng kam hisoblash vaqti</i>
<i>Xavfsizlik</i>	<i>Hash-based, Code-based</i>	<i>Eng yuqori kriptotahlilga chidamlilik</i>
<i>Xotira samaradorligi</i>	<i>RLWE, Izogeniya</i>	<i>Kamroq xotira talab qiladi</i>
<i>Amaliy qo'llash</i>	<i>LWE / RLWE</i>	<i>Eng balanslangan yechim</i>
<i>Barqarorlik</i>	<i>Code-based</i>	<i>Yillar davomida sinovdan o'tgan</i>
<i>Mezoni</i>	<i>Eng yaxshi algoritm</i>	<i>Izoh</i>

Algoritm tanlash quyidagi ko'p mezonli optimallashtirish masalasi bilan ifodalanadi:

$$\min(T(n), S(n)), \text{ sharti bilan } \Pr[\text{break}] \leq 2^{-\lambda}.$$

4. Xulosa.

Mazkur tadqiqotda post-kvant kriptografiya sohasining asosiy yo'nalishlari, ularning matematik asoslari hamda amaliy samaradorligi kompleks tarzda tahlil qilindi. Kvant kompyuterlarning rivojlanishi natijasida an'anaviy kriptografik algoritmlarning zaiflashuvi ehtimoli mavjudligi ilmiy jihatdan asoslandi va shu sababli kvantga chidamli yangi kriptografik yondashuvlarni ishlab chiqish zarurligi ko'rsatib berildi. Tadqiqot davomida panjara asosli, kodga asoslangan, ko'p o'zgaruvchili kvadratik va hash-funksiyaga asoslangan algoritmlar chuqur matematik modellar asosida o'rganildi hamda ularning hisoblash murakkabligi, xotira talablari va xavfsizlik darajasi o'zaro solishtirildi. Olingan natijalar shuni ko'rsatdiki, panjara asosli algoritmlar, ayniqsa LWE va uning halqa asosidagi modifikatsiyasi RLWE, samaradorlik va xavfsizlik o'rtasida optimal muvozanatni ta'minlaydi. Ushbu algoritmlar polinomial vaqt murakkabligiga ega bo'lib, yuqori o'lchamli parametrlar uchun ham barqaror ishlaydi. Shu bilan birga, kodga asoslangan kriptotizimlar yuqori darajadagi kriptotahlilga chidamliligi bilan ajralib turadi, biroq ularning katta kalit hajmi amaliy qo'llanishni murakkablashtiradi. Ko'p o'zgaruvchili tizimlar tezkor ishlashi bilan ajralib tursa-da, ularning xavfsizligi parametr tanlashga sezilarli darajada bog'liq. Hash-funksiyaga asoslangan algoritmlar esa konservativ



yondashuv sifatida eng yuqori ishonchlilikni ta'minlaydi, ammo samaradorlik va imzo hajmi jihatidan ma'lum cheklovlarga ega. Tahlillar natijasida post-kvant kriptografiyada yagona universal va barcha mezonlar bo'yicha ustun bo'lgan algoritm mavjud emasligi aniqlanib, optimal tanlov ko'p mezonli optimallashtirish masalasi sifatida qaralishi lozimligi ilmiy asosda isbotlandi. Shuningdek, real tizimlarda ushbu algoritmlarni joriy etishda hisoblash resurslari, xotira sig'imi, tarmoq yuklamasi va xavfsizlik talablari o'rtasidagi muvozanatni ta'minlash muhim ahamiyat kasb etadi. Mazkur tadqiqotning ilmiy yangiligi post-kvant kriptografik algoritmlarni yagona matematik va hisoblash mezonlari asosida kompleks tahlil qilish hamda ularni o'zaro solishtirishning tizimli modelini ishlab chiqishda namoyon bo'ladi. Tadqiqotda turli algoritmik yondashuvlar uchun hisoblash murakkabligi, xotira sarfi va xavfsizlik darajasi yagona formal apparat asosida ifodalanib, ularning o'zaro bog'liqligi chuqur tahlil qilindi. Shu bilan birga, panjara asosli, kodga asoslangan, multivariate va hash asosli tizimlar uchun umumiy optimallashtirish modeli taklif etildi, bunda xavfsizlik darajasi ehtimollik nuqtai nazaridan, samaradorlik esa polinomial va eksponensial murakkablik funksiyalari orqali ifodalandi. Tadqiqotda RLWE asosidagi algoritmlarning tezkorlik jihatidan ustunligi matematik asosda ko'rsatib berildi va ularning katta o'lchamli tizimlar uchun samarali yechim ekanligi ilmiy jihatdan asoslandi. Shuningdek, MQ tizimlarida xavfsizlikning parametr tanlashga bog'liqligi hamda kodga asoslangan algoritmlarda kalit hajmining o'sishi muammosi kompleks tarzda tahlil qilindi. Ushbu natijalar post-kvant kriptografiya sohasida algoritmlarni tanlash va baholash uchun yangi ilmiy yondashuvni shakllantiradi. Mazkur tadqiqot natijalari post-kvant kriptografik algoritmlarni real axborot xavfsizligi tizimlariga joriy etishda muhim amaliy ahamiyatga ega. Tadqiqot davomida olingan natijalar turli algoritmlarning samaradorligi va resurs talablarini aniq baholash imkonini berib, amaliy tizimlar uchun optimal kriptografik yechimlarni tanlashga yordam beradi. Ayniqsa, panjara asosli algoritmlarning muvozanatli xususiyatlari ularni zamonaviy tarmoq va bulutli tizimlarda qo'llash uchun maqbul ekanligini ko'rsatadi. Shuningdek, kodga asoslangan tizimlarning yuqori xavfsizligi ularni uzoq muddatli ma'lumotlarni himoya qilishda qo'llash imkonini beradi, hash asosli algoritmlar esa yuqori ishonchlilik talab qilinadigan raqamli imzo tizimlarida samarali foydalanilishi mumkin. Tadqiqot natijalari asosida gibrid kriptografik tizimlarni ishlab chiqish imkoniyati ham asoslab berildi, bu esa klassik va post-kvant algoritmlarni birgalikda qo'llash orqali xavfsizlik darajasini sezilarli oshirishga xizmat qiladi. Mazkur ish natijalari ilmiy tadqiqotlar, axborot xavfsizligi tizimlarini loyihalash hamda davlat va sanoat miqyosidagi kriptografik infratuzilmalarni modernizatsiya qilish jarayonlarida nazariy va amaliy asos sifatida qo'llanilishi mumkin.



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Issues of Optimizing the Service Life of Isuzu SAZ LE-60 Buses and Their Economic Significance

Tadjibayev Abdunabi Abduraxmonovich, Tashkent State Transport University, Professor,
Candidate of Technical Sciences

Mavlonov Mirsharof Farxod o'g'li, Tashkent State Transport University, Master's Student

Abstract: This article investigates the issues of optimizing the service life of Isuzu SAZ LE-60 buses and their economic significance. During the research, the impact of operational costs, operating conditions, and the technical service system on the service life of the buses was determined. According to the results of the economic analysis conducted, establishing an optimal service life makes it possible to reduce the costs of bus fleets, minimize unplanned repair work, and improve the efficiency of vehicle utilization. The research findings show that optimizing the service life of Isuzu SAZ LE-60 buses plays an important role in ensuring the sustainable operation of transport enterprises.

Keywords: Isuzu SAZ LE-60, service life, optimization, technical service, economic efficiency.

The importance of Isuzu SAZ LE-60 buses in Uzbekistan is also determined by their economic efficiency. The availability of local production facilitates the supply of spare parts, reduces technical service costs, and makes it possible to extend the operational service life of the buses. As a result, the overall operating expenses for transport enterprises are significantly reduced.

The change in the economic efficiency of buses during their operational period depending on mileage is influenced by two main factors:

- the costs associated with their production (design, manufacturing, testing, transportation to the place of operation, and other expenses), which determine the price of the bus – Q_{TV} ;
- operational expenses (technical service, repairs, and others) – $Q_E(L)$.

These expenses are always represented as negative values in the efficiency balance $Q_{TV} + Q_E(L)$.

The revenue generated during bus operation – $Q_D(L)$.

The dependence of the bus's efficiency $Q(L)$ on mileage is determined by the following formula:

$$Q(L) = Q_D(L) - (Q_{TV} + Q_E(L)) \quad (1.1)$$

The curve of economic efficiency versus mileage has a maximum point and intersects the abscissa (x-axis) twice.

Operational expenses consist of the following, namely:

$$Q_E(L) = Q_{H.M}(L) + Q_{TS-RT}(L) + Q_{Sh}(L) + Q_{YO.M}(L) + Q_{Q.X}(L) \quad (1.2)$$

where $Q_{H.M}(L)$ – driver's salary, in soums;

$Q_{TS-RT}(L)$ – costs for technical service (TS) and routine maintenance/repairs, in soums;

$Q_{Sh}(L)$ – costs for tires, in soums;

$Q_{YO.M}(L)$ – fuel and lubricants expenses, in soums;

$Q_{Q.X}(L)$ – enterprise overhead (additional indirect costs), in soums.

The driver's salary is determined as follows:

$$Q_{H.M}(L) = 0.001 \cdot Q_D(L) \cdot T_H \quad (1.3)$$

where $Q_D(L)$ – the revenue generated by buses during the operational period, in soums;

T_H – the driver's share in the total generated revenue, expressed as a percentage (%).

The revenue generated by buses during the operational period, ($Q_D(L)$), is determined as follows:

$$Q_D(L) = \beta \cdot C_K \cdot L \cdot \alpha_T(t) \quad (1.4)$$

where β – mileage utilization coefficient; C_K – fare per kilometer, soums /km; L – the total distance traveled by the bus since it was put into operation, km; $\alpha_T(t)$ – variation of the technical readiness coefficient of the bus fleet according to the age of the buses.

The mileage utilization coefficient (β) is determined as follows:

$$\beta = \frac{L_{KY} - 2 \cdot l_0}{L_{KY}} \quad (1.5)$$

where L_{KY} – the average distance traveled by the bus per day, km; l_0 – the distance from the bus depot to the starting or final stop of the route, km.

The fare per kilometer for a bus (C_K) is determined as follows:

$$C_K = \frac{N_y \cdot C_y}{L_{KY}} \quad (1.6)$$

where N_y – the total number of passengers transported by the bus during the day; C_y – the fare paid by a passenger when making a payment for the first time using a plastic card (1700), in soums.

In urban conditions, the fare revenue generated per kilometer by the Isuzu SAZ LE-60 is $C_K=7652$ soums /km [6].

The technical readiness coefficient for the fleet, $\alpha_T(t)$, depending on the age of the buses, is determined as follows:

$$\alpha_T(t) = \alpha_T(t_1) \cdot \exp(-K_t(t - 1)) \quad (1.7)$$

where $\alpha_T(t_1)$ – the technical readiness coefficient of the bus for the first year; K_t – the coefficient accounting for the rate of change in the bus's aging (0,020 – 0,035), t – the bus's service life in operation, in years.

The technical readiness coefficient of the bus, $\alpha_T(t_1)$, for the first year is determined as follows:

$$\alpha_T(t_1) = \frac{1}{1 + L_{KY} \cdot d_{TS-RT} \cdot K'_4 \cdot 0.001} \quad (1.8)$$

where L_{KY} – the average distance traveled by the bus per day, km; d_{TS-RT} – the specific downtime of the bus in technical service (TS) and routine maintenance (RT), day/1000km; K'_4 – the correction coefficient for the specific downtime in technical service (TS) and routine maintenance (RT), depending on mileage since the start of operation (equal to 0.7 within the range from 0 to $0.5L_{MT}$).

The costs for technical service (TS) and routine maintenance/repairs are determined as follows:

$$Q_{TS-RT}(L) = Q_{TS}(L) + Q_{RT}(L) \quad (1.9)$$

where $Q_{TS}(L)$ – costs for technical service (TS), in soums;

$Q_{RT}(L)$ – costs for routine maintenance and repair works, in soums

$$C_{TS} = \left(\frac{\Delta L}{L_1 \cdot K_1 \cdot K_3} - \frac{\Delta L}{L_2 \cdot K_1 \cdot K_3} \right) C_1 + \frac{\Delta L}{L_2} C_2 \quad (1.10)$$

where C_{TS} – specific cost of technical service (TS) works, soums/thousand km;

ΔL – annual mileage interval, thousand km;

C_1 – once 1 – cost of performing technical service (TS), in soums;

C_2 – once 2 – cost of performing technical service (TS), in soums;

L_1, L_2 – 1 and 2 standard periodicity of technical service (TS), thousand km;

K_1, K_3 – correction coefficients.

$$Q_{TS}(L) = C_{TS} \cdot L \quad (1.11)$$

Costs for repair works:

$$Q_T(L) = Q_{RT}(L) + Q_{E.Q}(L) \quad (1.12)$$

where $Q_{RT}(L)$ – costs for routine (current) repairs, in soums;

$Q_{E.Q}(L)$ – costs for spare parts, in soums;

$$Q_{RT}(L) = t_{RT} \cdot K_1 \cdot K_2 \cdot K_3 \cdot K_5 \cdot K_4(L) \cdot C_{RT} \cdot L \quad (1.13)$$

Where t_{RT} – specific scope (labor intensity) of routine repair works, worker-hours t/1000km;

K_1, K_2, K_3, K_5 – correction coefficients for the scope (labor intensity) of routine repair works;

$K_4(L)$ – correction coefficient for the scope of routine repair work depending on the vehicle's mileage since the start of operation;



C_{RT} – average hourly wage of a routine repair worker, soums /soat.

Costs for spare parts:

$$Q_{E.Q}(L) = C_{E.Q}(L) \cdot \Delta L \quad (1.14)$$

Where $C_{E.Q}(L)$ – specific costs of spare parts, soums/thousand km;

t – the service life of the bus, in years.

$$t = \frac{L}{\Delta L} \quad (1.15)$$

$$C_{EQ} = B \cdot L^n \quad (1.16)$$

where B – slope coefficient; n – degree coefficient.

The spare parts consumption of Isuzu SAZ LE-60 buses is calculated and analyzed in article [7], according to which $B=67,61$ and $n=1,48$.

Costs for tires:

$$Q_{SH}(L) = \frac{C_{SH} \cdot N \cdot (L - L_{SH})}{L_{SH}} \quad (1.17)$$

where C_{SH} – price of one tire, in soums; N – number of tires on the vehicle (excluding the spare tire); L_{SH} – average tire service life (resource), in thousand km.

Determination of fuel consumption costs:

$$Q_{YO.M}(L) = \frac{L_k \cdot N_l \cdot H_y}{100} \quad (1.18)$$

where L_k – the average distance traveled by the bus per day (km);

N_l – fuel consumption per 100 km of the bus (L)

H_y – fuel price (soums)

The enterprise's overhead costs account for 20–25% of all expenses, i.e. they are equal to 20–25% of the total costs:

$$Q_{Q.H}(L) = (Q_{HM}(L) + Q_{TX-JT}(L) + Q_{sh}(L) + Q_{YO.M}(L)) \cdot (0,2 \dots 0,5) \quad (1.19)$$

The price of the Isuzu SAZ LE-60 is 822,000,000 soums. Taking into account the subsidy, i.e., the portion of the bus price covered by the state (220 million soums), the calculations were carried out based on the adjusted cost.

To perform computer-based calculations of the service life of Isuzu SAZ LE-60 using the Visual Basic program “Optimization of Vehicle Service Life,” developed on the basis of Certificate DGU 15475, the initial data are presented in Table 1.



Table 1

Initial data

Initial data	Notation	Value
Type of transport vehicle	Bus	SAZ LE-60
Price of the transport vehicle, soums	Q_{TV}	602000000
Fare, soums	C_K	7652
Price of one tire, soums	C_{SH}	2250000
Average tire service life (resource), thousand km	L_{SH}	70
Number of tires on the vehicle, units	N	6
Road utilization coefficient	β	0,93
Driver's tariff rate as a percentage of performed work, %	T_H	10
Fuel price per liter, soums	H_y	12000
Fuel consumption per 100 km, liters	N_l	20
Cost of 1st technical service (TS), soums	C_1	4009000
Cost of 2nd technical service (TS), soums	C_2	5001000
Periodicity of 1st TS, thousand km	L_1	10
Periodicity of 2nd TS, thousand km	L_2	20
Specific labor intensity of routine maintenance (repair) work, worker-hours t/1000km	T_{RT}	3,3
Average hourly wage of workers	C_{RT}	48000
Slope coefficient of spare parts consumption	B	67,61
Power (exponent) coefficient of spare parts consumption	n	1,48

Additional data for calculating the technical readiness coefficient

Distance to major (complete) overhaul, thousand km	L_k	600
Annual (interval) mileage, thousand km	ΔL	90
Coefficient accounting for road condition category (distance)	K_1	0,8
Coefficient accounting for road condition category (labor)	K_{t1}	1,2
Coefficient accounting for vehicle type (distance)	K_2	1
Coefficient accounting for vehicle type (labor)	K_{t2}	1
Coefficient accounting for climatic conditions (distance)	K_3	0,9
Coefficient accounting for climatic conditions (labor)	K_{t3}	1,1
Specific downtime of vehicle in maintenance (TS) and repair (RT), days/1000 km	D_t	0,4



Coefficient accounting for number of vehicles in the transport enterprise (ATP)	K_5	0,95
Average daily mileage of the vehicle, km	L_{ky}	288,8
Coefficient K_4 accounting for mileage since vehicle start of operation:	K_4	
from 0 to 0,25 Lk	K_{41}	0,5
from 0,25 to 0,5 Lk	K_{42}	0,8
from 0,5 to 0,75 Lk	K_{43}	1
from 0,75 to 1,0 Lk	K_{44}	1,3
from 1,0 to 1,25 Lk	K_{45}	1,4
from 1,25 to 1,5 Lk	K_{46}	1,5
from 1,5 to 1,75 Lk	K_{47}	1,8
from 1,75 to 2,0 Lk	K_{48}	2,1
above 2 Lk	K_{49}	2,5
Correction factor for TTK (technical readiness coefficient) variation with mileage	K_t	0,02
Number of intervals	k	14
Technical readiness coefficient (for the first year), A_t	$\alpha_T(t_1)$	0,920

The calculation results are presented in Tables 2 and 3

Table 2

Calculation results

Intervals			Costs, million soums		Technical readiness coefficient	Income by interval, million soums	Driver's salary, million soums
Num ber	Start	End	Tire	Fuel		$Q_D(L)$	$Q_{H.M}(L)$
1	0	90	3,86	226,80	0,9205	589,54	58,95
2	90	180	21,21	453,60	0,9022	577,86	116,74
3	180	270	38,57	680,40	0,8844	566,42	173,38
4	270	360	55,93	907,20	0,8669	555,20	228,90
5	360	450	73,29	1134,00	0,8497	544,21	283,32
6	450	540	90,64	1360,80	0,8329	533,43	336,67
7	540	630	108,00	1587,60	0,8164	522,87	388,95



8	630	720	125,36	1814,40	0,8002	512,52	440,21
9	720	810	142,71	2041,20	0,7844	502,37	490,44
10	810	900	160,07	2268,00	0,7688	492,42	539,69
11	900	990	177,43	2494,80	0,7536	482,67	587,95
12	990	1080	194,79	2721,60	0,7387	473,11	635,26
13	1080	1170	212,14	2948,40	0,7241	463,75	681,64
14	1170	1260	229,50	3175,20	0,7097	454,56	727,09

Table 2 (continued)

Intervals			Costs, million soums		K4	(RT) costs, million soums	
Num ber	Start	End	Q _{TS}	Q _{E,q(L)}	K4(L)	Q _{jt(L)} by interval	ΣQ _{rt(L)}
1	0	90	56,31	0,05	0,50	8,94	8,94
2	90	180	112,63	0,15	0,74	13,23	22,17
3	180	270	168,94	0,27	0,92	16,45	38,61
4	270	360	225,25	0,41	1,12	20,02	58,64
5	360	450	281,56	0,57	1,32	23,60	82,23
6	450	540	337,88	0,75	1,42	25,46	107,69
7	540	630	394,19	0,94	1,58	28,32	136,01
8	630	720	450,50	1,15	1,90	33,89	169,90
9	720	810	506,81	1,36	2,24	40,12	210,02
10	810	900	563,13	1,59	2,50	44,69	254,71
11	900	990	619,44	1,83	2,50	44,69	299,40
12	990	1080	675,75	2,09	2,50	44,69	344,10
13	1080	1170	732,06	2,35	2,50	44,69	388,79
14	1170	1260	788,38	2,62	2,50	44,69	433,48

Table 3

Calculation results

Number	Intervals, thousand km		Income, million soums	Bus price, million soums	Total (sum), million soums	
	Start	End	Sum		Costs	Efficiency
	A(J)	B1(J)	Q _{D(L)}		Q _{E(L)}	Q(L)
1	0	90	589,54	602,00	1045,64	-456,11
2	90	180	1167,40	602,00	1510,12	-342,72
3	180	270	1733,82	602,00	1977,22	-243,40



4	270	360	2289,02	602,00	2447,41	-158,39
5	360	450	2833,23	602,00	2920,72	-87,49
6	450	540	3366,67	602,00	3395,03	-28,36
7	540	630	3889,54	602,00	3871,61	17,93
8	630	720	4402,06	602,00	4353,89	48,17
9	720	810	4904,43	602,00	4842,69	61,74
10	810	900	5396,85	602,00	5335,98	60,87
11	900	990	5879,52	602,00	5828,07	51,45
12	990	1080	6352,64	602,00	6318,98	33,66
13	1080	1170	6816,38	602,00	6808,73	7,66
14	1170	1260	7270,95	602,00	7297,34	-26,40

Based on Table 3, Figure 1 shows the graph of the change in economic efficiency of the Isuzu SAZ LE-60 depending on mileage.

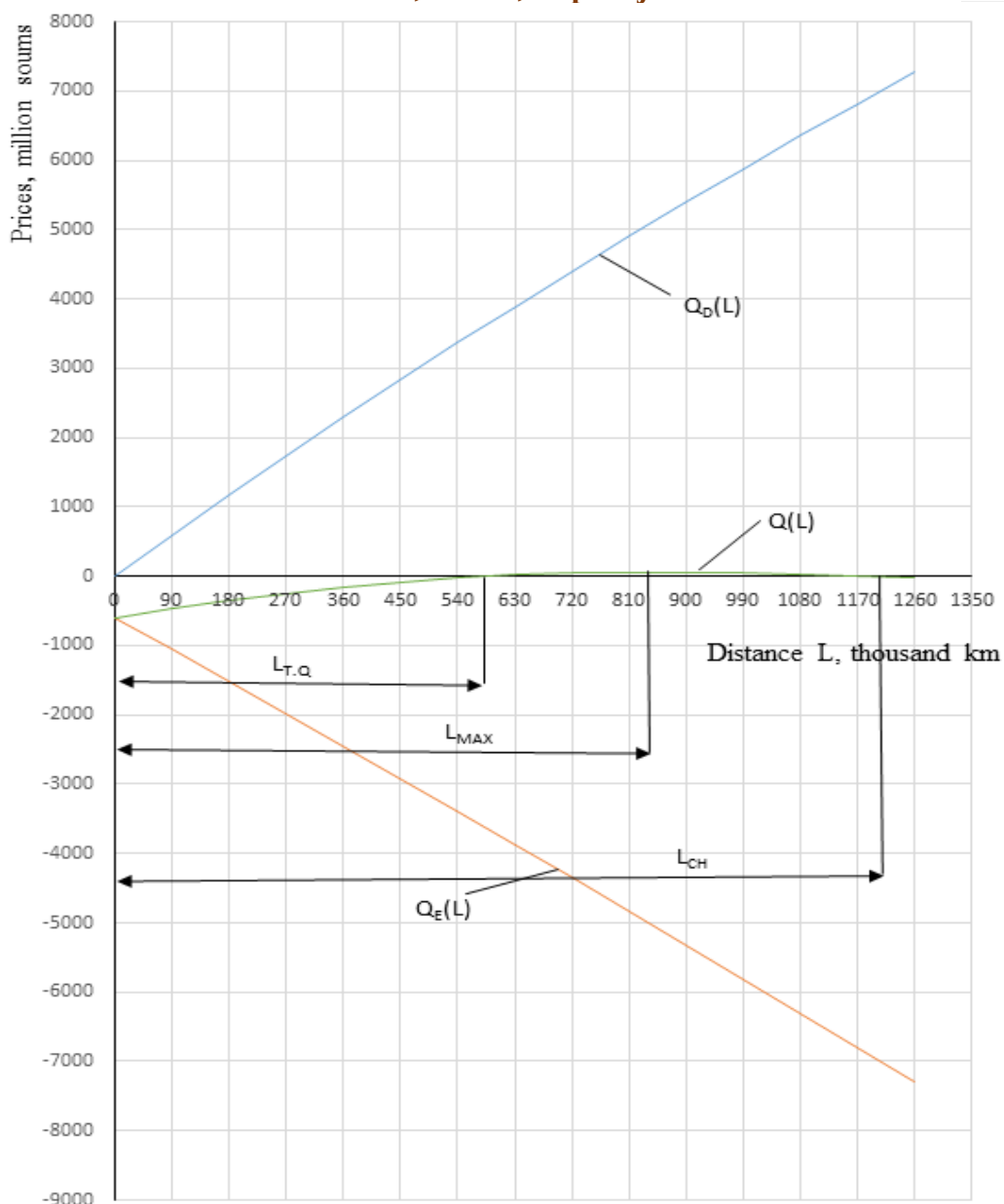


Figure 1: Graph of the variation of the bus's economic efficiency with mileage:

From Figure 1, it can be seen that the cost recovery mileage (service life) of the Isuzu SAZ LE-60 is 595.14 thousand km; the mileage up to the limiting condition is 1,190.23 thousand km, and the mileage at maximum efficiency is 810 thousand km (61.74 million soums).

The optimal service life (mileage) of the Isuzu SAZ LE-60 is within the following intervals:

$$L_{MAX} < L_E < L_{CH} \text{ that is } 810 < L_E < 1190,23 \text{ is within the range}$$

CONCLUSION

1. As a result of analyzing the operational process of the Isuzu SAZ LE-60 buses, it was determined that their cost recovery mileage is 595.14 thousand km, taking into account a state subsidy of 220 million soums.



2. The service life of the Isuzu SAZ LE-60 up to its limiting condition is 1,190.23 thousand km, during which the bus is considered technically fit for operation. However, during the exploitation period, technical service and repair costs gradually increase. In this context, the technical readiness coefficient is 0.9205 for the first age group, while it decreases to 0.7097 for the 14th age group.

3. According to the research results, the maximum economic efficiency mileage of the Isuzu SAZ LE-60 is 810 thousand km, and at this stage an economic effect of 61.74 million soums is observed. This mileage represents the most optimal balance between operating costs and revenues ($810,0 < L_E < 1190,23$).

4. In general, optimizing the service life of Isuzu SAZ LE-60 buses contributes to ensuring the financial stability of transport enterprises, improving the level of technical readiness, and increasing the efficiency of the passenger transportation system.

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Experimental Assessment of GTL Synthetic Diesel Fuel on the Performance and Fuel Consumption Characteristics of an ISUZU NQR71PL Diesel Vehicle

B.I. Bazarov¹, O.Z. Odilov², O.F. Ashurov¹

Tashkent State Transport University¹

Fergana State Technical University², Uzbekistan

Abstract. The present study investigates the operational feasibility of using gas-to-liquid (GTL) synthetic diesel fuel in an existing light-duty diesel vehicle without major structural modifications. The experimental object was an ISUZU NQR71PL diesel vehicle tested under field conditions using conventional petroleum diesel fuel and GTL synthetic diesel fuel. The study focused on the main indicators decisive for practical implementation: maximum vehicle speed, acceleration time up to 60 km/h, and steady-speed fuel consumption at 40, 50, 60, 70, 80 and 90 km/h. The experimental results showed that the traction and speed characteristics of the vehicle operating on GTL fuel remained close to those obtained using petroleum diesel fuel. The maximum speed was 104.17 km/h for petroleum diesel and 105.50 km/h for GTL fuel, while the acceleration time to 60 km/h increased from 15.91 s to 16.86 s. The volumetric fuel consumption of GTL fuel increased by approximately 4.6-6.1% depending on the speed mode. This increase is mainly explained by the lower density of GTL fuel and the corresponding reduction in the mass of fuel injected per cycle at equal volumetric delivery. At the same time, GTL fuel has important environmental and operational advantages, including a high cetane number, very low sulfur content, reduced aromatic hydrocarbons and improved combustion stability. The obtained results confirm that GTL synthetic diesel fuel can be used in conventional diesel vehicles under real operating conditions, provided that fuel-consumption norms and injection-control parameters are adapted to its physicochemical properties.

Keywords: GTL fuel; synthetic diesel; ISUZU NQR71PL; diesel vehicle; fuel consumption; field test; performance characteristics; low-carbon fuel.

1. Introduction

The transition of transport and energy systems to low-carbon and environmentally safer fuels is one of the central problems of modern mechanical engineering and vehicle operation. Diesel engines remain widely used in road transport, agricultural machinery and stationary power units because of their high thermal efficiency, reliability and fuel economy. However, conventional diesel fuel is associated with emissions of nitrogen oxides (NO_x), carbon monoxide (CO), unburned hydrocarbons (HC), particulate matter (PM) and greenhouse gases. Therefore, the use of synthetic motor fuels is considered a practical way to improve environmental performance while preserving the existing diesel-engine infrastructure [1-4].

GTL synthetic diesel fuel is produced from natural gas through synthesis-gas generation and subsequent Fischer-Tropsch synthesis. Compared with petroleum diesel fuel, GTL fuel generally has a higher cetane number, lower sulfur content, lower aromatic content and more homogeneous paraffinic composition. These properties improve ignition quality and combustion stability and may reduce smoke and particulate emissions [5-9]. For countries with available



natural gas resources and developed gas-processing infrastructure, GTL technology is especially relevant because it enables the conversion of domestic gas resources into high-quality liquid fuels.

In Uzbekistan, the introduction of GTL fuel has strategic importance due to the presence of a large gas-chemical production base and the need to modernize fuel supply for transport and energy systems. The national production of GTL components creates the scientific and practical basis for evaluating their compatibility with existing diesel vehicles and for developing rational fuel-consumption norms under real operating conditions [10-12]. Although many studies confirm the ecological advantages of GTL fuel, practical implementation requires field tests on real vehicles. The reason is that the fuel properties influencing combustion, injection, atomization and fuel economy are interdependent. For example, a high cetane number improves ignition, but lower density may reduce the injected fuel mass at the same volumetric pump delivery. Consequently, the vehicle can show similar speed performance but slightly different volumetric fuel consumption. This makes experimental verification essential [13-16]. The aim of this paper is to experimentally evaluate the effect of GTL synthetic diesel fuel on the performance and fuel consumption of an ISUZU NQR71PL diesel vehicle under field test conditions. The novelty of the study is the practical comparison of petroleum diesel and GTL fuel for a commercially used diesel vehicle in real operating modes, with emphasis on fuel consumption and traction-speed indicators relevant to operation in Uzbekistan.

2. Materials and Methods

The experimental study was carried out using an ISUZU NQR71PL diesel vehicle. This vehicle type is widely used for urban and regional freight transportation and represents a typical diesel platform for evaluating alternative and synthetic fuels. The vehicle was tested in technically serviceable condition, and the same vehicle configuration was used for both petroleum diesel and GTL synthetic diesel fuel in order to ensure comparability of the obtained results. Two fuels were used in the experiments: conventional petroleum diesel fuel and GTL synthetic diesel fuel. The main difference between the fuels lies in their physicochemical structure. Petroleum diesel fuel consists of a mixture of hydrocarbons with sulfur and aromatic components depending on the refining process. GTL fuel is predominantly paraffinic and is characterized by a higher cetane number, lower sulfur content and lower aromatic content. These properties directly influence ignition delay, heat release and exhaust-emission formation [5, 7, 9].

The measured operational parameters included maximum vehicle speed, acceleration time from standstill to 60 km/h and steady-speed fuel consumption. Fuel consumption was measured

at 40, 50, 60, 70, 80 and 90 km/h. These modes were selected because they cover the most typical operating range of a light-duty truck in urban, suburban and intercity traffic conditions. The tests were performed under comparable road, loading and environmental conditions. The general logic of the experiment was based on comparative testing. First, the vehicle was operated with conventional diesel fuel, and the required performance indicators were recorded. Then, under the same test protocol, the vehicle was operated with GTL synthetic diesel fuel. The difference between the results was used to estimate the effect of fuel type on operating performance.

2.1. Test object and fuel characteristics

The ISUZU NQR71PL test vehicle was selected because its diesel engine, fuel system and operating conditions are representative of practical transport use. When using GTL fuel, no major structural modification was introduced. This approach makes it possible to evaluate the direct applicability of GTL fuel as a drop-in or near-drop-in synthetic diesel fuel for existing vehicles. The comparison of fuel properties is summarized in Table 1. The values describe typical and experimentally relevant differences between petroleum diesel and GTL synthetic diesel fuel. In the context of vehicle testing, density, viscosity, cetane number and sulfur content are especially important. Density influences the mass of fuel injected per cycle; viscosity influences leakage and lubrication in the fuel system; cetane number affects ignition delay; sulfur and aromatic compounds influence emissions and deposits [6-9].

Table 1. Typical physicochemical characteristics of petroleum diesel and GTL synthetic diesel fuel

Parameter	Unit	Petroleum diesel	GTL synthetic diesel
Cetane number	-	48-52	60-70
Density at 15 deg. C	kg/m ³	820-845	about 765-790
Kinematic viscosity at 40 deg. C	mm ² /s	2.5-3.5	1.7-2.4
Sulfur content	ppm	up to 10 or more depending on standard	<5
Aromatic hydrocarbons	%	present	very low
Fuel type	-	petroleum-derived mixture	paraffinic Fischer-Tropsch fuel



Figure 1. Preparation of the ISUZU NQR71PL diesel vehicle for field testing under proving-ground conditions.



Figure 2. GTL synthetic diesel fuel filling and field-test preparation process for the ISUZU NQR71PL vehicle.

2.2. Experimental indicators and calculation procedure

The comparative assessment was based on three groups of indicators: traction-speed performance, acceleration performance and fuel consumption. Maximum speed characterizes the

ability of the vehicle to maintain high-speed operation. Acceleration time to 60 km/h characterizes the dynamic response of the vehicle and indirectly reflects the energy supply during transient engine operation. Fuel consumption at fixed speeds characterizes the operational economy of the vehicle.

The relative change in fuel consumption when switching from petroleum diesel to GTL fuel was calculated by Eq. (1):

$$\Delta q = ((q_{GTL} - q_D) / q_D) \times 100\%, \quad (1)$$

where q_{GTL} is the fuel consumption when operating on GTL fuel, and q_D is the fuel consumption when operating on petroleum diesel fuel.

The energy supplied to the engine during one injection cycle may be expressed in simplified form by Eq. (2):

$$Q_f = \rho_f \times V_f \times H_u, \quad (2)$$

where ρ_f is fuel density, V_f is injected volume and H_u is lower heating value. Eq. (2) explains why, at equal volumetric delivery, a lower-density fuel can supply a smaller mass of fuel per cycle, which may require a correction of injection duration or fuel-consumption norms.

3. Results

The field-test results obtained for the ISUZU NQR71PL vehicle using petroleum diesel fuel and GTL synthetic diesel fuel are presented in Table 2. The results show that the maximum speed of the vehicle changed only slightly when switching from petroleum diesel to GTL fuel. The maximum speed was 104.17 km/h for petroleum diesel and 105.50 km/h for GTL fuel. This means that the use of GTL did not reduce the maximum-speed capability of the vehicle. The acceleration time to 60 km/h increased from 15.91 s for petroleum diesel to 16.86 s for GTL fuel. The increase was 0.95 s, which corresponds to approximately 6.0%. This result indicates a small deterioration in acceleration dynamics. It can be associated with lower volumetric density of GTL fuel and the fact that the standard fuel system calibration was originally designed for petroleum diesel fuel. Fuel consumption increased in all tested steady-speed modes when GTL fuel was used. However, the increase remained moderate and did not indicate any operational limitation. The smallest absolute difference was observed near 60-70 km/h, while the highest relative difference was observed at 40 km/h. The general trend confirms that GTL fuel can be used in the vehicle, but its consumption norms should be determined separately rather than mechanically transferred from conventional diesel fuel.

Table 2. Field test results of the ISUZU NQR71PL vehicle using petroleum diesel and GTL synthetic diesel fuel

Indicator	Unit	Petroleum diesel	GTL synthetic diesel	Relative difference
Maximum speed	km/h	104.17	105.50	+1.28%
Acceleration time to 60 km/h	s	15.91	16.86	+5.97%

Table 3. Fuel consumption of the ISUZU NQR71PL vehicle at different steady-speed modes

Speed, km/h	Diesel, L/100 km	GTL, L/100 km	Absolute difference, L/100 km	Relative difference, %
40	15.42	16.36	0.94	6.10
50	15.06	15.95	0.89	5.91
60	13.84	14.55	0.71	5.13
70	14.04	14.68	0.64	4.56
80	14.42	15.22	0.80	5.55
90	14.62	15.46	0.84	5.75

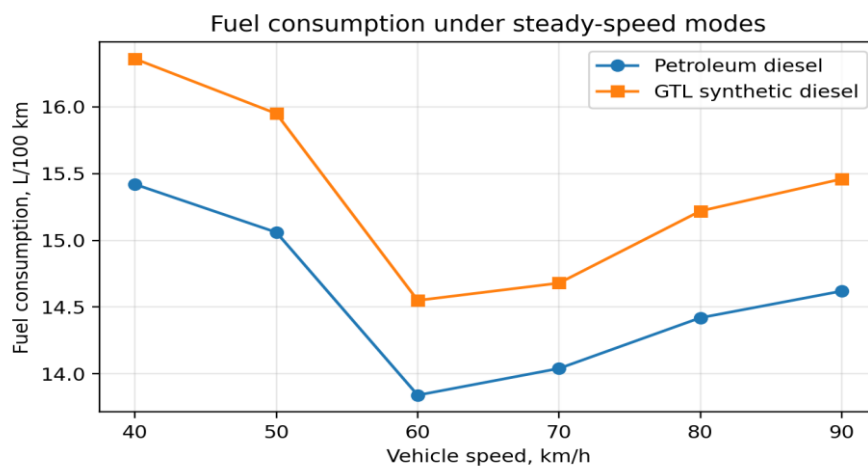


Figure 3. Comparative fuel consumption of petroleum diesel and GTL synthetic diesel fuel at different vehicle speeds.

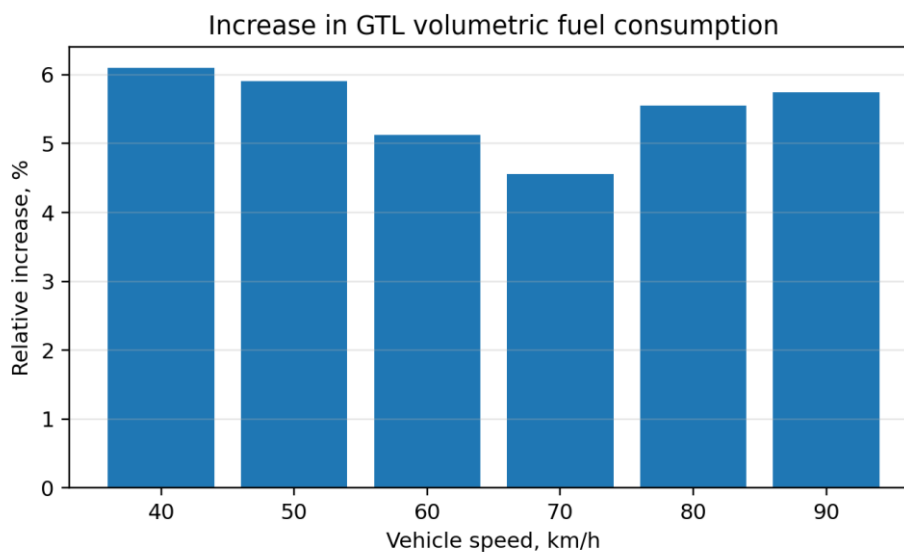


Figure 4. Relative increase in GTL volumetric fuel consumption compared with petroleum diesel fuel.

4. Discussion

The obtained results show that the use of GTL synthetic diesel fuel in the ISUZU NQR71PL vehicle does not require a radical change in vehicle operation. The maximum speed remained practically unchanged, which confirms that the energy potential of GTL fuel is sufficient to provide the required traction-speed characteristics. The small increase in acceleration time is operationally acceptable for this vehicle category, especially considering that the tests were performed without special optimization of injection maps. The increase in volumetric fuel consumption is the most important result from the point of view of practical implementation. GTL fuel has a lower density than conventional diesel fuel. Therefore, when the fuel pump delivers the same volume, the mass of injected fuel can be lower. In order to maintain the same engine power, the engine-control system or mechanical fuel supply may compensate by increasing the effective fuel delivery. As a result, fuel consumption expressed in liters per 100 km increases, while the energy efficiency may remain close to that of petroleum diesel fuel [6, 8, 14]. The consumption increase observed in this study is also consistent with the theoretical relation between fuel density, injected volume and lower heating value. GTL fuel may have a slightly higher lower heating value per unit mass, but its lower density reduces the energy per unit volume. Since vehicle fuel consumption is usually recorded in liters, this leads to a moderate increase in volumetric consumption. For operational accounting, this means that separate GTL fuel-consumption norms should be developed for diesel vehicles and stationary diesel units. From an environmental point of view, GTL fuel has significant advantages. Its high cetane number shortens ignition delay and contributes to smoother combustion. Low sulfur content reduces sulfur oxide emissions and improves the durability of exhaust after-treatment systems. The very low aromatic content reduces the tendency to form soot and particulate matter during combustion. Therefore, even if the volumetric consumption is slightly higher, the overall environmental profile of GTL fuel can be more favorable than that of conventional diesel fuel [4, 7, 9, 15].

The results are particularly relevant for Uzbekistan, where GTL production creates opportunities for domestic low-sulfur synthetic diesel fuel use in transport and stationary power systems. The implementation of GTL fuel can support energy security, diversification of the fuel base and reduction of harmful emissions from diesel vehicles. However, the practical transition should include fuel-quality control, adaptation of fuel-consumption standards, monitoring of fuel-system wear and further emission measurements under real operation.

4.1. Scientific and practical significance

The scientific significance of the study lies in the experimentally verified relationship between the physicochemical properties of GTL fuel and the operational performance of a diesel vehicle. The study confirms that fuel density and cetane number influence vehicle dynamics and fuel consumption in different ways. The practical significance lies in the possibility of using the obtained results to develop rational norms for GTL fuel consumption and to justify GTL application in transport fleets. For engineering practice, the results indicate that GTL fuel can be introduced into existing diesel vehicles without major structural modifications. Nevertheless, to obtain maximum benefit, it is advisable to adjust fuel-injection parameters, evaluate lubricant compatibility and conduct long-term durability tests of fuel-system elements.



Figure 5. PIUSI digital fuel-flow meter used for registering fuel consumption during GTL field testing.



Figure 6. Laboratory engine test stand used for supporting assessment of fuel-related performance parameters.



Figure 7. HORIBA gas-analysis display used to record exhaust-gas parameters during experimental evaluation.

The experimental photographs presented in Figures 1, 2, 5, 6 and 7 document the main field and laboratory stages of the GTL fuel testing process, including vehicle preparation, refuelling, fuel-flow measurement and exhaust-gas parameter registration.

5. Conclusions The field-test results of the ISUZU NQR71PL diesel vehicle operating on petroleum diesel and GTL synthetic diesel fuel allow the following conclusions to be drawn:

1. GTL synthetic diesel fuel provided traction-speed performance close to that of petroleum diesel fuel. The maximum speed was 104.17 km/h for petroleum diesel and 105.50 km/h for GTL fuel, indicating no practical loss of maximum-speed capability.

2. The acceleration time to 60 km/h increased from 15.91 s to 16.86 s when GTL fuel was used. The increase was about 6%, which can be explained by the lower density of GTL fuel and the absence of special adaptation of the fuel system calibration.

3. The volumetric fuel consumption of GTL fuel increased in all tested steady-speed modes. The increase was approximately 4.6-6.1%, confirming the need to establish separate GTL fuel-consumption norms for operational use.

4. Despite the moderate increase in volumetric fuel consumption, GTL fuel has significant environmental and operational advantages, including high cetane number, very low sulfur content, low aromatic content and improved combustion stability.

6. Recommendations for journal submission

Before submission, the manuscript should be completed with original experimental photographs, exact fuel certificate data, detailed weather and road-test conditions, and emission results if available. If the target journal requires a stricter format, the sections, reference style and figure resolution should be adapted to the journal template. For OAK-related publication



purposes, it is recommended to select a foreign journal that is officially recognized for the relevant technical sciences field and to verify the current status of the journal before submission.

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