JOURNAL OF TRANSPORT

ISSUE 2, 2025 vol. 2
E-ISSN: 2181-2438
ISSN: 3060-5164

RESEARCH, INNOVATION, RESULTS

TOSHKENT DAVLAT TRANSPORT UNIVERSITETI
Tashkent state transport university

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E-ISSN: 2181-2438
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VOLUME 2, ISSUE 2
JUNE, 2025

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TASHKENT STATE TRANSPORT UNIVERSITY

JOURNAL OF TRANSPORT

SCIENTIFIC-TECHNICAL AND SCIENTIFIC INNOVATION JOURNAL

VOLUME 2, ISSUE 2 JUNE, 2025

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The journal benefits from its official recognition under Certificate No. 1150 issued by the Information and Mass Communications Agency, functioning under the Administration of the President of the Republic of Uzbekistan. With its E-ISSN 2181-2438, ISSN 3060-5164 the publication upholds international standards of quality and accessibility.

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Analysis of energy consumption during the braking process of electrically driven mining dump trucks (Case Study: Komatsu 860E)

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Abstract: In open-pit mines, freight transportation accounts for a large portion of the mine's operating costs. Electric-powered quarry dump trucks, such as the Komatsu 860E, are widely used in such conditions. This article analyzes the energy consumption during deceleration (braking) and its recovery based on the real-life duty cycle of the Komatsu 860E quarry dump truck. As a result of the research, a mathematical model was developed and how much energy is lost or recovered through the engine and electric drive system during deceleration was estimated. Based on the test data, the changes in deceleration, speed, power, and time are analyzed. The results of the study show that, in the presence of an energy recovery system, 30–50% of the kinetic energy generated during the deceleration phase can be converted into electrical energy. This serves to optimize energy efficiency, energy conservation, and operational energy in quarry transport. Based on data obtained from the electronic control unit, the developed model takes into account not only the total energy consumption but also the amount of energy that can be recovered during braking, which was simulated accordingly. The study analyzes how the use of recoverable energy can reduce transportation costs and improve energy efficiency. Furthermore, enhancing the regenerative braking system and optimizing routes can further increase overall efficiency. This approach is evaluated as an economically and environmentally beneficial solution.

Keywords: Quarry dump truck, diesel-electric transmission, energy consumption, kinetic energy, power, angular velocity, energy recovery

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Elektr yuritmali karyer samosvallarining sekinlanish jarayonida energiya sarfini tahlil qilish (Komatsu 860e misolida)

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Annotatsiya: Ochiq usulda qazib olinadigan konlarda yuk tashish konning ekspluatatsion xarajatlarining katta qismini tashkil qiladi. Elektr yuritmali karyer samosvallari, Komatsu 860E kabi yuk mashinalari, bunday sharoitlarda keng qo‘llanilmoqda. Ushbu maqolada Komatsu 860E karyer samosvalining real ish sikli asosida sekinlanish (tormozlanish) jarayonida energiya sarfi va uni qayta tiklash uchun tahlil qilinadi. Tadqiqot natijasida matematik model ishlab chiqildi va sekinlanish jarayonida dvigatel va elektr yuritma tizimi orqali qancha energiya yo‘qotilishi yoki energiyani qayta tiklashi baholandi. Sinov ma’lumotlari asosida sekinlanish, tezlik, quvvat, vaqt bo‘yicha o‘zgarishi tahlil qilinadi. Tadqiqot natijalari shuni ko‘rsatadiki, energiyani qayta tiklash tizimi mavjud bo‘lgan sharoitda sekinlanish bosqichida hosil bo‘lgan kinetik energiyaning 30–50% bo‘lgan qismi elektr energiyasiga aylantirilishi mumkin. Bu esa karyer transportida energiya tejamkorligini, energiyani tejashni va ekspluatatsion energiyani optimallashtirishga xizmat qiladi. Elektron boshqaruv blokidan olingan ma’lumotlar asosida ishlab chiqilgan modelda umumiy energiya sarfi, tormozlanish vaqtida qayta tiklanishi mumkin bo‘lgan energiya miqdori ham hisobga olindi va simulatsiya qilindi. Tadqiqotda qayta tiklanadigan energiyadan foydalanish tashish xarajatlarini kamaytirishi va energiya samaradorligini oshirishi mumkinligi tahlil qilingan. Shu bilan birga, tormoz energiyasini qayta tiklash tizimini takomillashtirish va marshrutlarni optimallashtirish orqali samaradorlikni yanada oshirish mumkin. Bu yondashuv ekologik va iqtisodiy jihatdan foydali yechim sifatida baholandi.

Kalit so‘zlar: Karyer samosvali, dizel-elektr uzatma, energiya sarfi, kinetik energiya, quvvat, burchak tezlik, energiyani qayta tiklash

1. Kirish

Karyer sharaoitida ishlaydigan samosvallarning og‘ir yuk tashishi va karyer ichki texnologik yo‘llarda harakatlanganligi sababli ekspluatatsiya harajatlari yuqoridir. Turli dunyoga ko‘ra, ochiq karyerlarda qazish ishlarining umumiy tannarxida yuklarni avtomobilda yuk

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tashishi ulushi 50% atrofida yoki undan ham yuqori bo‘lishi mumkin.

So‘nggi kunlarda dizel-elektr uzatmaga ega karyer samosvallari (elektr transmissiyali) konlarda keng qo‘llanilmoqda An’anaviy mexanik transmissiyaga ega yuk mashinalariga nisbatan, elektr uzatma tizimi bir qator afzalliklarga ega. Jumladan, elektr transmissiyali yuk mashinasida murakkab mexanik uzatmalar o‘rnini elektr motorlari egallagan bo‘lib, harakatlanuvchi qismlarga kichik va texnik xizmat ko‘rsatish ishlab chiqarishi pastroq bo‘ladi.[1]

Karyer samosvallari sekinlanish bosqichida undan tushadigan (va agar tog‘dan tushayotgan bo‘lsa, potensial) energiya issiqlik ko‘rinishida yo‘qotiladi. An’anaviy mexanik tormozlashda tormoz kolodkalari va disklar ishqalanishi tufayli bu energiya atrof-muhitga issiqlik tarzida tarqab ketadi. Dizel-elektr karyer samosvallarda esa tormoz vaqtida elektromotorlar generatorga kelib chiqadigan energiyani elektr tokiga aylantirish imkoni tug‘iladi. Misol uchun, Komatsu 860E-1K rusumli karyer samosvali sekinlanish (tormozlanish) vaqtida 3469 kW (4650 ot kuchi) gacha quvvatni elektr energiyasiga aylantira oladi. Qayta ishlashda bunday energiya hali to‘liq foydali ishlatilmaydi: Komatsu 860E kabi dizel-elektr yuk karyer samosvallarining tormoz tizimi ishlab chiqargan tok maxsus rezistorli panellar orqali issiqlikka aylantirilib, atmosferaga tarqatiladi. Ya’ni, energiyani qayta tiklash tormozlash prinsipi qo‘llangan bo‘lsada, energiya akkumulyatorlarda saqlanmagani bois u “yo‘qotilgan” issiqlik sifatida bekor qilinadi. Bu esa sekinlanish jarayonidagi energiyani qayta tiklash va kengaytirish uchun katta imkoniyatlarni ko‘rsatadi. Ilmiy manbalarda, tormozlashda energiyani qayta tiklash orqali uni qayta ishlash yuk karyer samosvallarida ishlab chiqarish sarfiga qarab 20–30% gacha hosil bo’lishi mumkin. Demak, bunday texnologiya konchilikda yonilg‘i tejamkorligi, balki zararli gazlar emissiyasini kamaytirishda ham juda foydali bo‘lishi kutilmoqda.[2]

Komatsu 860E yuk karyer samosvali – zamonaviy ochiq konlar uchun mo‘ljallangan eng muhim avtosamosvallardan biri. Ushbu modelning nominal yuk ko'tarishi 254 tonnani tashkil etadi 860E dizel-elektr uzatmali bo‘lib, 16 silindrli 2700 ot kuchiga ega dvigatel va Siemens kompaniyasining AC elektr motorlari bilan jixozlangan. Bu samosval maksimal 64 km/soat tezlikda harakatlana oladi va og‘ir yuklarni tashishga moslashgan konstruksiyaga ega. Komatsu 860E-1K modellari konlarda trolley tarmog‘i (yuqori voltli kontakt liniyalari)ga ulanish bilan ishlashi ko‘zda tutilgan.[3]

Sekinlanish jarayonida esa elektr tormoz – dinamik retarder tizimi – katta rol o‘ynaydi. Komatsu 860E ning uzluksiz elektr tormoz (retarder) kuchi 4650 ot kuchigacha yetib, to‘rt g‘ildirakli ho‘l diskli xizmat tormozlari bilan ishlaydi. Bu yuk mashinasiga og‘ir yuk bilan ham tik qiyaliklardan havfsiz tushishni ta‘minlovchi ulkan tormozlash quvvatini beradi. Komatsu 860E kabi yuk karyer samosvallari hozirgi kunda oltin, temir rudasi, mis va qurilish jinslari kabi ochiq konda keng joriy etilmoqda. [5]

Ushbu tadqiqotining maqsadi – elektr transmissiyali karyer samosvali (Komatsu 860E-1K misolida) sekinlanish jarayonida qayta hosil qilish (energiyani tiklash) energiya miqdorini va uni maksimal darajada yig‘ish hamda tashish tannarxini kamaytirish bo‘yicha tavsiyalar ishlab chiqish.[6]

Bu esa yonilg‘i sarfini kamaytirib, har bir tonna yukni tashish uchun energiya sarfini kamaytiradi. Shu tariqa, tadqiqot natijalari ochiq konlarda transportdan foydalanishni boshqarishni asos yaratish va energiya tejamkor texnologiyani joriy etish uchun ilmiy manba yaratish imkonini beradi.

2. Tadqiqot metodologiyasi

Komatsu 860E yuk mashinasining real ishlash sikli bo'yicha yig‘ilgan ma‘lumotlar Microsoft Excel formatida to‘ldirilgan. Ma‘lumotlar sensori signallarni o‘z ichiga oladi:

- Tezlik (km/soat)
- Yogilg‘i sarfi (l)
- Dvigatel burchak tezligi (ayl/min)
- Elektr motor A va B momenti va quvvati (N•m, kVt)

Sekinalanish tezligi tezlikning pasayish jarayoni asosida olindi. Bu bosqichda harakat holatidan to‘xtash holatiga o‘tadi. Sensor ma‘lumotlarning tahlili davomida vaqtning boshlang‘ich boshlanish va tugash nuqtalari aniqlanib, ushbu oraliqdagi kinetik energiya hisoblanadi.[4]

Tadqiqotda sekinlanish vaqtida karyer samosvalining yo‘qotayotgan kinetik energiyasi quyidagi formula orqali hisoblandi:

$$E_k = \frac{1}{2} m \cdot (v_b^2 - v_t^2) \qquad (1)$$

Bu yerda:

E_k— yo‘qotilgan kinetik energiya (J)

m— yuk karyer samosvalining massasi (kg) (yuksiz yoki yuk bilan)

v - tezliklar (m/s)

Agar tormozlashda energiyani qayta tiklash tizimi mavjud bo‘lsa, kinetik energiya elektr energiyasiga aylanadi:[8]

$$E_{reg} = \eta \cdot E_k \qquad (2)$$

Bu yerda η — energiyani qayta tiklash (odatda 0,3–0,5 oralig‘ida, ya‘ni 30–50%).

Tahlilda Komatsu 860E yuk karyer samosvalining yuksiz va yuklangan holatdagi massasidan foydalanildi:

- yuksiz og‘irlik: 172 000 kg
- To‘liq yuklangan holat: 426 000 kg

Sensor ma‘lumotlaridagi elektr motor quvvati (kVt) va momenti (N•m) tahlili, sekinlanish vaqtida elektromotorlarning generator rejimida ishlashini ko‘rsatdi. Agar moment manfiy bo‘lsa, ya‘ni motor g‘ildiraklardan energiya olsa — bu energiyani qayta tiklash rejimini bildiradi. Sekinlanish quvvati (kVt) qiymatlari vaqt bo‘yicha integratsiya qilinib, qayta tiklanishi mumkin bo‘lgan energiya aniqlanadi (kVt-soat).

$$E = \int_{t_0}^{t_1} P(t)dt \qquad (3)$$

bu yerda:

P(t)– sekinlanish vaqtida elektromotorlar ishlab chiqarilgan quvvat (kVt),

$[t_1, t_0]$– sekinlanish jarayonining boshlanish va tugash vaqt oralig'i (s).

Amaliy hisob-kitoblar uchun bu integral hisob usulda, ya‘ni ma‘lumotlar diskret shaklida berilgan bo'lsa:

$$E \approx \sum_{i=1}^{n} P_i \cdot \Delta t \qquad (4)$$

P_i .– i-chi vaqt kesimida quvvat,

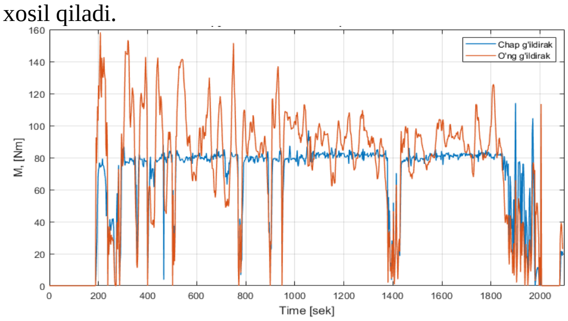
Δt – vaqt.

Agar P_i <0, ya‘ni elektromotorlar g‘ildiraklardan quvvat olayotgan bo‘lsa, bu energiyani qayta tiklash rejimi.

Avtomobilning ish jarayonini tahlil qilishda uning xarakatini oʻrganishdan boshlanadi. Misol uchun Komatsu 860E-1K samosvalini yuk ortilgan vaqtidan yukni toʻkishgacha boʻlgan koʻrib chiqamiz.

1-grafik. Komatsu 860E-1K samosvalining ish marshrutidagi harakatlanish tezligi

Elektrodvigatel momentini transmissiyaning uzatishlar nisbatiga koʻpaytmasi yetakchi gʻildirakdagi momentni xosil qiladi.

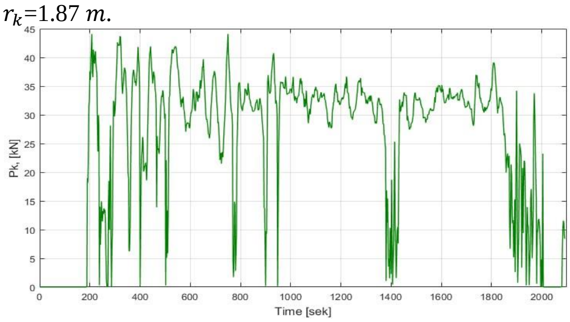


2-grafik. Elektrodvigatel rotoridagi burovchi moment

Yetakchi gʻildiraklardagi tortuvchi kuch quydagicha aniqlanadi.

$$P_k = \frac{M_k}{r_k} \qquad (5)$$

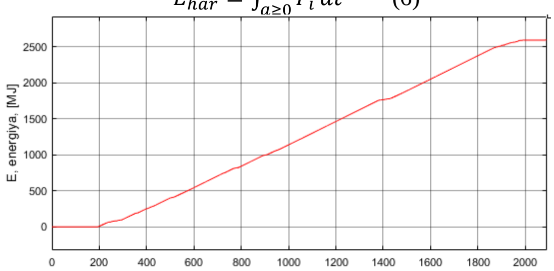
r_k - gʻildirash radiusi, m, shinaning markasi 50/90R57, r_k=1.87 m.



3-grafik. Yetakchi gʻildiraklardagi tortish kuchi

Samosvalni harakatlantirish uchun ishlatiladigan umumiy isteʻmol qilingan energiya E_{har} quyidagicha hisoblanishi mumkin

$$E_{har} = \int_{a\geq 0}^{9} P_i \, dt \qquad (6)$$



vaqt (s)

4-grafik. Marshrut boʻyicha sarflangan energiya

Avtomobilning oʻrtacha energiya isteʼmoli marshrut boʻyicha hisoblanadi va 2599 MJ energiya sarflagan. Ushbu sarflangan energiya uchun avtomobilning ichki yonuv dvigateli 8529 m masofaga 251.7 litr yoqilgi sarflagan.[10]

Yuqorida koʻrsatilgan energiya oqimiga koʻra, karyer samosvalining qayta tiklashi mumkin boʻlgan energiya quyidagi formula orqali aniqlanadi.[9]

$$E_{regen} = \int_{a\leq 0}^{0} P_i \, dt \qquad (7)$$

Qayta tiklangan tormozlash energiyasi avtomobilning kinetik energiyasidan sekinlashuv jarayonlarida elektr energiyasiga aylanadi va batareyada saqlanadi. Sekinlashmagan jarayonlarda tiklangan energiya oxir-oqibat avtomobilni quvvatlantirish uchun batareyadan chiqariladi. Tenglamalarni birlashtirib, tormozlashda qayta tiklashning elektr transport vositasining energiya sarfini kamaytirishga qoʻshgan hissasini quyidagilar orqali olish mumkin.[7]

$$\delta = \frac{\Delta E_{drive}}{E_{drive}} \cdot 100\% = \frac{\eta_{fd}\eta_g\eta_{gen}\eta_{charge}\eta_{discharge}\eta_m\eta_g\eta_{fd} \cdot E_{regen}}{E_{drive}} \qquad (8)$$

η_{fd} − asosiy uzatmaning f. i. k.

η_g − uzatmalar qutisining f. i. k.

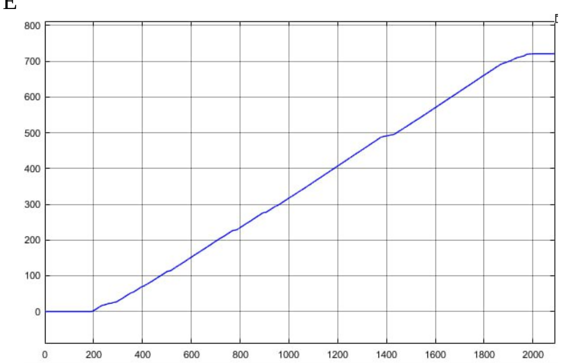
η_{gen} − generatorning f.i.k.

η_m − dvigatelning f.i.k.

η_{charge} − akkumlyatorning zaryadlanishda f.i.k.

$\eta_{discharge}$ − akkumlyatorning zaryadsizlanishda f.i.k.

E



vaqt (s)

5-grafik. Qayta tiklanishi mumkin boʻlgan energiya

3. Xulosa

Ushbu modelda karyer samosvali Komatsu 860E-1K yuk olib chiqish jarayonidagi energiya sarfini xisoblash keltirilgan. Xisob uslubi Elektron boshqaruv blokidan olingan maʻlumotlar orqali ifodalangan va matematik madeli ishlab chiqilgan. Matematik modelda samosvalning energiya sarfi bilan birgalikda tormozlanishdagi energiyani qayta tiklash mumkin boʻlgan energiya miqdori aniqlanib simulatsiya qilingan. Simulatsiya natijalari umumiy energiya sarfini va tormozlanishda qaytib olishinishi mumkin boʻlgan enrgiya miqdorini ifodalaydi.

Simulatsiya natijasida samosval sikli boyicha oʻrtacha 2500 MJ energiya is’temol qilib, rekurperativ tormozlanish ya’ni sekinlanish vaqtida 700 kJ energiyani issiqlikga aylantirib yuborgan. Sinov ishlari yukni tepalikga olib chiqilgani bois va chiqish davomida tormozlanish jarayoning vaqti harakatning kam qismini tashkil etadi. Samosval yukni toʻkib qaytish vaqtida bu energiya katta qismini tashkil qiladi.

Komatsu 860E-1K samosvalining energiya sarfi tahlili natijasida, qayta tiklanuvchi energiya imkoniyatlaridan to'liq foydalanish tashish tannarxini kamaytirishga yordam berishi aniqlandi. Tormozlanishda energiyani qayta tiklash tizimini takomillashtirish va marshrutlarni optimallashtirish orqali energiya samaradorligini oshirish mumkin. Elektron boshqaruv asosidagi monitoring esa harakatni yanada tejamkor qiladi. Umuman, bu yondashuv ishlab chiqarish xarajatlarini kamaytiradi va ekologik samaradorlikni oshiradi.

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