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Analysis of modern calculation methods for locomotive traction of trains based on the experience of developed countries

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Abstract: This article provides a comprehensive analysis of modern methods for calculating locomotive train traction, drawing on the experience of developed countries such as Germany, Japan, the USA, China, and various European nations. The article examines the transition from traditional empirical formulas used in modeling motion dynamics, such as the Davis equation, to more advanced techniques like multi-body dynamic modeling and numerical integration methods, including the fourth-order Runge-Kutta method. It also evaluates the effectiveness of energy-saving driving algorithms based on Pontryagin's maximum principle (coasting mode), the longitudinal dynamics of heavy freight trains (utilizing systems like TDEAS and LEADER), and the use of stochastic Monte Carlo methods for calculating braking curves within the ETCS. The research findings offer practical recommendations for enhancing the capacity, safety, and energy efficiency of railway transport.
Keywords: locomotive traction calculation, Davis equation, Runge-Kutta method, longitudinal dynamics, Pontryagin's maximum principle, Monte Carlo method, ETCS, ATO, energy efficiency, heavy-haul trains

Rivojlangan davlatlar tajribasi asosida poezdlarni lokomotivli tortishning zamonaviy hisoblash usullari tahlili

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Annotatsiya: Ushbu maqolada rivojlangan davlatlar (Germaniya, Yaponiya, AQSH, Xitoy va Yevropa davlatlari) tajribasi asosida poezdlarni lokomotivli tortishning zamonaviy hisoblash usullari har tomonlama tahlil qilingan. Maqolada harakat dinamikasini modellashtirishdagi an'anaviy empirik formulalardan (masalan, Devis tenglamasi) ko'p massali dinamik modellashtirish va to'rtinchi tartibli Runge-Kutta kabi sonli integrallash usulliga o'tish jarayonlari ko'rib chiqilgan. Shuningdek, Pontryaginning maksimum tamoyiliga asoslangan energiya tejovchi haydash algoritmlari (coasting/vibeg rejimi), og'ir yuk poezdlarining bo'ylama dinamikasi (TDEAS va LEADER tizimlari) hamda ETCS tizimidagi tormoz egri chiziqlarini hisoblash uchun stoxastik Monte-Karlo usullarining samaradorligi baholangan. Tadqiqot natijalari temir yo'l transportining o'tkazuvchanlik qobiliyati, xavfsizligi va energiya samaradorligini oshirish bo'yicha amaliy tavsiyalar beradi.
Kalit so'zlar: lokomotiv tortuv hisobi, Davis tenglamasi, Runge-Kutta usuli, bo'ylama dinamika, Pontryaginning maksimum prinsipi, Monte Karlo usuli, ETCS, ATO, energiya samaradorligi, og'ir yuk poyezdlari

1. Kirish

Jahon iqlim inqirozi va uglerod neytralligiga erishish bo'yicha xalqaro majburiyatlar kuchayib borayotgan bir sharoitda transport sektori energiya samaradorligini oshirish bo'yicha misli ko'rilmagan bosimga duch kelmoqda. Temir yo'l transporti tarixan ommaviy yo'lovchi va yuk tashishning eng ekologik toza usullaridan biri bo'lib kelgan. Yaponiya tajribasi yaqqol ko'rsatib turibdiki, temir yo'llar mamlakatdagi barcha yo'lovchi tashish hajmining qariyb 27 foizini bajarsa-da, transport sektori issiqxona gazlari tashlanmalarining atigi 7 foizini tashkil qiladi. Shunga qaramay, infratuzilmani o'tkazuvchanlik qobiliyatiga bo'lgan talabning uzluksiz o'sishi munosabati bilan rivojlangan mamlakatlardagi (Germaniya, Yaponiya, AQSH, Xitoy va Yevropaning boshqa davlatlari) temir yo'l operatorlari poezdlar harakatini boshqarishda mutlaqo yangi yondashuvlarni izlashga majbur bo'lmoqdalar [1-4]. Yangi temir yo'l liniyalarini qurish ulkan sarmoyalarni va uzoq muddatlarni talab qiladi, bu esa ilg'or hisoblash usullari va raqamlashtirish yordamida mavjud infratuzilmani optimallashtirishni mutlaq ustuvor vazifaga aylantiradi.

Ushbu optimallashtirishning markaziy elementi poezdlarning lokomotivli tortish hisobidir — bu harakat fizikasi, elektrotexnika, hisoblash matematikasi va avtomatik boshqarish nazariyasini birlashtirgan murakkab fanlararo jarayondir.

Zamonaviy lokomotiv tortish hisoblash usullari fundamental transformatsiyani boshdan kechirdi. Hozirgi vaqtda ular batafsil ko'p massali (multibody) dinamik modellashtirishga, bort kompyuterlarini energiya iste'molini boshqarish tizimlari bilan integratsiyalashga,

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avtoulagichlardagi (avtosepkalardagi) bo‘ylama siqilish va cho‘zilish kuchlarini hisoblashga, shuningdek tormozlanish egri chiziqlarini baholashning usullariga tayanadi. Yevropa poezdlar harakatini boshqarish tizimiga (ETCS) integratsiya qilingan algoritmlar yoki Amerikaning LEADER va Trip Optimizer tizimlari kabi avtomatlashtirilgan poezdlarni boshqarish (Automatic Train Operation — ATO) tizimlarini joriy etish real vaqt rejimida hisob-kitoblarni talab qiladi [5-9]. Bu hisob-kitoblar poezdning yo‘l profili, ob-havo sharoiti va tarmoqning joriy holatini hisobga olgan holda bir necha kilometr oldindagi harakatini bashorat qila olishi kerak.

Ushbu tadqiqotning maqsadi rivojlangan davlatlarning ilg‘or tajribasi asosida lokomotiv tortishni hisoblashning zamonaviy usullarini har tomonlama tahlil qilishdan iborat.

2. Tadqiqot metodologiyasi

Poyezdlar tortishi va harakatini zamonaviy modellashtirish klassik Nyuton mexanikasidan tortib stoxastik ehtimollik algoritmlari va optimal boshqaruv tamoyillarigacha bo‘lgan matematik modellarning murakkab ierarxiyasiga asoslanadi.

Har qanday poezd harakati simulyatorining (masalan, OpenTrack yoki RailSys) negizida yotadigan asosiy tamoyil Nyutonning ikkinchi qonunidir. Temir yo‘l transporti kontekstida harakat tenglamasi poezd tezlanishini tortish (yoki tormozlash) kuchi va turli qarshilik kuchlarining o‘zaro ta’siri natijasi sifatida tavsiflaydi. Asosiy differensial tenglama quyidagicha ko‘rinishga ega:

$$M_{eff}\frac{dv}{dt} = F_T - W_{tot} \qquad (2.1)$$

Bunda: M_{eff} — poezdning samarali (keltirilgan) massasi bo‘lib, u ham statik massani (kilogramm yoki tonnada), ham aylanadigan qismlarning (g'ildirak juftliklari, tortish elektr dvigatellari rotorlari, tishli uzatmalar) inersiyasini o‘z ichiga oladi. $\frac{dv}{dt}$ — poezd tezlanishi. F_T — lokomotiv tomonidan ishlab chiqariladigan umumiy tortish kuchi yoki tormozlash kuchi. W_{tot}— qarshilik kuchlarining umumiy yig'indisi, shu jumladan harakatga asosiy qarshilik, nishablikdan qarshilik (gravitatsion tashkil etuvchi) va egriliklar qarshiligi.

Qarshilik kuchlarini W_{tot} aniq baholash energiya iste’molini hisoblash uchun juda muhimdir. Bunday hisob-kitoblar uchun eng keng tarqalgan poydevor to‘g‘ri gorizontal yo‘l uchastkasida poezd harakatiga qarshilikni approksimatsiya qilish uchun empirik ravishda ishlab chiqilgan Devis tenglamasi hisoblanadi. Klassik shaklda u tezlikka bog‘liq kvadratik tenglamani ifodalaydi:

$$R = A + Bv + Cv^2 \qquad (2.2)$$

Tortish xususiyatlari, qarshilik va yo‘l profili doimiy ravishda o‘zgarib turadiganligi sababli, poezdning harakat tenglamasi oddiy analitik yechimga ega emas. Harakat vaqtini (Running Time Calculation) hisoblash uchun sonli integrallash usullaridan foydalaniladi. Tarixan, simulyatorlar Eyler usuliga tayanishi mumkin edi, bu keyingi tezlikni oddiygina joriy tezlik plyus tezlanishni vaqt qadamiga ko‘paytmasi sifatida hisoblaydi. Biroq, Eyler usuli uzoq masofalarda va yo‘l profilining keskin o‘zgarishlarida katta xatoga yo‘l qo‘yadi.

Agar yuqori tezlikdagi yo‘lovchi poezdlari uchun tarkibni moddiy nuqta yoki qattiq jism sifatida qarash mumkin bo‘lsa, AQSH, Avstraliya va Xitoyga xos bo‘lgan og‘ir yuk poezdlari (Heavy Haul) uchun bu yondashuv halokatli xatolarga olib keladi. Og‘ir vaznli poezd - bu yuzlab vagonlar va taqsimlangan lokomotivlardan tashkil topgan, egiluvchan-ishqalanish elementlari - avtoulagichlar va yutuvchi apparatlar bilan bog‘langan murakkab nochiziqli ko‘p massali (multi-particle) tebranish tizimidir.

Xitoyda ushbu muammoni hal qilish uchun Davlat tortish kuchi kalit laboratoriyasi (State Key Laboratory of Traction Power) negizida TDEAS (Train Dynamics and Energy Analyser/Simulator) texnologiyasi ishlab chiqilgan [10-12]. i-vagon uchun bo‘ylama dinamikaning matematik modeli barcha ta’sir etuvchi kuchlarni tahlil qilish orqali shakllantiriladi:

$$M_i\ddot{X}_i = F_{Ti} - F_{Di} + F_{ci} - F_{c(i+1)} - F_{Bi} - W_i \qquad (2.3)$$

Yutuvchi apparatlarning ilg‘or ponasimon-prujinali modellariga alohida e'tibor qaratiladi, ular tezlikka bog‘liq bo‘lgan ishqalanish, erkin harakat, chegara qat’iyligi va dastlabki taranglikni hisobga oladi. Avtoulagichdagi kuch tenglamasi quyidagicha ko‘rinishga ega:

$$F_c = F_s(x)\left[\frac{\tan(h)}{\tan(h)+\mu(v)}\right] \qquad (2.4)$$

Bunda x — apparatning deformatsiyasi, h — pona burchagi, $\mu(v)$ — vagonlarning nisbiy tezligiga bog‘liq bo‘lgan ishqalanish koeffitsienti, F_s — prujina kuchi. Nolga teng nisbiy tezlikda matematik uzilishlarni bartaraf etish uchun yaxshilangan silliqlash yondashuvlari qo‘llaniladi.

Rivojlangan davlatlar tajribasi

Yaponiya tajribasi. Shinkansen (Shinkansen) tarmog'i ishga tushirilgan 1964 yildan boshlab yuqori tezlikdagi yo‘lovchi tashishga asosiy e'tiborni qaratdi. Yapon muhandislari birinchilardan bo‘lib 250 km/soat dan yuqori tezlikda aerodinamik qarshilik energiyaning dominant iste’molchisiga aylanishini tahlil qilindi [13-17]. Shu munosabat bilan lokomotiv tortishi to‘liq motorli o‘qlarga ega bo‘lgan taqsimlangan motorvagonli tortishga almashtirildi, bu mavjud ilashishni oshirdi va og'ir tormoz reostatlaridan voz kechish imkonini berdi.

285-300 km/soat tezlikda harakatlanadigan zamonaviy seriyali poezdlar chuqur hisoblash optimallashtirishini o‘zida mujassam etgan. Ular alyuminiy kuzovlar, takomillashtirilgan aravacha ramalari, invertorlar o‘zgaruvchan tok dvigatellaridan foydalanadi. Asosiy yutuq yuqori samarali rekuperativ tormozlash paytida poezdning kinetik energiyasi qayta elektr energiyasiga aylanadi. Optimallashtirilgan aerodinamika, og'irlikni kamaytirish va rekuperatsiyaning kombinatsiyasi tufayli Tokio — Shin-Osaka yo‘nalishidagi energiya iste'moli dastlabki seriyali poezdlarga nisbatan 32-49% ga kamaytirildi.

Xitoy tajribasi. Xitoy dunyodagi eng yirik yuqori tezlikdagi temir yo‘llar tarmog'iga ega. Xorijiy texnologik platformalarga qaramlikni bartaraf etish uchun standartlashtirilgan elektropoezdlarning milliy platformasi yaratildi. 350 km/soat tezlikda harakatlanadigan poezd 40 000 dan ortiq butlovchi qismlardan iborat [18-24].

Xitoyning qarshilikni hisoblash maktabi 46 ta konseptual kuzov dizayni uchun aerodinamik quvurlarda keng ko‘lamli sinovlar va hisoblash gidrodinamikasi hisob-kitoblarini qo‘lladi. Natijada tanlangan bosh qism profili havo qarshiligini 12 foizga kamaytirishga imkon berdi va 100 yo‘lovchi-kilometrga solishtirma energiya iste'moli 17-20 foizga qisqarib, atigi 3.8 kVt·soatni tashkil etdi. Pekin-Shanxay aylanma reysi miqyosida bu bitta poezd uchun 5 000 kVt·soatdan ko‘proq energiyani tejaydi.

AQSH tajribasi (Og‘ir vaznli harakat va LEADER algoritmlari). Osiyodan farqli o‘laroq, AQSH temir yo‘l tizimi o‘ta og'ir va uzun yuk tashishlarga (30 000 – 40 000 tonnagacha) yo‘naltirilgan. Bu yerdagi asosiy muammo frontal aerodinamik qarshilik emas, balki tepalik relyefni yengishda yuzaga keladigan bo‘ylama dinamik kuchlardir (in-train forces).

AQSHda LEADER (New York Air Brake ishlanmasi) va Trip Optimizer (GE Transportation / Wabtec ishlanmasi) kabi mashinistga yordam berish tizimlari ustunlik qiladi. LEADER (Locomotive Engineer Assist / Display & Event Recorder) bort simulyatori bo‘lib, bir necha milya oldindagi bo‘ylama kuchlarni baholash uchun real vaqtda yuqori aniqlikdagi raqamli yo‘l xaritalari, poezd og‘irligi va tarkibi haqidagi ma’lumotlardan foydalanadi [24-29].

Ushbu tizimlarning asosiy funksionalligi taqsimlangan tortish rejimini boshqarish orqali amalga oshiriladi. Asinxron taqsimlangan quvvat algoritmlaridan foydalangan holda, tizim asosiy va yordamchi lokomotivlar o‘rtasidagi tortish va rekuperativ (yoki dinamik) tormozlash talablaridagi farqni bashorat qiladi. Tekis uchastkalarda tizim yoqilg'ini tejash uchun ortiqcha lokomotivlarni salt ishlash rejimiga o‘tkazishi mumkin, burilishlarda esa ulagichlar uzilishining oldini olish va bo‘ylama cho‘zilish kuchlarini kamaytirish uchun poezd dumi qismidagi lokomotivlarga ko‘proq quvvat beradi. Union Pacific kompaniyasi ushbu texnologiyalarni muvaffaqiyatli integratsiya qildi; bir hisobot yilida Trip Optimizer bilan jihozlangan lokomotivlar poezd uzunligi, ob-havo sharoiti va yo‘l holatini hisobga olgan holda boshqaruvchining optimal pozitsiyalarini hisoblab, 9.8 million milya masofani bosib o‘tdi va bu dizel yoqilg'isi sarfini keskin qisqartirdi.

Germaniya va Yevropa tajribasi. Yevropada asosiy e'tibor mavjud liniyalardagi to‘siqlarni o‘tkazuvchanlik qobiliyatini oshirish va xalqaro yo‘nalishlarning uzluksizligiga qaratilmoqda. Ushbu muammoni hal qilish uchun Deutsche Bahn (DB) va Yevropa operatorlari OpenTrack, FBS va RailSys kabi dasturiy majmualaridan foydalanadilar. Obyektga yo‘naltirilgan yondashuvga asoslangan OpenTrack tortishning har qanday turi uchun harakat va energiya iste'moli tenglamalarini yechadi, diskret va sirpanuvchi blok-uchastkalar ishlashini simulyatsiya qiladi hamda elektr tarmoqlari simulyatorlari bilan hamkorlik qiladi [30-34]. Hisoblashlarni taqqoslash shuni ko‘rsatadiki, integratsiyalashgan algoritmlar eskirgan jadval tuzish tizimlariga nisbatan pog'onali va aniq energiya iste'moli grafiklarini beradi, ayniqsa og'ir yuk poezdlari Sharqiy Saksoniyaning tik qiyaliklarida quvvat chegarasida ishlaganda.

Energiya tejovchi “Green Wave” strategiyasini faol joriy etmoqda. Mintaqaviy poezdlar RESY dasturiy ta’minotiga ega telematik tizimlar bilan jihozlangan bo‘lib, ular dispetcherlik markazlari ma’lumotlariga tayangan holda mashinistlarga nishabliklar yoki qizil signallar oldidan tortishni oldindan o‘chirish bo‘yicha tavsiyalar beradi. Bu orqali energiyaning 10% dan 13% gacha qismini tejaydi. Inson omilini istisno qilish poezdlar orasidagi intervallarni qisqartirishga va bitta yo‘lda soatiga 24 ta poezd o‘tkazish qobiliyatiga erishishga imkon berdi.

3. Xulosa

Germaniya, Yaponiya, AQSH, Xitoy va boshqa rivojlangan mamlakatlar tajribasi asosida poezdlarni lokomotivli tortishning zamonaviy hisoblash usullarini tahlil qilish temir yo‘l muhandisligida paradigmaning o‘zgarishi to‘g'risida bir qator fundamental xulosalar chiqarishga imkon beradi:

Birinchidan, qarshilikni hisoblashning an’anaviy statik usullari (Devis kabi tenglamalar) va tayanch kinematika algoritmlari o‘z o‘rnini murakkab ko‘p massali dinamik modellar va yuqori tartibli sonli integrallash usullariga bo‘shatib berdi. Bo‘ylama kuchlarni va avtoulagichlarga ta’sirini hisoblash orqali modellashtirish (TDEAS, LEADER, Trip Optimizer tizimlari) xavfsizlikni ta’minlash va infratuzilmaning yemirilishini minimallashtirish uchun ajralmas vositaga aylandi, xususan AQSH va Xitoydagi o‘ta og'ir yuk poezdlari segmentida.

Ikkinchidan, tortish hisob-kitoblarining diqqat markazi lokomotivning tarkibni “torta olish” qobiliyatini oddiygina aniqlashdan tortib, global energetik optimallashtirishga o‘tdi. Kuzovlarni aerodinamik jihatdan takomillashtirish (Xitoy Fuxing poezdlarida bo‘lgani kabi) va rekuperatsiya tizimlarini keng miqyosda joriy etish (Yaponiyadagi N700 Shinkansen seriyasi) bilan birlashgan holda Pontryaginning maksimum tamoyilining amaliy qo‘llanilishi (tortish va vibeg fazalarini hisoblash) o‘tgan o‘n yilliklar modellariga nisbatan 30% dan 50% gacha energiya tejash imkonini beradi.

Uchinchidan, matematik modellashtirish tarmoq trafigini uzluksiz boshqarishning asosi bo‘ldi. Yevropaning ETCS standarti doirasida tormoz egri chiziqlarini hisoblash uchun ehtimollikdagi Monte-Karlo usullarini joriy etish, elektr tarmoqlari simulyatsiyalarini poezdlar harakati bilan integratsiyalash va avtomatik boshqarish (ATO) tizimlarini ishlab chiqish yangi yo‘llarni qurmasdan mavjud liniyalarning o‘tkazuvchanlik qobiliyatini tubdan oshirish imkonini beradi.

Uglerodsiz iqtisodiyotga o‘tish sharoitida intellektual bort hisoblash majmualari va dispetcherlik simulyatorlari (OpenTrack va RailSys kabi) endi faqat loyihachilarning yordamchi vositalari bo‘lib qolmaydi. Ular bevosita harakatni boshqarish jarayonlariga integratsiyalanib, temir yo‘lni yagona, raqamli va maksimal darajada energiya tejaydigan kiberfizik organizmga aylantirmoqda. Rivojlangan mamlakatlar tajribasi global miqyosda transport tizimlarini barqaror rivojlantirish uchun moslashishi zarur bo‘lgan tayyor metodologik (matematik) va amaliy yechimlar jamlanmasini taqdim etadi.

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CONTEXT / MUNDARIJA

M. Miralimov, K. Juraev, Kh. Urazov
*Analysis of the state of bridges exploited in the Republic of Uzbekistan ……………………………………………………………….**203***

S. Norkulov
*The importance of foreign experience in the development of the metro transport system and recommendations for Uzbekistan……………………………………………………………….**207***

Sh. Anarova, N. Khujakulov
*Fractal geometry and patterns modeling methods ………………**210***

N. Khujakulov
*Computer modeling of geometric patterns based on fractal models……………………………………………………………….**215***

M. Malikov
*A theoretical basis for the influence of road pavement texture on traffic safety and skid resistance …………………………………..**221***

N. Abdullaev
*Analysis of modern calculation methods for locomotive traction of trains based on the experience of developed countries……………**225***