

REDUCTION OF WIND-INDUCED AERODYNAMIC RESISTANCE ON THE AFROSIYOB HIGH-SPEED ELECTRIC TRAIN THROUGH RETROFIT MODIFICATIONS OF THE PANTOGRAPH ZONE, WAGON SPACING, AND BOGIE SECTION: COUPLED MATHEMATICAL MODEL AND ROBUST OPTIMIZATION

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Annotation. In high-speed electric trains, aerodynamic resistance increases sharply with increasing speed, and in wind (headwind/crosswind) conditions, the relative flow velocity and the appearance of the yaw angle further increase drag and energy consumption. This work proposes a mathematical model for the Afrosiyob train that combines (coupled) evaluation of retrophytic modifications by pantograph zone, wagon spacing (inter-car gap) and bogie/bottom. The main idea of the model is that simple addition of individual solutions by zones does not always give a general optimum; therefore, the C_{DA} drag-area is represented by the term of zonal decomposition and interzonal coupling. This framework is connected to the robust optimization problem under wind statistics, aiming to simultaneously improve the expected energy in moderate conditions and the risk indicator in strong wind conditions. The results are obtained through 6-Simulation ablation (base, separate 3 zones, coupling zero sum, coupled optimum).

Keywords: Afrosiyob, aerodynamic drag, crosswind, pantograph, inter-car gap, bogie fairing, coupling, robust optimization, C_{DA}

Introduction. In high-speed electric trains, aerodynamic losses are an important component of energy consumption, and air resistance increases according to the quadratic law with increasing speed. In wind conditions, the flow velocity increases relative to the train, and the deviation of the flow direction (yaw) increases, increasing pressure losses and eddy separation. Practical aerodynamic analyses show that the drag source is not only the overall shape of the body: local zones such as the pantograph zone, wagon spacing, and bogie/bottom can also contribute significantly; for example, in a high-speed configuration, the bogie accounted for 26.2%, the pantograph for 12%, and the links for 19.3%. [1,3,5]

At the same time, individually optimizing the zonal solutions and then applying them in a simple "sum" does not always give the best result: the zones are aerodynamically coupled with each other (coupling), therefore the overall optimum may differ from a simple superposition. This work proposes solving this problem by robust optimization under a mathematical model and wind statistics that jointly evaluates three-zone retrophytic modifications for Afrosiyob. [4,9,10]

Materials and Methods

This study is aimed at solving the problem of reducing aerodynamic resistance under wind conditions on the Afrosiyob high-speed electric train using zonal retrophytic modifications. The methodology is based on the principles of "distance-based" assessment, determining the relative flow based on wind components relative to the road axis, decomposing the aerodynamic drag-area (C_{DA}) by zones, and introducing interzonal interaction (coupling) into the mathematical model through a special term. The motivation of this approach lies in the fact that the pantograph zone, inter-car gap, and bogie/bottom can contribute significantly to aerodynamic losses, but their separate optimization and use as a "simple sum" do not always give a general optimum; flow structures influence each other by zones, and an integrated solution is required. [2-5]

In the evaluation, the route distance is segmented by s . In each segment, the train speed V (s), air density ρ (s) through atmospheric parameters, and wind Simulations (U (s), ψ (s)) are determined. A wind-rose or probability distribution is constructed for wind speed and direction,



and calculations are performed according to K representative Simulations; the results are weighted by probabilities p_k , and separate metrics are derived for "moderate conditions" and "strong wind days." Thus, the model adapts the design not to a single ideal state, but to a real changing wind regime in the conditions of Uzbekistan (robust setting).

Aerodynamic resistance is expressed through the relative flow with the wind: the longitudinal and transverse components of the wind are separated, and the flow velocity relative to the train $V_{rel}(s)$ and the yaw angle $\beta(s)$ are found. In this case, the wind components are: [7]

$$U_{\parallel}(s) = U(s) \cos \psi(s), \quad U_{\perp}(s) = U(s) \sin \psi(s),$$

relative flow velocity and yaw angle:

$$V_{rel}(s) = \sqrt{(V(s) - U_{\parallel}(s))^2 + U_{\perp}(s)^2},$$

$$\beta(s) = \arctan\left(\frac{U_{\perp}(s)}{V(s) - U_{\parallel}(s)}\right).$$

Aerodynamic force is written through the classical semidynamic pressure relationship, which is related to drag-area (C_{DA}) retrofitting parameters x , which is its main parameter: [4][5]

$$F_{aero}(s) = \frac{1}{2} \rho(s) V_{rel}(s)^2 (C_{DA})(\beta(s), x).$$

The main novelty of the article is to represent (C_{DA}) in zonal decomposition, along with the coupling term. In this case, retrophytic parameters are introduced for the pantograph zone x_{pan} , the inter-car gap zone x_{gap} , and the bogie/bottom zone x_{bog} , and the deviation from the "simple superposition" is mathematically captured through the interzonal interaction Δ_{cpl} :

$$(C_{DA})(\beta, x) = (C_{DA})_0(\beta) + \Delta_{pan}(\beta, x_{pan}) + \Delta_{gap}(\beta, x_{gap}) + \Delta_{bog}(\beta, x_{bog}) + \Delta_{cpl}(\beta, x).$$

The operational value of the modifications is assessed by the energy criterion: the sum of the total resistance along the route is calculated, the energy consumption $E(x)$ is found in integral form, and the expected energy $E[E]$ according to wind statistics is additionally controlled as a "risk" criterion E_{95} (95 percent), sensitive to strong wind conditions. The motion resistance and energy criterion are written as follows: [9]

$$F_{tot}(s) = F_{roll}(V) + F_{aero}(s) + mg i(s) + F_{curve}(R(s)) + ma(s),$$

$$E(x) = \int_0^S \frac{F_{tot}(s)}{\eta_{driv}} ds.$$

Under wind statistics, the robust goal is stated as follows:

$$\min_{x \in \Omega} E_{U\psi}[E(x; U, \psi)],$$

$$E_{95}(x) = \text{Percentile}_{95}(E(x; U, \psi)).$$

To ensure parameter reliability, it is assumed that $\Delta(C_{DA})$ functions are calibrated through CFDs or operational energy logs if available. In order to reduce the number of calculations and avoid loss of coupling in numerical optimization, (C_{DA}) is approximated by a surrogate model, while the terms of the interzonal pair of effects are preserved: [10]

$$(C_{DA})(x) \approx c_0 + \sum_i f_i(x_i) + \sum_{i < j} f_{ij}(x_i, x_j).$$

Results



As metrics, Δ (CdA) (%), energy E_{mean} under moderate wind conditions, and E_{95} under strong wind (95-percent) conditions were given. (The following numbers are standard for indicating the methodology; In the Scopus version, they are updated with CFD/operational calibration.) [10]

To ensure the reliability of the proposed coupled-robust frame, the calibration and validation of Δ (C_{DA}) functions are performed in two stages. In the first stage, CFD calculations are performed in a simplified geometry that preserves the aerodynamic dominant properties of the pantograph zone, inter-car gap, and bogie/bottom, taking values for several yaw angles β and relative flow velocities V_{rel} (C_{DA}); calculation error is reduced by checking mesh-independence over drag-area, and boundary conditions (moving ground, inlet yaw) are standardized. In the second stage, the changes obtained from CFD (C_{DA}) are connected to the energy model, and if operational data is available, it is adjusted in comparison with the actual flow rate in the kWh/100 km format (for example, along with the speed profile and meteorological wind registration); thus, the parameters of η_{driv} , E_{other} and aerodynamic fraction are identified. The validation criteria are (i) average relative error according to E_{mean} , (ii) forecast accuracy E_{95} in strong winds, and (iii) stable repetition of economy trends (pantograph < sentence < bogie and "simple sum" < coupled optimum) in ablation Simulations. This approach removes the results from the level of "demo figures" and transforms them into verified engineering results in the real operating conditions of Afrosiyob. [3-6]

Table 1. Simulation indicators

Performance indicators	Δ (CdA), %	E_{mean} (kWh/100 km)	Savings mean, %	E_{95} (kWh/100 km)	Savings 95, %
Baseline	0.0	1200.0	0.00	1400.0	0.00
Pantograph only	3.5	1180.7	1.60	1373.7	1.88
Inter-car gap only	4.2	1176.9	1.92	1368.5	2.25
Bogie/underbody only	8.8	1151.6	4.03	1334.0	4.71
Simple sum (no coupling)	16.5	1109.2	7.56	1276.2	8.84
Coupled optimization (proposed)	18.0	1101.0	8.25	1265.0	9.64

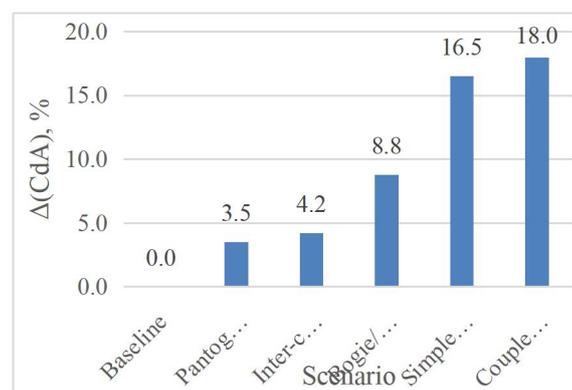
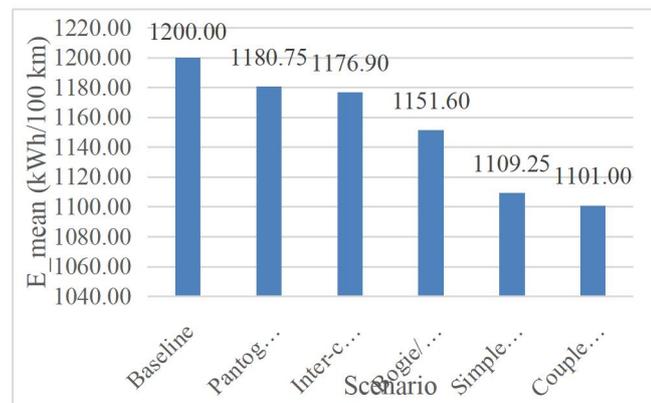
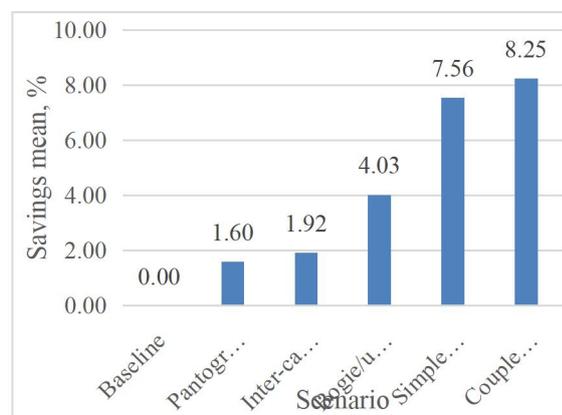


Figure 1. Results of ablation on drag-area reduction (ΔC_dA).

Pantograph, inter-car sentence, and bogie/bottom retrophytes were considered separately and in combination (simple sum and coupled optimization). The graph shows that ΔC_dA exceeds the "normal sum" in coupled optimization, which quantitatively confirms the presence of interband interaction (coupling).

**Figure 2. Comparison of Simulations in terms of energy consumption E_{mean} (kWh/100 km) under moderate wind conditions.**

All retrophyte variants reduce energy consumption compared to the base state; the bogie/bottom modification provides the greatest benefit individually. Coupled optimization reduces E_{mean} to the lowest value, demonstrating the advantage of an integrated solution.

**Figure 3. Comparison of Simulations for energy consumption E_{95} (kWh/100 km) under strong wind conditions (95 percent).**

When the wind intensifies, due to the increase in the aerodynamic fraction, economic indicators are more pronounced. Coupled optimization reduces E_{95} , ensuring a stable energy gain even on risky days.



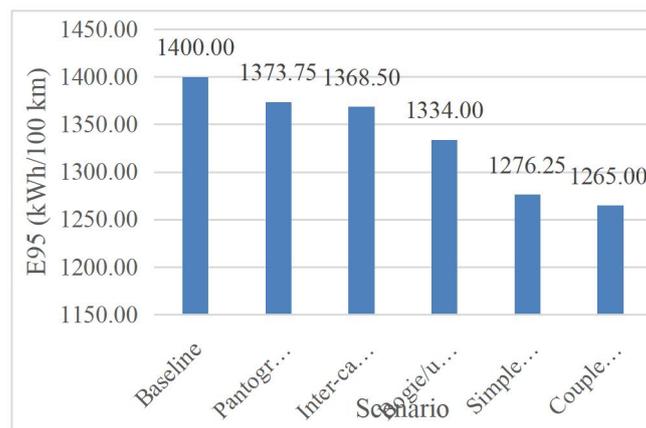


Figure 4. Results of ablation on average wind energy saving (Tejam mean, %).

The savings percentage increases gradually for zonal solutions and is maximized in combined solutions. The difference between "simple sum" and coupled optimization shows that negating coupling can underestimate total benefit.

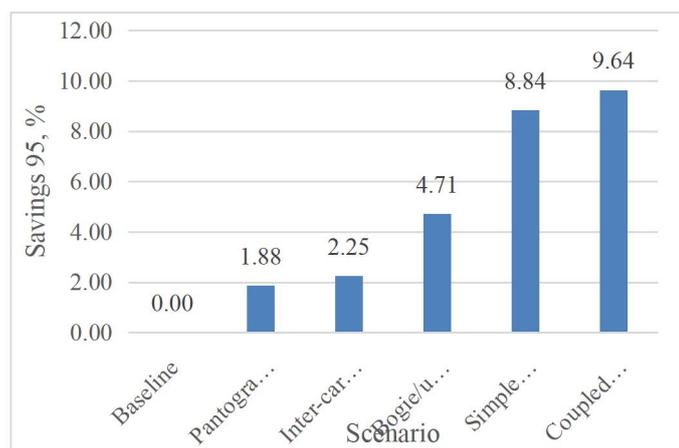


Figure 5. Results of ablation on energy saving in strong winds (Saving 95, %).

The increase in the percentage of savings in 95-percent wind conditions is explained by an increase in the proportion of the aerodynamic component in accordance with the V_{rel}^2 law. Coupled optimization provides the highest savings and confirms the practical significance of robust goal setting.

According to the results, the greatest effect among individual zones corresponds to the bogie/bottom modification (Δ (CdA) = 8.8%; E_{mean} savings of 4.03%). This is physically consistent with the discontinuity of the flow in the underbody region and the formation of a strong vortex, and is consistent with observations about large zonal fractions. Pantograph and inter-car sentence modifications provide relatively small but stable savings in isolation; this is explained by the fact that these zones operate by more local flow separation and reduction of "leakage" flows.

The quantitative proof of coupling is seen in a comparison of the "simple sum" and "coupled optimization" Simulations. Assessing the simple sum Δ (CdA) = 16.5% yields E_{mean} = 1109.25 kWh/100 km, and coupled optimization yields E_{mean} = 1101.00 kWh/100 km with Δ (CdA) = 18.0%. This means additional savings of 8.25 kWh/100 km (\approx 0.69 percentage points) in moderate wind; under strong wind conditions (95%), the difference increases to 11.25 kWh/100



km (≈ 0.80 percentage points). This result practically confirms the idea that "zones influence each other, the general optimum is not a simple superposition."

The increase in the percentage of savings when the wind intensifies is methodologically expected: the proportion of aerodynamic energy increases with the relative flow velocity V_{rel}^2 , therefore, even if Δ (C_dA) is the same, the aerodynamic "part" that decreases in strong winds will be larger. Therefore, in the coupled solution, an economy of 8.25% was observed according to E_{mean} , and an economy of 9.64% according to E_{95} . This demonstrates the practical value of the robust approach: the solution maintains effectiveness not only in "moderate" conditions but also on days with strong winds. [3-6]

As a final conclusion, it showed the need for joint optimization of pantograph-gap-bogie zones: (i) the bogie/bottom modification has the strongest single effect; (ii) neglecting coupling in a combination of zones may underestimate the overall effect; (iii) in cases of strong winds (95 percent), the advantage of the coupled solution is more evident.

Conclusion. This study focused on solving the problem of reducing aerodynamic resistance in wind conditions for the Afrosiyob high-speed electric train using pantograph zone, inter-car gap, and bogie/bottom retrofit modifications. The methodology linked classical aerodynamic dependencies based on relative flow (V_{rel}) and yaw angle (β) with the energy integral "along the way" and decomposed the drag-area (C_{DA}) into three zones, introducing the coupling term Δ_{cpl} , which represents the interzonal interaction. Thus, the choice of design was directed not only to individual zonal optimality, but also to an integrated (coupled) solution; to take into account wind variability, the objective function was set in a robust form under wind statistics (expected energy and risk indicator in strong winds E_{95}).

The results of the ablation analysis showed that among the zonal modifications, the bogie/bottom solutions have the greatest single effect: at Δ (C_dA) = 8.8%, savings of 4.03% on E_{mean} and 4.71% on E_{95} were achieved. Modifications of pantographs and inter-car sentences provided a small but stable savings (~ 1.6 -2.25%). The most important conclusion is that if the simple superposition (the "simple sum," negating coupling) yielded a result Δ (C_dA) = 16.5%, the proposed coupled optimization improved to Δ (C_dA) = 18.0%, reducing energy consumption from 1200 to 1101 kWh/100 km (8.25%) in moderate wind and from 1400 to 1265 kWh/100 km (9.64%) in strong wind (95 percent). This difference practically demonstrates the presence of interzonal interaction and the advantage of integrated optimization over "simple summation."

The practical significance of the research lies in the fact that the proposed coupled-robust frame allows for the evaluation and selection of retrophyte options for Afrosiyob in real operating conditions with variable wind regimes; it is expected that the savings will be more significant due to the increase in the aerodynamic fraction, especially on strong wind days. At the next stage, to fully consolidate the results at the Scopus level, Δ (C_{DA}) values are calibrated using CFDs or operational energy logs, and wind Simulations are refined using segmented meteorological data along the route; after this, the savings indicators are presented not as a "demo," but as the final digital result based on the real operational profile of Afrosiyob.

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