Mathematical modeling of air distribution dynamics due to piston effect of trains in long railway tunnels

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Abstract. The stationary and nonstationary problems on air flow under piston effect of trains in long railway tunnels are solved using the methods of computational aerodynamics. The comparison of the results reveals erroneous calculation of air exchange in case of the stationary problem formulation. The validity of calculating tunnel ventilation by integration of the static air distribution network models and the quasi-dynamic models of piston effect is justified.

1. Introduction
Piston effect adds essentially in air exchange in long railway tunnels [1–4]. First, when a train enters a tunnel, such air flow is nonstationary. Then the nonstationarity lowers, i.e. air flow rate tends to a constant value. It is possible to determine the total air exchange due to piston effect using the methods of (1) computational aerodynamics in the nonstationary problem of mobile network and (2) static network air distribution with the quasi-dynamic piston effect model [5–10]. The first method allows tracing the air flow dynamics at high precision but needs high computational power and much time (nearly 40 days with a cluster of 42 hard cores to calculate air flow in case on train in a tunnel 15 km long). The second method is less accurate but power-unfussy and the computation time is 1–2 s, which enables fast and multi-variant analysis. The key difference of the results of the two method lies in the possibility to study dynamic processes in the first case and to analyzes stationary or weak-nonstationary processes in the second case. This paper focuses on the estimate of error of the air distribution calculation without regard to air flow dynamics, i.e. the static problem, and aims to justify the validity of the quasi-dynamic modeling of piston effect without regard to transitions to different operation conditions in a railway tunnel. To this effect, a series of computational experiments was carried out using the method of computational aerodynamics (in ANSYS Fluent [11]) for the same problem (same computed models) in the stationary and nonstationary formulations. The resultant total air exchanges in one train pass along the tunnel, obtained using the mentioned methods are compared.

2. Mathematical modeling and results
In the simulation, the train is assumed to be fixed in the center of the tunnel. Such approach allows reducing the computation time. We solve the stationary and nonstationary plane and axially symmetric problems. The stationary problem offers an ideal scenario when a train is in the tunnel for an infinite time, and the air flow rate due to piston effect in the tunnel assumes the maximum hypothetical value in this case. The nonstationary problem enables estimating dynamics of approach of the real-time air flow rate in the tunnel to the maximum possible value at limited running time of the train in the tunnel and subject to the tunnel length and the train speed.
In the calculation, the tunnel is 15343 m long, the train is 1100 m long and the train speed is 75 km/h (20.8 m/s). It is assumed that the tunnel and train have equivalent hydraulic diameters of 7.8 and 3.9 m, respectively. The roughness of the tunnel walls is 0.01 m. The input data conform with the parameters of the Severomysky Tunnel of the Baikal–Amur Railway [12]. The air flow rates in the tunnel are measured in two model cross-sections: in the tunnel and in the tunnel clearance. The stationary value is denoted a stat.

The air flow rate due to piston effect in the tunnel is calculated in three variants: 1—the train enters the tunnel and runs at the zero initial air velocity in the tunnel; 2—the trains runs in the tunnel soon after another train has passed in the same direction, and the air flows in the same direction; 3—the trains runs in the tunnel soon after the opposite train has passed, i.e. the air flow is directed towards the model train.

**Variant 1.** The train moves in the tunnel at the zero initial flow velocity in the tunnel (Figure 1). Such working conditions are possible when the first train after repair shift is passed through the tunnel. It is seen that the moving train accelerates air in the tunnel while the air flow rate in the tunnel clearance essentially lowers. It is interested that the air flow is accelerated up to the hypothetically reachable maximum. Thus, in the quasi-dynamic calculations of static air distribution using a network model, it is possible to use the piston effect model with the train representation as a combination of permanent fans with the assigned clearance resistance [5, 6] at the floating error not higher than 25% for Variant 1 at the zero initial air velocity in the tunnel. The error is determined as a ratio of \( \text{area difference} \) to \( \text{area} \) (Figure 1). Physically, the areas of these figures are equal to the air volume passed through the tunnel under piston effect during the train pass. In Figures 1–4, tonnel stands for the tunnel, zazor means the tunnel clearance; zazor stat and tonnel stat curves show the hypothetically minimum air flow rate in the tunnel clearance and the hypothetically maximum air flow rate in the tunnel, respectively.

![Figure 1. Air flow rates in tunnel during train run at zero initial air velocity.](image)

After the train pass, in the time span before another train enters the tunnel, the accelerated air flow gradually decelerates under the action of viscous friction forces. Figure 2 illustrates deceleration dynamics of air flow in 15 min, which conforms to the traffic frequency of four trains per hour. The initial flow rate in the tunnel is assumed from the calculation of Variant 1 (Figure 1).

![Figure 2. Air flow dynamics in tunnel after train pass.](image)
Variant 2. In case of high traffic frequency, every next train enters the tunnel where the air flow accelerated by the previous train has no time to decelerate down to sufficiently low value to be neglectable. Figure 3 shows the calculated air flow rates in the tunnel entered by a train 900 s after the previous train left (4 pairs of trains an hour). Given the train-side air flow velocity, the air flow rate dynamics is much higher than in Figure 1, and the error of the quasi-dynamic model in the static air distribution network computation goes beneath 10%. The error is determined in the same way as in Variant 1.

![Figure 3](image3.png)

**Figure 3.** Air flow rate in tunnel during train run at side initial air flow velocity.

At the traffic frequency of 6 trains an hour, there is minimum one train in the tunnel any time, and there can be two trains in the tunnel sometimes, when one train enters the tunnel via the western face and another trains leaves the tunnel via the eastern face. In this case, air flow never decelerates as it has no time for that. The traffic frequency of 6 trains per hour is the standard estimate for the Severomuysky Tunnel, such the said air distribution mode is the standard working conditions in this tunnel. The error of the quasi-dynamic network modeling is decreased down to a negligible value.

Variant 3. Let us discuss the reverse motion in the tunnel when one train enters the tunnel via one face soon after another train has left the tunnel via the other, opposite face. In this case, the air flow is directed oppositely to the train, and, to become co-directed with the train, air flow is to overturn. The calculation results are shown in Figure 4. The initial air flow rate in the tunnel has a negative value, i.e. the air flow has an opposite direction relative to the train motion. However, the dynamics of change in the air flow rate is much higher than at the zero and nonzero initial c-directed air flow velocities, and the co-directed air flow rates reaches the maximum values much faster. The calculation error without regard to the dynamics is 19.5%.

![Figure 4](image4.png)

**Figure 4.** Air flow rate in tunnel during train run at opposite initial air flow velocity.

3. Conclusions

The quasi-dynamic modeling of settled air distribution in a long railway tunnel produces erroneous air exchange estimates. The error can reach 25% in one train pass in different working conditions of the
tunnel. In the one-way (standard) regime of the tunnel operation, the error is not higher than 10%, which allows using this model in the tunnel ventilation design.

**Acknowledgements**
The study was supported in the framework of R&D Project No. AAAA-A17-117091320027-5.

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