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RESISTANCE FORCES WHEN DRIVING A PASSENGER CAR

The discrepancy between the calculated and experimental values of vehicle drag force in the 30–160 km/h range is explained by the use of a constant exponent, $\alpha = 2$, in the aerodynamic drag formula. Based on road tests, an average $\alpha(v)$ relationship was obtained, with a minimum $\alpha = 1.98$ at around 120 km/h and a maximum $\alpha = 2.15$ at around 33 km/h. Including a variable α reduces the discrepancy by a factor of 5–10, increasing the accuracy of modeling and fuel consumption calculations.

Factor analysis revealed that the main differences between the calculated and experimental forces are due to imperfections in the aerodynamic drag model, especially during the transition from laminar to turbulent flow. Other factors—vehicle vibrations, H/B ratio, final drive ratio, and tire profile—have a significantly lesser influence. Aerodynamics is the most important factor: the C_x and $C_x \cdot F$ indices have virtually equal influence.

The average $\alpha(v)$ relationship is similar for all vehicle categories, although significant variability remains within each group. The introduction of variable α significantly reduces the discrepancies between theory and experiment, enabling more accurate calculations and predictions of vehicle dynamics. This allows engineers to adjust computational models, take real-world aerodynamic effects into account during design, and assess the impact of speed on air resistance. This approach also provides a basis for optimizing body and chassis design aimed at reducing fuel consumption and improving vehicle efficiency in real-world driving conditions. Furthermore, the use of variable α helps identify critical speed ranges where air resistance has the greatest impact on vehicle dynamics and can serve as a starting point for further research into improving vehicle aerodynamics and energy efficiency.

Key words: car, wheel, resistance, aerodynamics, air resistance.

INTRODUCTION

Modern automotive development is characterized by a strong focus on reducing greenhouse gas emissions, which is directly related to lower fuel consumption. Even a reduction in fuel consumption by a few tenths of a liter per 100 km is considered significant. One of the primary ways to achieve this goal is by reducing the drag that occurs when the vehicle is moving. At medium and high speeds, air resistance has the greatest impact. In production vehicles, its value becomes comparable to rolling resistance at speeds of approximately 70–75 km/h, and significantly exceeds it at higher speeds (approximately 3–4 times at speeds of 130–150 km/h). Therefore, improving the accuracy of aerodynamic drag measurement and calculation methods is an important engineering challenge.

ANALYSIS OF LITERARY DATA AND PROBLEM STATEMENT

A generally accepted formula is used to determine the aerodynamic drag force:

$$P_w = k * F * v^2 / 3,6^2 \quad (1)$$

where k is the streamlining coefficient, $N \cdot s^2 \cdot m^{-4}$; $k = 0.5 C_x \cdot \rho_v$ (where C_x is the aerodynamic drag coefficient and ρ_v is the air density, kg/m^3); F is the vehicle's frontal area, m^2 .

However, as noted in [1, 2], the results of calculations using this formula do not completely coincide with road test data. In some cases, the discrepancies are quite significant, with the greatest difference observed at speeds above 80–100 km/h (Fig. 1).

According to the analysis given in source [1], the main reason for the observed discrepancies is related to the use of an overly simplified aerodynamic drag model.

Two possible hypotheses were put forward: a change in the value of the coefficient C_x and a change in the exponent at a speed equal to "2". The choice between them is determined by how the coefficient C_x is interpreted.

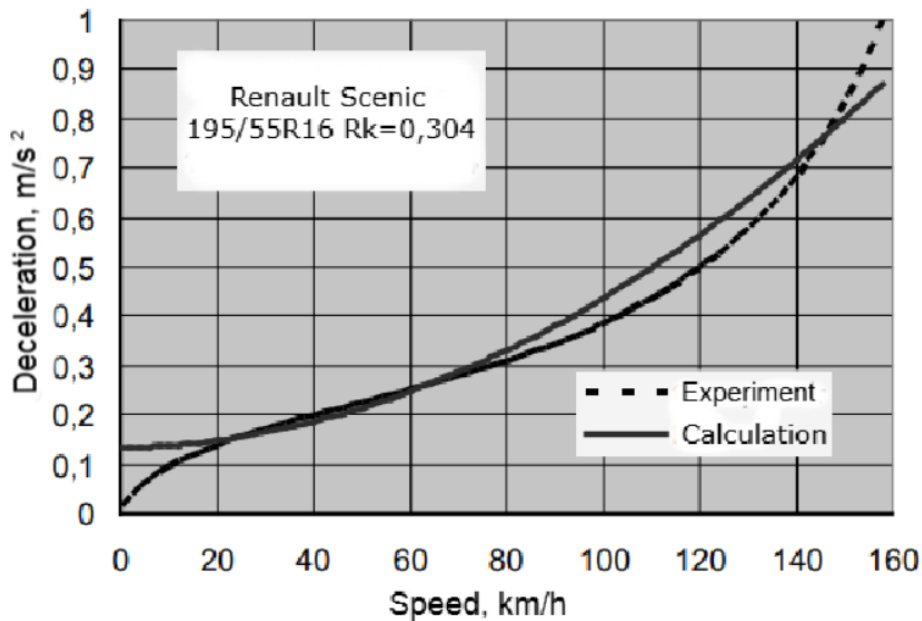


Fig. 1. Analysis of the influence of factors on the differences between calculated and experimental resistance forces.

AIM AND TASKS OF THE RESEARCH

If the coefficient C_x is considered a constant characteristic of an object, determined solely by its shape and surface condition, then the hypothesis of variability of the exponent with velocity should be accepted. In the example given in [1], the value of this exponent ranges from 1.95 to 2.1.

If the coefficient C_x is treated not as an intrinsic property of the object, but as the result of mathematical transformations, that is, as a variable quantity, its value can vary between 0.3 and 0.5. However, this option is considered less likely.

The first hypothesis appears preferable, as it allows for a more unambiguous explanation of the phenomenon under consideration and requires less variability in the calculated exponent. Furthermore, this approach better reflects the complexity of the processes occurring in the transition region from laminar to turbulent flow, where existing theoretical models do not provide high estimation accuracy.

We were unable to find any data in the available publications that would confirm or refute this hypothesis as it applies to automobiles (with the exception of outdated information discussed in [1]). However, this view is generally accepted in a number of other fields.

RESEARCH RESULTS

For example, when calculating the deceleration of a bullet in flight, R [3], the following formula is used:

$$R = A * v^m \quad (2)$$

In this formula, the exponent m varies significantly depending on speed and can take values in the range of 1.5 to 3. For speeds from 0 to 840 ft/s (i.e., 0–256 m/s), the average value $m = 1.6$ is given.

In [4], devoted to studying air resistance during a body's fall at low speeds, an exponent of 2.5 was obtained, while other studies by the same author provide a value of 2.7.

In [7], based on a large number of examples, the discrepancies between calculated and experimentally obtained values of drag (ΔF) were examined, and empirical formulas for corrections to standard calculation methods were proposed. However, an analysis of the factors causing these discrepancies was not conducted in this study.

To improve the accuracy of traction and speed calculations by refining mathematical models of vehicle drag, several problems must be addressed:

- analyze the factors causing differences between calculated and experimental drag values;
- develop empirical relationships suitable for the practical determination of vehicle drag forces in the speed range of 30–160 km/h;
- determine the average dependence of the exponent in the aerodynamic drag formula on vehicle speed.

The study analyzed a set of field test results published in Autoreview magazine and processed using the methodology of [6, 7]. Methods applied in experimental design theory [5] were used in data processing.

The set of factors was formed based on parameters available in publicly available vehicle specifications and specialized literature. Since the driving conditions under consideration are dominated by air resistance, aerodynamic parameters were chosen as the primary factors: the aerodynamic drag coefficient C_x and the product $C_x \cdot F$ (sometimes referred to as the "effective drag area" or "drag area").

The second most significant source of additional drag was vehicle oscillations, determined by suspension characteristics and geometric design parameters, in particular the ratio of the center of mass height h_c to the wheelbase B . It is this ratio, all other things being equal, that influences the oscillations of the sprung mass, leading to additional energy losses in the shock absorbers and tires.

Since suspension parameters and the value of h_c are typically not available in publicly available vehicle specifications, the overall vehicle height H was used instead of the center of mass height, assuming a certain correlation between these quantities.

The next factor was the final drive ratio u_0 . As this parameter increases, the influence of the transmission's idle resistance on vehicle coasting increases. Finally, the influence of tires was taken into account using the aspect ratio (AFR). All factors considered were converted to relative values ranging from 0 to 5.

The most significant factor (Fig. 2) was the vehicle's aerodynamic characteristics. The C_x and $C_x \cdot F$ product have virtually equal influence, allowing either to be used in the calculations. The second most influential parameter is the H/B ratio.

The remaining factors have a significantly lesser impact. An unexpected result was the negative influence of the final drive ratio, while the tire aspect ratio, on the contrary, showed a positive effect. Clearly, these factors require a more detailed analysis.

In general, it is possible to approximate the correction to the calculated values using the following empirical relationship:

$$\sum A = 96 + 102(C_x F - 0,83) - 130\left(\frac{H}{B} - 0,56\right) \tag{3}$$

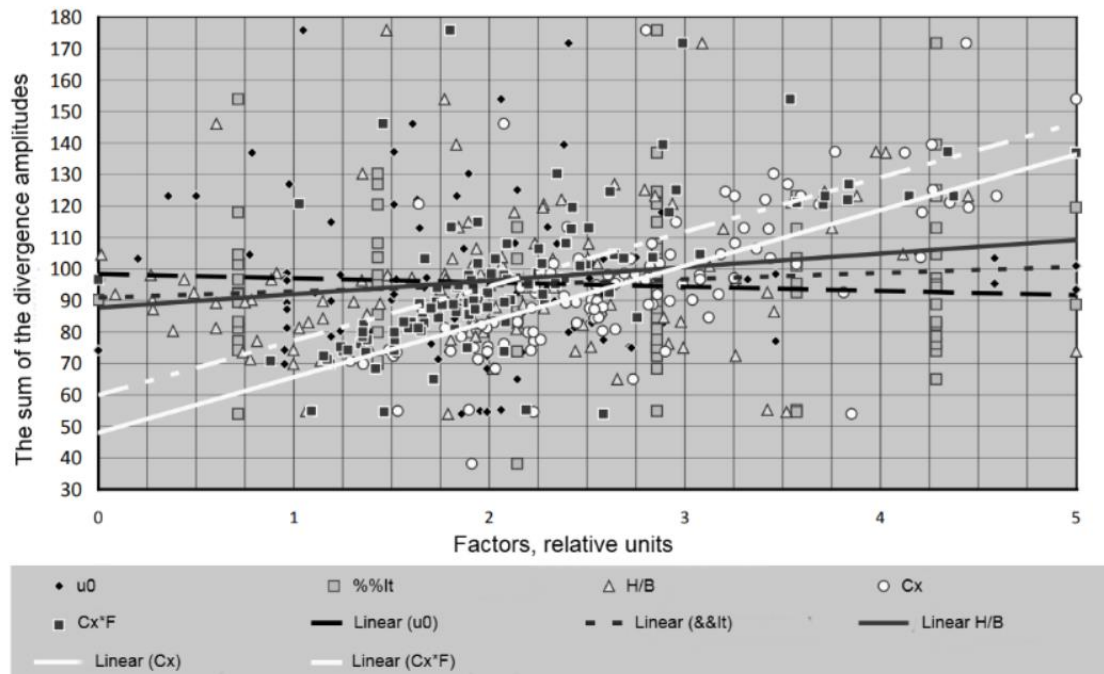


Fig. 2. Analysis of the influence of factors on the differences between calculated and experimental resistance to movement

DISCUSSION OF THE RESEARCH RESULTS

As noted in [1], a hypothesis was put forward regarding the variability of the exponent α in the aerodynamic drag formula, and its possible dependence on speed was demonstrated using the example of a

Ford Mondeo sedan coasting. Using the above-described experimental data set, similar calculations were performed and the $\alpha(v)$ dependencies were analyzed for 96 passenger cars.

The nature of the resulting dependencies was similar for all vehicles; however, the variability of the exponent, especially at low speeds, remained significant (Fig. 3, A).

An attempt to classify the data set by the H/B ratio did not yield the expected result: the variability of α in each category remained high. Nevertheless, the average $\alpha(v)$ dependencies for all vehicles were quite close to each other (Fig. 3, B).

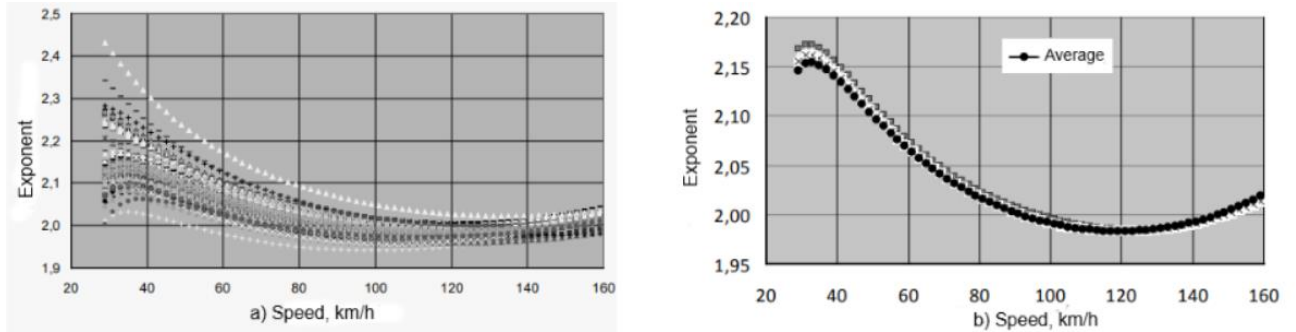


Fig. 3. A) Variation in the calculated dependence $\alpha(v)$ for different vehicles; B) Calculated dependencies $\alpha(v)$ by vehicle groups and average

Therefore, the exponent value was averaged for all vehicles. The resulting average curve practically coincides with the curve for the largest category. The section of the dependence in the speed range from 29 to 160 km/h is well approximated by a sixth-degree polynomial.

$$\begin{aligned}
 n = & -1,074 * 10^{-12} * V^6 + 6,596 * 10^{-10} * V^5 - \\
 & 1,628 * 10^{-7} * V^4 + 2,053 * 10^{-5} * V^3 - \\
 & 1,359 * 10^{-3} * V^2 + 4,101 * 10^{-2} + 1,719
 \end{aligned}
 \tag{4}$$

The variable exponent was then included in the generally accepted aerodynamic drag formula, and the difference between theoretical and experimental drag values for several examples was calculated using the adjusted model.

As the diagrams in Figure 4 show, this difference was significantly reduced—by a factor of 9 for the Mazda 6 and by a factor of 7 for the Ford C-Max.

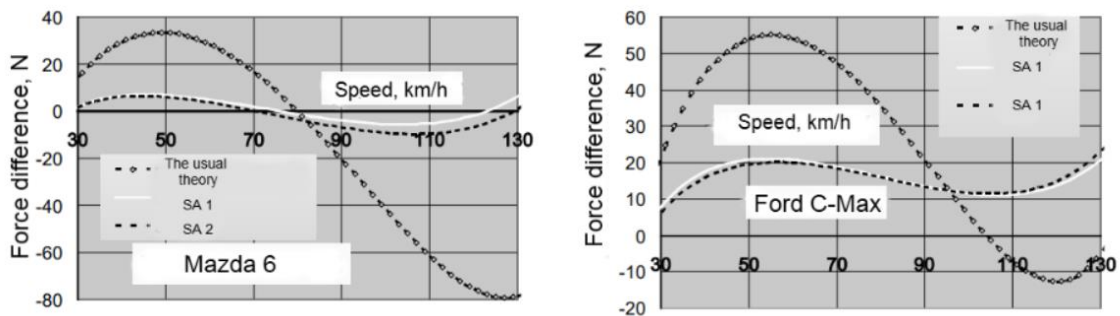


Fig. 4. Discrepancy between experimental and theoretical values of the drag forces of a passenger car when calculated using conventional theory, using a model with variable $\alpha(v)$ for a given category (SA 1), and using an overall average $\alpha(v)$ for all categories (SA 2)

CONCLUSIONS

The final decision on whether to consider the C_x coefficient or the velocity exponent α as the variable should rest with aerodynamicists. Any aerodynamic test can, with virtually no additional cost,

simultaneously record airflow velocity and air resistance after the fan is turned off. Analyzing large volumes of such data will deepen our theoretical understanding of the process.

For automotive and transportation engineers, as well as specialists in applied automotive science, practical certainty is important. In this context, the most convenient option is to use a constant C_x coefficient for a specific vehicle and a variable α exponent for all vehicles.

Factor analysis revealed that the main discrepancies between the calculated and experimental values of drag force in the speed range of 30–160 km/h are primarily due to the imperfections of the mathematical model of aerodynamic drag in laminar-turbulent flow around a vehicle. The influence of the other factors considered was significantly weaker.

Based on the conducted research, an empirical relationship was derived that allows for the calculation of a correction to the standard calculation of the resistance forces to vehicle movement at the specified speeds.

The average dependence of the exponent α in the aerodynamic drag formula on speed, $\alpha(v)$, was estimated and approximated. Calculations taking variable α into account reduced the discrepancies between calculated and experimental values of the drag force during vehicle coasting by a factor of 5-10, indirectly confirming the hypothesis of the variability of the exponent α .

Moreover, the average dependence $\alpha(v)$ is virtually identical for different vehicle categories, although its variability remains significant within each category.

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Ю.В. Зибцев, П.А. Ворошилов. Сили опору під час керування легковим автомобілем.

Розбіжність між розрахунковими та експериментальними значеннями сили опору транспортного засобу в діапазоні 30–160 км/год пояснюється використанням постійного показника степеня, $\alpha = 2$, у формулі аеродинамічного опору. На основі дорожніх випробувань було отримано середнє значення залежності $\alpha(v)$ з мінімальним значенням $\alpha = 1,98$ на швидкості близько 120 км/год та максимальним значенням $\alpha = 2,15$ на швидкості близько 33 км/год. Включення змінної α зменшує розбіжність у 5–10 разів, підвищуючи точність моделювання та розрахунків витрати палива.

Факторний аналіз показав, що основні відмінності між розрахунковими та експериментальними силами зумовлені недосконалістю моделі аеродинамічного опору, особливо під час переходу від ламінарного до турбулентного потоку. Інші фактори — коливання транспортного засобу, коефіцієнт H/B , передаточне число головної передачі та профіль шин — мають значно менший вплив. Аеродинаміка є найважливішим фактором: індекси C_x та $C_x \cdot F$ мають практично однаковий вплив.

Середнє значення залежності $\alpha(v)$ подібне для всіх категорій транспортних засобів, хоча значна мінливість залишається в межах кожної групи. Введення змінної α значно зменшує розбіжності між теорією та експериментом, що дозволяє здійснювати точніші розрахунки та прогнози динаміки

транспортного засобу. Це дозволяє інженерам коригувати обчислювальні моделі, враховувати реальні аеродинамічні ефекти під час проектування та оцінювати вплив швидкості на опір повітря. Цей підхід також забезпечує основу для оптимізації конструкції кузова та шасі, спрямованої на зменшення витрати палива та підвищення ефективності транспортного засобу в реальних умовах руху. Крім того, використання змінної α допомагає визначити критичні діапазони швидкостей, де опір повітря має найбільший вплив на динаміку транспортного засобу, і може служити відправною точкою для подальших досліджень щодо покращення аеродинаміки та енергоефективності транспортних засобів.

Ключові слова: автомобіль, колесо, опір, аеродинаміка, опір повітря.

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