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Łukasz GRABOWSKI [0000-0003-3069-8860]*, Arkadiusz DROZD**,
Mateusz Marcin KARABELA [0009-0003-0215-6252]**,
Wojciech KARPIUK [0000-0002-3690-4605]***

AERODYNAMIC AND ROLLING RESISTANCES OF HEAVY DUTY VEHICLES. SIMULATION OF ENERGY CONSUMPTION

Abstract

The main objective of the work was to develop a comprehensive model of energy consumption simulation of heavy duty vehicles using the VECTO simulation tool. The research issue was the impact of aerodynamic drag and rolling resistance on fuel consumption and emissions under various driving conditions described in four driving cycles: Urban Delivery, Regional Delivery, Urban, and Suburban. Each cycle differed in driving time, distance and average speed to represent different operational scenarios. The methodology involved defining vehicle parameters such as weight, aerodynamic coefficients and tyre rolling resistance. The main findings show that the impact of both aerodynamic drag and rolling resistance on fuel consumption can be efficiently modelled. It has been proven that the proposed modifications to aerodynamic drag and rolling resistance can reduce fuel consumption by more than 8%. The lowest fuel consumption was achieved in the Regional Delivery cycle, while the Urban cycle had the highest fuel consumption due to frequent vehicle stops. The results show that optimization of vehicle design and its performance can significantly improve energy efficiency and reduce emissions. A computational modelling tool such as VECTO can contribute to sustainable transport solutions and improve the efficiency of heavy duty vehicle.

1. INTRODUCTION

Modern computer techniques and modelling play a key role in the analysis of energy transformations in vehicle powertrains. They enable a detailed understanding and optimization of these processes, which is essential for improving vehicle energy efficiency and reducing emissions (Na & Cebon, 2022), (Di Pierro et al., 2024).

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[*] Lublin University of Technology, Faculty of Mechanical Engineering, Department of Engineering Thermodynamics, Fluid Mechanics and Aviation Propulsion Systems, Poland, l.grabowski@pollub.pl
[**] Graduate, Lublin University of Technology, Faculty of Mechanical Engineering, Poland
[***] Poznan University of Technology, Faculty of Civil Engineering and Transport Institute of Combustion Engines and Powertrains, Poland, wojciech.karpiuk@put.poznan.pl

The dynamic modelling of drive systems allows the simulation of real operating conditions of engines and other drive elements of vehicles. The use of advanced algorithms and computational techniques makes it possible to accurately predict the performance of the powertrain under various operating conditions. The analysis of energy transformations in propulsion systems is crucial for understanding how energy is transformed and used in a vehicle (Colucci et al., 2023), (Krause et al., 2023), (De Robbio et al., 2022). Computer techniques allow modelling of these processes with high precision, which enables optimization of the drive system design in terms of energy efficiency. The models take into account, among other things, energy losses due to friction, aerodynamic drag and energy efficiency of individual components. Computer simulation of drive systems allows testing various design solutions without the need to build physical prototypes

An example is an article (Eswaranathan et al., 2024) describing research on the main factors influencing carbon dioxide emissions from passenger vehicles in Sri Lanka. The study combines system dynamics modelling with decomposition analysis to identify and assess the impact of various factors on the energy efficiency of vehicles. Data on petrol, diesel and electric vehicles registered in 2015-2019 were analysed. In his work (Zhang et al., 2019) he described the development of a model for analysing the energy consumption of electric vehicles (EVs) and the assessment of energy efficiency in various operating conditions. Modelling results showed that different driving cycles (e.g. urban and motorway) have a different impact on energy consumption, with the motorway driving pattern being characterised by higher energy demand due to higher air and rolling resistance at higher speeds.

The following software is most often used for modeling combustion engines: AVL CRUISE, GT-SUITE, VECTO or MATLAB/Simulink, which, although not typically used for engine applications, is eagerly used by engine researchers. The software is commonly used to simulate and analyse the operation of internal combustion engines, hybrid and electric systems. With these tools, detailed analyses of energy efficiency, fuel consumption and exhaust emissions under different operating conditions can be carried out.

AVL CRUISE software enables modelling and simulation of vehicle propulsion systems. It is used to analyse and optimise the performance of engines, driveline systems and support systems, such as energy recovery systems. AVL Criuse has been used, among other things, to model the energy efficiency of an electric vehicle with extended range (Wahono et al., 2015). Power unit components such as battery, electric motor, and generator were modelled and calculations were carried out for Japan 08 and NEDC driving cycles. It was shown that the use of the range extension system resulted in a dozen percent increase in the road travelled by the vehicle.

GT-SUITE is a comprehensive multi-physics modelling tool that allows the simulation of entire propulsion systems, including engines, turbochargers, exhaust systems and cooling systems. It allows analysis of the influence of various design parameters on the energy efficiency of the vehicle. Md. Nurun Nabi et al. developed a thermodynamic model of combustion, performance and emissions with reference diesel and methanol, ethanol and hydrogen using the commercial GT-SUITE software. The diesel and two alcohol blends (10% methanol–90% diesel, and 10% ethanol–90% diesel) were directly injected into the cylinder, while hydrogen was fumigated at the inlet port. In addition to engine performance, the use of GT-SUITE allowed for the estimation of exergy and energy indicators for four fuels.

Another example is the opensuorce software VECTO (Vehicle Energy Consumption Calculation Tool). It is a tool developed by the European Commission for the precise determination of CO2 emissions and fuel consumption of vehicles under simulated driving conditions (Grabowski, 2021). VECTO takes into account different technical and operational aspects, allowing for a more accurate assessment of the energy efficiency of vehicles and support in regulatory and certification processes. An exemplary application is included in papers (Di Pierro et al., 2024; Seo & Park, 2023; Broekaert et al., 2021).

The work (Broekaert et al., 2021) analysed waste heat recovery from lorries using a Rankine cycle (ORC). Tests were carried out on a class 5 heavy duty vehicle with an ORC system. Tests showed that heat recovery reduced fuel consumption by 3.1% in the WHVC cycle, 2.5% in the RDC cycle and 1.9% in real driving. No significant reductions in pollutant emissions were observed. VECTO accurately calculated fuel consumption with an error in the range of 0.5 – 1.5% for single drives and less than 0.5% for repeat averages.

The paper (Fontaras et al., 2013) describes the development of the VECTO simulation tool for monitoring CO2 emissions and fuel consumption of heavy goods vehicles in Europe. The tool uses input data such as vehicle weight, air drag, tyre rolling resistance and engine torque maps. Simulations showed that the tool accurately predicts fuel consumption, enabling certification of vehicles in terms of CO2 emissions and fuel consumption. Tests confirmed simulation accuracy with error below +-4% for individual test cycles.

The subject of model research is also the energy efficiency of vehicles (Basma et al., 2022), (Tong et al., 2021). Road transport is an important element of modern logistics, and its energy efficiency has a direct impact on operating costs and the environment. Heavy goods vehicles, which are responsible for a large part of freight transport, play an important role in exhaust emissions and fuel consumption. Understanding and improving the energy efficiency of these vehicles is important to ensure the sustainable development of road transport.

The energy efficiency of heavy goods vehicles depends on a number of factors, including vehicle design, driving conditions and the propulsion technologies used (Qiu et al., 2022). Diesel-powered lorries are highly energy efficient, but these engines generate higher emissions of nitrogen oxides and particulate matter (Bajerlein et al., 2024).

Continuous learning and improvement of energy transformation processes in heavy goods vehicles is crucial for the sustainable development of road transport. Computer techniques such as modelling with the certified software such as AVL CRUISE or VECTO, enable efficient and accurate evaluation of fuel consumption and exhaust emissions. They reduce costs and time for experimentation, helping to accelerate innovation in the automotive industry. Computer and modelling techniques are essential for the analysis and optimisation of energy transformations in the propulsion systems of vehicles. They enable the understanding of processes occurring in drive systems. They allow for the analysis of the impact of individual parameters on fuel consumption and exhaust emissions. At the same time, computer simulations are less costly and time-consuming than road experiments, allowing more design iterations and optimising vehicle design.

Therefore, the purpose of this article was to develop a truck model in VECTO software and conduct a study of the effects of rolling resistance and air resistance on fuel energy consumption. The study aimed to simulate real operating conditions and accurately determine the energy efficiency of the vehicle under different scenarios. Energy efficiency is expressed in kilowatt-hours of energy contained in fuel per kilometre of road travelled.

2. ANALYSIS OF FORCES ACTING ON THE VEHICLE

The basic driving force is the driving force acting on vehicle wheels. Depending on the circumstances, while driving downhill, the positive force will be the force of fall. In the case of a vehicle run-off, the positive forces are those resulting from the inertia of rotating masses. Braking forces of the vehicle are due to the internal resistance of the propulsion system, the forces absorbed by the inertia of the rotating masses during acceleration, rolling resistance, air resistance, and hill resistance.

The net driving force (Fn_d) is the difference between the driving force) and the sum of the resistance forces. This formula can be as follows:

$$Fn_d = F_d - F_{rr} - F_{ror} - F_{ar} - F_{ilr} - F_{ir} \tag{1}$$

where F_d is the driving force, F_{rr} is the rising resistance force, F_{ror} is the rolling resistance force, $F_{ar}$is the air resistance force,F_{ilr} is the internal resistance force, and F_{ir} is the inertia resistance force.

The uphill resistance force$(F|⬚|rr)$ is determined by the mass of the vehicle (m), the acceleration of the ground (g) and the angle of inclination of the road (α):

$$F_{rr} = m * g * ctg\alpha \tag{2}$$

The rolling resistance force (F_{ror}) is determined by the mass of the vehicle (m), the standard acceleration of gravity (g) and the rolling resistance coefficient (f):

$$F_{ror} = m * g * f \tag{3}$$

The air resistance force (F_{ar}) is expressed as the product of the air resistance coefficient (C_x), the front surface area of the vehicle (A), the air density (ρ) and the square of the vehicle relative speed (v_w^2):

$$F_{ar} = \frac{C_x * A * \rho * v_w^2}{2} \tag{4}$$

The internal resistance force) is expressed as the ratio of the sum of the internal resistance moments (M_{ilr}) to the radius of the dynamic wheel ($R|⬚|d$):

$$F_{ilr} = \frac{M_{ilr}}{R_d} \tag{5}$$

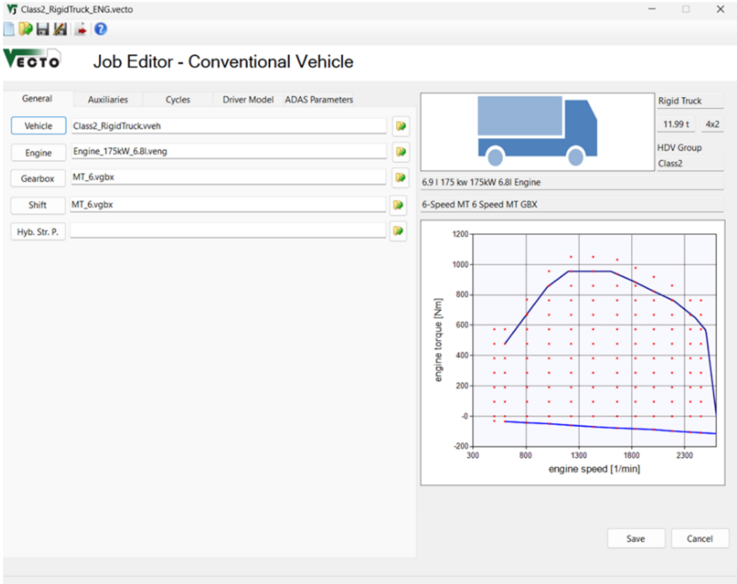
The inertial resistance force (F_{ir}) is expressed as the product of the reduced mass factor (δ), the vehicle weight (Q), the standard acceleration of gravity (g) and the speed derivative versus time ($\frac{dV}{dT}$):

$$F_{ir} = \delta \frac{Q}{g} \frac{dV}{dT} \tag{6}$$

These formulas are used to determine the energy required to propel a vehicle and, consequently, to calculate fuel consumption and carbon dioxide emissions. If these parameters are well understood, the energy efficiency of vehicles can be better managed and their impact on the environment can be minimised. They are also used in the process of modelling fuel consumption in vehicles.

3. FUEL CONSUMPTION MODEL ASSUMPTION

One of the simulation tools for modelling fuel consumption and energy efficiency described in the introduction is VECTO. This open source tool can simulate fuel consumption and CO_2 emissions of vehicles above 3,500 kg. It is written in the C programming language. VECTO was initially intended to serve as a platform for customers to check and verify the fuel consumption and carbon dioxide emissions of purchased vehicles. However, in accordance with the European Commission Regulation No. 2017/2400, a testing methodology based on VECTO (Joint Research Centre et al., 2021) was created. This methodology takes into account the diversity of the heavy-duty vehicle sector and the high degree of personalisation of individual vehicles. Since 1 January 2019, VECTO has become an essential tool for obtaining an EU vehicle type-approval certificate for newly built vehicles with a DMC above 3,500 kg. Figure 1 shows the VECTO window. This window contains links to individual submodels of the engine vehicle, the gearbox.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Rigid Truck
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4x2
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6.9 l 175 kw 175kW 6.8l Engine
6-Speed MT 6 Speed MT GBX

Fig. 1. VECTO window

The object of the simulation tests was a 4x2 lorry. Such an axle configuration means that the vehicle has two axles and the rear one is the driving axle. The vehicle is equipped with a drive unit generating 175 kW with an engine capacity of 6,800 cm^3. The vehicle's engine is powered by diesel fuel. A 6-speed gearbox was used in the vehicle. The maximum load capacity is 5,430 kg and the permissible gross vehicle weight is 12,000 kg. The road-legal vehicle corresponding to the VECTO model vehicle is the Mercedes-Benz ATEGO 1224.

Besides the possibility of mathematically described energy processes that occur in the vehicle, VECTO also contains recorded driving cycles. The driving cycle is a recording of speed profiles of the object's slope as a function of time. Four driving cycles, i.e

1. Cycle Urban Delivery
2. Regional Delivery
3. Urban
4. Suburban

were selected to run a simulation to test the energy efficiency of a heavy vehicle. The Urban Delivery cycle lasted 3,224 seconds and had a distance of 27.8 km. The average speed achieved by the vehicle then was 31 km/h. The second cycle was the Regional Delivery cycle which lasted 1,567 seconds, and the vehicle covered a distance of 25.8 km. The average speed achieved during this cycle was 59.3 km/h. The Urban cycle was the longest cycle, i.e. 8.333 seconds. At that time, the vehicle traveled a distance of 39.6 kilometers and reached an average speed of 17.1 km/h. The last driving cycle was the Suburban cycle of 3.171 seconds. In the Suburban cycle, the vehicle covered a distance of 23.5 km with an average speed of 26.7 km/h. The speed and slope time courses for each cycle are shown in Annex 1.

The first step in the simulations was to determine the basic vehicle parameters such as mass, air drag coefficient, front surface of the vehicle and density of the medium the vehicle moves in. Then, the driving cycles were selected. In the first cycle, the test vehicle was unladen so its a mass was 6,570 kg. The air density during the simulation was 1.188 kg/m^3. The vehicle tyres were 235/75 R17.5 for the front axle and 265/75 R17.5 for the driving axle.

One of the important factors affecting fuel consumption is air drag. In the VECTO tool, the air drag value is calculated from the cross-section of the front surface of vehicle A and the coefficient C_x. The standard calculated product of $C_x \cdot A$ for the lorry under test is 4.06 m^2. In order to reduce air resistance, fairings are most commonly fixed above the driver's cab to reduce the surface angle of attack of the front of the trailer above the tractor outline. Other ways to reduce air resistance can be to remodel the shape of the cabin so that it has as few as possible surfaces perpendicular to the direction of driving. A less costly procedure and still measurably beneficial may be to replace standard mirrors by cameras monitoring the area around the lorry. There are many methods, both analytical and experimental, for determining the drag coefficient. Examples of research results in this field are included in the papers (Czyż et al., 2018a; 2018b). In this article, due to the scope of the planned work, the literature value for a typical truck (Bayındırlı et al., 2016) was used. For the calculation it was assumed that the air coefficient CX is equal to 0.7.

For the purposes of this study, the $C_x \cdot A$ ratio was reduced by 10%. A 10% reduction in the drag coefficient is possible by installing cab fairings and a deflector. For example, results in this area are included in the paper (Khosravi, et al., 2015). The simulation was also carried out on a vehicle with a gross vehicle weight (GVW) 5430 kg, the total weight of which was 12,000 kg. The remaining vehicle parameters left unchanged as in the previous simulation.

Another important factor affecting vehicle energy consumption is rolling resistance. There are two axles, i.e. steering and driving in the 4x2 vehicle under test. Double 265/70 R19.5 tyres are fitted on the driving axle, whereas 235/70 R19.5 tyres on the front axle. For the simulation, certain changes were made to the rolling resistance coefficient of the tyres used. In accordance with ISO 28580, a Rolling Resistance Coeficient (RRC) has been established for all tyres which is the border value for the ties with the lowest rolling resistance. A further set of simulations was carried out for an RRC of 8 which is the border value for graded tyres with the highest rolling resistance. The energy loss is the difference between the energy transferred from the vehicle to the tyre and the amount of energy required to roll the tyre.

4. RESULTS AND ANALYSIS OF SIMULATION TESTS

This chapter presents an analysis of the findings on the impact of rolling resistance and air resistance on the fuel consumption of heavy goods vehicles. The research covered different vehicle configurations and different road conditions to comprehensively evaluate the impact of resistance on fuel consumption. All results took into account the unladen mass of the vehicle (6570 kg) and the vehicle mass including gross vehicle weight (12000 kg).

The basis for the simulation were the results presented in Table 1, where the vehicle's standard air resistance coefficient and standard rolling resistance coefficient were used.

Table 2 shows the effect of the reduced aerodynamic resistance coefficient on fuel consumption, whereas Table 3 shows the effect of the reduced rolling resistance on fuel consumption. Figures 2 and 3 illustrate the examples of the instantaneous fuel consumption in the simulated route.

Tab. 1. Fuel consumption depending on cycle and load with standard air resistance and rolling resistance forces

Driving cycle	Mass of vehicle [kg]	Consumed fuel [g]	Average combustion [g/km]	Travelled distance [km]	Highest instantaneous fuel consumption [g/s]
Urban Delivery	6,570	4,400.2	158.28	27.8	8.20
	12,000	5,958.1	214.32		9.77
Regional Delivery	6,570	3,808.8	147.63	25.8	8.14
	12,000	4,706.7	182.43		9.77
Urban	6,570	8,441.6	213.17	39.6	7.10
	12,000	11,600.1	292.93		9.77
Suburban	6,570	4,271.7	181.77	23.5	6.12
	12,000	6,159.7	262.11		9.77

The research was based on the simulations of fuel consumption in various driving cycles. Parameters such as vehicle mass, air resistance coefficient (C_x), front surface of the vehicle were analysed. The simulations included four described in the chapter 3 driving cycles: Urban Delivery, Regional Delivery, Urban and Suburban.

The examples of the calculation results are given in Figures 2 and 3. The article presents only selected results of calculations, because detailed results would not show significant differences, which are crucial for research analysis. Therefore, representative examples are presented to illustrate the processes discussed.

Figure 2 shows the fuel consumption as a function of time for the Regional Delivery cycle of the unladen vehicle and with reduced air resistance. The graph shows how the fuel consumption changes at different times, reflecting different phases of the driving cycle. The graph shows the variability of fuel consumption over time depending on the instantaneous values of vehicle load, with a number of maximum values reaching 7-8 g/s. Figure 3 illustrates the fuel consumption as a function of time in the Regional Delivery cycle for a vehicle without load and with reduced rolling resistance. As in Figure 2, this chart shows the changes in fuel consumption at different times in the driving cycle, but under different resistance conditions. Fuel consumption varies from around 137.33 g/km for light vehicles in the Regional Delivery cycle to as much as 277.89 g/km for heavy vehicles in the Urban cycle.

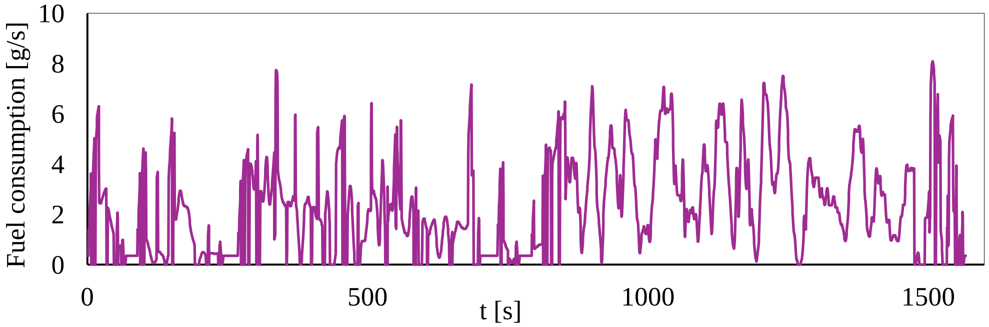

Fig. 2. Fuel consumption vs. time for the Regional Delivery cycle for an unladen vehicle and with a reduced air resistance

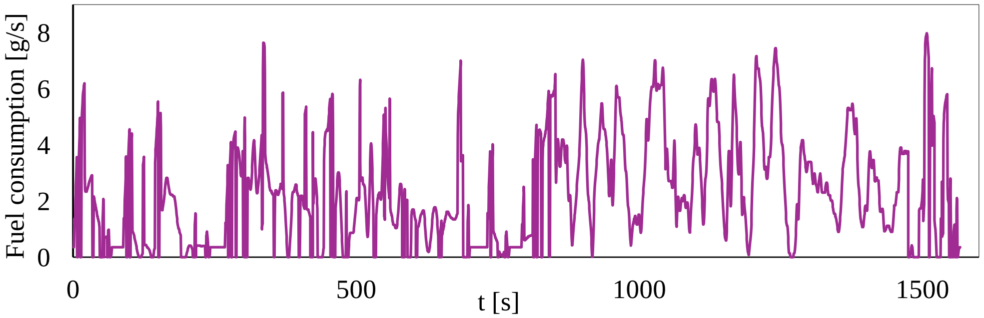

Fig. 3. Fuel consumption vs. time in the Regional Delivery cycle for an unladen vehicle and with a reduced rolling resistance

Table 2 shows the fuel consumption according to the driving cycle and load after a 10% reduction in air resistance. The driving cycles to be investigated are: Urban Delivery, Regional Delivery, Urban and Suburban. When the average combustion in the assumed cycles is compared, it is clear that the lowest values are achieved in the Regional Delivery cycle, whereas the highest in the Urban one. These values are higher for heavier vehicles, which is in line with the expectations due to higher load and the resulting higher fuel consumption. The average speed and acceleration in the Urban Delivery, Regional Delivery, Urban and Suburban cycles have a significant impact on fuel consumption. Higher average speeds and intensive accelerations, especially in urban cycles, lead to an increase in the average fuel combustion, which is evident in the fuel consumption values of these cycles.

Tab. 2. Fuel consumption vs. the driving cycle and load after a 10% reduction of air resistance

Driving cycle	Mass of vehicle [kg]	Consumed fuel [g]	Average combustion [g/km]	Travelled distance [km]	Highest instantaneous fuel consumption [g/s]
Urban Delivery	6,570	4,318.2	155.33	27.8	8.15
	12,000	5,878.4	211.45		9.77
Regional Delivery	6,570	3,643.4	141.22	25.8	8.09
	12,000	4,554.4	176.53		9.77
Urban	6,570	8,397.1	212.05	39.6	7.07
	12,000	11,540	291.41		9.77
Suburban	6,570	4,235.8	180.25	23.5	6.03
	12,000	6,121.2	260.48		9.77

Table 3 shows the data on the fuel consumption according to the driving cycle and load after a reduction of rolling resistance. The lowest values of average fuel consumption were recorded in the Regional Delivery cycle for both vehicle weights. The highest values of average fuel consumption occurred in the Urban cycle, which may result from numerous stops of the vehicle due to urban traffic. The Regional Delivery cycle is the most fuel efficient, while the Urban cycle is the least efficient. These results suggest that the optimisation of routes and driving style in urban conditions can result in significant fuel savings.

Tab. 3. Fuel consumption vs. the driving cycle and load after a reduction of rolling resistance

Driving cycle	Mass of vehicle [kg]	Consumed fuel [g]	Average combustion [g/km]	Travelled distance [km]	Highest instantaneous fuel consumption [g/s]
Urban Delivery	6,570	4,143.9	149.06	27.8	8.04
	12,000	5,542.1	199.36		9.77
Regional Delivery	6,570	3,543.0	137.33	25.8	7.98
	12,000	4,294.4	166.45		9.77
Urban	6,570	8,105.4	204.68	39.6	6.87
	12,000	11,004.5	277.89		9.77
Suburban	6,570	4,058.9	172.72	23.5	5.87
	12,000	5,781.0	246.00		9.77

The following Table 4 shows the fuel consumption in the individual driving cycles after a reduction of rolling resistance and a reduction of aerodynamic drag by 10%. The driving cycles analysed are Urban Delivery, Regional Delivery, Urban and Suburban for vehicles weighing 6,570 kg and 12,000 kg. The highest fuel consumption and average combustion are observed in the Urban cycle, which is due to frequent stopping and starting. The lowest fuel consumption and average combustion occur in the Regional Delivery cycle due to smooth driving. The highest instantaneous fuel consumption is similar for all driving cycles for vehicles of 12,000 kg, at approximately 9.77 g/s. These values are slightly lower for vehicles weighing 6,570 kg. Rolling and air resistance can improve energy efficiency, which is more evident for heavier vehicles.

Table 4. The fuel consumption in the individual cycles after a reduction of rolling resistance and a reduction of aerodynamic drag by 10%

Driving cycle	Mass of vehicle [kg]	Consumed fuel [g]	Average combustion [g/km]	Travelled distance [km]	Highest instantaneous fuel consumption [g/s]
Urban Delivery	6,570	4,056.5	145.92	27.8	7.99
	12,000	5,463.7	196.54		9.77
Regional Delivery	6,570	3,378.4	130.95	25.8	7.93
	12,000	4,148.1	160.78		9.77
Urban	6,570	8,057.5	203.47	39.6	6.87
	12,000	10,958.5	276.73		9.77
Suburban	6,570	4,053.2	171.58	23.5	5.78
	12,000	5,736.8	244.12		9.77

As part of the analysis of the findings, the energy efficiencies for the vehicles in various configurations were compared. Equation 8 was used to calculate the value of the energy efficiency E_C depending on the driving distance.

$$E_C = \frac{G_{kg} * W_D}{D} \tag{8}$$

The calculations were made taking into account the total fuel mass consumed in the single cycle (G_{kg}, the calorific value of the fuel $(W|\square|D)$ and the distance (D). The findings are shown in Table 5 and Figure 4.

Tab. 5. Comparison of the energy performance of the vehicle in the simulations

Driving cycle	Mass of vehicle [kg]	Energy efficiency of standard vehicle [kWh/km]	Energy efficiency of vehicle with reduced air resistance [kWh/km]	Energy efficiency of vehicle with reduced rolling resistance [kWh/km]	Energy efficiency of high rolling resistance vehicle [kWh/km]	Modified vehicle energy efficiency [kWh/km]
Urban Delivery	6,570	1.95	1.91	1.83	1.97	1.79
	12,000	2.64	2.60	2.45	2.70	2.42
Regional Delivery	6,570	1.82	1.74	1.69	1.86	1.61
	12,000	2.24	2.17	2.05	2.31	1.98
Urban	6,570	2.62	2.61	2.52	2.66	2.50
	12,000	3.60	3.58	3.42	3.67	3.40
Suburban	6,570	2.24	2.22	2.12	2.28	2.11
	12,000	3.22	3.20	3.03	3.29	3.00

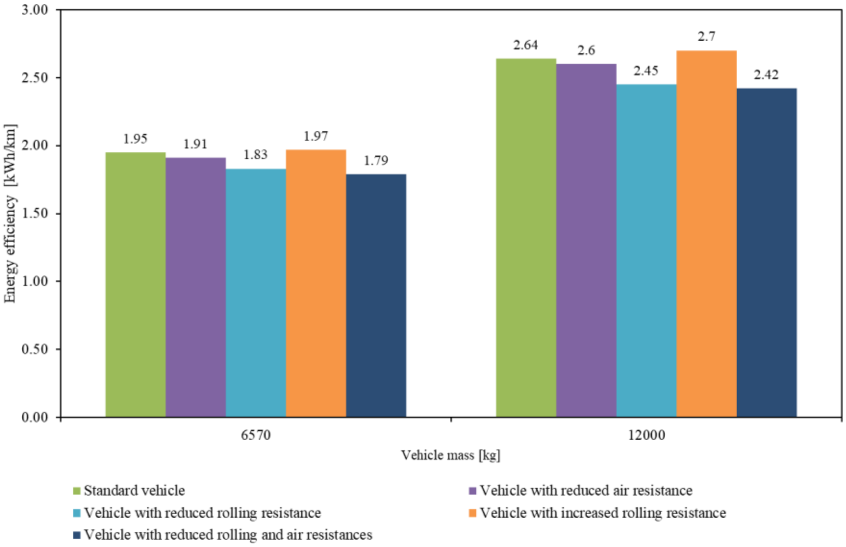

Fig. 4. Comparison of the energy efficiency of the vehicle vs. the vehicle weight and the modifications made in the Urban Delivery cycle

The analysis of the findings shows that it is possible to specify the energy efficiency of heavy goods vehicles by reducing rolling and air resistance if modelled with VECTO. Table 6 and Figure 4 show a comparison of the energy efficiency of the vehicle depending on the weight of the vehicle and the modifications in various driving cycles. There are the data on the energy performance of a standard vehicle, a vehicle with a reduced air resistance and a vehicle with a reduced rolling resistance in different driving cycles (Urban Delivery, Regional Delivery, Urban, Suburban) for the tested vehicles. The changes in the energy efficiency of both lighter and heavier vehicles are similar. It is clear that reducing rolling resistance and air resistance can improve energy efficiency both for vehicles of 6570 kg and 12000 kg, but this improvement is greater for a heavier vehicle.

In addition, the percentage differences in energy efficiency were calculated by comparing the results obtained from the individual variants to those of an unmodified vehicle.

Tab. 6. Percentage comparison of the energy performance of the vehicle in the simulations

Driving cycle	**Vehicle mass [kg]**	**The difference between the standard vehicle and the vehicle with:**			
		reduced air resistance [%]	**reduced rolling resistance [%]**	**increased rolling resistance [%]**	**reduced air resistance and reduced rolling resistance [%]**
Urban Delivery	6,570	-2.1	-6.2	+1.0	-8.2
	12,000	-1.5	-7.2	+2.3	-8.3
Regional Delivery	6,570	-4.4	-7.1	+2.2	-1.5
	12,000	-3.1	-8.5	+3.1	-1.6
Urban	6,570	-0.4	-3.8	+1.5	-4.6
	12,000	-0.6	-5.0	+1.9	-5.6
Suburban	6,570	-0.9	-5.4	+1.8	-5.8
	12,000	-0.6	-5.9	+2.2	-6.8

Comparing the results with the results given in the tricky publication, the following examples can be cited. The results of the research included in the paper (Fontaras et al., 2013) confirm that the VECTO tool, used in the current article, is an effective tool for predicting fuel consumption in heavy goods vehicles. VECTO has been shown to accurately simulate fuel consumption with an error of less than 4 % in different driving cycles, confirming its usefulness in assessing the energy efficiency of vehicles. On the other hand, in a study (Na and Cebon 2022), it was shown that tyres with low rolling resistance can deliver fuel savings of up to 3% for heavy commercial vehicles. These studies also highlighted that the benefits of rolling resistance reduction are more pronounced for heavier vehicles, which is in line with the results of the paper, which show greater fuel savings at higher vehicle weights. The report (Curry et al., 2021) concludes that the use of aerodynamic devices can reduce fuel consumption in trucks by up to 25% at high speeds on the highway. These studies confirm that improved aerodynamics are more beneficial at higher speeds, which is in line with the results of the current paper, which indicate greater efficiency in regional and highway driving conditions.

The results of the paper are consistent with those in the literature, confirming that the reduction of aerodynamic and rolling drag has a significant impact on the fuel efficiency of trucks. A comparison with other studies highlights that both improving aerodynamics and reducing rolling resistance are effective strategies for increasing the energy efficiency of trucks in different driving conditions.

5. SUMMARY

Simulation tests carried out using the VECTO tool enabled the analysis of different vehicle configurations regarding fuel consumption and emissions. The results of the simulation can be used to optimize vehicle design and develop new technologies to reduce fuel consumption and pollutant emissions. Particular attention was paid to reducing rolling resistance and aerodynamic drag, which have a significant impact on the fuel consumption of trucks. Simple modifications, such as replacing tyres with lower friction models, can bring significant energy benefits. Based on the results, the following conclusions can be drawn:

- Impact of rolling resistance: Simulations have shown that rolling resistance has the greatest impact on the fuel consumption of the trucks tested. Reducing rolling resistance by using the right tyres can reduce fuel consumption by 6% compared to a standard vehicle.
- Impact of aerodynamic drag: Aerodynamic modifications to the vehicle body structure lead to a reduction in energy consumption of up to 8%. This underlines the importance of optimizing the air flow around the vehicle.
- Optimisation of operating conditions: Simulations have made it possible to determine the optimal driving conditions in which the vehicle's powertrain achieves maximum efficiency. These results can support the development of more efficient operational strategies.
- Modification synergy: The use of simultaneous technological changes, such as the reduction of rolling resistance and the improvement of aerodynamics, brings synergistic effects in terms of reducing fuel consumption and CO_2 emissions.

- Variation by conditions: The results show significant differences in fuel consumption depending on the driving cycle and vehicle weight. This confirms the need to adapt operational strategies in various operating conditions, including urban traffic.

Taken together, the results of the study highlight the need to further optimise truck design to reduce fuel consumption. In particular, further research into the synergistic effects of aerodynamic modifications and technologies that reduce rolling resistance is essential. This will allow for a full assessment of their impact on the energy efficiency of vehicles under real operating conditions.

Authors Contributions

Łukasz Grabowski: Conceptualization, Methodology, Validation, Supervision. Arkadiusz Drozd: Investigation, Writing - original draft. Mateusz Karabela: Data curation, Visualisation. Wojciech Karpiuk : Writing - review & editing,.

Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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APPENDIX 1

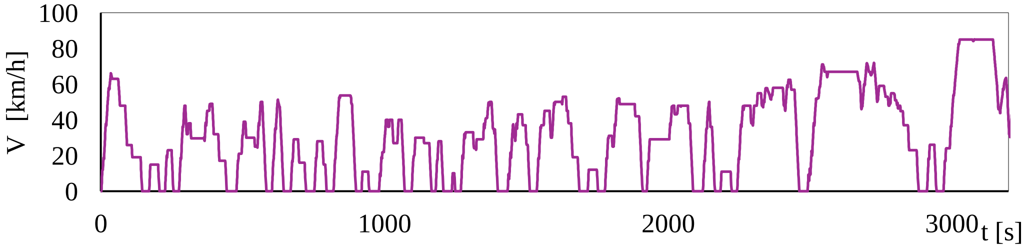

Fig. 2A. Urban Delivery cycle time function speed

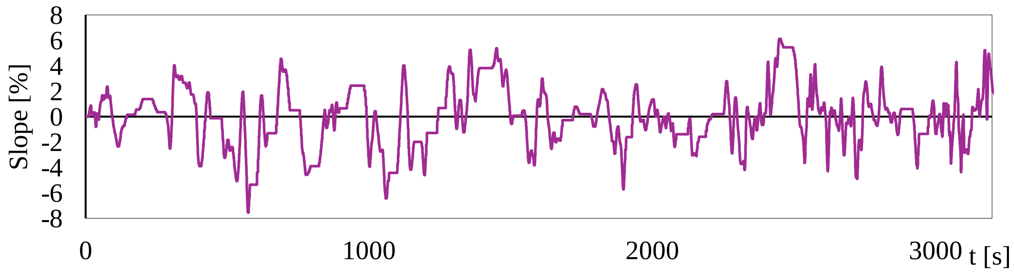

Fig. 3A. The slope of the road as a function of the Urban Delivery cycle time

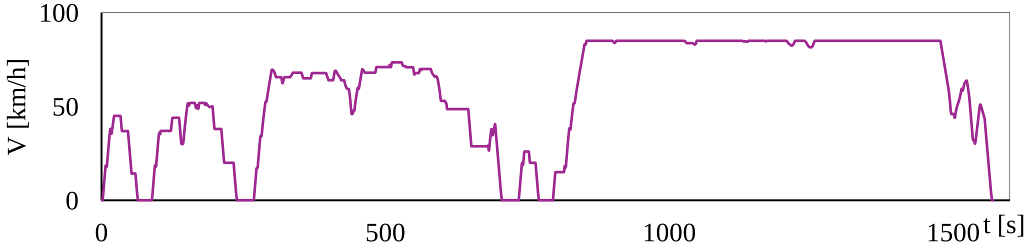

Fig. 4A. Speed versus time in the Regional Delivery cycle

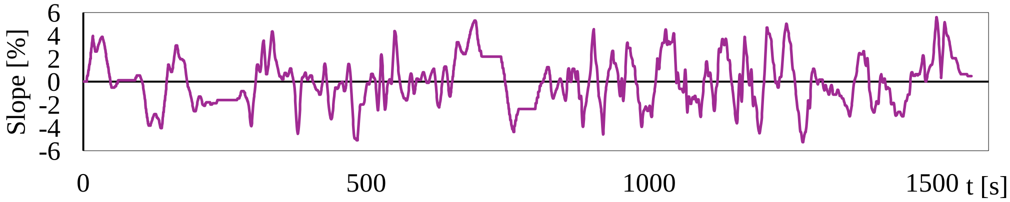

Fig. 5A. Road slope as a function of Regional Delivery cycle time

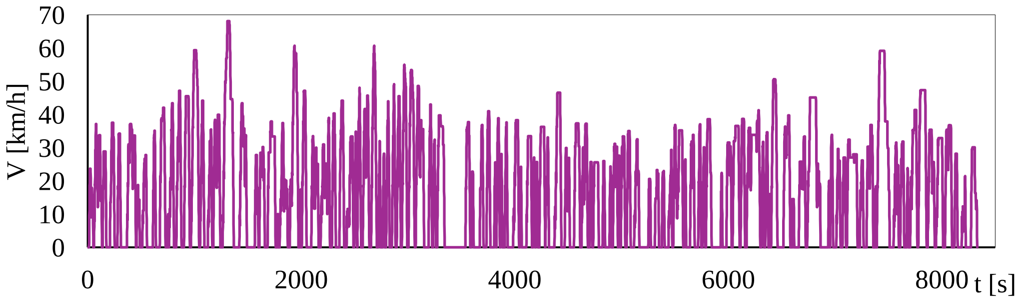

Fig. 6A. Speed as a function of Urban cycle time

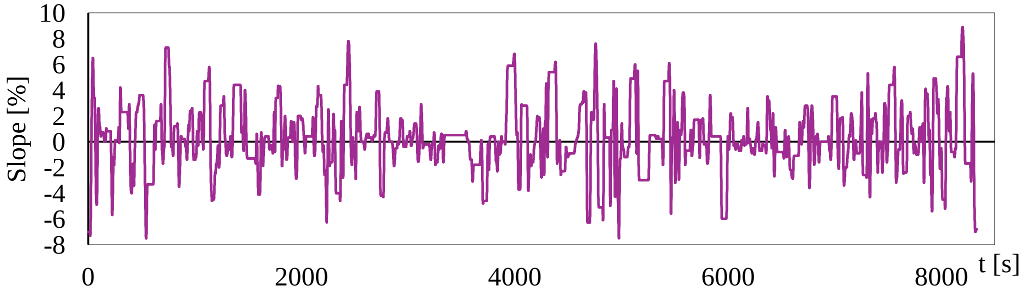

Fig. 7A. The slope of the road as a function of the Urban cycle time

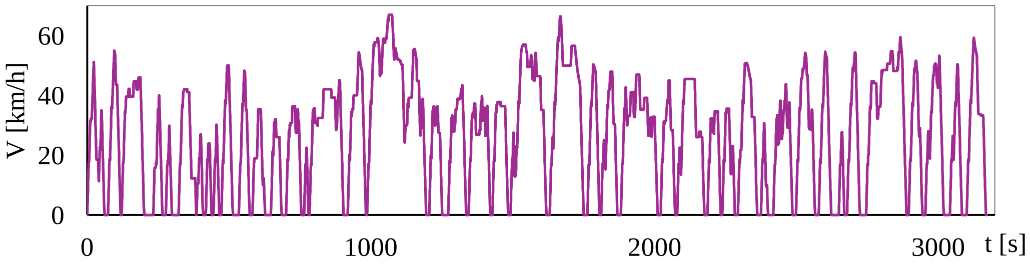

Fig. 8A. Speed as a function of the Suburban cycle time

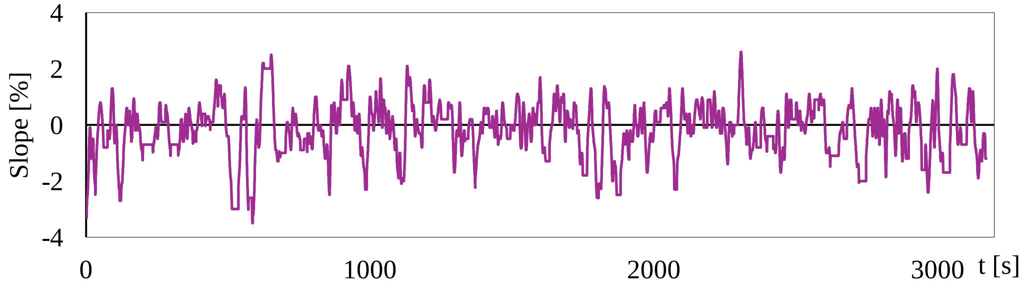

Fig. 9A. The slope of the road as a function of the time of the Suburban cycle