CHEMICAL ENGINEERING TRANSACTIONS
VOL. 114, 2024

A publication of
AIDIC
The Italian Association
of Chemical Engineering
Online at www.cetjournal.it

Guest Editors: Petar S. Varbanov, Min Zeng, Xuechao Wang, Bohong Wang

ISBN 979-12-81206-12-0; **ISSN** 2283-9216

DOI: 10.3303/CET24114173

Analysis of the Aerodynamic Parameters of Road Vehicles Affected by Weather Conditions

Péter Brúnó*,[a], István Lakatos[b]

[a]MouldTech Systems Kft., Zalaegerszeg, Hungary
[b]Department of Road and Rail Vehicles, Audi Hungarian Faculty of Vehicle, Széchenyi István University, Győr, Hungary
peter.bruno@sze.hu

Optimizing the aerodynamic parameters of road vehicles is essential due to their impact on the environment. It is a special aim of developments, including electric and non-electric vehicles. A lot of research is being conducted according to energy efficiency and range. These parts are the most significant directions of development. Aerodynamic parameters such as drag coefficient exert a significant influence on vehicle energy efficiency. The purpose of this paper is to investigate the aerodynamic parameters of the Ahmed body in rainy weather conditions. Different types of rain and vehicle speeds are studied and compared to each other to examine their effect on the drag coefficient. The examination is carried out using the Computational Fluid Dynamics (CFD) method. In the two-phase simulations, the rain is modeled as solid particles. Results can be used to obtain the most fuel- or electricity-efficient rain type-vehicle speed combinations and thereby can help to contribute a more sustainable transport. The results clearly show that rain has a measurable effect on the drag coefficient. As the rain intensity increases, the drag coefficient increases, too. However, there are uncertainties in the upward trend. As airspeed increases, the increasing trend becomes more stable.

1. Introduction

The energy consumption of road vehicles within the automotive industry is one of the most researched areas today. The appearance of electric vehicles has changed the structure of the automotive sector. The most important factors for a road vehicle today are a low drag coefficient and a long range. To achieve these goals, several types of examination must be carried out.

The research into energy efficiency in electric vehicles is extensive. A range of parameters are studied to improve vehicle energy consumption. The studies can be divided into two main parts. The first part is the construction design of vehicles, including battery temperature, regenerative braking, air conditioning, and so on. The second part is the analysis of vehicle body shape and the impact of additional elements on aerodynamic properties.

The battery type has a significant impact on energy efficiency. It has been proven that the construction of batteries and their temperature affects the electric vehicle's range (Hang 2023). Data-based analysis proves the connection between energy efficiency and environmental temperature (Dongxu et al., 2023). The results of the segmented test method, which was carried out at -1 °C and different energy levels, clearly show that moisture has a significant impact on electric consumption and efficiency, particularly in relation to regenerative braking (Hua et al., 2023). It is not just the batteries and the temperature that affect energy efficiency. Driving style also affects consumption. It is a fact that frequent acceleration and braking have a negative impact on overall energy efficiency. This is despite the fact that regenerative brakes have increased energy recovery (Gwangryeol et al., 2023). There are numerous studies in the field of consumption optimization. Advanced equivalent consumption minimization strategy (ACEMS) will decrease fuel consumption by almost 30 % in urban areas (Sahwal et al., 2024). The use of short-trip segment division (S-TSD), algorithms, and deep neural networks (DNN) in comparison with real-world driving data will undoubtedly improve the energy efficiency of an electric vehicle (Yingjiu et al., 2023). It is clear that energy consumers for passenger comfort have a significant impact on energy consumption. Heating, ventilating, and air-conditioning will undoubtedly decrease the battery level. The research clearly shows that an optimal recirculation ratio improves passenger comfort while reducing energy consumption

Paper Received: 29 April 2024; Revised: 15 August 2024; Accepted: 6 November 2024
Please cite this article as: Brúnó P., Lakatos I., 2024, Analysis of the Aerodynamic Parameters of Road Vehicles Affected by Weather Conditions, Chemical Engineering Transactions, 114, 1033-1038 DOI:10.3303/CET24114173

(Lesage et al., 2024). Passenger comfort is important, but safety is more important. To achieve appropriate air quality, significant energy is used (Ning et al., 2024). To optimize air quality, a series of rigorous examinations have been conducted, including linear losses-to-power scaling and the geometric scaling method (Aroua et al., 2023). Overall, energy consumption is a trending research field. Several methods are used to analyze the efficiency of vehicles. Artificial neural networks (Bukola, 2023a), simulation methods (Bukola, 2023b), and path-finding algorithms (Zhaohui et al., 2022) are the most suitable methods for analyzing and gaining data on the vehicle's energy consumption parameters. By using the measured data, energy consumption can be decreased. Vehicle dynamics are also a crucial factor in optimizing consumption (Zhang et al., 2024). While analyzing the dynamic parameters during operation is difficult and time-consuming, machine learning can help to optimize the examination (Md. Nurun et al., 2023). The routing problem can be solved using the mixed integer linear mathematical model proposed by Hajiaghaei-Keshteli (2023) or two-stage adaptive robust optimization (Jeong et al., 2024).

The shape of the vehicle and the additional parts impact energy efficiency. It is a proven fact that aerodynamic forces acting on a vehicle can increase driving stability and energy consumption (Hitoshi, et al., 1995). These two parameters have the greatest impact on the vehicle development process. This field is under-researched, but there are already some relevant papers on the topic. The examination of aerodynamic forces can be conducted using a variety of measurement methods. CFD simulations are the ideal tool for monitoring and measuring a wide range of fluid mechanics parameters, including the wing-in-ground effect (Juhee, 2018). To compare the CFD simulations with test-track measurements, time-dependent simulations (e.g. large Eddy simulation) should be created, where the acting forces can be collected (Takuji et al., 2013). The results clearly demonstrate that unsteady aerodynamic forces have a significant impact on aerodynamic parameters. Weather conditions can also be analyzed, such as strong crosswinds with detached eddy simulations (Winkler et al., 2016). Wind tunnel measurement is a vital tool in aerodynamic development. It is possible to measure aerodynamic parameters, such as the drag coefficient, in a wide range of driving conditions (Watkins, 2008). The test track measurement tool is the most validated and complicated of these methods. The right equipment allows for certified methods to be carried out. For example, the energy consumption of different vehicles can be measured (Hanzhengnan, 2022).

This study examines the energy consumption and travel range of electric and hybrid vehicles from several points of view. However, there is a clear need for further investigation into the effect of weather conditions on the drag coefficient. It also significantly affects energy consumption. For example, wind, temperature difference or rain. To obtain data on the degree of influence of weather conditions on the aerodynamic properties, several types of investigation must be carried out.

This paper will demonstrate that the effect of rain on energy consumption can be quantified. The investigation will increase the accuracy of the current expected energy consumption according to the weather conditions. The information will also help with the range optimization method, which will allow us to modify the planned stopping places in the case of electric vehicles, where the traveling range is critical.

2. Theoretical background of aerodynamic forces

A body in a flow is affected by a force. This is the aerodynamic force if the friction is not neglected (Lajos, 2019). The resultant is the sum of the force from pressure difference and from the shear stress. The basis of these stresses are the deformation speed and the viscosity, depicted in Figure 1a. The aerodynamic force can be obtained as (Lajos, 2019.),

$$F_{aer} = F_{shear} + F_{normal} = \tau_0 \cdot \underline{e} \cdot d\underline{A} - \int_A (p - p_{inf})\, d\underline{A}. \tag{1}$$

where τ_0 is the local shear stress, $\underline{e}$ is the unit vector parallel to the unit area, $\underline{A}$ is the unit surface, p is the local pressure, p_{inf} is the static pressure in the free stream zone. In vehicle aerodynamics, the aerodynamic force is divided into three components, as Eq(2) and Figure 1b.

$$F_{aer} = F_x + F_y + F_z \tag{2}$$

where $F_x = -F_D$ (drag force), $F_y = F_S$ (side force), $F_z = F_L$ (lift force). In addition to the forces, three different moments also exist. The rolling moment acts on the x-axis, the pitching moment acts on the y-axis, and the yawing moment acts on the z-axis.

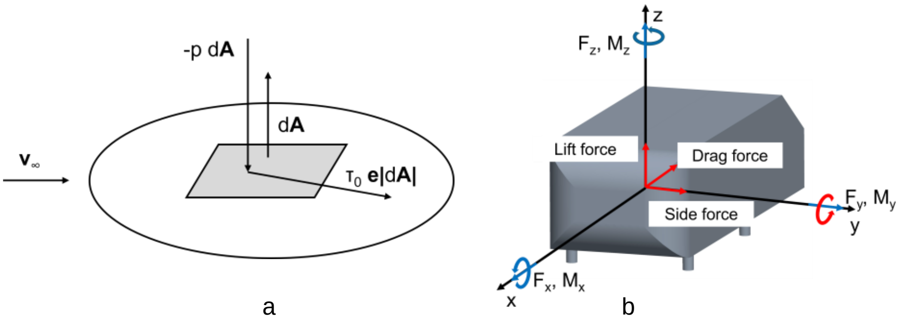


Figure 1: Aerodynamic force acting on a unit surface (a). Components of the aerodynamic forces and moments on a vehicle (b).

3. Simulation environment

The objective of the research was to ascertain the impact of precipitation on the aerodynamic characteristics of an Ahmed body. The Ahmed body is a simplified vehicle. This geometry is the go-to for CFD simulations because it can be meshed easily and there are plenty of measurement data available for comparison of simulation results. However, it must be acknowledged that the multiphase simulation model is highly sensitive to the geometry and the numerical mesh. Given the unique nature of this analysis, a simplified geometry was applied to investigate the basic thesis.

Figure 2 depicts the geometry, which is designed to represent the Ahmed body as accurately as possible. The body is a 400x40 mm rectangular shape, placed in a 2000x200 mm computational volume. This allows for two body lengths in front of the model, three body lengths behind, and three body heights above. A distance of 20 mm is placed between the bottom of the body and the ground.

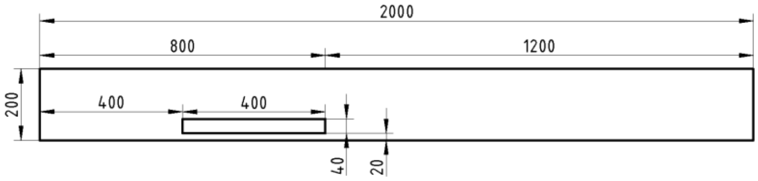


Figure 2: Dimension of the implemented geometric configuration

The boundary conditions are defined in accordance with the general settings (Figure 2). The inlet is defined as a velocity inlet with the air phase set. The volume is divided into two parts at the top. Rain is injected at the rain injection part and defined as a symmetry wall setting. The roof is also defined as a symmetry. The volume outlet is a pressure outlet. The body and ground are set as walls.

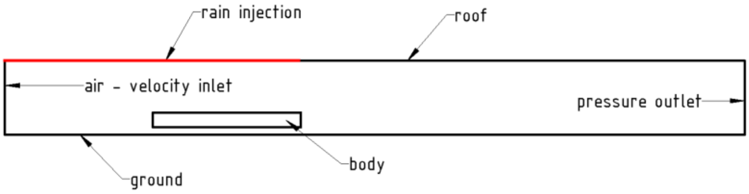
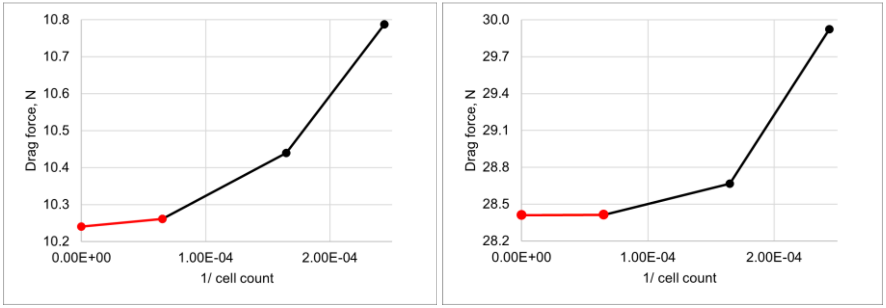


Figure 3: Boundary conditions of the applied geometry

To create a CFD simulation study, the simulation environment and numerical mesh must be investigated first (Kristóf, 2019). The most appropriate mesh setting is determined using a mesh convergence method, specifically the Grid Convergence Index (GCI) method (Ismal, 2008). The GCI method determines the discretization and relative error of the numerical results. Furthermore, the GCI method provides information about the refinement of the numerical mesh. If the parameters are not fine enough, this will be indicated. The calculations show that the discretization error is 2.34 % and that the relative error between the smoothest and the reference mesh is 1.91 %. These results are satisfactory for the purposes of this study. Furthermore, the results are presented in the form of Richardson plots (Péter and Lakatos, 2023) in Figure 3 for visualization purposes. The plots clearly show the 1/cell count on the x-axis and the drag force on the y-axis for the three meshes and the calculated "infinite" case. It is evident that the slope of the function is decreasing in the negative x direction. The red line, which connects the results of the finest and the infinite mesh, has the smallest slope. This proves that the mesh has the right structure and that an examination with different parameters can be performed.



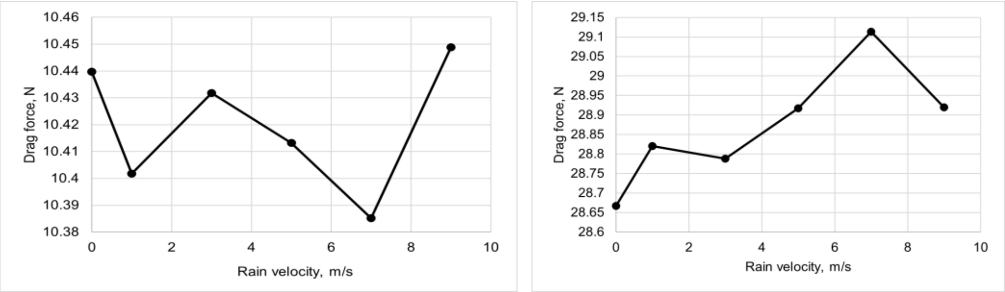
a b

Figure 4: Richardson plot at air velocity (a)15 m/s and (b) 25m/s

The simulation is defined as a steady state, and the flow is laminar. The laminar flow simplification was crucial because the simulation was highly unstable with a turbulence model. It is important to note that, regarding this simplification, the near-wall flows are not defined accurately. However, the aim of this paper is to provide information about the relevance of the thesis, namely that rain could affect the aerodynamic properties of a vehicle. The simulation is built using the Eulerian model, which is capable of modeling both continuous and granular phases. The air was set as the continuous phase with a velocity magnitude at the inlet boundary condition. The rain is defined as a granular particle with a defined velocity magnitude. The particle size of the rain was defined using the Rosin-Rammler model, with a minimum particle size of 0.1 mm, a maximum of 9 mm, and a mean diameter of 5 mm. The rain flow rate was 0.03 kg/s. These settings are based on an average rain parameter. The simulations were completed without any error messages and the convergence was stable and clear in all cases.

4. Results

In this phase, the results of the calculations will be analyzed. The same simulation environment was used in all cases. The only parameter that was changed was the rain - and air inlet velocity. This study investigated how different levels of rain affect the aerodynamic properties of the applied body. The simulations were carried out with different rain inlet velocities and different air velocities. The rain inlet velocity was studied in increments of 1 m/s, up to a maximum of 9 m/s. Nine different rain intensity cases were studied with two different air velocities (15 and 25 m/s). Figure 4a shows the distribution of the drag force. The x-axis shows rain intensity, and the y-axis shows drag force. The air inlet velocity is 15 m/s. The simulations have a high uncertainty, but the drag forces have a clear increasing trend. In Figure 4b, the drag force distribution is shown with the same settings as in Figure 4a, but the air inlet velocity is 25 m/s. The simulation results are more stable than in the previous case. The drag force distribution has an upward trend as the rain intensity increases. The results clearly show that the rain has a measurable effect on the drag force.

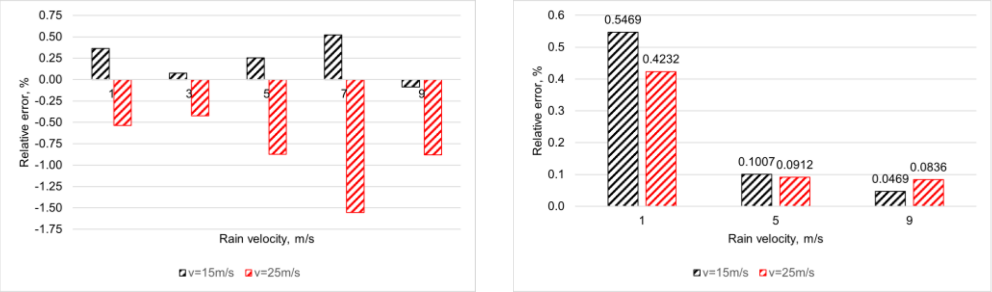


a b

Figure 5: Drag force distribution in case of different rain intensity (a) v_{air} = 15 m/s and (b) v_{air} = 25 m/s.

To more accurately express and understand the results, the relative error with respect to the "no rain" case is calculated. These data allow us to examine the rise in drag force in greater detail. The relative error falls within the range of 0.5 to 1.75 %. This result clearly demonstrates that rain has a significant impact on the drag coefficient. A 1 % increase in drag coefficient can lead to a notable reduction in travel range. Figure 5a shows the relative error distribution of the drag force.

The rain is a transient process. The CFD simulations should be transient to correctly model the rain. However, in transient simulations, the drag force became constant after a certain time. Consequently, steady-state simulations are compared to transient simulations in order to ascertain the accuracy of the steady-state case and its suitability for application. The simulations are compared in three different rain inlet velocity cases (1, 5, and 9 m/s). Figure 5b clearly demonstrates the relative error difference of the drag force. The x-axis shows the rain inlet velocity, and the y-axis shows the relative error of the drag force. The relative error was calculated from the steady-state results with respect to the transient. The results present that the difference between the cases is under 0.5 %. This proves that the steady-state simulations are correct for this case. In this case, using steady-state simulations helps the development process in the early stages find the right direction for the research. The implementation of steady-state simulations has the potential to reduce the computational capacity and time required for analysis, facilitating the examination of a greater number of cases.



a

b

Figure 6: Relative error distribution of the drag force with respect to (a) v_{air}=0 m/s case, (b) transient simulation case in case of different rain intensity

5. Conclusion

The multiphase flow simulation was successfully carried out with the described simplifications. The numerical results clearly show an increasing accent trend as the rain intensity rises. The drag force is increased by between 0.5 % and 1.75 % due to the rainy weather. Although the simulation environment is not entirely accurate, the results are still valuable. Further investigations are justified based on the study to examine more precisely the effect of rain on vehicle aerodynamics properties. 3D simulations should be carried out to get more valuable results. The applied model should be changed to the Ahmed body or to a road vehicle, which will allow us to compare the simulation result to literary data or test-track measurements. This will validate the simulation results.

Acknowledgments

The research was supported by the European Union within the framework of the National Laboratory for Autonomous Systems. (RRF-2.3.1-21-2022-00002)

References

Aroua A., Lhomme W., Verbelen F., Ibrahim M.N., Bouscayrol A., Sergeant P., Stockman K., 2023, Impact of scaling laws of permanent magnet synchronous machines on the accuracy of energy consumption computation of electric vehicles. eTransportation, 18, DOI: 10.1016/j.etran.2023.100269.

Bukola P.A., 2023, Electric vehicles survey and a multifunctional artificial neural network for predicting energy consumption in all-electric vehicles. Results in Engineering, 19, DOI: 10.1016/j.rineng.2023.101283.

Bukola P. A., 2023, A multivariable output neural network approach for simulation of plug-in hybrid electric vehicle fuel consumption. Green Energy and Intelligent Transportation, 2, DOI: 10.1016/j.geits.2023.100070.

Dongxu Y., Hai L., Menghan L., Hang X., 2023, Data-driven analysis of battery electric vehicle energy consumption under real-world temperature conditions. Journal of Energy Storage, 72, DOI: 10.1016/j.est.2023.108590.

Gwangryeol L., Jingeun S., Jungwon H., Yunsung L., Suhan P., 2023, Study on energy consumption characteristics of passenger electric vehicle according to the regenerative braking stages during real-world driving conditions. Energy, 283, DOI: 10.1016/j.energy.2023.128745.

Hajiaghaei-Keshteli M., Rahmanifar G., Mohammadi M., Gholian-Jouybari F., Klemeš J.J., Zahmatkesh S., Fusco G., Colombaroni C., 2023, Designing a multi-period dynamic electric vehicle production-routing problem in a supply chain considering energy consumption. Journal of Cleaner Production, 421, DOI: 10.1016/j.jclepro.2023.138471.

Hang X., Yu L., Jingyuan L., Hanzhengnan Y., Xiaopan A., Kunqi M., Yongkai L., Xi H., Hao Z., 2023, Study on the influence of high and low temperature environment on the energy consumption of battery electric vehicles. Energy Reports, 9, 835-842, DOI: 10.1016/j.egyr.2023.05.120.

Hanzhengnan Y., Yu L., Jingyuan L., Kunqi M., Yongkai L., Hang X., 2022, Investigations on fuel consumption characteristics of heavy-duty commercial vehicles under different test cycle. Energy Reports, 8, 102-111, DOI: 10.1016/j.egyr.2022.10.261.

Hitoshi F., Kazuo Y., Hiroshi C., Kunio N., 1995, Improvement of vehicle aerodynamics by wake control. JSAE Review, 16, 151-155, DOI: 10.1016/0389-4304(95)00007-T.

Hua Z., Kunqi M., Yu L., Jingyuan L., Hanzhengnan Y., Xiaopan A., Yongkai L., Hang X., Xi H., Hao Z., 2023, Research on the influence of soak in the cold environment on the energy consumption of electric vehicles. Energy Reports, 9, 656-661, DOI: 10.1016/j.egyr.2023.05.113.

Ismal B. C., Urmila G., Patrick J., Roache J. F., Christopher J. F., 2008, Procedure for Estimation and Reporting of Uncertainty Due to Discretization in CFD Applications. Journal of Fluids Engineering, 130, DOI: 10.1115/1.2960953

Jeong J, Ghaddar B., Zufferey N., Nathwani, J., 2024, Adaptive robust electric vehicle routing under energy consumption uncertainty. Transportation Research Part C Emerging Technologies, 160, 10.1016/j.trc.2024.104529.

Juhee L, 2018, Computational analysis of static height stability and aerodynamics of vehicles with a fuselage, wing and tail in ground effect. Ocean Engineering, 168, 12-22, DOI: 10.1016/j.oceaneng.2018.08.051.

Kristóf G., 2019, Computational Fluid Dynamics (in Hungarian), 1-st ed, Budapest, Hungary, ISBN 978-963-454-412-8

Lajos T., 2019, Basics of fluid mechanics (in Hungarian), 6-th ed, Budapest, Hungary, ISBN 978-963-12-2885-4.

Lesage M., Chalet D., Migaud J., Krautner C., 2024, Optimization of air quality and energy consumption in the cabin of electric vehicles using system simulation. Journal of Environmental Management, 358, DOI: 10.1016/j.jenvman.2024.120861.

Md. Nurun N., Biplob R., Fazlur R., Wisam A. H., Muyeen S. M., 2023, Parametric analysis and prediction of energy consumption of electric vehicles using machine learning. Journal of Energy Storage, 72, DOI: 10.1016/j.est.2023.108226.

Ning L., Kai X., Chenxing L., Jiaming Z., Jinpeng Y., 2024, New control methodology of electric vehicles energy consumption optimization based on air conditioning thermal comfort. Applied Thermal Engineering, 241, DOI: 10.1016/j.applthermaleng.2024.122375.

Péter B., Lakatos I., 2024, Comparison of Different Turbulence Models and Wall Treatment Methods for Vehicle Aerodynamics Investigations. Periodica Polytechnica Transportation Engineering, 52(1), 67–74, DOI: 10.3311/PPtr.22671

Sahwal C. P., Sengupta S., Dinh T. Q., 2024, Advanced Equivalent Consumption Minimization Strategy for Fuel Cell Hybrid Electric Vehicles. Journal of Cleaner Production, 437, DOI: 10.1016/j.jclepro.2023.140366.

Takuji N., Makoto T., Mariano V., Herbert O., Yasuaki D., 2013, Coupled analysis of unsteady aerodynamics and vehicle motion of a road vehicle in windy conditions. Computers & Fluids, 80, DOI: 10.1016/j.compfluid.2012.09.028.

Watkins S., Vino G., 2008, The effect of vehicle spacing on the aerodynamics of a representative car shape. Journal of Wind Engineering and Industrial Aerodynamics, 96, 1232-1239, DOI: 10.1016/j.jweia.2007.06.042.

Winkler N., Drugge L., Trigell A. S., Efraimsson G., 2016., Coupling aerodynamics to vehicle dynamics in transient crosswinds including a driver model. Computers & Fluids, 138, 26-34, DOI: 10.1016/j.compfluid.2016.08.006.

Yingjiu P., Wenpeng F., Wenshan Z., 2023, Development of an energy consumption prediction model for battery electric vehicles in real-world driving. A combined approach of short-trip segment division and deep learning: Journal of Cleaner Production, 400, DOI: 10.1016/j.jclepro.2023.136742.

Zhang L., Liu X., Liu S., Guo H., Shi K., 2024, Low energy consumption traction control for centralized and distributed dual-mode coupling drive electric vehicle on split ramps. Energy, 289, 10.1016/j.energy.2023.129878.

Zhaohui Q. H., Shao, F. W., Yu F, Liang S., 2022, A reliable energy consumption path finding algorithm for electric vehicles considering the correlated link travel speeds and waiting times at signalized intersections. Sustainable Energy, Grids and Networks, 32, DOI: 10.1016/j.segan.2022.100877.