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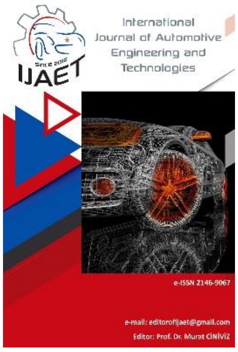

Original Research Article

Reducing fuel consumption of a light-duty vehicle by incorporating CuO nanoparticles in compressor lubricant of air-conditioning system

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ABSTRACT

This experimental study aims to investigate the effects of copper (II) oxide (CuO) nanoparticles (~50 nm, 99.9% trace metal basis) incorporation in polyalkylene glycol (PAG) lubricant of a compressor included in air-conditioning (AC) system of a light duty passenger car. Observations on fuel consumption in real-world driving tests while the AC system is fully running were conducted. In order to determine the impacts of CuO nanoparticle incorporation in PAG oil, friction (pin-on-disc tribotester) and wear tests were carried out along with surface visualization analyses of scanning electron microscopy (SEM) and atomic force microscopy (AFM) on the disc samples laser-cut from the spare AC compressor vanes. Morphology and thermal stability of the CuO nanoparticles were also investigated via SEM and thermal gravimetric (TG) analyses, respectively. Wear rate (WR), average coefficient of friction (μ_a) and surface roughness analyses on the specimen surfaces were conducted to procure a comprehensive knowledge about the tribological improvement of CuO nanoparticles. All analyses were repeated on the identical metal samples in PAG lubricant bath (PL) and CuO nanolubricant (NL) separately under the same conditions and average of the test results were taken into account to minimize error. The results demonstrate that reductions of 15.5% in average coefficient of friction, 33% in wear rate and 9% in average surface roughness were achieved resulting in a decrease of 7.7% in fuel consumption at designated driving conditions.

Keywords: CuO nanoparticles, AC rotary compressor, nanolubricant, fuel consumption.

1. Introduction

The relationship between gasoline prices and new car fuel economy has been under scrutiny due to worries about rising oil prices, energy security, and global warming. By investing in cars with better fuel economy, consumers can lessen their susceptibility to price hikes or volatility. Furthermore, several nations employ gasoline tariffs or fuel economy regulations to lower oil imports and carbon dioxide (CO_2) emissions [1,2].

There are several mechanical factors affecting fuel consumption of the vehicles such as tire [3-7] and road conditions [8], vehicle aerodynamics [9-13], air intake pressure [14-17] and temperature [18,19], fuel properties [20-22], etc. as well as driving behaviors [23-25]. Among these, impact of air conditioning (AC) system of the vehicle on fuel consumption draws special attention due to being a compulsory equipment for thermal comfort of the driver and the passengers. Aforementioned parameters affecting fuel economy may be intervened in to minimize consumption but the effect of AC unit on fuel economy can just be reduced by increasing the overall efficiency of the system. The energy required to run an automotive air conditioning system is much more than the energy needed for an engine to drive a mid-sized vehicle at a steady speed of 56 km/h [26]. Few studies have revealed that the fuel consumption of traditional internal combustion engine (ICE) vehicles might increase by as much as 30% due to HVAC systems [27-29].

The one of the very effective ways of increasing efficacy of the AC system of a vehicle is to enhance rheological properties of AC system's compressor lubricant by incorporating appropriate nanoparticles in the compressor oil [30-36]. In order to reduce compressor wear and to boost compressor uniformity, proper lubrication is essential. The proper lubrication is provided by lubricants to these compressors to avoid excessive friction on the piston ring and cylinder wall surfaces. By minimizing wear between two contacting and sliding surfaces and lowering frictional power losses in the compressor, lubrication also helps to avoid rust and corrosion formation [37]. Tribological performance of automotive AC systems can be further enhanced by the use of nanolubricant additives because of the formation of protective coatings and rolling effects on the friction surfaces [38, 39]. Similar to ball bearings, which use a rolling mechanism to reduce friction between the worn surfaces, nanoparticles exhibit similar behavior (rolling effect) [40]. By adding nanoparticles to standard lubricants, friction can also be decreased since the nanoparticles cover the spaces between the worn surfaces and form a thin layer (oil film). As a result, wear can be decreased and weight carrying capacity can be raised. Furthermore, nanolubricants yield to improve extreme pressure resistance, load carrying and anti-wear abilities as well as absorbing heat from the friction and minimize thermal and structural wear by separating fretting pairs [41, 42].

CuO nanoparticles step forward as an additive to lubricants to enhance the tribological features in mechanical systems due to its tribo-sintering to the worn surface, reducing metal-to-metal contact and good heat rejection property preventing overheat [43, 44]. This experimental study presents a comprehensive tribological analysis on compressor of an automotive AC system running on CuO incorporated lubricant (NL) to observe the variation of compressor work and its effects on fuel economy considering real-world driving conditions at designated vehicle under standard conditions. Though there are several studies on tribological improvement of CuO nanolubricants [45-56], no other study has been found elsewhere consisting of comprehensive tribological analyses and fuel consumption data of a real-world vehicle driving conditions. Thus, it is believed that this study will be a guide in terms of fuel efficiency of automotive systems in these times when oil prices are increasing rapidly.

2. Material and Methods

2.1. Friction and wear tests

A pin-on-disc tribotester with oil heater (Fig. 1) was utilized to create wear and physical friction on disc samples (62–65 HRC, E=210 GPa, υ=0.35, Ø20) laser-cut from the spare compressor vanes of the AC unit. Above the typical load of 20 N, it was found that every sample surface employed in the experimental analysis experienced significant surface damage. Thus, 20 N load was applied onto the disc specimens submerged in two different oil media (PL and NL) and friction analyses were performed 5 times for each sample and averaged to reduce data scattering at sliding distance of 400 m, sliding speed of 0.5 m/s and oil temperature of 60°C (average automobile AC compressor working temperature) for each oil bath ambient.

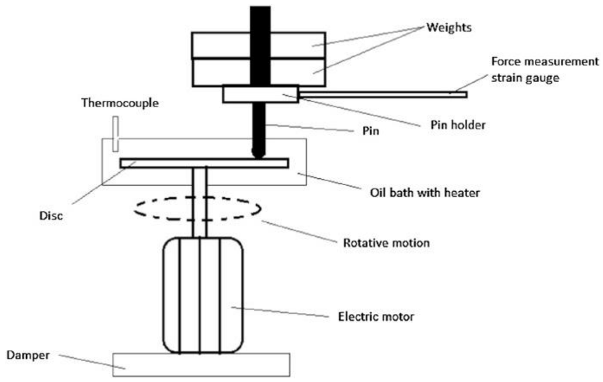


Fig. 1. Illustration of pin-on-disc tribometer

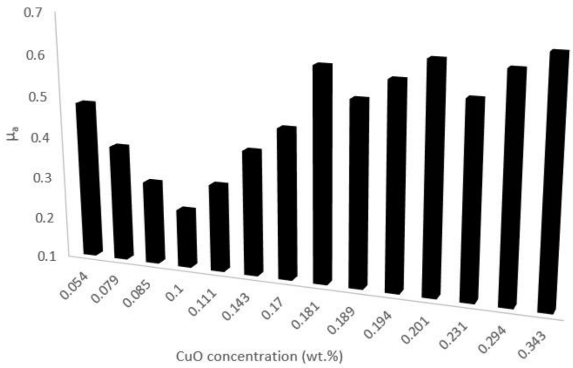


Fig. 2. CuO concentration vs. average coefficient of friction

Initially, 1 mL of base oil was added to the disc surface at appropriate time intervals until the total volume of oil in the bath reached 10 mL for both NL and PL. Before and after each test, hydrocarbon solvents were used to clean every component of the experimental apparatus, including the oil tanks, discs, pin holder, and pin. CuO nanoparticles were dispersed in polyalkylene glycol (PAG) lubricant (oil of AC compressor of the vehicle) by 0.1 wt.%. Above the 0.1 wt.% of nanoparticle concentrations, excess increment in an average coefficient of friction (μ_a) was inevitable due to agglomeration of particles on the metal disc samples (Fig. 2). Based on the concentration results, 0.1 wt.% of CuO nanoparticles was the optimum amount to be used in both friction and driving tests. 130 mL of lubricant with CuO nanoparticles was subjected to 3 hours of sonication at 0.25 kW and 44 kHz subsequent to 1 hour of magnetic stirring. SEM analyses of the nanoparticles and worn sample surfaces were carried out using a device with a magnification range of 6,000–1,000,000×. The wear rate of the samples was obtained by precisely weighing the disc samples before and after the wear tests. An equipment was utilized for AFM studies which has a cantilever paired with a 20× objective, 480 × 360 µm of field of view (CCD 1 Mpixel), and direct on-axis vision of the sample surface. The nanoparticles' thermal stability (TG) was assessed between 0°C and 420°C.

2.2. Real-world vehicle tests

The lubricant in AC compressor of the test vehicle was evacuated and the inner housing of the compressor was vacuumed into low pressure to get rid of any contaminations and moisture. In the first stage, the oil chamber of the compressor was charged with pure PAG lubricant before the activation of the AC system. The system consists of a rotary type compressor with vanes and other air conditioning units (evaporator, condenser, capillary tubes, expansion valve) in which the R132a refrigerant cycles. The compressor was driven by the internal combustion engine through a belt. The vehicle was equipped with sensors to record data simultaneously at 1 Hz on fuel consumption, load, engine revolutions per minute (rpm), vehicle speed, cabin and outside temperatures. Through the OBD system, integrated with its special software on a laptop, the engine control unit (ECU) provided information on the engine's speed and load as well as the vehicle's speed and fuel consumption. Commercially available OBDII readers were used in this study and the OBD data from a variety of light-duty passenger vehicle technologies can be read by these devices. Each driving test with each compressor lubricant was conducted with 2 people in the car, on the same 10 km section of a rural road (no traffic) within the same test duration and same day time to standardize the test conditions (Table 1). Each test with different compressor lubricants was repeated 5 times and average values were taken into consideration.

3. Results and Discussion

3.1. Tribological analyses

The tribological features of mechanical systems are significantly influenced by the geometry of the nanoadditive within the structure, i.e. the sphere-like shape of the nanoadditive is useful in minimizing wear due to rolling effect.

Table 1. Conditions for each driving tests

Description	Definition
Atmospheric temperature	34°C, clear sky
Atmospheric pressure	0.92 bar
Average wind speed	4 km/h blowing from the rear of the vehicle
Road type	Dry tarmac
Average road slope	3% uphill
Road length	10 km
Vehicle type	Light duty passenger car
Vehicle curb weight	1080 kg
Vehicle speed	60 km/h
Engine speed	2000 rpm
Vehicle engine specs	Naturally aspirated, 1.2 liters, 75 HP max. power at 5500 rpm, 108 Nm max. torque at 4250 rpm
Total test duration	120 min
Extra vehicular weight	Driver: 75 kg, data acquisitor person: 80 kg
AC system type	Manual
AC system status	Maximum cooling mode (min. temperature, max. blow speed, windows fully closed, inner air loop off)
AC compressor	12 V, rotary type with vanes
AC compressor lubricant and oil capacity	Pure PAG (PL), CuO incorporated PAG (NL), 130 mL

SEM images of CuO nanoparticles prove that the spherical geometry of the nanoparticles is very influential on separation of vane tips and the inner housing of the compressor as well as facilitating easy rotation of the vanes (Fig. 3a). Thus, decrease in compressor work is an expected outcome yielding a reduction in both engine load of the compressor and fuel consumption. SEM images of the worn disc samples (laser-cut from compressor vanes) in PL and NL baths are depicted in Fig. 3b and Fig. 3c., respectively. It is clearly seen that the sample surface which underwent abrasion process (wear test) in the NL bath has lower roughness and smoother surface than that of the sample fretted in the PL bath. The higher viscosity of NL than that of PL facilitates entrainment of the fluid into the crevices and hollows on the friction surfaces leading a smoother surface (polishing effect) with improved tribological characteristics (lower friction and wear). Nevertheless, high viscosity triggers the formation of thicker oil film between the vane tips and housing surface in the context of separating the friction surfaces. Furthermore, rolling effect of spherical CuO nanoparticles yields smooth operation of the rotary system.

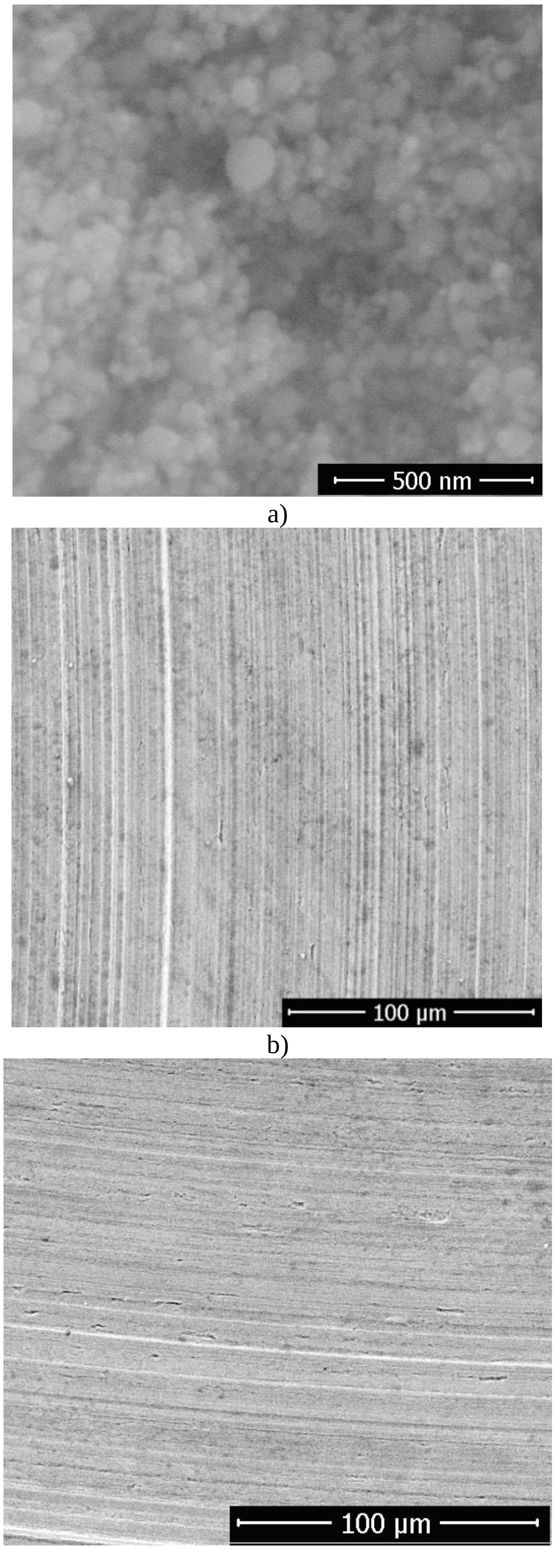


Fig. 3. (a) SEM images of; (a) CuO nanoparticles, (b) worn surface in PL bath, (c) worn surface in NL bath

The coefficient of friction (μ) fluctuation as a function of sliding distance for a normal load of 20 N is shown in Fig. 4. Average coefficient of friction (μ_a) for samples submerged in PL was found to be 0.45 whereas it was 0.38 for samples tested in NL bath (15.5% reduction). Rolling and polishing effects of CuO nanoparticles in the oil bath facilitate smoother surface and reduced coefficient of friction values when compared to that of sample surface in PL bath. Lower average coefficient of friction for NL bath also confirms the SEM images of the worn surfaces or vice versa.

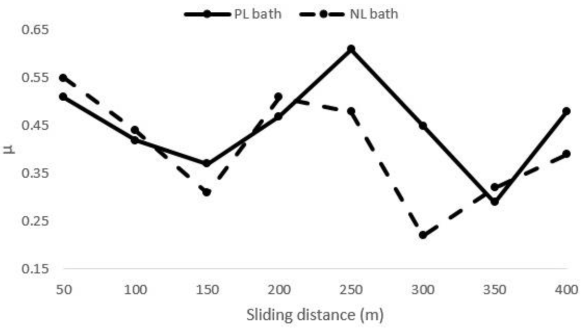


Fig. 4. μ vs. sliding distance

Thermogravimetric techniques reveal details regarding how the temperature effect alters the structure of nanoparticles. A high level of thermal stability, or the absence of peaks, means that the sample does not degrade at that temperature range [57, 41, 58]. TG analysis results of the CuO nanoparticles is demonstrated in Fig. 5. As can be seen from the graph, there is no sharp peak indicating that thermal stability of the nanoparticles was maintained even above temperature of 400°C proving that the nanoparticles never undergo decomposition, thermal cracking, melt down, etc. considering working temperatures of compressor lubricant.

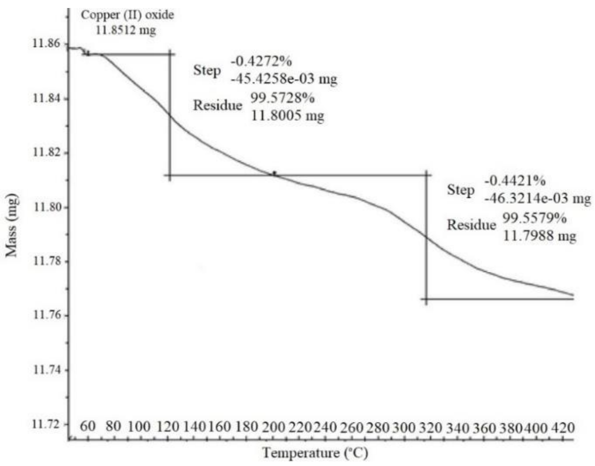


Fig. 5. Thermal stability of CuO nanoparticles

Wear rate of fretting surfaces and their roughness parameters are of great importance in order to determine the tribological improvement of CuO nanoparticles. Table 2 depicts the average surface roughness (R_a) and wear rates (WR) of the specimens. The entrainment of nano-size particles to the grooves of the sample surface induces smoother operation due to polishing effect and lower surface roughness in NL bath. Harsher surface (higher roughness) of the sample in PL bath causes increase in coefficient of friction and consequently higher mass loss and wear rates are inevitable. The wear rates of the surfaces were computed using Eqs. (1) and (2) [59-61]:

$$WSV = TA * RMA \tag{1}$$

$$WR = \frac{WSV}{F * \partial} \tag{2}$$

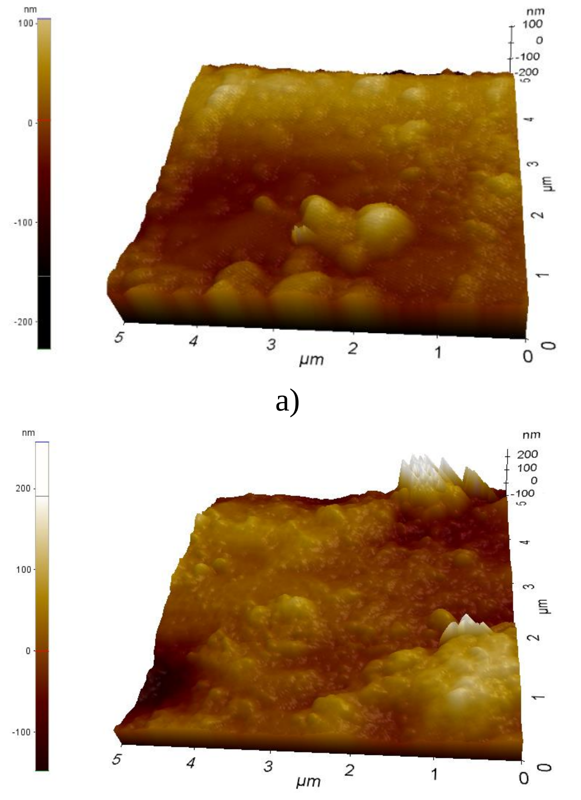
Table 2. Wear and roughness test results

Sample		Submerged in PL bath	Submerged in NL bath
Mass (g)	**Before wear test**	0.7281	0.8435
	After wear test	0.7246	0.8413
	Mass loss	0.0035	0.0022
	WR (mm^3/Nm)	***31.4*10^{-9}***	***21.1*10^{-9}***
R_a (μm)	**Test 1**	1.22	1.04
	Test 2	0.91	0.93
	Test 3	0.84	0.84
	Mean R_a	***0.99***	***0.91***

AFM imaging was utilized to investigate the surface morphology of the substrates, with a scan size of 10 μm × 10 μm (Fig. 6). It can be seen that the surface thickness of the sample worn in NL bath is higher than that of the sample worn in PL bath. AFM image confirms that sample in PL bath underwent severe abrasion in wear tests and lost more material than that of the sample worn in NL bath. Mass loss and wear rate analyses also validate this phenomenon.

3.2. Fuel consumption analysis

The test vehicle's ECU utilizes the approximated technique to report fuel usage via the OBD port. As the car has no fuel consumption data monitoring feature, the fuel usage was calculated using Eq. 3 [62]. It makes use of information from the mass airflow sensor, the gasoline stoichiometric air-fuel ratio of 14.7, and the fuel density (880 g/L).



a)

b)

Fig. 6. AFM images of; (a) worn surface in PL bath, (b) worn surface in NL bath

$$V_{fuel} = \frac{MAF}{AFR*\rho} \tag{3}$$

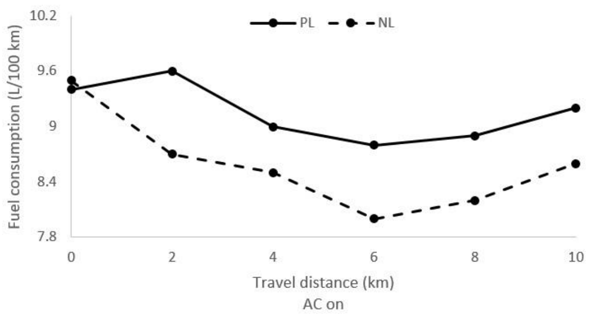


Fig. 7. Fuel consumed vs. travel duration (AC on)

The required data shown in Eq. (3) were acquired via OBD system and the specific fuel consumption—measured in liters of gasoline consumed per 100 kilometers traveled (L/100 km) was used as a derivation of the V_{fuel}. All driving tests were conducted considering the conditions mentioned in section 2.2 and Table 1. The results depicted that, at the end of the 10 km long road, when the compressor of the AC system of the vehicle ran on PL and NL separately under aforementioned conditions, the calculated average fuel consumptions were to be about 9.1 L/100 km and 8.4 L/100 km, respectively which corresponds to 7.7% reduction in average fuel consumption/100 km (Fig. 7). Thanks to CuO nanoparticles, improvement of tribological features of compressor oil conveys reduction in compressor work and compressor load on engine crank making the engine deliver the same or more power with lesser fuel consumption.

4. Conclusions

CuO nanoparticles were successfully incorporated in PAG lubricant of a AC compressor equipped in a light duty passenger car to observe the tribological improvements and their effect on fuel consumption. In the tribological test section of the study, related analyses were conducted on disc samples directly laser-cut from the spare vanes of the compressor to determine the effectiveness of CuO nanoparticle incorporation in PAG lubricant. All visual and computational analyses confirm each other and improvement in tribological characteristics of the compressor oil was clearly proved. Surface analyses (SEM, AFM) of the samples after abrasion tests depicted that the surface worn in NL bath underwent lower wear and mass loss along with smaller coefficient of friction (15.5% reduction). The real-world fuel consumption results also confirmed the tribological test results. SEM and TG analyses plainly showed the sphere-like geometry and high thermal stability of the CuO nanoparticles leading to improved tribological performance of the system. However, the tribological performance tends to decrease when the CuO fractions in PAG oil exceeds 0.1 wt.% due to reduction in dispersion of the nanoparticles in the lubricant leading to huddling of particles and increased friction. It is deduced from the real-world driving tests that roughly 8% fuel saving can be achieved by using CuO nanolubricant in compressor oil of the AC system. Considering the AC system is responsible for 30% of fuel consumption of an average light duty vehicle and rapidly increasing oil prices, CuO incorporation in compressor oil of the AC system is a good and promising way of fuel saving due to its superior tribological enhancement properties.

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CRediT authorship contribution statement

Ali Can Yılmaz: Conceptualization, Investigation, Validation, Writing-Original Draft, Editing. **Özlem ERDEM:** Conceptualization, Investigation, Formal analysis, Methodology

Declaration of conflicting interests

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.

Nomenclature

V_{fuel} : volumetric fuel consumption (L/s)
MAF : mass airflow introduced in the engine (g/s)
P : density of the fuel (g/L)
AFR : air-fuel ratio
WSV : worn surface volume (mm^3)
TA : trace area (mm^2)
RMA : trace length in one rotation (mm)
WR : wear rate (mm^3/Nm)
F : normal load (N)
∂ : sliding distance (m)

5. References

1. T. Klier and J. Linn, “Fuel prices and new vehicle fuel economy — Comparing the United States and Western Europe,” J. Environ. Econ. Manage., vol. 66, no. 2, pp. 280–300, 2013.
doi: 10.1016/j.jeem.2013.03.003.
2. H. Allcot, "The welfare effects of misperceived product costs: data and calibrations from the automobile market. American Economic J.: Economic Pol., vol. 5, no. 3, pp. 30-66, 2013.
doi: 10.1257/pol.5.3.30.
3. J. Thomas, S. Huff and B. West, "Fuel economy and emissions effects of low tire pressure, open windows, roof top and hitch-mounted cargo, and trailer," SAE Int. J. Passeng. Cars - Mech. Syst. vol. 7, no. 2, pp. 862-872, 2014.
doi: 10.4271/2014-01-1614.
4. S. d'Ambrosio, R. Vitolo, N. Salamone and E. Oliva, "Active tire pressure control (ATPC) for passenger cars: Design, performance, and analysis of the potential fuel economy improvement" SAE Int. J. Passeng. Cars - Mech. Syst. Vol. 11, no. 5, pp. 321-339, 2018.
https://doi.org/10.4271/2018-01-1340.
5. L. J. Bachman, "Do changes in temperature and inflation pressure affect rolling resistance during road and track testing for fuel economy of class 8 tractor-trailers?" Tire Science and Technol. vol. 46, no. 2, pp. 93–104, 2018.
doi: https://doi.org/10.2346/tire.18.460203.
6. S. d’Ambrosio, R. Vitolo, "Potential impact of active tire pressure management on fuel consumption reduction in passenger vehicles" J. Auto. Eng. vol. 233, no. 4, pp. 961-975, 2019.
doi:10.1177/0954407018756776.
7. W. H. Waddell, “Effect of inflation pressure on tire rolling resistance and vehicle fuel economy,” pp. 77–79, 2017.
8. C. Samaras, Y. Choueiri, J. Lund, M. Woody and P. Vaishnav, “Measuring of traction and speed characteristics as well as of fuel economy of a car in road conditions measuring of traction and speed characteristics as well as of fuel economy of a car in road conditions,” 2016.
doi: 10.1088/1757-899X/142/1/012101.
9. J. Abinesh and J. Arunkumar, “CFD analysis of aerodynamic drag reduction and improve fuel economy,” Int. J. Mech. Eng, vol. 3, no. 4, pp. 430-440, 2014.
10. Y. Onishi, K. Ogawa, J. Sawada, Y. Suwa et al., "On road fuel economy impact by the aerodynamic specifications under the natural wind," SAE Technical Paper, pp. 12, 2020.
https://doi.org/10.4271/2020-01-0678.
11. Y. Cho, C. Chang, A. Shestopalov and E. Tate, "Optimization of active grille shutters operation for improved fuel economy," SAE Int. J. Passeng. Cars - Mech. Syst. vol.10, no. 2, pp. 563-572, 2017.
https://doi.org/10.4271/2017-01-1513.
12. L. Dalessio, B. Duncan, C. Chang, J. Gargoloff et al., "Accurate fuel economy

prediction via a realistic wind averaged drag coefficient," SAE Int. J. Passeng. Cars - Mech. Syst. vol. 10, no. 1, pp. 265-277, 2017.
https://doi.org/10.4271/2017-01-1535.

13. Y. Pourasad, A. Ghanati and M. Khosravi, “Optimal design of aerodynamic force supplementary devices for the improvement of fuel consumption and emissions,” 2017.
doi: 10.1177/0958305X16681686.

14. W. Pan, C. Yao, G. Han, H. Wei and Q. Wang, “The impact of intake air temperature on performance and exhaust emissions of a diesel methanol dual fuel engine,” Fuel, vol. 162, pp. 101–110, 2015.
doi: 10.1016/j.fuel.2015.08.073.

15. N. R. Abdullah, et.al. "M. Engineering, “Fuel economy and exhaust emissions of a small gasoline,” vol. 6, pp. 949–958, 2014.
http://dx.doi.org/10.15282/jmes.6.2014.21.0091.

16. M. Guo, N. Shimasaki, K. Nishida, Y. Ogata and Y. Wada, “Experimental study on fuel spray characteristics under atmospheric and pressurized cross-flow conditions,” Fuel, vol. 184, pp. 846–855, 2016.
doi: 10.1016/j.fuel.2016.07.083.

17. J. Hu, et al. “E ff ects of pilot injection strategy of diesel fuel on combustion characteristics in a premixed methanol-air mixture atmosphere in a CVCC,” Fuel, vol. 234, no. 92, pp. 1132–1143, 2018.
doi: 10.1016/j.fuel.2018.07.160.

18. T. Balasubramani, S. Jeyapaul, K. Karthick, M. Karthick, G. Manikandan, "Fuel efficiency improvement in a petrol engine by using water injection." Int. J. Latest Trends in Eng. Technol., vol. 6, no. 4, 2016.

19. C. Cinar, A. Uyumaz, H. Solmaz, F. Sahin, and E. Yilmaz, “Effects of intake air temperature on combustion , performance and emission characteristics of a HCCI engine fueled with the blends of 20 % n-heptane and 80 % isooctane fuels,” Fuel, vol. 130, pp. 275–281, 2015.
doi: 10.1016/j.fuproc.2014.10.026.

20. Á. Ramos, J. Barba, and C. Dolores, “Improving fuel economy and engine performance,” Energies, vol. 13, pp. 1–14, 2020.
doi:10.3390/en13133499.

21. P. Iodice, G. Langella, and A. Amoresano, "Ethanol in gasoline fuel blends: Effect on fuel consumption and engine out emissions of SI engines in cold operating conditions," Appl. Therm. Eng. vol. 130, no. 3, pp. 1081-1089, 2018.
https://doi.org/10.1016/j.applthermaleng.2017.11.090 1359-4311.

22. C. Orlebar, A. Joedicke and W. Tudzinski, "The effects of octane, sensitivity and k on the performance and fuel economy of a direct injection spark ignition vehicle," SAE Technical Paper, 2014.
https://doi.org/10.4271/2014-01-1216.

23. Y. Huang, N. C. Surawski, B. Organ, J. L. Zhou, O. H. H. Tang, and E. F. C. Chan, “Science of the total environment fuel consumption and emissions performance under real driving : Comparison between hybrid and conventional vehicles,” Sci. Total Environ., vol. 659, pp. 275–282, 2019.
doi: 10.1016/j.scitotenv.2018.12.349.

24. M. Zhou, H. Jin, and W. Wang, “A review of vehicle fuel consumption models to evaluate eco-driving and eco-routing,” Transp. Res. Part D, vol. 49, no. 5, pp. 203–218, 2016.
doi: 10.1016/j.trd.2016.09.008.

25. T. Tang, X. Luo, and K. Liu, “Impacts of the driver’s bounded rationality on the traffic running cost under the car-following model,” Physica A, vol. 457, pp. 316–321, 2016.
doi: 10.1016/j.physa.2016.03.113.

26. R. Farrington and J. Rugh, “Impact of vehicle air-conditioning on fuel economy, tailpipe emissions, and electric vehicle range preprint,” no. September, 2000.

27. M. Bentrcia, M. Alshitawi, and H. Omar, “Developments of alternative systems for automotive air conditioning-A review,” J. Mech. Sci. Tech. vol. 32, no. 4, pp. 1857–1867, 2018.
doi: 10.1007/s12206-018-0342-2.

28. T. Onoda, “IEA policies—G8 recommendations and an afterwards,” Energy Policy, vol. 37, no. 10, pp. 3823–3831, 2009.
doi: 10.1016/j.enpol.2009.07.021.

29. A. Subiantoro, K. T. Ooi, and U. Stimming, “Energy saving measures for automotive air conditioning (AC) system in the tropics,” 15th International Refrigeration and Air Conditioning Conference at Purdue, July 14-17, 2014.

30. A. Elagouz, M. K. Ahmed, W. H. Azmi, and M. Z. Sharif, "Composite nanolubricants in automotive air conditioning system : An investigation on its performance composite nanolubricants in automotive air conditioning system," Mat. Sci Tech., vol. 469, 2019.
doi: 10.1088/1757-899X/469/1/012078.

31. N. N. M. Zawawi, W. H. Azmi, and M. F. Ghazali, "Tribological performance of Al_2O_3–SiO_2/PAG composite nanolubricants for application in air-conditioning compressor," Wear, vol. 492–493, pp. 204238, 2022.
doi: 10.1016/j.wear.2022.204238.

32. M. Z. Sharif, W. H. Azmi, A. A. M. Redhwan, R. Mamat, and T. M. Yusof, "Performance analysis of SiO_2/PAG nanolubricant," Int. J. Refrig., vol. 75, pp. 204–216, 2017.
doi: 10.1016/j.ijrefrig.2017.01.004.

33. A. H. Hamisa and W. H. Azmi, "The stability of TiO_2/POE nanolubricant for automotive air-conditioning system of hybrid electric vehicles," Mat. Sci. Eng., vol. 863, 2020.
doi: 10.1088/1757-899X/863/1/012050.

34. A. O. Pag et al., "Optimization of air conditioning performance with Al_2O_3-SiO_2/PAG composite nanolubricants using the response surface method," Lubricants, vol. 10, pp. 243, 2022.
https://doi.org/10.3390/lubricants10100243 2022.

35. A. A. M. Redhwan, W. H. Azmi, G. Najafi, M. Z. Sharif, and N. N. M. Zawawi, "Application of response surface methodology in optimization of automotive air-conditioning performance operating with SiO_2/PAG nanolubricant," J. Therm. Anal. Calorim., vol. 135, no. 2, pp. 1269–1283, 2019.
doi: 10.1007/s10973-018-7539-6.

36. M. Z. Sharif, W. H. Azmi, A. A. M. Redhwan, R. Mamat, and G. Najafi, "Energy saving in automotive air conditioning system performance using SiO_2/PAG nanolubricants automotive air conditioning," J. Therm. Anal. Calorim., vol. 135, no. 2, pp. 1285–1297, 2019.
doi: 10.1007/s10973-018-7728-3.

37. M. Kamal et al., "Tribology International Improving the tribological characteristics of piston ring assembly in automotive engines using Al_2O_3 and TiO_2 nanomaterials as nano- lubricant additives," Tribol. Int., vol. 103, pp. 540–554, 2016.
doi: 10.1016/j.triboint.2016.08.011.

38. M. K. A. Ali, H. Xianjun, R. F. Turkson, Z. Peng and X. Chen, "Enhancing the thermophysical properties and tribological behaviour of engine oils using nano-lubricant additives," RSC Adv., vol. 6, no. 81, pp. 77913-77924, 2016.
doi: 10.1039/C6RA10543B.

39. W. Dai, B. Kheireddin, H. Gao and H. Liang, " Roles of nanoparticles in oil lubrication," Tribol. Int. vol. 102, pp. 88-98, 2016.
http://dx.doi.org/10.1016/j.triboint.2016.05.020.

40. Y. Y. Wu, W. C. Tsui, and T. C. Liu, "Experimental analysis of tribological properties of lubricating oils with nanoparticle additives," vol. 262, pp. 819–825, 2007.
doi: 10.1016/j.wear.2006.08.021.

41. Y. Peng, Y. Hu, and H. Wang, "Tribological behaviors of surfactant-functionalized carbon nanotubes as lubricant additive in water," Tribol. Lett., vol. 25, no. 3, pp. 247–253, 2007.
doi: 10.1007/s11249-006-9176-7.

42. A. Krishnamurthy, A. Razak, B. S. Halemani, A. Buradi, A. Afzal, and A. S. C, "Materials Today : Proceedings Performance enhancement in tribological properties of lubricants by dispersing TiO_2 nanoparticles," Mater. Today Proc., vol. 47, pp. 6180–6184, 2021.
doi: 10.1016/j.matpr.2021.05.083.

43. L. Peña-parás, J. Taha-tijerina, L. Garza, R. Michalczewski, and C. Lapray, "Effect of CuO and Al_2O_3 nanoparticle additives on the tribological behavior of fully formulated oils," Wear, vol. 333, pp. 1256–1261, 2015.
doi: 10.1016/j.wear.2015.02.038.

44. A. H. Battez et al., "CuO , ZrO_2 and ZnO nanoparticles as antiwear additive in oil lubricants," Wear, vol. 265, pp. 422–428, 2008.
doi: 10.1016/j.wear.2007.11.013.

45. A. S. Pisal and D. S. Chavan, "Experimental Investigation of tribological properties of engine oil with CuO

nanoparticles," International Conference on Theoretical and Applied Research in Mechanical Engineering (ICTARME 2014), ISBN: 978-3-643-24819-03, Goa, 18th May, 2014.

46. C. Rajaganapathy, D. Vasudevan, and S. Murugapoopathi, "Tribological and rheological properties of palm and brassica oil with inclusion of CuO and TiO_2 additives," Mater. Today Proc., vol. 37, pp. 207–213, 2021. doi: 10.1016/j.matpr.2020.05.032.

47. S. Borhan, S. Zeinali, and M. Ghasem, "Experimental investigation of MoS_2/diesel oil nano fluid thermophysical and rheological properties," Int. Commun. Heat Mass Transf., vol. 108, pp. 104298, 2019. doi: 10.1016/j.icheatmasstransfer.2019.104298.

48. S. M. Hisham, K. Kadirgama, D. Ramasamy, and S. Rahman, "Enhancement of tribological behaviour and thermal properties of hybrid nanocellulose/copper(II)oxide nanolubricant," vol. 1, no. 1, pp. 47–54, 2020. https://doi.org/10.37934/arfmts.72.1.4754

49. A. Sajeeb and P. K. Rajendrakumar, "Experimental studies on viscosity and tribological characteristics of blends of vegetable oils with CuO nanoparticles as additive," vol. 14, no. 6, pp. 1121–1125, 2019. doi: 10.1049/mnl.2018.5595.

50. A. C. Yilmaz, "Tribological Enhancement features of various nanoparticles as engine lubricant additives: An experimental study," Arab. J. Sci. Eng., vol. 45, no. 2, pp. 1125–1134, 2020. doi: 10.1007/s13369-019-04243-5.

51. P. Dev, S. Tanmoy, M. Shariq, and B. M. S. Charoo, "Tribological behavior of rice bran and sesame greases using h-BN and CuO nanoparticles," Biomass Convers. Biorefinery, no. 0123456789, 2023. doi: 10.1007/s13399-023-04528-8.

52. H. Gupta, S. K. Rai, N. S. Krishna, and G. Anand, "The effect of copper oxide nanoparticle additives on the rheological and tribological properties of engine oil," J. Dispers. Sci. Technol., vol. 42, no. 4, pp. 622–632, 2021. doi: 10.1080/01932691.2020.1844017.

53. N. F. Azman, S. Samion and M. Hakim, "Investigation of tribological properties of CuO/palm oil nanolubricant using pin-on-disc tribotester," Green Mat., vol. 6, no. 1, pp. 1-47, 2018. doi: https://doi.org/10.1680/jgrma.17.00026.

54. M. A. Hassan, M. H. Sakinah, K. Kadirgama, D. Ramasamy, M. M. Noor, M. M. Rahman, "Tribological behaviour improvement of lubricant using copper (II) oxide nanoparticles as additive," Int. J. Mech., Aero, Int., Mech, Manuf. Eng., vol. 10, no. 2, pp. 363-371, 2016.

55. P. Nallasamy, N. Saravanakumar, G. Rajaram, and R.K. Rishwin Kumar, "Experimental study on the tribological properties of CuO-based biodegradable nanolubricants for machine tool slideways," Int. J. Surf. Sci. Eng., vol. 12, no. 3, pp. 194-206, 2018.

56. A. Raina, and A. Anand, "Tribological investigation of diamond nanoparticles for steel/steel contacts in boundary lubrication regime," Appl. Nanosci., vol. 7, no. 7, pp. 371–388, 2017. doi: 10.1007/s13204-017-0590-y.

57. H. Peng, G. Ding, H. Hu, and W. Jiang, "Influence of carbon nanotubes on nucleate pool boiling heat transfer characteristics of refrigerant e oil mixture," Int. J. Therm. Sci., vol. 49, no. 12, pp. 2428–2438, 2010. doi: 10.1016/j.ijthermalsci.2010.06.025.

58. Y. Peng, Y. Hu, and H. Wang, "Tribological properties of engine oil with carbon nano-horns as nano-additives," Tribol. Letters, vol. 25, no. 3, pp. 45–53, 2007. doi: 10.1007/s11249-014-0330-3.

59. D. Wang, H. Tan, W. Chen, S. Zhu, J. Cheng, and J. Yang, "Tribological behavior of Ni_3 Al–Ag based self-lubricating alloy with Ag_2MoO_4 formed by high temperature tribo-chemical reaction," Tribol. Int., vol. 153, p. 106659, 2020. doi: 10.1016/j.triboint.2020.106659.

60. S. Boopathi et al., "An experimental study on friction stir processing of aluminium alloy (AA-2024) and boron nitride (BN_p) surface composite," Mater. Today Proc., vol. 59, no. 2022, pp. 1094–1099, 2024. doi: 10.1016/j.matpr.2022.02.435.

61. B. Cicek and T. Aydogmus, "The effect of basalt fiber addition on physical dry wear in al-cu alloy used in the automotive industry," Int. J. Auto. Sc. and Technol., vol. 6, no. 4, pp.

379-385, 2022.
https://doi.org/10.30939/ijastech..1196790.
62. A. E. Mogro, and J. I. Huertas, "Assessment of the effect of using air conditioning on the vehicle ' s real fuel consumption," Int. J. Interact. Des. Manuf., vol. 15, no. 2, pp. 271–285, 2021. doi: 10.1007/s12008-021-00750-8.