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Coolant Characterization and Predictive Monitoring System for Heavy-Duty Trucks using Machine Learning

Teo Yen Khai Ivan[1], Pei Yi Lee[1], Leong Seng Wong[1], Clarence Chin[2], William Liang[2] and Siong Fong Sim[1]**

[1]Faculty of Resource Science & Technology, Universiti Malaysia Sarawak, 94300 Kota Samarahan, Sarawak, Malaysia

[2]Hexa BRT Sdn Bhd, Lot 922, Block 7 MTLD, Jalan Demak Laut 3, Demak Laut Industrial Park, 93050, Kuching, Sarawak, Malaysia

*Corresponding author (e-mail: sfsim@unimas.my)

Over 50% of engine failures are attributed to poor coolant system maintenance. This study reports on a fleet test of automobile coolants and the development of a monitoring system to evaluate coolant performance. The fleet test was conducted on six trucks, where parameters such as pH, reserve alkalinity (RA), ethylene glycol (EG) content, and functional characteristics of the coolant were measured over eight months, and then subjected to regression learning. A coolant monitoring system was also developed to record and visualize coolant performance. The tensile strength of the radiator hose was examined to assess the impact of coolant on hose integrity. The study identifies pH as the most suitable indicator of coolant health against mileage with its stable degradation trend and clear threshold, though insensitive to coolant dilution. The C-O vibration of EG, as detected by Fourier Transform Infrared (FTIR) analysis, corresponded well with EG content determined using a refractometer. There was no evidence that coolant affects the tensile strength of the radiator hose. The Gaussian Process Regression (GPR) model was used to predict coolant degradation and estimates the optimal replacement mileage at of 111,473.65 km. This study introduces a data-driven coolant management approach to enhance reliability, cut maintenance costs, and reduce downtime.

Keywords: Fleet test; Fourier Transform Infrared; visual basic for applications; tensile strength test; Machine Learning

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An engine coolant is a mixture of fluids added to the cooling system of an engine which functions as temperature regulator, corrosion preventer, and boiling point elevator. Typically, coolant comprises of water and ethylene glycol (EG) in an equal ratio with additives added to offer anti-corrosion features [1]. In recent years, the integration of nanoparticles such as aluminum oxide into coolant base fluids has been actively explored, given that nanofluids offer improved thermal performance in automotive radiators-resulting in benefits such as reduced fuel consumption, increased power output, and lowered emissions [2-4]. Essentially, coolants can be categorized into three technology types, namely Inorganic Addictive Technology (IAT), Organic Additive Technology (OAT), and Hybrid Organic Additive Technology (HOAT), based on their formulation [5-6].

IAT coolants contain inorganic substances such as silicates, which are effective anti-corrosion agents. However, they deplete quickly, resulting in a shorter coolant lifespan and pose a risk of deposits and sediment formation that may block water channels in the cooling system [7]. This led to the development of OAT coolants, which became widely used in the 1990s due to their improved lifespan, enhanced efficiency, and environmentally friendly properties [8]. The carboxylate constituent provides metal corrosion sites which is suitable to be used in most vehicles to prevent corrosion. The first OAT coolant containing mono- and dicarboxylic salts was introduced in 1995. It exhibited extended life span up to 700,000 miles [9]. Subsequently, alternatives to carboxylic salts including sebacic acid, 2-ethyl caproate, and hexanedioic acid were reported to possess superior efficiency in inhibiting cavitation corrosion even in minute concentrations [10]. HOAT coolants were then introduced, combining both inorganic and organic additives to offer the best of both worlds—extended service intervals and enhanced system protection [11].

Coolant degrades over time, with EG breaking down into acidic by-products that put engine metal components at risk of corrosion. This degradation is accelerated under high-temperature and oxidative conditions, potentially causing serious damage to vehicle engines. In fact, more than 50% of engine failures result from poor coolant system maintenance [12]. Any maintenance resulting from the breakdown of engines due to overheating and corrosion can be substantial. In the commercial trucking sector, coolant issues account for approximately 60% of engine breakdown [13].

Coolant is crucial for freight and logistic companies. Typically, a unit of carrier truck requires 35 L of coolant to absorb the heat energy produced from the engine over a long duration. Proper coolant levels and quality are essential for maintaining the temperature of vehicles' engines, preventing overheating and ensuring optimal performance. Despite the importance of coolant maintenance, it is often overlooked in the preventive maintenance schedules of many logistics companies.

In summation, coolant is an important component for heavy-duty trucks which are an important asset of logistics companies. Yet, it is often overlooked that prolonged usage of the coolant would lead to its degradation, thus further harming the vehicles by causing corrosion. This leads to this reported study which aims to explore the possibility of creating a model built from data obtained by continuous laboratory tests, and serves to provide information for managers in the logistics field on the timing for the coolant to undergo maintenance.

This paper examines the characteristics of coolants used in heavy-duty trucks, assesses coolant degradation and its impact on the tensile strength of hoses, and predicts coolant lifespan using the machine learning strategy. A coolant monitoring system was developed using Visual Basic for Applications (VBA) to assess coolant performance and facilitate the early diagnosis of vehicle issues based on coolant pH, reserve alkalinity (RA), and ethylene glycol (EG) degradation. The findings from this study have significant implications for the maintenance and operational efficiency of heavy-duty trailer trucks, enabling fleet operators to implement proactive maintenance strategies that reduce unexpected breakdowns and costly repairs. They also contribute to the overall longevity of vehicles' cooling system and help lower long-term operational costs. Furthermore, the VBA system enhances fleet management by ensuring that coolant remains within optimal performance levels. It aims to introduce a new direction for managers to monitor their vehicles' condition by providing the information of the physiochemical qualities of the coolant the vehicle is using, and make appropriate decisions in maintaining the condition of the fleet.

EXPERIMENTAL

Fleet Test

A proprietary HOAT coolant product was used for the fleet test, which involved six trucks (A–F) from Hexagon Highs, a local freight company. These trucks were deployed for consignment trips within local areas. Before the test, the old coolant was flushed out from the radiator using tap water and replaced with new coolant. After refilling, the mileage readings of the trucks were recorded. Coolant samples were collected monthly over a period of eight months for analyses, including pH, RA, EG content, and Fourier Transform Infrared (FTIR) spectroscopy.

During the sampling, the engine was initially run for approximately 20 minutes. When the coolant temperature reaches 70°C, the radiator's thermostat would open, allowing the coolant to circulate throughout the engine. The temperature of the coolant in the radiator is continuously monitored via the dashboard. The coolant samples were collected from the reservoir located at the upper part of the engine when the temperature is approximately 70°C. Approximately 35 mL of coolant was taken using a pipette to minimize the loss of coolant available for the engine. In instances where the coolant level was too low, the coolant was collected from the bottom of the truck instead, and fresh coolant was refilled into the truck radiator.

Tensile Strength Test Preparation

The effect of the coolant on the radiator hose was also examined based on the tensile strength. Three different types of radiator hoses: the upper hose, lower hose, and bleed hose, from three trucks, as shown in Figure 1, were replaced with new hoses for the fleet test. The upper radiator hose connects the thermostat to the radiator; the lower radiator hose lies at the bottom of the radiator where the cooled coolant is directed upwards back to the coolant reservoir. Whereas the coolant bleed hose is located between the upper part of the radiator and the expansion tank. They were removed for tensile strength analysis after 4 months of use. A set of new hoses were also analyzed for comparison. The effect of the coolant on tensile strength was also examined in a laboratory setting to gain a more comprehensive understanding under controlled conditions. Four sets of hose samples were prepared: one as a control (unused hose), one was treated with the propriety coolant, one was treated with a commercial coolant, whereas the last set was treated with a 1:1 water-ethylene glycol solution. The treated hose samples were submerged in the coolants inside sealed beakers and continuously heated at 110°C for a month, with continuous aeration. The upper radiator hose was selected for this experiment as it is exposed to high temperatures during operation.

(a) (b) (c)

Figure 1. The radiator hoses studied: (a) upper radiator hose, (b) lower radiator hose, and (c) radiator bleed hose.

Laboratory Analysis

According to the American Society of Testing of Materials (ASTM), coolant solutions should be alkaline to help inhibit the corrosion of metals, and that reserve alkalinity is a parameter for assessing the depletion of the coolant [14]. Hence, the collected coolant samples had their pH measured using a pH meter (Apera pH 8500) and the RA determined according to ASTM D1121-11 [14]. Briefly, a 10 mL sample of coolant was diluted to about 100 mL with water and titrated potentiometrically with 0.100 N hydrochloric acid to a pH of 5.5. During the titration process, the sample was constantly stirred using a magnetic stirrer to ensure it is always in a homogeneous state, and the pH was monitored using a pH meter (Apera pH 8500). The EG content was measured using an RHA-218 ATC refractometer. Fourier-Transform Infrared (FTIR) spectroscopy, generally performed with the purpose of identifying chemical compositions based on their functional groups [15], was performed to support the tracking of EG degradation, as well as the degradation of the additives. This can be achieved by monitoring the height of the peaks of absorption bands of certain functional groups such as O−H stretching, C−O bending, N−H stretching and bending, and C−H stretching, which had been reported to be possible to be identified through FTIR [16].

The functional group characteristics of the coolant samples were determined using an FTIR spectrometer equipped with an attenuated total reflectance (ATR) accessory with a diamond crystal (Nicolet iS10 FTIR Spectrometer). The samples were scanned between 4000 and 400 cm^{-1} with 32 scans at the resolution of 8 cm^{-1}. Each spectrum was corrected with empty diamond as the background. The spectra were collected in 5 replicates and subjected to analysis using the peak detection and matching algorithm developed in Matlab [17]. The band at 1083 cm^{-1} assigned to C-O stretching in EG and the band at 1720 cm^{-1} indicative at carbonyl group (C=O) in glycolic acid were monitored.

The tensile strength test was determined according to the Standard Test Method for Vulcanized Rubber and Thermoplastic Elastomers (ASTM D412) [18] and Standard Test Method for Tensile Properties of Polymer Composite Materials (ASTM D3039/ D3039M-08) [19]. The samples were cut into specimens with dimensions of 113 mm × 30 mm, with tolerance of ± 1 mm. The positions for clamping were marked 20 mm from both ends of the specimen. The thickness, width, and length (excluding the clamping section of the specimen) were measured using vernier calipers. The test was performed with the elongation rate of 20 mm/min using a Shimadzu Autograph AGS-X Table-TOP Precision Universal Tester and the results were analyzed using TRAPEZIUM Lite X software. Two parameters were measured: maximum force and maximum stroke. Maximum force represents the maximum stress a hose can withstanding before breaking, while maximum stroke denotes the maximum elongation observed in a stretched sample before breaking.

Coolant Monitoring System in Visual Basic Application (VBA) & Statistical Analysis

A Visual Basic Application (VBA) system was developed as a database for coolant performance. This system includes features for data analysis and visualization. It records the pH, RA, and EG levels of coolant samples, along with the vehicle registration number, sampling dates, and mileage of the test vehicles prior to sampling. The system also features data visualization tools to help users identify vehicles with abnormal coolant conditions. The coolant characteristics and performance data collected through this system are used to create a database for predicting coolant degradation. Analysis of Variance (ANOVA) was performed to compare the tensile strength characteristics at 95% confidence level. Tukey's test was used for multiple comparisons.

Prediction of Coolant Degradation Based on Machine Learning

After a period of data collection, the pH, RA, and EG content of the coolant samples were compiled along with their respective mileage of the test trucks taken during sampling. The compiled data of 123 entries of 4 variables (RA, pH, EG, and mileage) were evaluated using Matlab to derive a model for coolant degradation assessment. EG, RA, and mileage were used as the predictive variables to predict the pH. The model performance was determined based on R^2 and Root Mean Squares Error (RMSE). The data were split into training and test sets with two thirds of the data being assigned into the training set and the remaining into the test set. The prediction was repeated for 10,000 iterations. In each iteration, the data in the training set were subjected to model fitting, whereas the test set was used in attempt to predict the response based on the model obtained from the training set. The RMSE was calculated and its mean value was obtained as an overall assessment on the reliability of the model.

RESULTS AND DISCUSSION

The VBA interface for the coolant monitoring system is shown in Figure 2. The VBA system was developed to monitor coolant performance and enable early diagnostics of engine failures. The core function of this system is to record and visualize the coolant characteristics. The system is user friendly, allowing data entry and visualization through buttons located at the top of the interface.

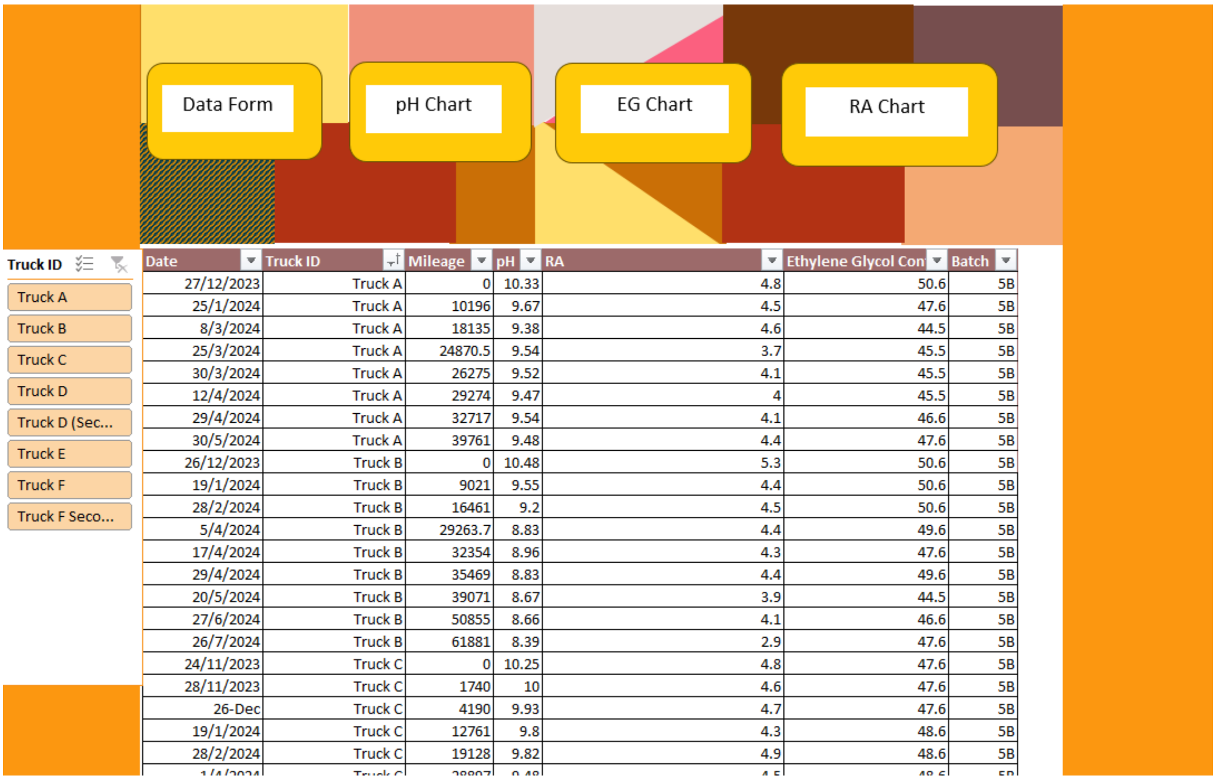
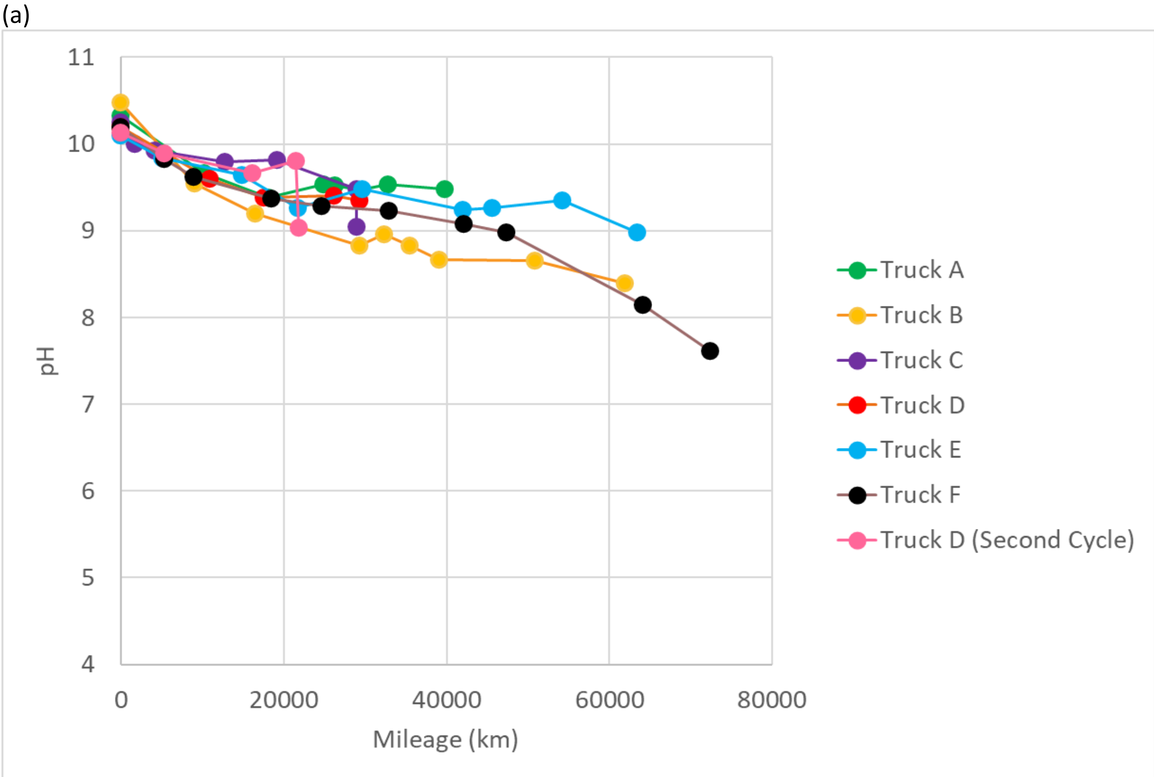


Figure 2. The VBA interface for the coolant monitoring system.

The pH, RA, and EG content of the coolant in relation to distance travelled by the six trucks are shown in Figure 3. There was a decrease in pH with increasing distance, which is normal due to the acidification of the coolant from the oxidation of EG. Ideally, the coolant's pH should be maintained above 8. The RA showed more significant fluctuations. The recommended RA for coolant is above 2 mL. Some trucks, specifically Trucks C, D, and F, exhibited RA values below 2 mL after traveling certain distances. The decreased RA corresponded with reduction in % EG (which is ideally maintained at 50%), whereas its increase correlated with the coolant refill which was performed when the coolant levels in the trucks were too low. The plummeting RA and EG are associated with the addition of water to the radiator during the fleet test, which dilutes the EG and coolant additives. The trucks experienced some engine issues, and after repairs the coolant was topped up with water. This suggests compromised cooling efficiency, placing these trucks at a higher risk of overheating. Truck B on the other hand was observed to have foaming coolant, likely due to the depletion of the anti-foaming agent, which caused coolant loss. When the engine is running, accelerated fluid flow and intense engine vibration contribute to this issue [20]. The anti-foaming agent is commonly added to coolant to replace the gas-liquid interface molecules of bubbles with surfactant molecules [21].

The pH of the coolant is an indicator its lifespan. A coolant with a pH less than 8 indicates that it may not provide adequate protection against engine corrosion. During the fleet test, the pH of the coolant remained relatively stable, although a reduction was observed. This observation is likely due to the presence of corrosion inhibitors in the coolant, such as sodium metasilicate that offers a good buffering capacity against the formation of acidic compounds resulting from the oxidation of EG. pH does not provide a good indication on the depletion of EG, which is an important component for the cooling properties of the coolant. The significant drop in RA and EG was not accompanied by a comparable reduction in pH. With the VBA system, a platform for monitoring of coolant and diagnosis of vehicles' breakdowns is established.

(a)



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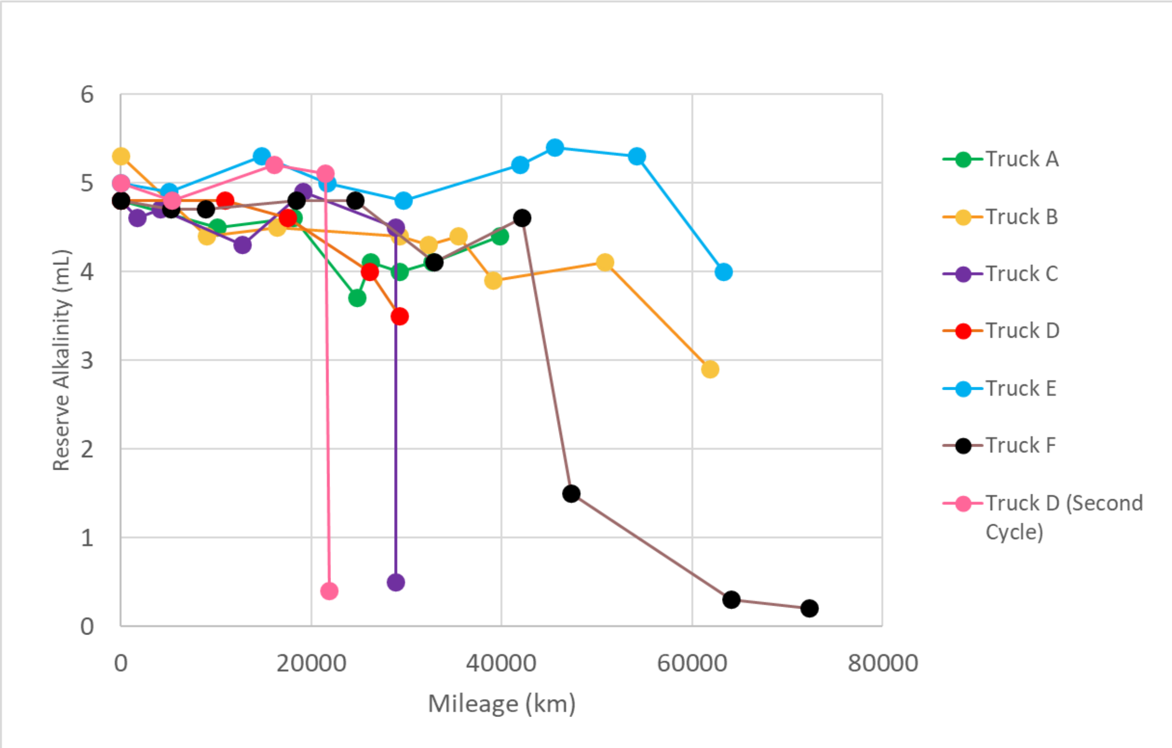

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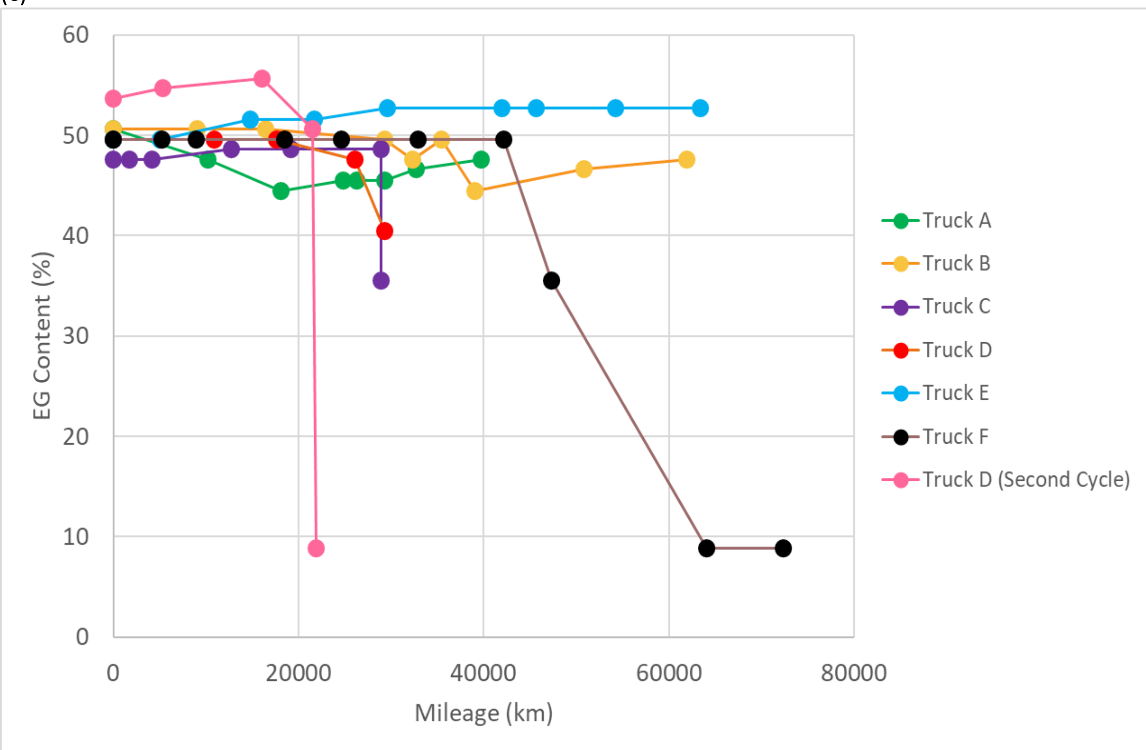


Figure 3. (a) pH, (b) reserve alkalinity, and (c) EG content of the coolant against trucks' mileage.

Table 1. Summary of FTIR absorption bands identified and their respective functional groups.

Wavelength	Functional Groups
596 cm^{-1}	C-Cl tension
860 cm^{-1}	C-H bending of 1,2.4-trisubstituted/1,3-disubstituted benzene derivative
1040 cm^{-1}	C-O skeletal vibration of EG
1073 cm^{-1}	C-C skeletal vibration of EG
1200 cm^{-1}	C-N stretching of amine
1400 cm^{-1}	O-H bending of carboxylic acid
1640 cm^{-1}	C=C stretching of alkenes, N-H bending of amines
2883 cm^{-1}	C-H stretching of alkanes
2948 cm^{-1}	N-H stretching of amine salts
3274 cm^{-1}	O-H stretching of alcohol

Table 1 shows a summary of the functional groups identified in the FTIR spectra of the coolant samples of all six test trucks, which is depicted in Figure 4. Several major absorption bands at ~596, 860, 1040, 1073, 1200, 1400, 1640, 2883, 2948, and 3274 cm^{-1} were identified. The bands at 1040 and 1073 cm^{-1} are assigned to the C-O and C-C skeletal vibration of EG [22]. It is hypothesized that the degradation of EG, which leads to the formation of acidic compounds, would give rise to an absorption band at 1720-1700 cm^{-1}, representing C=O stretching. The peak at 1720 cm^{-1} was not found throughout the fleet test. Instead, the absorption band at 1038 cm^{-1} showed a corresponding indication with the EG content as determined by the refractometer (Figure 5). The remaining absorption bands identified are assigned to the other components in the coolant.

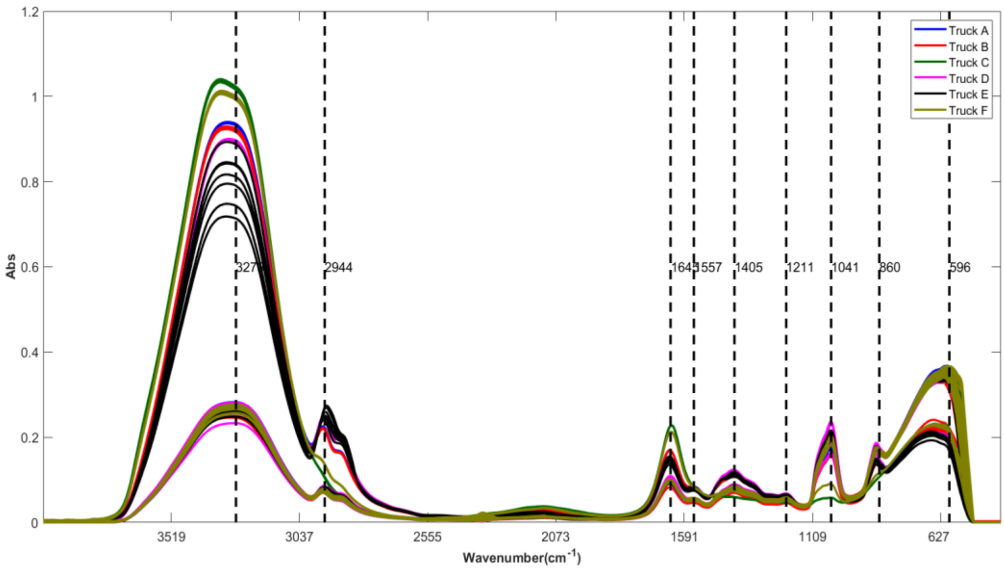
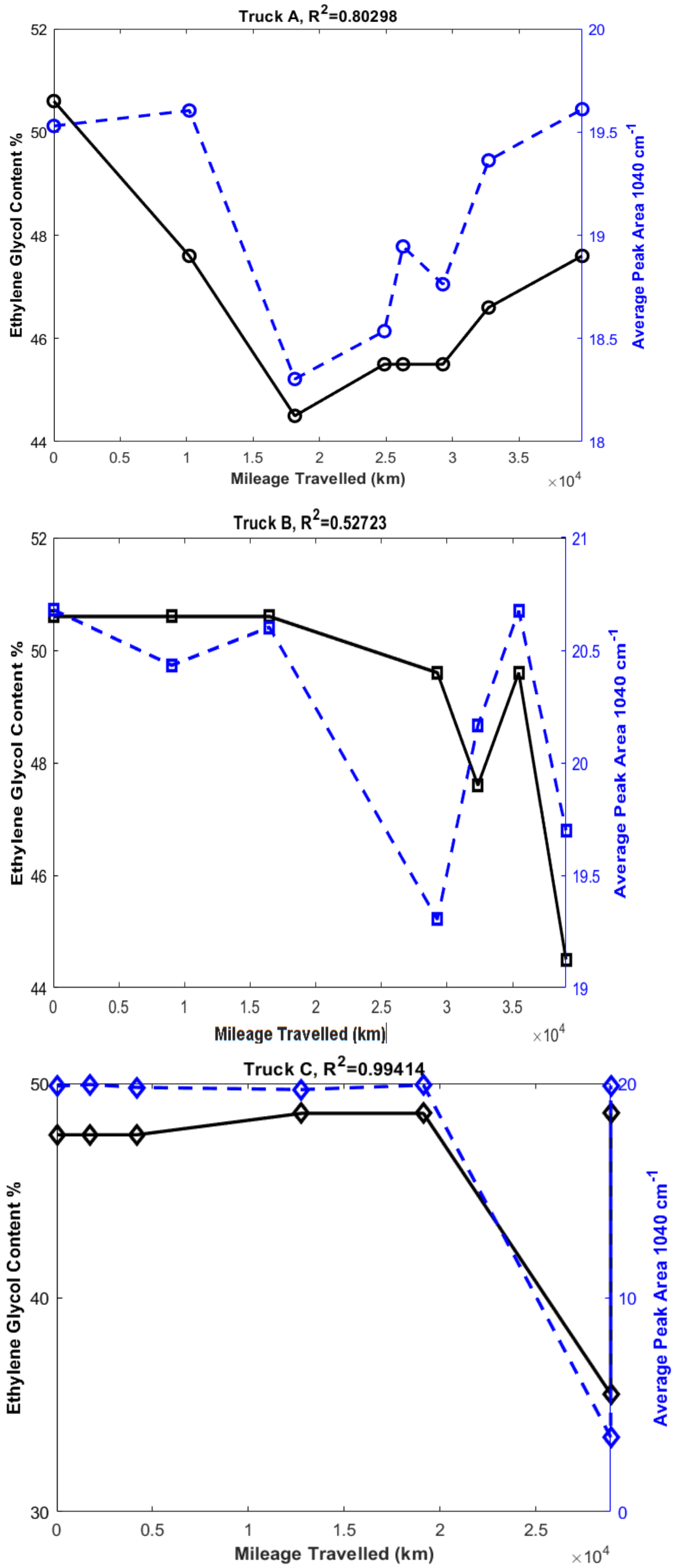
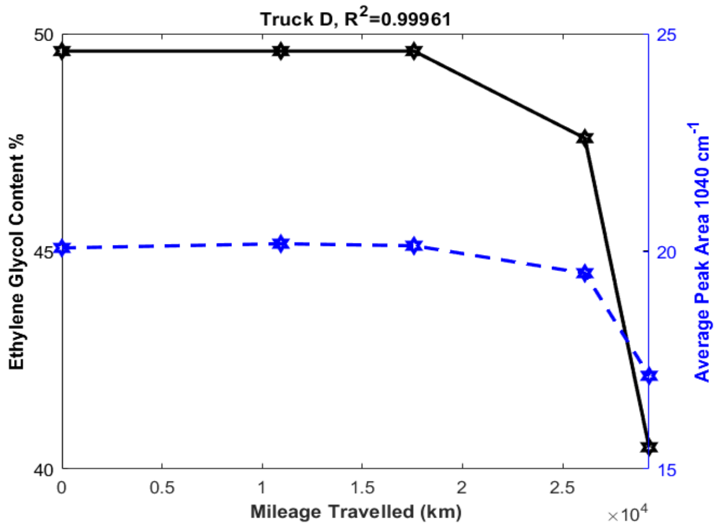
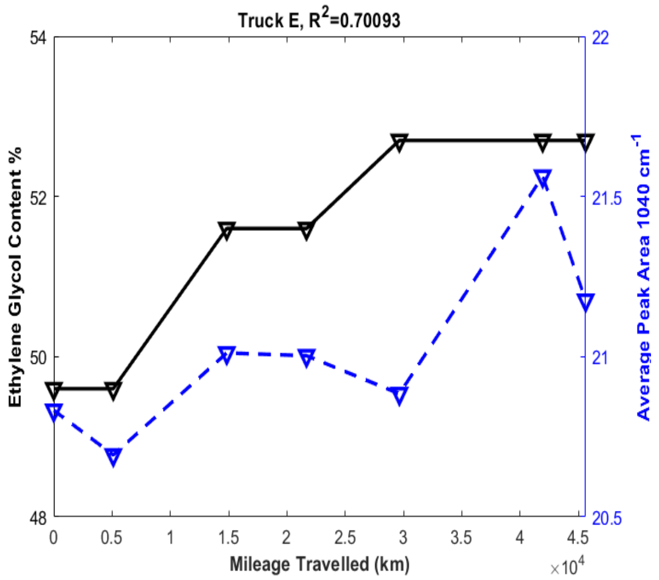
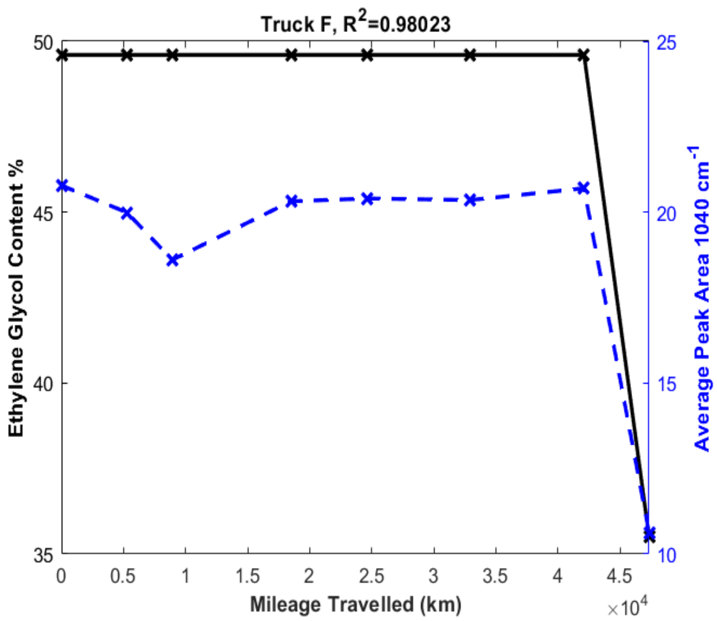


Figure 4. FTIR Spectra of coolant samples of test trucks.


Truck A, R²=0.80298
Ethylene Glycol Content %
Average Peak Area 1040 cm⁻¹
Mileage Travelled (km)
×10⁴
Truck B, R²=0.52723
Ethylene Glycol Content %
Average Peak Area 1040 cm⁻¹
Mileage Travelled (km)
×10⁴
Truck C, R²=0.99414
Ethylene Glycol Content %
Average Peak Area 1040 cm⁻¹
Mileage Travelled (km)
×10⁴


Truck D, R²=0.99961
Ethylene Glycol Content %
Average Peak Area 1040 cm⁻¹
Mileage Travelled (km)
×10⁴


Truck E, R²=0.70093
Ethylene Glycol Content %
Average Peak Area 1040 cm⁻¹
Mileage Travelled (km)
×10⁴


Truck F, R²=0.98023
Ethylene Glycol Content %
Average Peak Area 1040 cm⁻¹
Mileage Travelled (km)
×10⁴

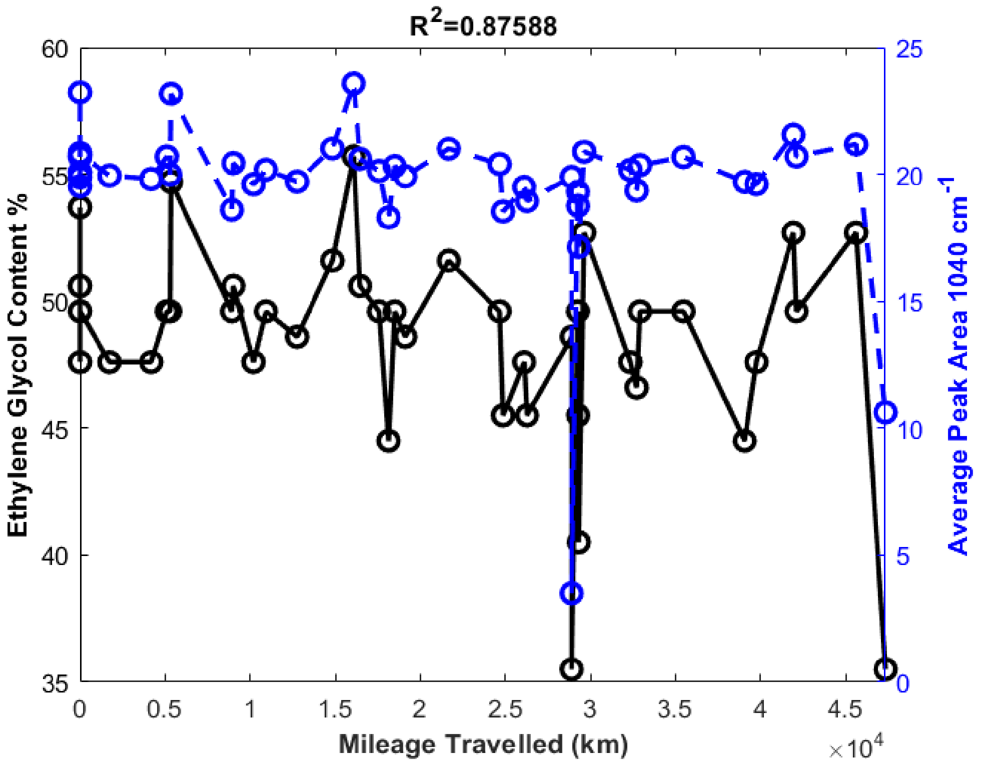
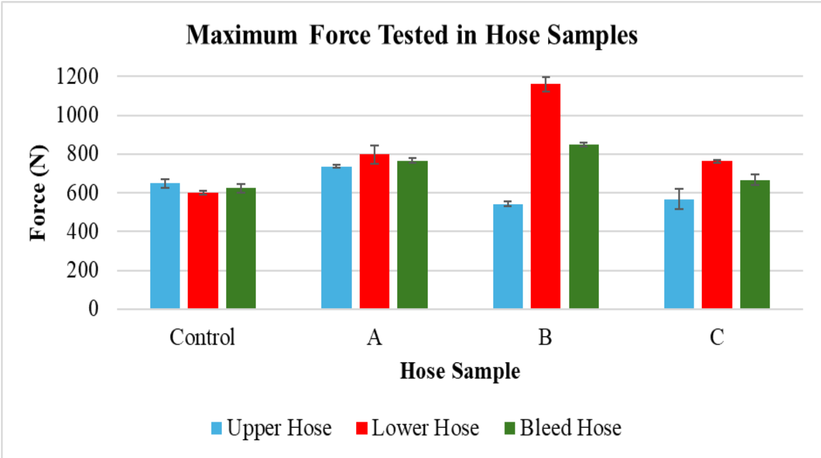


Figure 5. Comparison of the absorption of 1040 cm^{-1} in FTIR and the EG content measured using the refractometer.

The tensile strength test was performed to consider the possibility that the coolant blend might cause undesirable changes to the properties of the radiator hose. Previous literatures reported that under constant exposure of high temperature and oxidation, the ethylene-propene diene monomer (EPDM) exhibits an increase of crosslink density, leading to increased tensile strength and decreased elongation [23]. Whereas recent studies reported on observations of radiator hose samples under exposure of high levels of ethylene glycol and high temperature causes a decrease in tensile strength compared to an unaged hose [24]. This phenomenon may result in the failure of the radiator hose, causing issues such as coolant leakage and hose explosion [25].

Results of the preliminary tensile strength test data revealed no significant change in the tensile properties of the hoses from the test trucks, suggesting coolant safety. The maximum force and maximum stroke of the radiator hoses from the test trucks are shown in Figure 6. Based on the results demonstrated, it is suggested that exposure to the coolant would cause the hoses to exhibit an increase in maximum force and a decrease in maximum stroke. Certain acidic compounds in the coolant, such as sodium 2-ethylhexanoate, may react with fillers in rubber and disrupt their network structure, leading to reduced elasticity [26]. Additionally, the incorporation of foreign molecules into the rubber's molecular network requires more force to break it. Table 2 summarizes the p-values for comparisons of tensile strength between the Control and the test hoses. A p-value of less than 0.05 indicates a significant difference between the two designated groups (bold).

Statistically, there was a significant difference in tensile strength among the different groups of samples—A, B, C, and Control—across all three types of hoses ($p < 0.05$). In general, groups B and C demonstrated a significant increase in maximum force and a decrease in maximum stroke compared to the Control for all three types of hoses, indicating hardening of the hoses. An exceptionally high maximum force was observed in set B, which notably came from the truck reported to have foaming coolant. The implosions caused by the foaming may have eroded the rubber's surface, allowing coolant to diffuse into the rubber matrix and disrupt crosslinking interactions, as set B also had the lowest overall maximum stroke. Similarly, set C was obtained from Truck C, which had underlying issues reported during the fleet test. For this reason, the changes in tensile strength for samples B and C due to the coolant could not be thoroughly analyzed. Sample A was unaffected by any underlying issues, providing a clear representation of the coolant's effect on the radiator hose under actual running conditions. The tensile strength of samples A was comparable to the control across all hose types, except for the upper hose. The increase in maximum force was only observed in the upper radiator hose, suggesting that this phenomenon may not be due to the coolant but rather the result of exposure to high temperature and pressure. Radiator hose hardening occurs on the surface as a result of thermo-oxidative aging. This condition is typical for the upper radiator hose due to its proximity to the engine and its role in transporting heated coolant [27].



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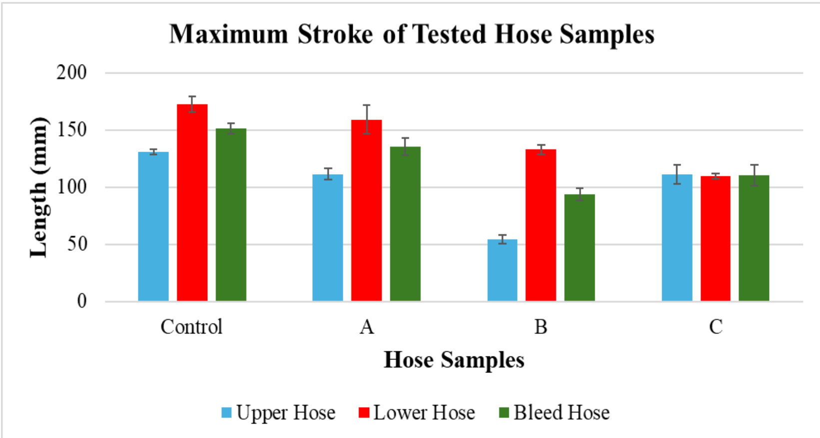


(b)

Figure 6. (a) Maximum force and (b) maximum stroke of hose samples obtained from test trucks.

Table 2. Summary of Tukey's test for the tensile strength characteristics of three hoses in test trucks.

	p-value					
	Upper Hose		Lower Hose		Bleed Hose	
Groups	Max Force	Max Stroke	Max Force	Max Stroke	Max Force	Max Stroke
Control vs A	**0.037**	0.828	0.162	0.828	0.999	0.184
Control vs B	**7.66×10^{-5}**	**0.010**	0.930	**0.010**	0.431	**0.0004**
Control vs C	0.153	**0.001**	0.995	**0.001**	0.393	**0.0035**

The tensile strength of the upper hose samples submerged in the proprietary coolant was measured and compared with that of untreated hoses, a commercial coolant blend, and with a 1:1 water-EG solution. Figure 7 shows the maximum force and maximum stroke of hose samples prepared in the lab setting. The results showed that the hose samples exposed to coolant show a decrease in maximum force compared to control, which is stipulated to be due to the extreme heating in the experiment. Kwak & Choi established that radiator hoses subjected to thermal aging would lead to decrease in tensile strength and elongation [27]. There was no difference in maximum force between the two coolant blends (proprietary and commercial Coolants). The hose samples submerged in the water-EG solution experienced the worst degradation in maximum force, and the change in maximum elongation was similar to the other treated hoses.

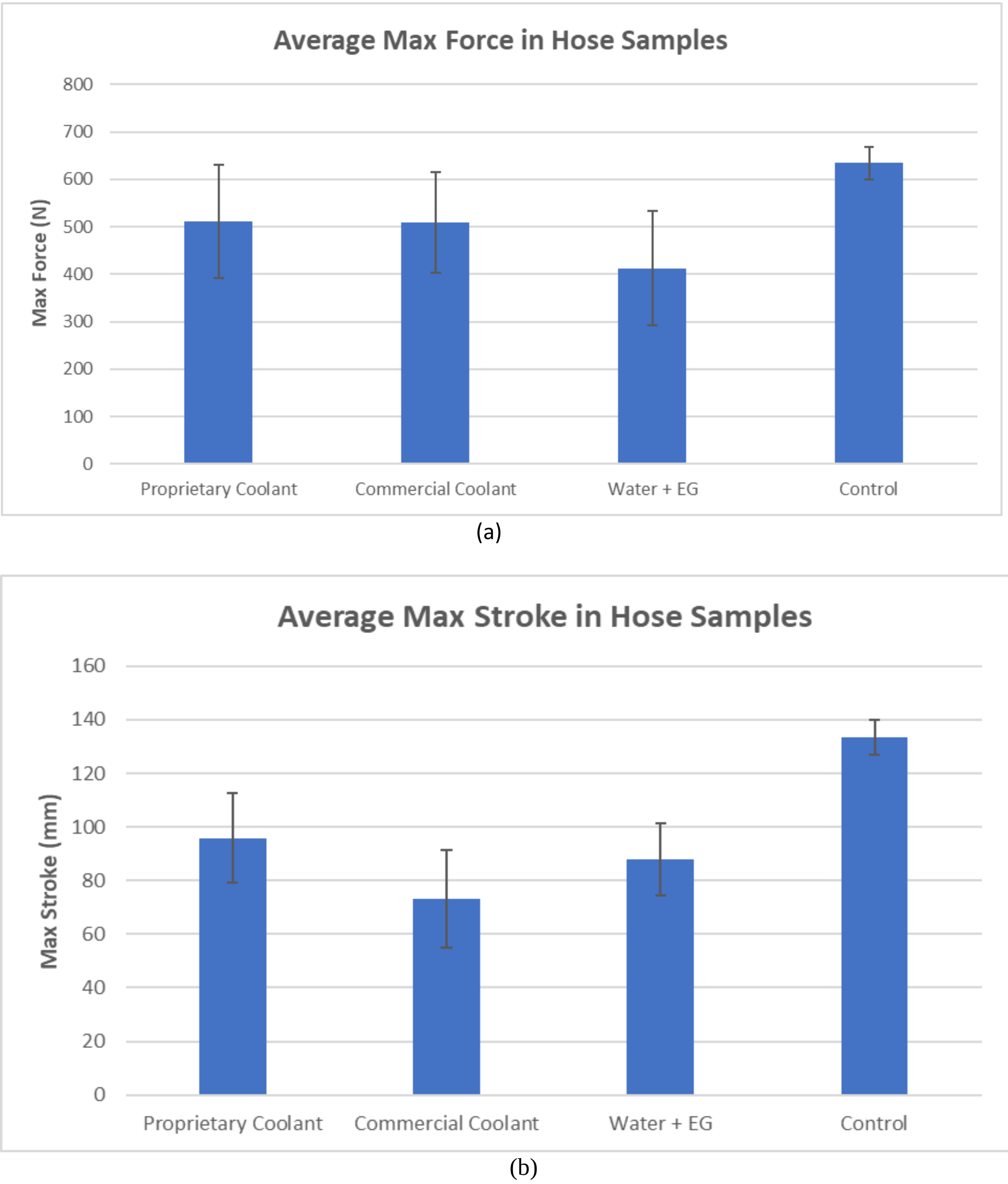


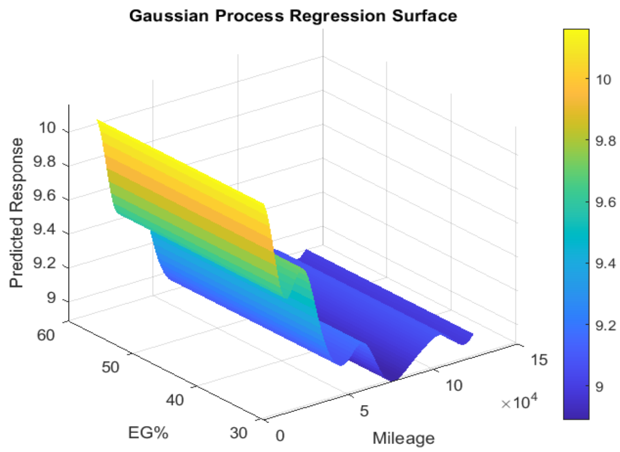
Figure 7. (a) Maximum force and (b) maximum stroke of hose samples prepared in the lab setting.

It has been proposed that vehicle health monitoring should adopt data-driven strategies and machine learning algorithms instead of the conventional ways of fixing issues only when they are detected [28]. Hence, the coolant health data collected during fleet test were taken for regression learning to assess the possibility of predictive maintenance. Mileage and EG were used to predict the coolant's pH. Several regression models including linear, tree, and gaussian were tested, with their RMSE and R^2 values documented in Table 3. Among these, Exponential Gaussian Process Regression (GPR), a non-parametric model, demonstrated the highest R^2 of 0.615, as shown in Table 3. As the R^2 value was the highest, it is deduced to be the most fitting model of coolant degradation and thus subjected for further data training.

Figure 8(a) shows the regression model; the data were split into 10,000 training and test sets where the models resulted in a mean RMSE value of 0.35 and R^2 of 0.573. The histograms of RMSE and R^2 over 10,000 iterations are shown in Figures 8(b) and (c). The model shows a moderate accuracy, as depicted in the scatter plot in Figure 8(d). The model predicts coolant degradation and estimates the optimal replacement mileage. It predicts that the pH will reach 8 at the mileage of 111,473.65 km, with an EG content of 6.22%. The ASTM D3306 specifies that both concentrated and pre-diluted EG coolant should have a pH between 8 and 11 [29].

Table 3. Validation data of different regression models for pH against mileage and EG content.

Model	RMSE	RMSE %	R^2
Linear	0.3943	4.078	0.49
Interactions Linear	0.4	4.136	0.478
Stepwise Linear	0.3943	4.077	0.49
Fine Tree	0.3852	3.983	0.513
Coarse Tree	0.45	4.654	0.336
Squared Exponential GPR	0.3516	3.636	0.594
Rational Quadratic GPR	0.3625	3.749	0.569
Exponential GPR	0.3426	3.543	0.615



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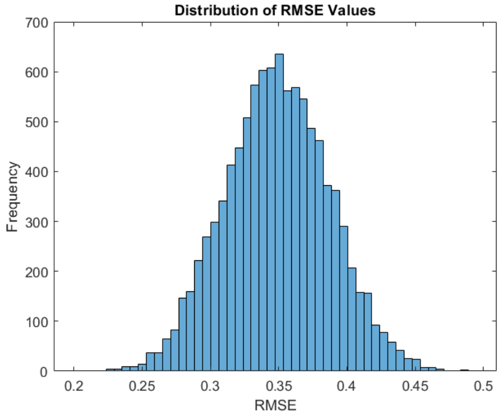

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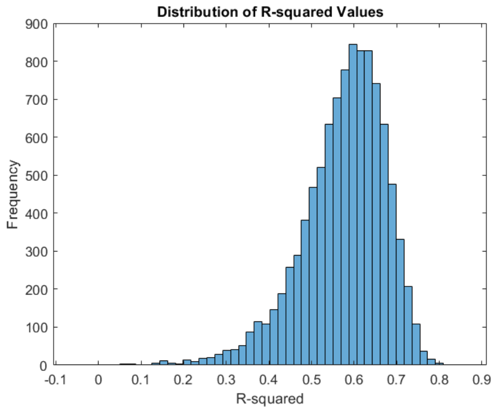

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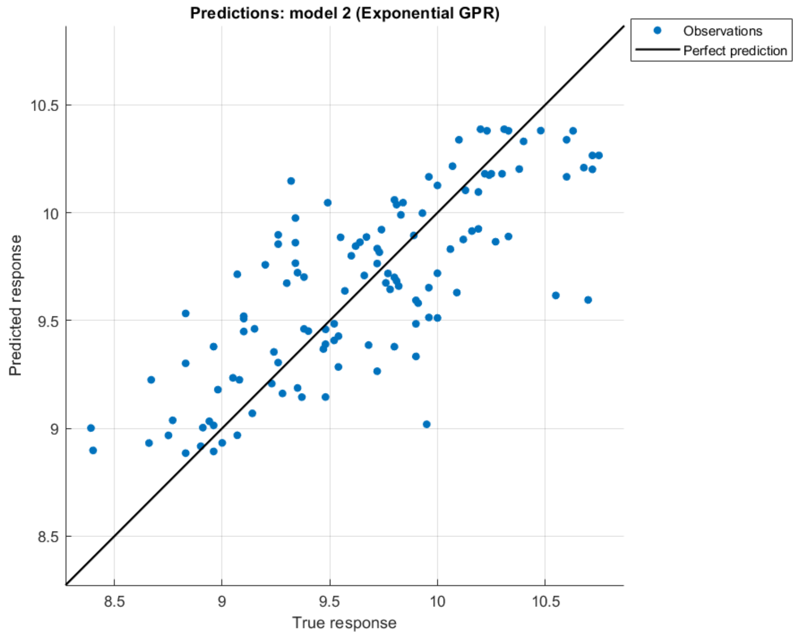

(d)

Figure 8. (a) The GPR Model obtained from the pH and EG percentage of the coolant samples, and the corresponding mileage of the test trucks; the histograms of (b) RMSE and (c) R^2 for 10,000 iterations of testing; and (d) the scatter plot of observations against prediction of the GPR model.

The GPR model has a moderate R-squared value despite being the highest among the tested models. GPR has been described as a non-linear, non-parametric regression tool for data points with scattered, high-dimensional input [30]. In actual usage, the coolant degradation observed may not be affected just by the chemical process in the coolant, but also by other factors such as contamination of exhaust gas and frequency of coolant refill. These factors would affect the degradation of the coolant irregularly, hence the GPR model was chosen.

However, as GPR is a probabilistic model which works by using available data, in operational use certain users may find that the model greatly deviates with their experience. With addition of data points, the model may have greater reliability to be used.

CONCLUSION

The VBA coolant monitoring system provides an efficient platform for monitoring coolant performance. The tested parameters—pH, RA, and EG content—effectively offered insights into coolant performance and potential alterations, such as dilution. While the pH of the coolant can indicate its lifespan, it does not directly correlate with reserve alkalinity or EG content.

The results of tensile strength test reveal that the usage of the coolant would not lead to detrimental changes on the durability of the radiator hose. Machine learning strategy was implemented to predict the coolant degradation, allowing data-driven decision for optimal coolant replacement intervals. For the fleet industry, this study highlights a data-driven approach for coolant management, improving vehicle reliability, reducing maintenance costs, and minimizing downtime. By integrating predictive model, the maintenance schedule can be optimized, enhancing the overall operational efficiency of the fleet operators. However, at the current stage, more data is required to ensure its reliability, as the model is probabilistic in nature and lies the possibility for users to have an experience that largely deviates from what the model presents.

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