

Assessment of evaporation losses of petroleum products during transportation in Malawi

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DISCLAIMAR

I PETER KALIATI declare that this research study is a product of my own work submitted to Ndata School of Climate and Earth Sciences of the Malawi University of Science and Technology. All sources of information used in this correctly cited and referenced, and any assistance rendered has fully been acknowledged.



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ABSTRACT

Petroleum products contain Volatile Organic Compounds (VOCs) with different boiling points. The objective of this study was to evaluate the amount of evaporation loss of petroleum products (petrol and diesel) during transportation in Malawi. The study used the descriptive research design as it aimed at answering the what, when and how questions. Two mathematical models were also used; pressure loss and evaporation loss percentage models. Based on the results, it was found that evaporation loss amounted to total volume loss of 5,021,345.649 liters from 2015 to 2022 due to pressure changes. The results also give a total volume loss of 3,597,925.4592 liters from 2015 to 2022 as a result of travel time and temperature changes during transportation. Reduction of evaporation loss of petroleum products during transportation will give attractive economic returns as well as air pollution. This reduction could be achieved by reducing the vapour space capacity inside the tank trucks by maximum filling of tanks trucks when loading the petroleum products. Reduction in ambient temperature and pressure can also be achieved by plantation of trees along the roads. This increases the shadow area around the tank's truck during transportation which would be considered as metrological condition control action. The use of vapour recovery systems, maintaining the tank wall thicknesses and pressure management are also some control measures that can be implemented to reduce the evaporation losses of petroleum products during transportation in Malawi.

Key words: Evaporation loss, Temperature, Pressure, Pressure losses and Travel time.

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iii. List of abbreviations/ acronyms

API	American Petroleum Institute
APRG	Air Permit Reference Guide
DCCM	Department of Climate Change and Mereological Services
POC	Product of Combustion
VOCs	Volatile Organic Compounds
MPMS	Manual of Petroleum Measurement Standards
NOCMA	National Oil Company of Malawi
Vg	Vapour space volume
V_l	Liquid fuel volume
P	Atmospheric pressure
S1	Vapour saturation on leaving terminal, fraction of 1 .00
S2	
P_f	Vapour saturation upon arrival a t unloading station, fraction of 1.00
%EV	Fuel vapour pressure
T	Percentage evaporated
	Temperature in degree Celsius
t	Time in minutes
GoM	Government of Malawi
L	Litres

Table 1.1: Abbreviations

SECTION 1: INTRODUCTION

Evaporation loss is a natural process in which part of liquid turns to vapor and vanishes into the atmosphere. Petroleum products have several hydrocarbon compounds in which some of them evaporate and could be released into the atmosphere at ambient temperature and pressure (Alhaj, Alzubair and Gadir. 2014)

1.1. Background of the study

Liquid petroleum products are transported throughout the world on a regular basis (Ramazanov, 2008). During transportation, Losses in liquid petroleum may be caused by different factors: physical and chemical characteristics of the products, method of loading and unloading product, operations to transport the carrier to a loading terminal, characteristics of transportation equipment. (Hernández et al., 2016).

These factors at different proportions may affect the total loss. Usually these factors can be evaluated after having significant practical experience in the field of transportation and storage of specific products (Brooke and Crookes, 2007). It is considered that the main losses are usually caused by evaporation. Special methods have been developed to estimate losses caused by evaporation under various circumstances. However, methods of calculation usually include some parameters that are hard or impossible to estimate (Hernández et al., 2016).

Jurušs and Seile, (2017), Handling, transportation and storage of liquid petroleum products includes a variety of activities. Each activity may cause loss due to evaporation of the liquid or technical reasons. It is believed that handling and storage of liquid petroleum products may cause leakage losses. However, the most significant losses occur through evaporation when transition from the liquid phase to gas phase takes place (Zhang et al., 2013).

During the process of loading petroleum products into tankers, services of independent inspections are often used. The inspectors may document the weight of the good as measured on the tanker, where the acceptable difference between the measurement performed on the shore and on the board of the vessel may vary up to 0.3% losses due to evaporation (Jurušs and Seile, 2017).

During transportation, when the total sending volume is lower than the measured volume in the mixing tank in a gathering station, the phenomenon is known as **oil losses**. There are two categories of oil losses namely; individual and group losses. Individual loss occurs when oil from one tanker has not been mixed yet with other oils. This includes emulsion and evaporative losses. Group loss occurs during the process of mixing oils in the same tank or pipeline (Hermawan, Kristanto, & Hariyadi. 2021)

1.2. Problem Statement

Although there has been researches that have been conducted in the sector of evaporation losses of petroleum products, little has been documented on how evaporation losses of these products occur during transportation. Alhaj, Alzubair and Gadir (2014) conducted their study in Sudan and found that gasoline evaporates from internal floating roof storage tanks. The study however focused on evaporation losses of petroleum products from storage tanks not during transportation. The study by Hermawan, Kristanto and Hariyadi (2021) focused on evaporation losses of various petroleum products in Mid-continent Field from storage tanks and found that petroleum products are lost from storage tanks due evaporation. Jurušs and Seile (2017) investigated loss rates for petroleum products in Latvia and found that the loss observed result solely from the nature of the petroleum products. The research was however focused on liquid petroleum products losses due to natural wastage in customs, procedures and not on the evaporation losses of petroleum products during transportation. Therefore, this study will further address evaporation losses of petroleum products during transportation as opposed to evaporation losses of these products in storage tanks and their natures. This research bridges the above gap by assessing evaporation losses of petroleum products during transportation in Malawi.

1.3. Main and specific objectives

The main objective of this research study is to assess the evaporation losses of petroleum products during transportation in Malawi.

The specific objectives of the study are:

- To determine the effects of pressure on evaporation losses of petroleum products during transportation.
- To evaluate the effects of travel time on the rates of evaporation losses of petroleum products during transportation.
- To examine the influence of temperature on evaporation losses of petroleum products during transportation.
- To evaluate the economic impacts of evaporation losses of petroleum products during transportation

1.4. Research questions

This study seeks to answer the following questions:

1. What effect does pressure has on evaporation losses of petroleum products?
2. What are the effects of travel time on the rates of evaporation losses of petroleum products during transportation?
3. How does temperature influence the evaporation losses of petroleum products during transportation?
4. What are the economic impacts of evaporation losses of petroleum products during transportation?

1.5. Significance of study

This research will prove a number of various important aspects. First, the research aids scholars and investigators who can use the study findings as a basis for their theoretical framework. Future researchers who will undertake studies in this field will also be able to compare their findings with the findings of this study, hence make useful conclusions. The study will also provide recommendations for future studies for which future researchers would adopt for their studies.

The study is also beneficial to government of Malawi. The government through the understanding of how evaporation loss affects the performance of petroleum sector will be able to come up with joint policies that informs how the losses of petroleum products through evaporation will be implemented. The government would also adopt the study findings and come up with regulations and policies through the petroleum

products regulating associations that ensure optimal performance in the petroleum industry.

1.6. Study Area

The research study was done in two selected areas located in the southern region of Malawi namely; Blantyre and Lower-shire. These areas were randomly selected as they experience different pressures and temperatures. For example, the mean daily temperature for Blantyre is 25.3°C whereas lower shire has 35.2°C as its mean daily Temperature. (GoM, 2023).

Figure 1.1 below shows the Map of Southern Malawi showing some districts including Blantyre and Nsanje district.

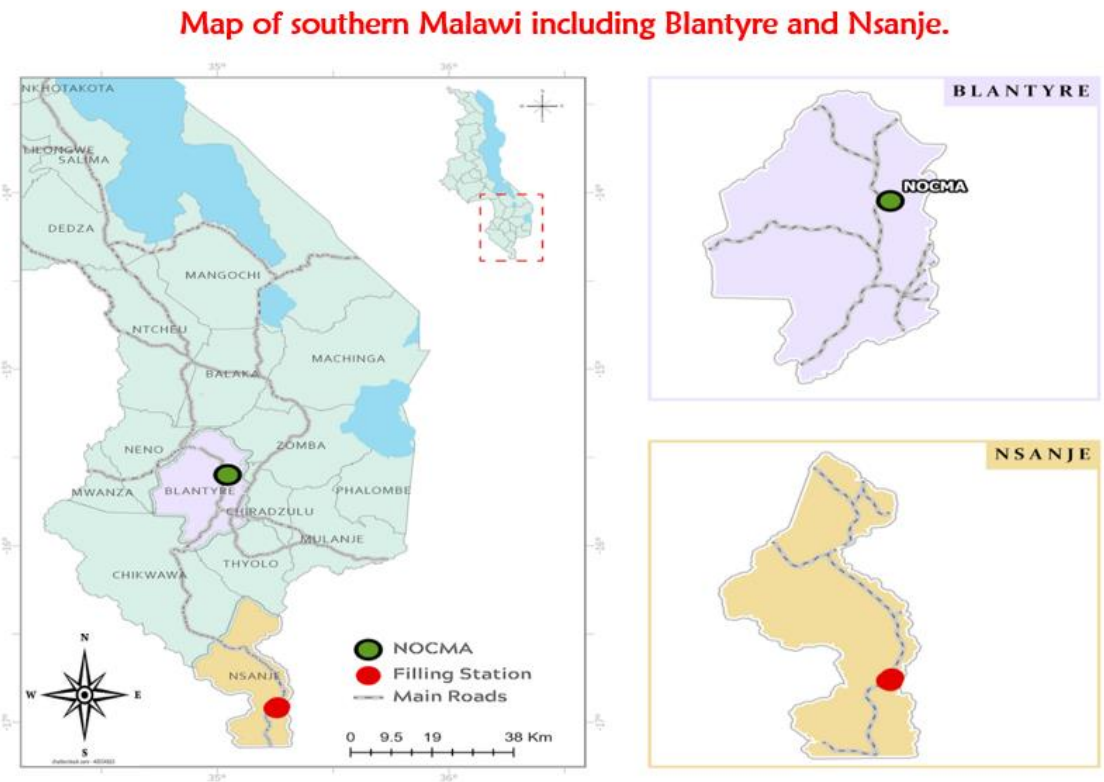


Figure 1.1: Map of Southern Malawi

SECTION 2: LITERATURE REVIEW

In this section, an empirical review of the recent and related literatures linked to this research is provided. The chapter also discusses some sources of evaporation losses in

the empirical review. The sources are withdrawal loss mechanisms, Rim seal area loss mechanisms, Displacement loss, flash losses and loading losses. The chapter then provides the summary of the literature review.

2.1. Empirical review

Investigation has further shown that the gasoline in crude oil evaporates from one-half to six-tenths as rapidly as the same gasoline after being distilled and stored in the storage tanks (Thompson, 2017).

Bhatia and Dinwoodie (2004) conducted the study and observed that losses of petroleum products occurring due to its nature during transportation may differ for different products. The study again showed that losses may also occur in the storage process because of the difference in density of different products received in the same reservoir, as well as losses resulting from the nature of petroleum products.

Alhaj, Alzubair and Gadir (2014) studied and found sources of evaporation losses of gasoline in the internal floating storage tanks in Sudan. The sources are withdrawal loss mechanisms, Rim seal area loss mechanisms and Displacement loss.

2.1.1. Withdrawal loss mechanisms

Withdrawal loss occurs during stock liquid withdrawal. When the floating deck descends with the liquid level, some liquid remains in a coating on the tank wall and the support column. When this liquid is exposed to the air, some evaporation occurs to the atmosphere before the exposed area is covered again.

2.1.2. Rim seal area loss mechanisms

The potential mechanism in this loss is found to be vertical mixing of vapor in the gap between the tank shell and the seal resulting from diffusion and air turbulence. The change in temperature and pressure causes the rim vapor space to breath. As temperature increases, an expansion of gas occurs in the rim vapor space which expels the air vapor mixture to the atmosphere. As the rim vapor space temperature decreases, the vapor in the rim space contracts. Fresh air is drawn into the rim vapor space resulting

in reduction of concentration of hydrocarbon vapor in this space and so more liquid evaporates.

2.2.3. Displacement loss

When the tank is filled with liquid, the vapor is compressed in the tank. Air vapor mixture is forced out through a vapor vent which represents a displacement loss. This loss is similar to the working loss in a fixed roof tank.

2.2.4. Flash losses

Flash losses occur when the pressure of a liquid is decreased or the temperature is increased. Flash emissions occur when produced crude oil or condensate is exposed to high temperature or low pressure during the transfer from the production separators (sources) into atmospheric storage tanks (APRG, 2012).

Figure 2.1 below shows flash loss of oil in the storage tank as a result of pressure and temperature changes.

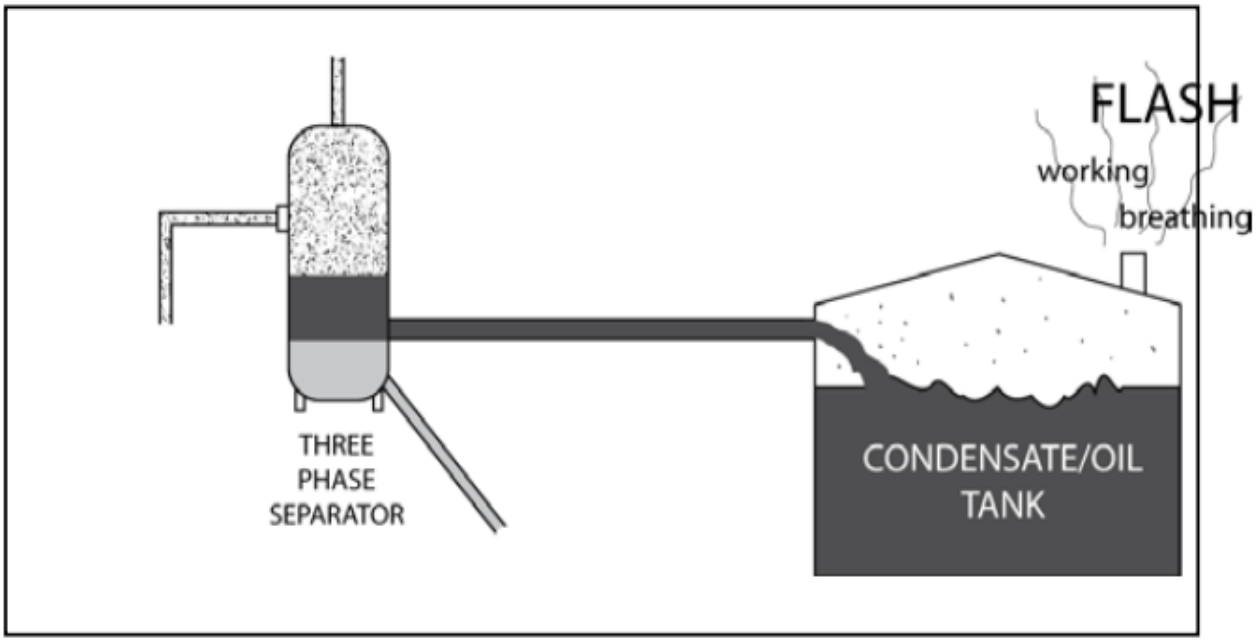


Figure 2.1: Flash losses

Figure 2.2 below shows a sample of oil and gas site where VOCs are being emitted and lost into the atmosphere at various stage where oil and gas are being stored and transported.

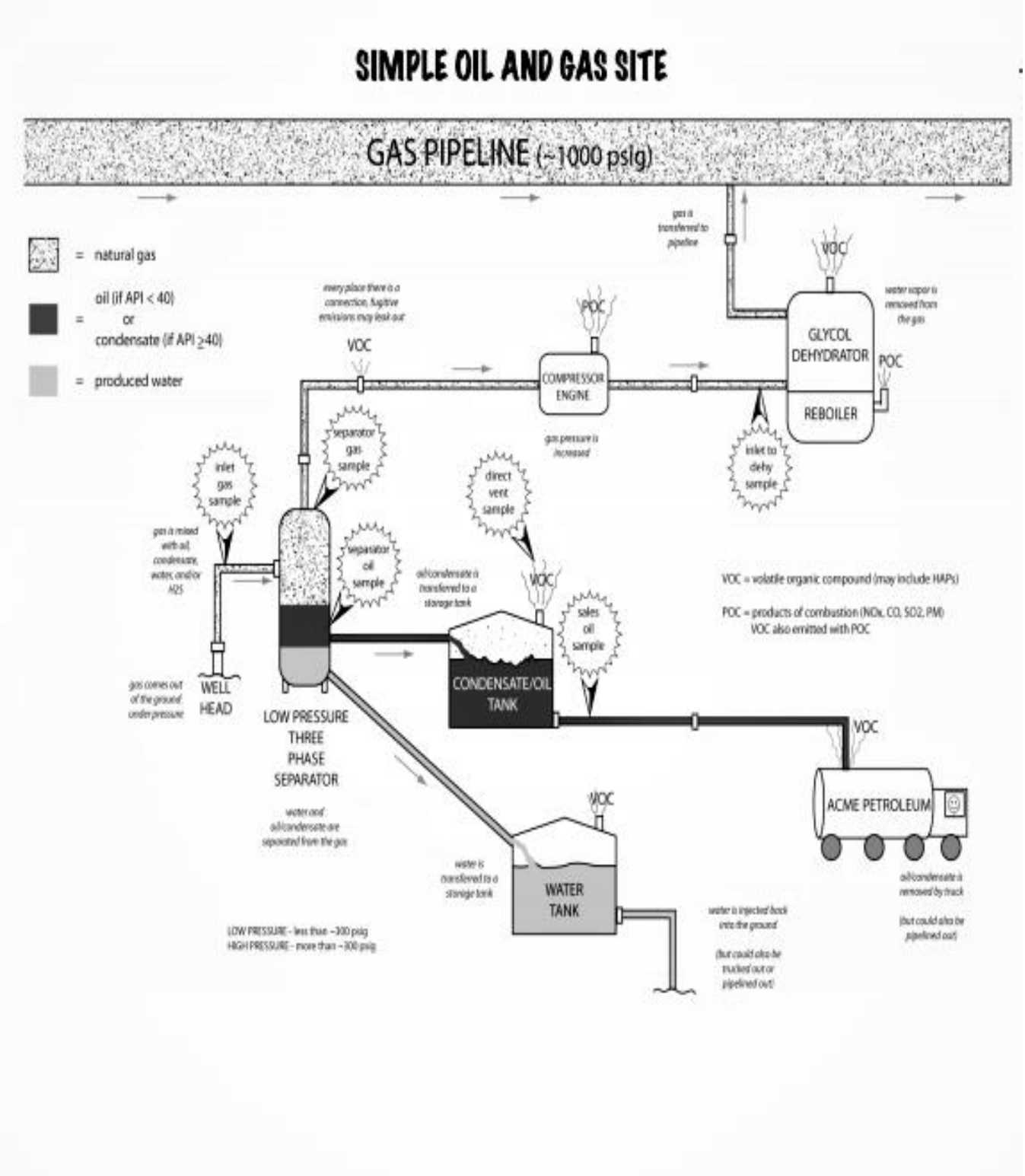


Figure 2.2: oil losses in various stages of handling at a sample of oil and gas site

2.2.5. Loading losses

Thompson (2017) explained evaporation losses of petroleum products during loading. Loading losses are regarded as the primary source of evaporative emissions from rail tanks, tank trucks, and marine vessel operations. These losses occur as organic vapors in empty cargo tanks are displaced to the atmosphere by the liquid being loaded into the tanks.

These vapors are a composite of:

- vapors formed in the empty tank by evaporation of residual product from previous loads
- vapors transferred to the tank in vapor balance systems as product is being unloaded
- Vapors generated in the tank as new product is being loaded (Thompson, 2017).

Figure 2.3 below shows the loading loss of petroleum products in the tank. In this figure, the fill pipe dispensing the cargo is lowered only part way into the cargo tank. Significant turbulence and vapor/liquid contact occur during the splash loading operation, resulting in high levels of vapor generation and loss.

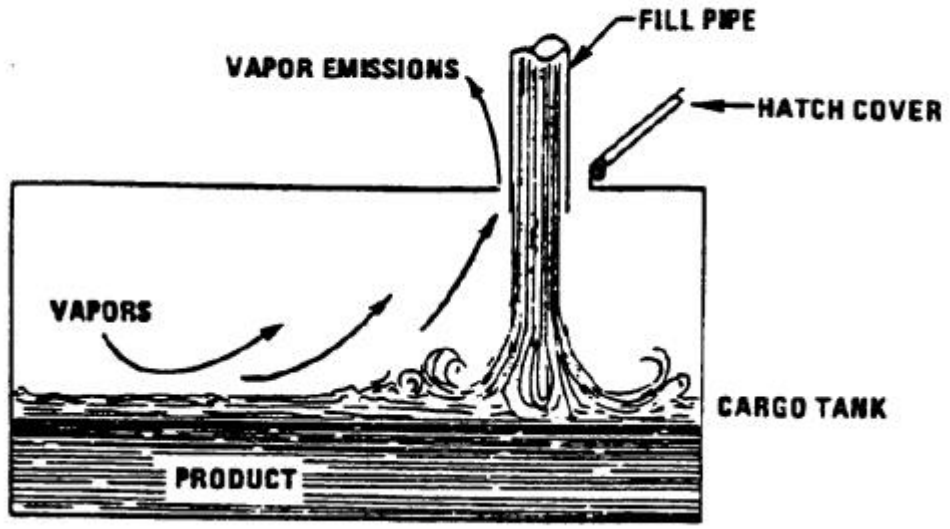


Figure 2.3: Loading loss

2.2. Summary of literature review and knowledge gaps

A review of the above studies has indicated that evaporation has a negative influence on losses of petroleum products. Studies by Alhaj, Alzubair and Gadir (2014), Thomson, (2017), APRG, (2012), Bhatia and Dinwoodie, (2004) and Hernández et al., (2016) found that there is a loss of petroleum products from storage tanks due to evaporation process. The study by Jurušs and Seile, (2017) investigated loss rates for petroleum products and found that the losses observed result from the nature of the petroleum products and not on the evaporation losses of petroleum products during transportation. The above studies however presented gaps that this study seeks to address. This research seeks to fill this gap by assessing evaporation losses of petroleum products during transportation in Malawi.

SECTION 3: METHODOLOGY

3.1. Introduction

In this section, the mathematical model techniques to be applied while conducting the study are described. It first gives an explanation for the research design that will be applied to do the rest of the research. It then discusses the data collection procedure and the procedure for gathering the relevant data and the analysis of data methods.

3.2. Research design

This is the strategy used by analyst under various components of the research which logically and coherently make sure that the problem of the research is clearly addressed (Akhtar, 2016). This study used the descriptive research design that is applied in explaining current situation regarding the study variables (Dulock, 2013). This design was applied to explain what, when and how questions but do not answer the why question.

This design is suitable for this investigation because the researcher is not permitted to manipulate information obtained regarding the study variables. The study will obtain data concerning the temperature, fuel vapour pressure, vapour saturation, loading volume (liquid fuel volume) and travel times as variables in the selected study areas.

The study will then examine the linkages between the data variables. Therefore, the descriptive research design is suitable for this study.

3.3. Data collection

Monthly temperature, vapour pressure, and vapour saturation data of the study areas for a period of 7 years ranging from 2015 to 2022 were collected from Department of Climate Change and Meteorological service (DCCM).

Fuel loading volume and travel time data for a period of 7 years ranging from 2015 to 2022 were collected from National Oil Company of Malawi (NOCMA).

3.4. Data analysis

The collected data was analyzed using descriptive statistics. Descriptive statistics included the measurement of central tendency and dispersion. The mean vapour pressure and temperature during the period of 2015 to 2022 were determined. Presentation of the analyzed descriptive data was in the form of tables and graphs.

The collected data was also analyzed using two mathematical model techniques; Pressure loss and Evaporation loss percentage models. Microsoft Excel was used to perform all the needed calculations and data analysis processes.

3.4.1 Pressure loss model

This model states that for truck transit with a full fuel load from the leaving terminal, venting is assumed to occur until the fuel vapor space is saturated to the fuel vapor pressure. When this state is reached, no further pressure increases occur (Nichols, R.A. 1977). The following equation is used to estimate pressure losses from tanks with open vents and full fuel loads:

$$\text{Fuel Volume loss (gm/gal)} = \mathbf{0.7507} \times \left(\frac{\mathbf{Vg}}{\mathbf{Vl}}\right) \times \mathbf{P} \times \left[\frac{\mathbf{In\ (P-S1 \times Pf)}}{\mathbf{In(P-S2 \times Pf)}}\right] + \frac{\mathbf{Pf}}{\mathbf{P}} \times (\mathbf{S2 - S1})$$

where;

V_g = vapor space volume,

V_l= liquid fuel volume (same units as V_g),

P = atmospheric pressure, psia

S1 = vapor saturation on leaving terminal, fraction of 1 .00

S2 = vapor saturation upon arrival a t unloading station, fraction of 1.00

P_f= fuel vapor pressure, psia

3.4.2 Evaporation loss percentage model

This model is dependent on temperature and time. According to Fingas 2017, there are several models that are used to predict the percentage of evaporated petroleum products. For diesel and petrol, the mathematical model below is used to make accurate predictions of percentage evaporated:

$$\%EV = (-0.02+0.013T) \times \ln(t)$$

where;

%EV= percentage evaporated

T= Temperature in degree Celsius

t= time in minutes.

3.5. Limitations of the study

Lack of data access was the first limitation. Difficulty in accessing actual data limits the accuracy of the study as some data which were provided was based on assumptions. For example, vapour pressures and amount of travel times during transportation process were all based on assumptions. This affected the accuracy of the results.

Time constraints was another limitation in this study. The timeframe was short to access the required results. This limits the depth of the study.

Measurement tool errors was also considered as another limitation. Errors in data collection tools led to inaccurate results.

SECTION 4: DATA ANALYSIS, RESULTS AND DISCUSSION

4.1. Pressure losses

From the loading and leaving station of tank trucks location (Blantyre district), we calculate the annual average fuel vapour pressure. Table 4.1 shows the calculation of annual average fuel vapour pressure.

Table 4.1 Average annual fuel vapor pressure for Blantyre

N3 =AVERAGE(B3:M3)

	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1	urface Pressure (kPa)													
2	YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL AVERAGE PRESSURE
3	2015	94.7	94.8	95.0	95.2	95.4	95.6	95.6	95.5	95.3	95.1	94.9	9-	95.2
4	2016	94.8	94.8	94.9	95.2	95.6	95.8	95.7	95.6	95.3	94.9	94.9	94.9	95.2
5	2017	94.7	94.8	95.0	95.3	95.5	95.6	95.7	95.5	95.3	95.0	94.9	94.9	95.2
6	2018	94.8	94.8	94.8	95.2	95.4	95.6	95.9	95.5	95.2	95.2	95.0	94.9	95.2
7	2019	94.8	94.9	94.9	95.2	95.5	95.7	95.6	95.6	95.4	94.9	94.8	94.8	95.2
8	2020	94.8	94.9	95.0	95.2	95.5	95.7	95.7	95.4	95.3	95.1	94.8	94.8	95.2
9	2021	94.7	94.7	94.9	95.3	95.5	95.6	95.8	95.5	95.3	95.0	94.8	94.8	95.2
10	2022	94.7	94.6	95.0	95.2	95.4	95.6	95.7	95.5	95.3	95.1	95.0	94.8	95.2
11														

After we calculate the annual average fuel vapour pressures of loading station in Blantyre, then we use this value and other needed values from the loading station of; vapour space capacity V_g (L), liquid fuel volume V_l (L), atmospheric pressure P (psia), fuel vapour pressure P_f (psia), vapour saturation on leaving station (S_1), having a fraction of 1.00 and vapour saturation upon arrival at offloading station having a fraction of 1.00 (S_2) from the collected data to calculate the estimate values of pressure losses. Tables 4.2 and 4.3 in the appendix K show the results of estimate of the total pressure losses in Gm/gal of both petrol and diesel respectively as they are being transported within Blantyre district.

Upon arriving at the offloading station of tank trucks location (Lower Shire), we calculate the annual average fuel vapour pressure. Tables 4.4 shows the calculation of annual average fuel vapour pressure at the offloading station.

Table 4.4 Annual average fuel vapour pressure for lower shire

N13

	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1	Surface Pressure (kPa)													
2	YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	AVERAGE ANNUAL PRESSURE
3	2015	98.5	98.5	98.9	99.0	99.3	99.5	99.5	99.4	99.1	98.9	98.6	98.7	99.0
4	2016	98.6	98.6	98.7	99.0	99.5	99.7	99.6	99.5	99.1	98.7	98.7	98.6	99.0
5	2017	98.5	98.6	98.8	99.2	99.4	99.5	99.6	99.4	99.2	98.7	98.7	98.7	99.0
6	2018	98.6	98.5	98.6	99.0	99.2	99.5	99.8	99.4	99.0	99.1	98.8	98.7	99.0
7	2019	98.6	98.7	98.7	99.0	99.3	99.6	99.5	99.4	99.2	98.7	98.6	98.6	99.0
8	2020	98.5	98.7	98.8	99.0	99.4	99.6	99.6	99.3	99.1	98.9	98.6	98.6	99.0
9	2021	98.4	98.4	98.7	99.2	99.3	99.5	99.8	99.4	99.1	98.8	98.6	98.6	99.0
10	2022	98.5	98.4	98.8	99.1	99.3	99.5	99.6	99.3	99.2	98.9	98.8	98.6	99.0
11														

After we calculate the annual fuel vapour pressure of the offloading station in lower shire, we use this value and other needed values from the offloading station of; vapour

space capacity V_g (L), liquid fuel volume V_l (L), atmospheric pressure P (psia), fuel vapour pressure P_f (psia), vapour saturation on leaving station (S1), having a fraction of 1.00 and vapour saturation upon arrival at offloading station, having a fraction of 1.00 (S2) from the collected data to determine the estimate values of pressure losses. Tables 4.5 and 4.6 in appendix L show the results of estimate of the total pressure losses in Gm/gal of both petrol and diesel as they are being transported within lower shire.

The total pressure losses for both petrol and diesel during the whole journey were calculated and tables 4.7 and 4.8 in the appendix M show the total losses of petrol and diesel respectively.

Figure 4.1 below shows the graph of total volume losses of petrol due to pressure (L) against the year. In 2015, the volume of petrol loaded was higher than all the years and in this year; there was little fuel vapour pressures, as such the amount of vapours being released into the atmosphere were more. This results in a huge volume loss of petrol in this year. However, from 2016 to 2017, the loading volume of petrol was closely related. The fuel vapour pressures were also a bit higher. This results in a volume loss of petrol at a considerable low rate as less vapour was released from tank trucks during transportation.

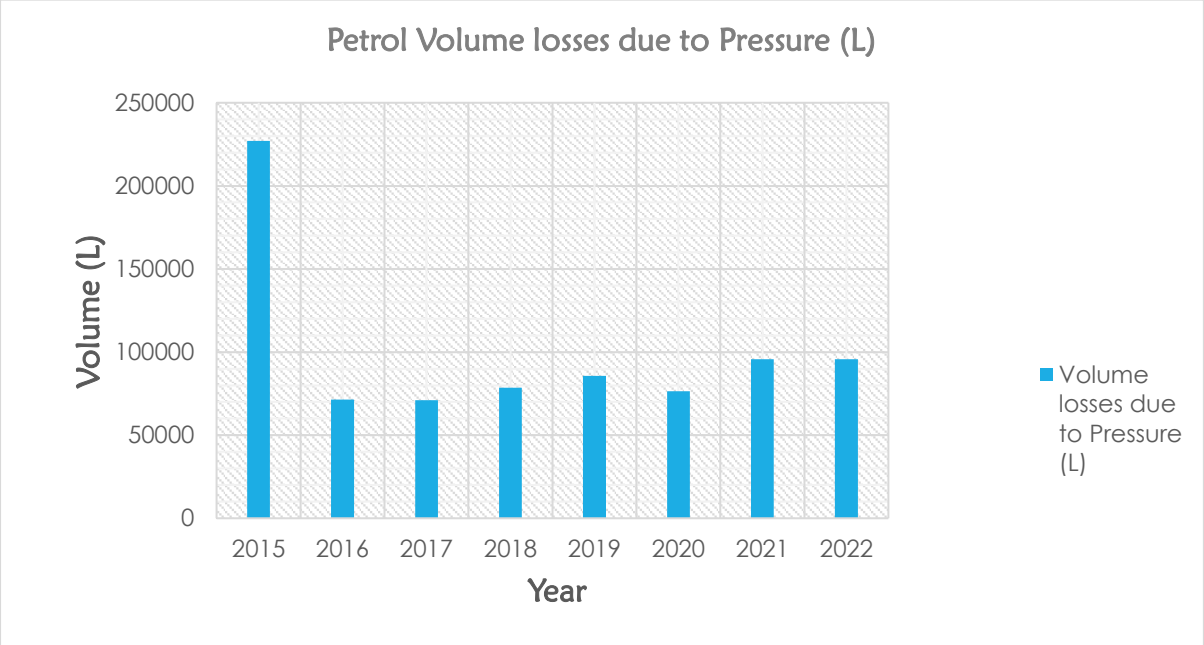
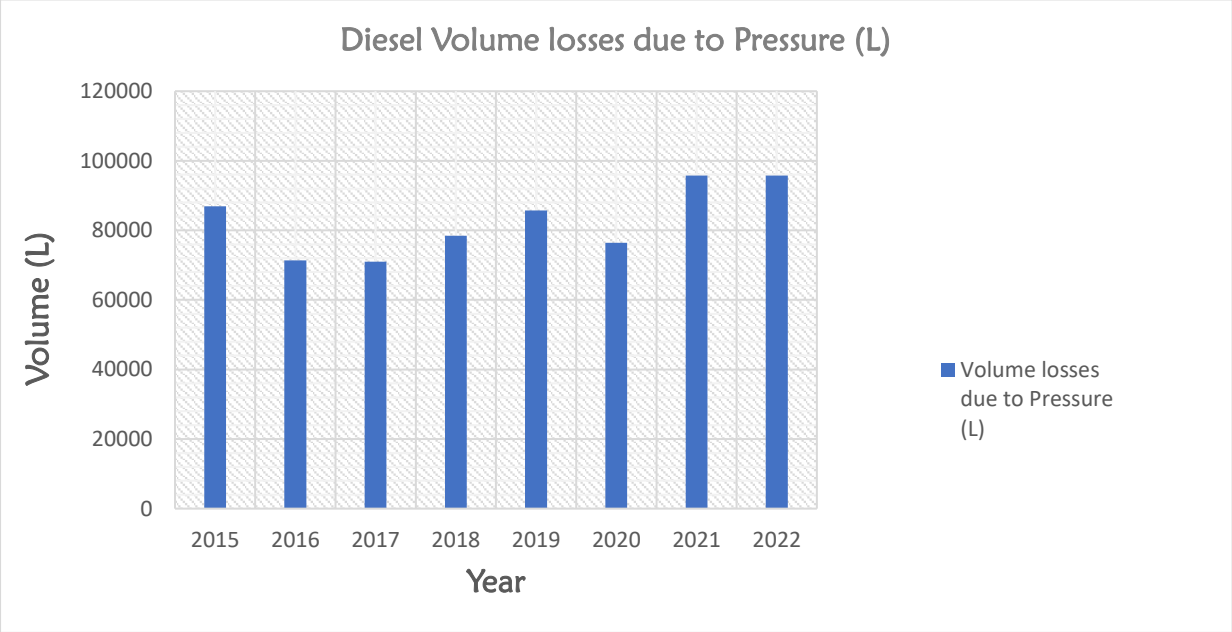


Figure 4.2 below shows the graph of total volume losses of diesel due to pressure (L) against the year. The trend of volume losses of diesel in this figure are higher in 2015,

2019, 2021 and 2022 because the fuel vapour pressures were lower. This results in more vapour production in the tank trucks as such more vapour vanishes into the atmosphere in those years whereas in the other years, the fuel vapour pressures were high resulting in lower vapour production from tank trucks. This releases low vapour into the atmosphere hence lower volume losses of diesel in the years 2016, 2017, 2018 and 2020.



4.2. Losses due to temperature and travel time

From the loading and leaving station of tank trucks location (Blantyre district) to the offloading station (lower- shire), we calculate both the average annual temperatures of the loading and offloading station and with the provided travel time, the evaporation percentage of petrol and diesel were calculated. Refer to appendix N for the table of evaporation loss percentages.

After calculating the percentages of evaporation losses, the obtained results were multiplied with the loading volume of petrol and diesel respectively to determine the volume loss in liters as a result of temperature and travel times, then the volume losses were found. Tables 4.10 and 4.11 in the appendix N show the volume losses of petrol and diesel respectively.

Figure 4.3 shows the graph of volume of petrol loss due to temperature and time against year. In figure below, the years 2016, 2017, 2018 and 2022; the volume losses of petrol were lower than the other remaining years. This is because the travel times and temperatures were minimal. This implies that the tank trucks were exposed to lower temperatures for short period of time as such the amount of vapour produced and released into the atmosphere was lower hence lower volume losses of petrol in these years whereas in the years 2015, 2019, 2020 and 2021; the volume losses of petrol were higher due to huge temperatures and travel times. This means that the amount of petrol that turns to vapour and vanishes into the atmosphere was higher as the tank trucks were exposed to higher temperatures for a long period of time.

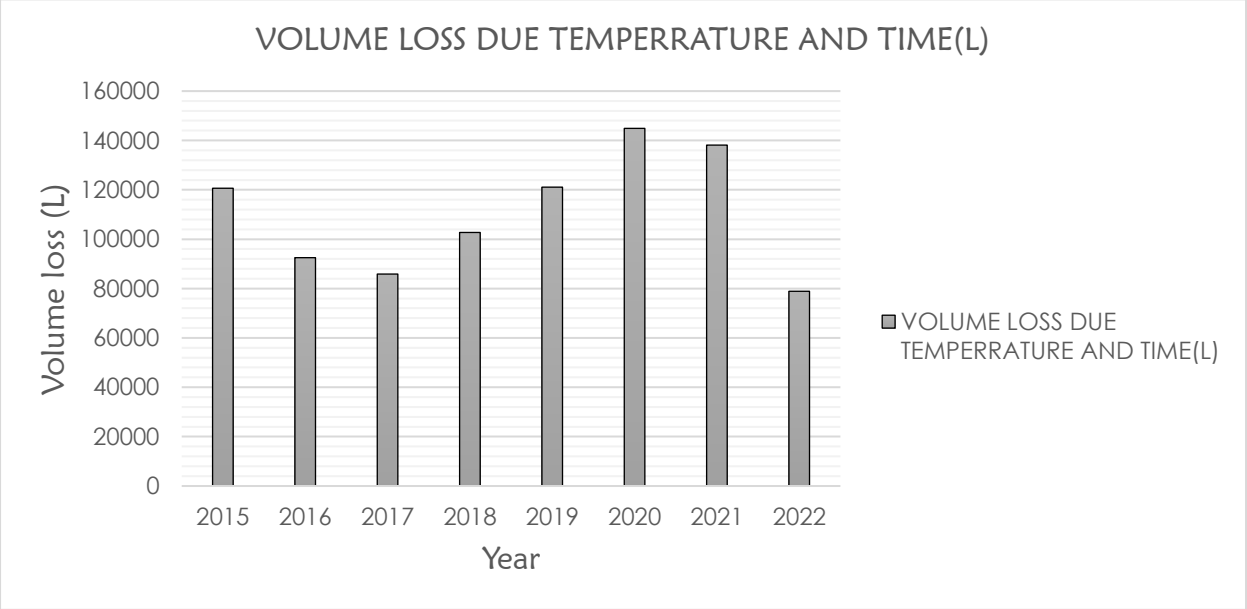
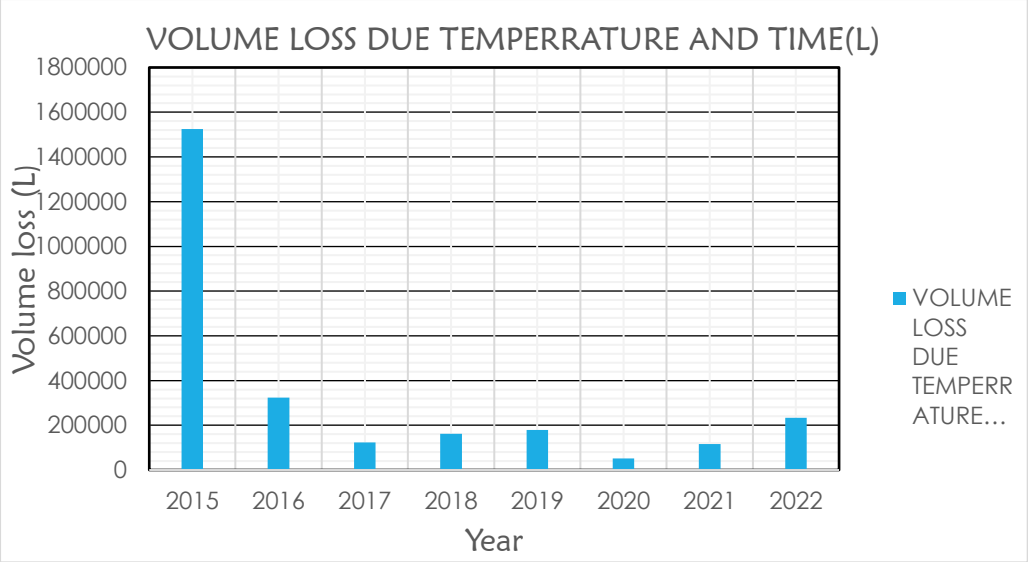


Figure 4.4 graph shows the volume losses of diesel due to temperature and time against year. In this figure, the year 2015 has higher volume losses compared to 2020 where losses were very minimal. This occurs because in 2015, the temperature was high and fuel pressures were low and the volume of loading diesel was huge with comparison to 2020. 2020 has the lowest volume losses because the loading volume was low in this year; as such less vapour was produced and vanished into the atmosphere. In the years 2016, 2017, 2018, 2019 and 2022; the volume losses of diesel did not differ a lot as the temperature, fuel vapour pressures and loading volume were linearly related as they did not show the huge differences.



4.3. Economic Impacts

Hydrocarbon products have high demand in all the countries. This demand is growing at an average of 0.8% per year because they are cheap fuels (Alhaj, Alzubair, and Gadir, 2014). In Malawi, the price of petrol and diesel at filling stations changes with times.

The total estimated evaporation losses of petrol and diesel respectively in each year at different temperature, travel time and pressure and their total money loss due to this evaporation loss are shown in tables 5.1 and 5.2 below. Table 5.1 shows the amount of money lost due evaporation losses of petrol from 2015 to 2016.

Year	Total volume losses	Annual average Pump price (MK)	Money lost due to losses (MK)
2015	442318.1246	723.05	319818120.00
2016	238274.3289	767.5	182875547.40
2017	234142.6968	824.7	193097482.00
2018	262682.9831	911.8	239514344.00
2019	302619.9348	899	272055321.40
2020	333773.1505	808.78	269949048.70
2021	342871.2306	961.27	329591827.80
2022	235936.6103	2023.23	477354028.00
Total			2,284,255,719.00

Table 5.2 shows the amount of money lost due evaporation losses of diesel from 2015 to 2016.

Year	Total volume losses	Average annual pump price (MK)	Money lost due to losses (MK)
2015	2806092.932	723.05	2028945494.00
2016	654579.2776	767.5	502389595.60
2017	306303.3043	824.7	252608335.10
2018	367772.8572	911.8	335335291.20
2019	406429.7114	899	365380310.50
2020	168724.1266	808.78	136460699.10
2021	302903.7607	961.27	291172298.10
2022	510869.486	2023.23	1033606470.00
Total			4,945,898,494.00

From the above tables, we show that the most economical loss is associated with diesel which gives maximum money loss due to maximum volume loss while petrol has minimum money loss due to minimum volume loss.

SECTION 5: CONCLUSIONS AND RECOMMENDATIONS

5.1. Conclusions

From figure 4.1; it is shown that the evaporation loss of petrol from tank trucks was influenced by pressure during transportation and the calculated losses of petrol due to pressure gives a total loss of 1590982.192 liters from 2015 to 2022.

From figure 4.2; it is shown that the evaporation loss of diesel from tank trucks was also influenced by pressure during transportation and the calculated losses of diesel due to pressure gives a total loss of 4862263.457 from 2015 to 2022.

From figure 4.3; it is shown that the evaporation loss of petrol from tank trucks was also influenced by temperature and travel time during transportation and the calculated volume losses of petrol due to temperature and travel time gives a total volume loss of 884745.4962 liters from 2015 to 2022.

From figure 4.4; it is shown that the evaporation loss of diesel from tank trucks was also influenced by temperature and travel time during transportation and the calculated volume losses of diesel due to temperature and travel time gives a total volume loss of 2713179.963 liters from 2015 to 2022.

From table 5.1 and table 5.2; it is shown that evaporation loss of petrol and diesel contributed to total money loss of MK 2,284,255,719.00 and MK 4,945,898,494.00 respectively from 2015 to 2022.

Finally, the ambient temperatures, vapour pressures and travel time have an effect on evaporation loss of petroleum products during transportation in Malawi. This evaporation losses also negatively affect the country's economy as it results in huge volume losses that contribute to money loss.

3.6. Recommendations

There are five areas of controls that can be implemented to control the evaporation losses of petroleum products during transportation in Malawi.

3.6.1. Reducing the vapour space capacity inside the tanks

This can be achieved by ensuring the maximum filling of tank trucks as well as maintaining the tank trucks and breathing equipment in the tank trucks. The more petroleum product in the tank, the less space there is for vapour to form. Therefore, keeping tank trucks full can help to reduce evaporation losses during transportation.

3.6.2. Metrological conditions

Reduction in daily ambient temperature and average liquid surface temperature including vapour pressures can be achieved by plantation of trees along roads. Tree plantations will have the direct effect in reducing temperature and pressure by providing shades to the tank trucks.

The temperatures are also relatively low in the morning and night than in the noon as such transportation of liquid petroleum products can be best done during the morning and night hours to ensure low evaporation losses as these hours have lower temperatures which cannot turn liquid petroleum products into vapours.

3.6.3. Use of vapour recovery systems

These systems capture and store vapour that form inside tanks, preventing them from escaping into the atmosphere. Vapour recovery units and condensation systems are the examples of the vapour recovery systems that can be used to minimize evaporation losses.

3.6.4. Tank thickness

The walls of tank trucks should be design with higher thickness. The higher the tank trucks wall's thickness, the lower the temperature that reaches the petroleum products inside the tank trucks. This reduces the vapour production inside the tanks hence reducing evaporation losses as less vapour vanishes into the atmosphere.

3.6.5. Pressure management

Proper management of tank truck pressure prevents the release of vapour. This can be achieved through the use of pressure-vacuum relief valves.

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APPENDICES

Appendix A

Table A: Monthly temperatures for Blantyre district in degree Celsius

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
2015	25.5	24.4	26.6	24.7	24.8	22.6	23.0	24.6	28.3	31.2	30.4	30.0
2016	28.0	28.9	28.7	25.8	23.0	22.3	21.5	23.8	29.0	31.6	30.5	28.5
2017	27.7	27.6	26.7	25.9	25.7	24.9	25.1	27.7	32.3	35.6	33.0	28.8
2018	26.9	27.3	26.6	25.3	24.6	22.4	24.8	26.9	29.7	27.4	28.1	27.0
2019	25.6	27.1	25.8	25.7	24.7	21.8	23.7	26.4	27.9	30.5	30.9	28.5
2020	26.4	27.4	26.4	24.7	24.9	21.1	21.3	25.3	27.4	29.2	31.8	28.5
2021	27.2	27.5	25.6	24.7	23.2	22.5	22.1	25.1	27.3	29.3	30.8	31.3
2022	25.7	25.9	26.0	25.7	24.2	20.1	21.9	24.7	27.3	31.2	29.2	26.7

Appendix B

Table B: Monthly vapour surface pressures for Blantyre district in kilopascals

Surface Pressure (kPa) YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
2015	94.7	94.8	95.0	95.2	95.4	95.6	95.6	95.5	95.3	95.1	94.9	94.9
2016	94.8	94.8	94.9	95.2	95.6	95.8	95.7	95.6	95.3	94.9	94.9	94.9
2017	94.7	94.8	95.0	95.3	95.5	95.6	95.7	95.5	95.3	95.0	94.9	94.9
2018	94.8	94.8	94.8	95.2	95.4	95.6	95.9	95.5	95.2	95.2	95.0	94.9
2019	94.8	94.9	94.9	95.2	95.5	95.7	95.6	95.6	95.4	94.9	94.8	94.8
2020	94.8	94.9	95.0	95.2	95.5	95.7	95.7	95.4	95.3	95.1	94.8	94.8
2021	94.7	94.7	94.9	95.3	95.5	95.6	95.8	95.5	95.3	95.0	94.8	94.8
2022	94.7	94.6	95.0	95.2	95.4	95.6	95.7	95.5	95.3	95.1	95.0	94.8

Appendix C

Table C: Monthly vapour saturation for Blantyre district (dimensionless).

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
2015	0.95	0.94	0.85	0.72	0.5	0.2	0.2	0.5	0.75	0.98	0.95	0.96
2016	0.94	0.92	0.8	0.64	0.4	0.1	0.3	0.6	0.78	0.96	0.97	0.93
2017	0.98	0.96	0.88	0.7	0.45	0.11	0.2	0.5	0.76	0.93	0.9	0.95
2018	0.92	0.93	0.87	0.8	0.6	0.3	0.2	0.4	0.8	0.94	0.95	0.96
2019	0.96	0.93	0.82	0.76	0.5	0.3	0.3	0.7	0.77	0.98	0.95	0.98
2020	0.97	0.94	0.9	0.78	0.5	0.2	0.1	0.61	0.75	0.94	0.92	0.97
2021	0.95	0.94	0.91	0.81	0.7	0.4	0.2	0.7	0.82	0.95	0.93	0.96
2022	0.96	0.95	0.89	0.85	0.67	0.25	0.4	0.6	0.79	0.96	0.98	0.97

Appendix D

Table D: Monthly temperatures for lower shire in degree Celsius

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
2015	30.3	31.7	32.7	31.9	31.6	29.6	30.3	31.6	35.4	38.0	37.8	37.2
2016	34.1	34.3	32.6	32.3	29.5	28.3	28.0	30.9	36.2	39.0	37.9	32.5
2017	29.9	30.0	29.3	29.8	30.2	28.8	28.2	30.6	35.0	38.4	34.9	31.8
2018	33.5	33.8	34.0	29.0	30.3	28.5	28.8	33.7	36.6	35.1	35.4	36.2
2019	32.6	33.9	32.0	32.6	30.8	28.3	29.8	32.2	34.0	37.4	37.6	36.5
2020	32.6	33.5	33.5	34.2	31.8	28.6	27.3	31.6	34.6	36.1	39.9	36.1
2021	32.9	33.1	32.9	32.0	30.9	29.1	28.6	31.3	35.4	37.0	37.5	35.4
2022	32.7	33.0	31.9	32.2	30.9	26.2	28.4	31.6	34.6	36.7	37.1	36.6

Appendix E

Table E: Monthly vapour surface pressures for lower shire in kilopascals

Surface Pressure (kPa)												
YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
2015	98.5	98.5	98.9	99.0	99.3	99.5	99.5	99.4	99.1	98.9	98.6	98.7
2016	98.6	98.6	98.7	99.0	99.5	99.7	99.6	99.5	99.1	98.7	98.7	98.6
2017	98.5	98.6	98.8	99.2	99.4	99.5	99.6	99.4	99.2	98.7	98.7	98.7
2018	98.6	98.5	98.6	99.0	99.2	99.5	99.8	99.4	99.0	99.1	98.8	98.7
2019	98.6	98.7	98.7	99.0	99.3	99.6	99.5	99.4	99.2	98.7	98.6	98.6
2020	98.5	98.7	98.8	99.0	99.4	99.6	99.6	99.3	99.1	98.9	98.6	98.6
2021	98.4	98.4	98.7	99.2	99.3	99.5	99.8	99.4	99.1	98.8	98.6	98.6
2022	98.5	98.4	98.8	99.1	99.3	99.5	99.6	99.3	99.2	98.9	98.8	98.6

Appendix F

Table F: Monthly vapour saturation for lower shire (dimensionless).

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
2015	1	1	1	1	1	1	1	1	1	1	1	1
2016	1	1	1	1	1	1	1	1	1	1	1	1
2017	1	1	1	1	1	1	1	1	1	1	1	1
2018	1	1	1	1	1	1	1	1	1	1	1	1
2019	1	1	1	1	1	1	1	1	1	1	1	1
2020	1	1	1	1	1	1	1	1	1	1	1	1
2021	1	1	1	1	1	1	1	1	1	1	1	1
2022	1	1	1	1	1	1	1	1	1	1	1	1

Appendix G

Table G: annual loading volume of petrol, diesel and vapour space capacity both in liters

Volume of petrol and diesel and vapor space capacity both in liters

YEAR	PETROL	DISEAL	VAPOUR SPACE CAPACITY
2015	2456456	31037140	20710
2016	1909391	6672833	36793
2017	1841438	2656033	25343
2018	2093949	3288621	17272
2019	2472190	3655303	25890
2020	2905042	1041905	40162
2021	2756073	2310332	42190
2022	1633757	4837835	23180

Appendix H

Table H: annual travel time for the transportation of petroleum products in minutes

Time (mins)

YEAR	TIME
2015	153300
2016	141400
2017	164250
2018	167900
2019	151110
2020	175200
2021	208050
2022	153300

Appendix I

The pressure loss model

$$\text{Fuel Volume loss (gm/gal)} = \mathbf{0.7507} \times \left(\frac{\mathbf{Vg}}{\mathbf{Vl}}\right) \times \mathbf{P} \times \left[\frac{\mathbf{In\,(P-S1\times Pf)}}{\mathbf{In(P-S2\times Pf)}}\right] + \frac{\mathbf{Pf}}{\mathbf{P}} \times (\mathbf{S2} - \mathbf{S1})$$

Appendix J

Evaporation loss percentage model

$$\%EV = (-0.02+0.013T) \times \ln(t)$$

Appendix K

Table 4.2 Petrol pressure losses within Blantyre district

	A	B	C	D	E	F	G	H
1		PRESSURE LOSSES OF PETROL						
2	YEAR	AVERAGE FUEL VAPOR PRESSURE(PSIA) {Pf}	Vl	Vg	P	S1	S2	PRESSURE LOSSES {Gm/gal}
3	2015	13.80263359	2456456	20710	14.7	0.708333	1	0.124984491
4	2016	13.80819336	1909391	36793	14.7	0.695	1	0.286496529
5	2017	13.80577607	1841438	25343	14.7	0.693333	1	0.288011655
6	2018	13.80444656	2093949	17272	14.7	0.7225	1	0.260594144
7	2019	13.80130407	2472190	25890	14.7	0.745833	1	0.23862799
8	2020	13.80335877	2905042	40162	14.7	0.715	1	0.267616139
9	2021	13.80166667	2756073	42190	14.7	0.7725	1	0.213597222
10	2022	13.80130407	1633757	23180	14.7	0.7725	1	0.213591611

Table 4.3 Diesel pressure losses within Blantyre district

	A	B	C	D	E	F	G	H
1		PRESSURE LOSSES OF DIESEL						
2	YEAR	AVERAGE FUEL VAPOR PRESSURE(PSIA) {Pf}	Vl	Vg	P	S1	S2	PRESSURE LOSSES {Gm/gal}
3	2015	13.80263359	31037140	54743	14.7	0.708333	1	0.242715637
4	2016	13.80819336	6672833	36693	14.7	0.695	1	0.286496529
5	2017	13.80577607	2656033	23340	14.7	0.693333	1	0.288011655
6	2018	13.80444656	3288621	19270	14.7	0.7225	1	0.260594144
7	2019	13.80130407	3655303	15890	14.7	0.745833	1	0.23862799
8	2020	13.80335877	1041905	40170	14.7	0.715	1	0.267616139
9	2021	13.80166667	2310332	86190	14.7	0.7725	1	0.213597222
10	2022	13.80130407	4837835	24189	14.7	0.7725	1	0.213591611

Appendix L

Table 4.5 Petrol pressure losses within Lower-shire

	A	B	C	D	E	F	G	H
1		PRESSURE LOSSES OF PETROL						
2	YEAR	AVERAGE FUEL VAPOR PRESSURE(PSIA) {Pf}	Vl	Vg	P	S2	S2	PRESSURE LOSSES {Gm/gal}
3	2015	14.3587323	2456456	20710	14.7	0.70833	1	0.058755856
4	2016	14.3587323	1909391	36793	14.7	0.695	1	0.297919276
5	2017	14.3587323	1841438	25343	14.7	0.69333	1	0.29954725
6	2018	14.3587323	2093949	17272	14.7	0.7225	1	0.271057702
7	2019	14.3587323	2472190	25890	14.7	0.74583	1	0.248266063
8	2020	14.3587323	2905042	40162	14.7	0.715	1	0.278383585
9	2021	14.3587323	2756073	42190	14.7	0.7725	1	0.222218476
10	2022	14.3587323	1633757	23180	14.7	0.7725	1	0.222218476
11								

Table 4.6 Diesel pressure losses within Lower-shire

E9 | 14.7

	A	B	C	D	E	F	G	H
1		PRESSURE LOSSES OF DIESEL						
2	YEAR	AVERAGE FUEL VAPOR PRESSURE(PSIA) {Pf}	Vl	Vg	P	S1	S2	PRESSURE LOSSES {Gm/gal}
3	2015	14.3587323	31037140	54743	14.7	0.708333	1	0.237585535
4	2016	14.3587323	6672833	36693	14.7	0.695	1	0.297919276
5	2017	14.3587323	2656033	23340	14.7	0.693333	1	0.29954725
6	2018	14.3587323	3288621	19270	14.7	0.7225	1	0.271057702
7	2019	14.3587323	3655303	15890	14.7	0.745833	1	0.248266063
8	2020	14.3587323	1041905	40170	14.7	0.715	1	0.278383585
9	2021	14.3587323	2310332	86190	14.7	0.7725	1	0.222218476
10	2022	14.3587323	4837835	24189	14.7	0.7725	1	0.222218476

Appendix M

Table 4.7 total pressure losses for petrol being transported within Blantyre and Lowershire.

C17

	A	B	C	D
1		TOTAL PRESSURE LOSSES OF PETROL (Gm/gal)		
2	YEAR	BLANTYRE PRESSURE LOSSES(Gm/gal)	LOWER SHIRE PRESSURE LOSSES(Gm/gal)	TOTAL PRESSURE LOSSES OF PETROL (Gm/gal)
3	2015	0.124984491	0.058755856	0.183740347
4	2016	0.286496529	0.297919276	0.584415805
5	2017	0.288011655	0.29954725	0.587558905
6	2018	0.260594144	0.271057702	0.531651846
7	2019	0.23862799	0.248266063	0.486894053
8	2020	0.267616139	0.278383585	0.545999725
9	2021	0.213597222	0.222218476	0.435815698
10	2022	0.213591611	0.222218476	0.435810087

Table 4.8 total pressure losses for diesel being transported within Blantyre and Lowershire.

A1

	A	B	C	D
1		TOTAL PRESSURE LOSSES OF DIESEL (Gm/gal)		
2	YEAR	BLANTYRE PRESSURE LOSSES(Gm/gal)	LOWER SHIRE PRESSURE LOSSES(Gm/gal)	TOTAL PRESSURE LOSSES OF DISEAL (Gm/gal)
3	2015	0.242715637	0.237585535	0.480301173
4	2016	0.286496529	0.297919276	0.584415805
5	2017	0.288011655	0.29954725	0.587558905
6	2018	0.260594144	0.271057702	0.531651846
7	2019	0.23862799	0.248266063	0.486894053
8	2020	0.267616139	0.278383585	0.545999725
9	2021	0.213597222	0.222218476	0.435815698
10	2022	0.213591611	0.222218476	0.435810087

Appendix N

Table 4.9 shows the average annual temperature in degree Celsius, travel time in minutes and evaporation loss percentages.

	YEAR	TIME(MINS)	AVERAGE ANNUAL TEMPERATURE	EVAPORATION LOSS(%)
2015	153300	33.17804212	4.911158244
2016	141400	32.96432138	4.844972717
2017	164250	31.40893004	4.663344213
2018	167900	32.905	4.905871214
2019	151110	33.13	4.897791741
2020	175200	33.31666667	4.987839864
2021	208050	33.01882345	5.01141983
2022	153300	32.64972222	4.829151385

Table 4.10 shows the volume loss of petrol due to temperature and travel time during transportation

D2 =PRODUCT(B2:C2)/100

	A	B	C	D
1	YEAR	EVAPORATION LOSS(%)	VOLUME OF PETROL(L)	VOLUME LOSS DUE TEMPERRATURE AND TIME(L)
2	2015	4.911158244	245 6	120640.4413
3	2016	4.844972717	1909391	92509.47302
4	2017	4.663344213	1841438	85872.59241
5	2018	4.905871214	2093949	102726.4412
6	2019	4.897791741	2472190	121082.7176
7	2020	4.987839864	2905042	144898.843
8	2021	5.01141983	2756073	138118.3889
9	2022	4.829151385	1633757	78896.5988
10				

Table 4.11 shows the volume loss of diesel due to temperature and travel time during transportation

D2 =PRODUCT(B2:C2)/100

	A	B	C	D
1	YEAR	EVAPORATION LOSS(%)	VOLUME OF DIESEL(L)	VOLUME LOSS DUE TEMPERRATURE AND TIME(L)
2	2015	4.911158244	3103 0	1524283.06
3	2016	4.844972717	6672833	323296.9383
4	2017	4.663344213	2656033	123859.9612
5	2018	4.905871214	3288621	161335.511
6	2019	4.897791741	3655303	179029.1284
7	2020	4.987839864	1041905	51968.55294
8	2021	5.01141983	2310332	115780.436
9	2022	4.829151385	4837835	233626.3759
10				