ADDIS ABABA UNIVERSITY

ADDIS ABABA INSTITUTE OF TECHNOLGY

African Railway Center of Excellency (ARCE)

Graduate Program in Railway Engineering (Rolling Stock)

Analysis of Addis Ababa Light Rail Train wheel profile integrity and onboard spray type wheel flange lubrication system design

A Thesis Submitted to the School of Graduate Studies of Addis Ababa

University in Partial Fulfillment of the Degree of Master of Science in Railway Engineering

(Rolling Stock)

By

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July, 2021

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DECLARATION

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ABSTRACT

A wheel flange lubricator sprays lubricant on the wheel flange which comes into contact with the rail at curves, consequently decreasing the wear rate. Electric Multiple Units (EMUs) of Addis Ababa Light Rail Transit (AALRT) are integrated with solid stick wheel flange lubrication mechanism. However, nowadays, AALRT EMUs solid stick lubrication system is not functional because of material cost and lack of availability. This study aims to assess the wear distribution on different wheels of the EMU at different lines and provides a better and effective lubrication system, which is placed onboard of the vehicles. The lubricant of new lubrication system is easily available and cost effective, whereas the mechanism includes curve sensor, oil, pressurized air, nozzle, oil reservoir, oil pump and the lubricating system pump speed which is about 1200RPM was calculated numerically to obtain the oil flow rate. Average tread diameter of North-South line train is 656.2 mm show a total percentage loss of 0.57% when compared to East-West line with an average wheel diameter of 658.3 mm and a percentage loss of 0.25%. The analysis results indicate that North-South line EMU wheel flange wears faster than that of East-West line. It was also found that the trailer car wheels' thicknesses are worn faster than other two motor bogie wheels. Our designed lubrication system replaces the previous lubrication system (solid stick) and is intended to be operated by priority of fast wearing axle wheels and corresponding vehicles. The oil tanks were estimated to be 0.5m^3while the flow rate through the spray nozzle is calculated to be approximately 0.326e-3m^3/s and the standard flow rate at the curve is approximately 0.3e-3m3/s which gives a difference of 0.026e-3m^3/s with a corresponding error of 7.9%. This is a clear indication that the design process met the international standard for the design of such system. Similarly, the oil flow rates at curves track were seen to be at the acceptable limits.

Keywords: Addis Ababa Light Rail Transit (AALRT), Wear, Flowrate, Wheel flange lubrication system, Flowrate

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LIST OF ABBREVIATIONS

AALRT	Addis Ababa Light Rail Transit
Mc1	Motor car one
Mc2	Motor car two
Tp	Trailer car
CNR	China National Railway
EMU	Electric Multiple Unit
C_w	Circumferential of the wheel
L_c	Length of the curve
Nr	Revolution of a wheel in one second
V_t	Train speed
t	Average time to finish curve
V	Volume of lubricant needed for four trains
Q	Total flow rate
Q_{1t}	Flow rate for one train
Ap	Area of the pipe
V	Speed of lubricant in the pipe
D	Diameter of the pipe
Ac	Area of hydraulic cylinder

CHAPTER ONE

Introduction

1.1 Background

Railway is one of the main transport system in the world like airways, highway and sea transport. Utilizing advanced computer technology, intelligent information processing technology and control technology, collect, transmit, and analyze railway transport constantly in order to increase the safety and reliability of rail transport. Rail transport plays key role in the socio-economic and on the environment, which makes this mode of transport the best land transportation option for passengers and goods. In developed countries like Ethiopia, railway transportation is becoming a reliable and regular form of transport a bulk goods with high speed and certainty. In addition, train travel brings much safety, convenience and comfort to passengers than other means of transportation systems. The idea of constructing a railway in Ethiopia is to link the Ethiopian capital with the coast appears to have been first conceived by Menelik's Swiss adviser, Alfred Ilg, who had first arrived in Ethiopia in 1877. The Addis Ababa-Djibouti railway parallels meter-gauge Ethio-Djibouti Railways, between Addis Ababa and Djibouti, which began operating between Dire Dawa and Djibouti in 1901, and was later extended to Addis Ababa, though trains have not run on the line since 2008[6]. Currently the new rail transport in Ethiopia was built, the Addis Ababa Light Rail (North-East and East-West lines) which opened in 2015 and, of a one electrified standard gauge rail line, the Addis Ababa-Djibouti Railway, which started passenger services in October 2016[6] and freight services in January 2018.

The number of railway passengers as well as freight volumes has increased significantly in recent years in Ethiopia. Nevertheless, the railway company is still confronted with serious problems caused by premature failure of assets that require costly and time-consuming maintenance work. The railway assets in general can be categorized into two types: The first one is the infrastructure which consists of fixed assets such as tracks, points and interlocking, bridges, signaling system, electrical units, etc. The other one is the rolling stock which includes assets that can move on railway, e.g. locomotives, passenger coaches, freight cars. A rolling stock is a multi-component system that consists of wheels, bogies, doors, traction control unit, brake control unit, coupler, HVAC, pantograph, etc. A failure of any of rolling stock components can cause a complete failure of the system and consequently lead to traffic delays and disruptions, passenger inconvenience and economic losses for train operating companies. Among the rolling stock components, wheel is the most critical component of rolling stock, and it needs the most attention because of friction between wheel flange and the rail results the wheel flange and rail wear.

The loss or displacement of material from a contacting surface of wheel flange and rail is referred to as wear. Efficient lubrication of the wheel-rail interface helps the rail industry to reduce wear and fatigue, which results in enhancement of asset life, growing of rail industry's business and improving reliability of service.

In this research, an endeavor was made to examination both North-East and East-West lines of AALRT train wheel flange wear and design innovative lubrication mechanism that improve the operation and solve the bottleneck issue of AALRT.

1.2 Statement of the problem

One of the failure modes in the railway industry is wheel wear. Wheel wear has become a major concern for AALRT. Depending on the track design, wheel material and operational conditions, the wheels are expected to last for more than 560km journey. The wheel flanges are designed to have a wearing trend of 1mm per 10,000 km unlike the scenario in current operation. The wheel wear is also causing all sorts of other problems. To compensate the rapid wear of the flange, the wheel undergoes re-profiling which leads to reduction of the wheel diameter and this cause for the rolling stock gangway to be lowered. Thus, this minimum clearance leads to under floor vehicle equipment damaging the way-side signal equipment, and also causing unwanted contact with the guard rail. The vehicle is only elevated to default position by inserting shim under the secondary suspension of the middle bogie which is carried out routinely every time the wheel diameter is reduced. Over a century or more, a large number of solutions has been proposed, which ranges from stationary track lubricators for directly applying lubricant to the rails at selected locations to reservoirs of a liquid lubricant mounted on the rail. Although none of those absolute lubrication system can be effective for the state of art technology. Meanwhile, the Addis Ababa Rail Transit rolling stock integrates solid stick wheel flange lubrication mechanism (see Figure 1.7). But because of the unavailability of consumable solid lubricant in local market, it incurs high cost short life time and currently, the company is obligated to operate without any lubrication. Due to such scenario the company incurred to additional cost for whole wheel-set replacement and worn wheel derailment risk. This study will introduce innovative robust lubrication mechanism that enhance the operation and alleviate the bottleneck problem.

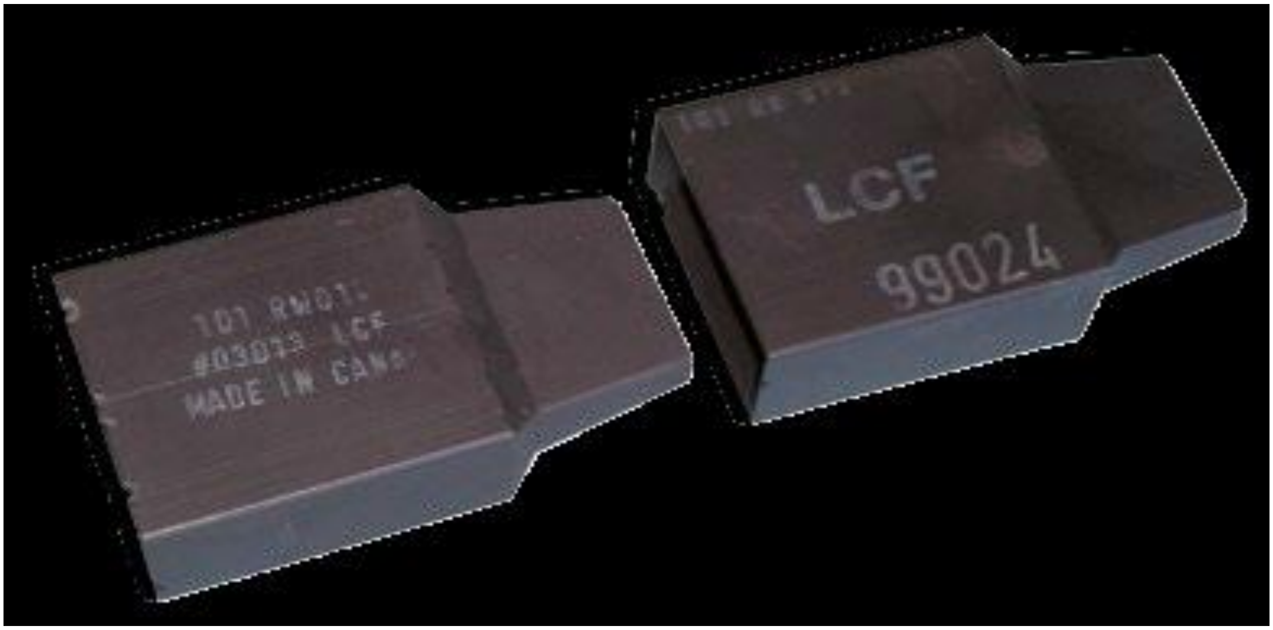


Figure 1.7 Solid stick lubrication systems

1.3 Objectives

1.3.1 General Objective

The overall objective of this project is to solve AALRT Company EMUs wheel wear problem by carefully assessing which train axle wheels are subjected to higher wear and designing an appropriate lubrication system. Specifically this study aims to design a better lubrication system of wheel flange by using oil, an available and cheap lubricant.

1.3.2 Specific Objectives

The specific objectives that will attain the general objective are listed down as follows.

- Studying the wheel profile wear of AALRT.
- Studying the wheel rail contact and its influence on wheel wear.
- Determine important parameters to consider when investigating causes of wheel wear by using literature review.
- Analyzing actual wheel wear measurement data of AALRT EMUs to determine how long the wheel will give service at this situation and which axle is subjected to highest wear of the wheels.
- Determining the quantity of lubricant that is needed within train interval.
- Modeling AALRT wheel flange lubrication system by using simulation studio software.

1.4 Significance of the study

This design research will be critical in addressing the issues underlying wheel wear and providing the best solution to AALRT's wheel problem. The result of this study will reduce downtime while increasing operational reliability and readiness. It will reduce wear, extending the time between reconditioning and replacing wheel sets and rails significantly. It will improve safety by lowering the risk of derailment caused by; for example, wheel "climbing" on the rail, as well as significantly lowering noise emissions. Also, it may increase the sustainability of good environment through the use of rapidly biodegradable oils. In addition to these outcomes, this research will control wheel flange lubrication system, using curve sensor technology, which will increase the awareness of technology value in rolling stock.

1.5 Scope of the research

The study focuses on the operational conditions of AALRT vehicles as well as the general wheel maintenance activities performed at the depots. Because equipment is not purchased and this system model is not changed to the actual system, data collection in this work is limited to data collected from AALRT documents about lubrication systems.

1.6 Research Methodology

1.6.1 Literature review and data collection

A) Literature review: search and evaluate available literatures which are related to this research topic

B) In this study, the first duty implemented in this research was data collection from track engineers, track inspectors and discussed with rolling stock staffs. The respondents will respond to provided questions as a primary data and then through inspections, the extent of wheel wear is going to be investigated. Based on the inspection and analysis work undertaken for the investigation, possible causes are considered to represent potential factors, and also this gives the general understanding that the staff experts have on the issue of wheel wear and its seriousness.

General simulation to be implemented in automation studio software.

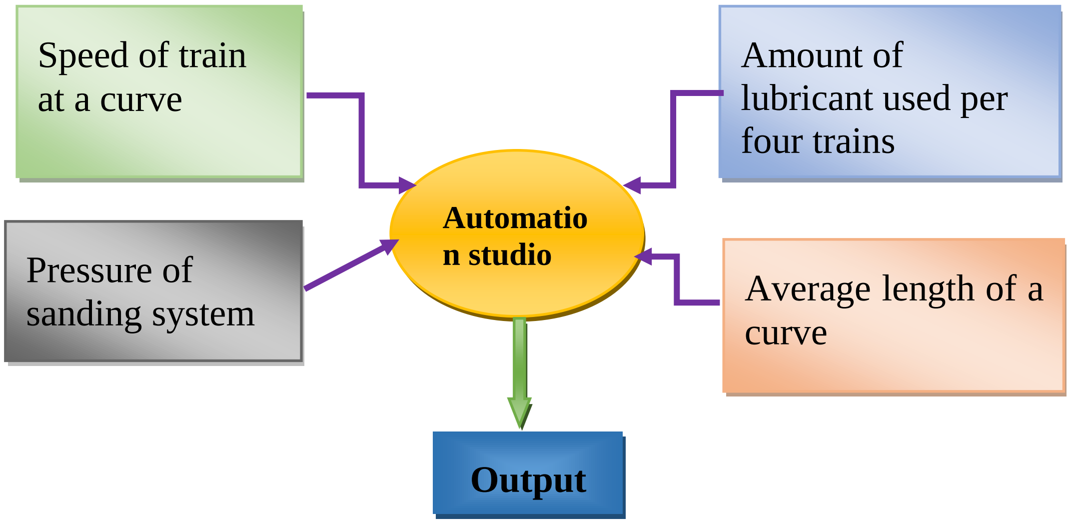


Figure 1.8 Analysis In Automation Studio

1.6.2 Research Tasks

The research method for designing of wheel flange lubrication system has considered the complexity and dynamics associated with the problem that has been dealt in this research, and mechatronics are considered to be appropriate for modeling this new system.

Analyze the problem and data collection

This is the most important phase for modeling and simulating process. In this phase, the problem is identified, defined and clearly stated. Showing and clearly defining the problem by collecting and using data's which shows the problem of lack of lubrication and important of onboard lubrication from different sources (journals, articles, researches and interview).

Modeling and simulating system

- Modeling, applying different overload percentage and simulations are done based on the data collected and calculated values.
- Virtual 3D model of lubricating system are modeled by automation software
- Simulation is carried out under speed of train at a curve, amount of lubricant used per four train, average length of one curve and pressure of sanding system.

1.6.3 Recommendation, Future work and Conclusions

Evaluation of generated data depends on the analysis and simulation. This research recommends using appropriate lubrication mechanism to reduce the friction between wheel and rail.

CHAPTERTWO

Literature Review

In order to design on board spray type wheel flange lubrication system, analysis of old lubrication system of wheel flange lubrication of Addis Ababa Light Train, the literature related to wheel rail wear, effect of lubrication on wheel and rail wear and wheel flange lubrication of AALRT has been reviewed.

2.1 Rail Transport

Rail transport (also known as train transport) is a means of transferring passengers and goods like airways, highway and sea transport, which are running on rails. Rail transport is employed to mainly carry passengers and goods (especially cargos), and can run on both single fixed-type and dual-type rails and it essentially covers light rail, heavy rail, and tram as well as funicular and monorail rail means [2]. Utilizing advanced computer technology, intelligent information processing technology and control technology, collect, transmit, and analyze railway transport constantly in order to increase the safety and reliability of rail transport. Rail transport plays key role in the socio-economic and on the environment, which makes this mode of transport the best land transportation option for passengers and goods. It can be considered to be the best option based on several criteria, such as low traffic congestion, high number of passengers and goods carried less fuel usage and thus reduced emissions, reduced cost, reduced accidents, increased speed, and reduced use of land [1].

Railroads transformed the world in the 19th century and supported the industrial expansion of the early 20th century (see Figure 1.1 a), then declined in the face of airline and highway competition. To survive, railroads were forced to rationalize their systems, develop more efficient operations, and introduce new services. At the turn of the twenty-first century, railroads remain dominant for bulk transportation, provide the backbone of rapidly growing intermodal freight services, and compete successfully with airlines in medium distance markets (Figure 1.1(b)). Highway congestion, limited airport capacity, and environmental concerns guarantee a continued role for rail systems in the twenty-first century.

a)

b)

Figure 2.1 a) Steam engine train[2], b) Japanese 500 series high-speed rail, 2005[3]

2.2 Rail Transport in Ethiopia

The idea of constructing a railway to link the Ethiopian capital with the coast appears to have been first conceived by Menelik's Swiss adviser, Alfred Ilg, who had first arrived in Ethiopia in 1877. Having on that occasion taken no less than seven months to make the 700km journey from the coast to the then capital of Ankober he was fully aware of the inconvenience of mule transport, the high costs of which greatly hindered trade in low priced commodities, such as coffee, skins and wax, which constituted the bulk of Ethiopia's exports. Traders at this time often took about six weeks on the journey which was almost inevitably accompanied by considerable stealing as it was very difficult adequately to supervise the muleteers [4].

The Addis Ababa-Djibouti railway parallels meter-gauge Ethio-Djibouti Railways, between Addis Ababa and Djibouti, which began operating between Dire Dawa and Djibouti in 1901, and was later extended to Addis Ababa, though trains have not run on the line since 2008[5].

Rail transport in Ethiopia currently operates, the Addis Ababa Light Rail as depicted in Figure 1.2, which opened in 2015 and, of a one electrified standard gauge rail line, the Addis Ababa-Djibouti Railway, which commenced freight operations in October 2016[5].

Figure 2.2 NS line AALRT vehicle at Minilik II square

The Addis Ababa-Djibouti Railway is the first part of a planned railway network that links landlocked Ethiopia to its neighbors. The Addis Ababa-Djibouti railway was constructed and is operated by Chinese contractor CREC. It currently carries both freight and passenger service. A 400 km long rail line from Awash to Kombolcha is currently accomplished and from Kombolcha to Weldiya is under construction by Turkish company Yapi Merkezi with various European subcontractors.

The Ethiopian Railway Corporation has plans for several new lines including links to adjacent countries and further afield. ERC will build these in two phases. A railway from Mek'ele to Awash will link the capital with northern Ethiopia by connecting to the Addis Ababa-Djibouti Railway at Awash, its construction on the railway began in February 2015 and the China Communications Construction Company is the prime contractor for the northern half of the railway, from Mekelle to Weldiya [6]. Funding for the $1.5 billion northern segment was provided by the Exim Bank of China. Yapı Merkezi is responsible for the southern half of the railway, from Weldiya to Awash. A consortium of lenders, including Türk Eximbank, the Swedish National Export Credits Guarantee Board, Denmark's Export Credit Board, and Swiss Export Risk Insurance, provided funding for the $1.7 billion southern segment [7].

A railway from Addis Ababa to Bedele will run westward from the capital to Bedele. The prime contractor is Andrade Gutierrez, and funding was provided by the Brazilian Development Bank; the construction on the project began in May 2015[8].

A railway from Weldiya to Tadjoura will provide Ethiopia with a second outlet to the sea at the port of Tadjoura in Djibouti. The line will connect to the Mek'ele-Awash railway at Weldiya. The project is being supervised by the Overseas Infrastructure Alliance (India), and the Indian government has committed $300 million so far with the funding coming from the Indian government. However, the project has been delayed five times and has not yet been tendered as of May 2015.

2.3 About AALRT

The opening of AALRT, one of the first of its kind in Ethiopia and sub-Saharan countries, has brought about a tremendous development in the transportation sector of the country. Designed to relieve growing road congestion as the city's population passes six (6) million inhabitants, the 34km two-line network serving 39 stations has been constructed by China Railway Engineering Corp at an estimated cost of US$475m. The project has been 85% funded by loans from Export-Import Bank of China [8]

The first route to open is the 16.9 km north-south Blue Line linking Menelik Square to Kality, serving 22 stations. The second route is the 17.4 km east-west Green Line from Ayat to Tor-Hailoch, serving 22 stations. The two routes share tracks for 2.7 km in the city centre between Lideta and Stadium[8] which is constructed over ground as shown in figure 1.3 . The network is operated by a vehicle of 70% low-floor trams supplied by CNR Changchun. With trams running at up to 70 km/h, the two routes are designed to carry up to 15,000 passengers per hour in each direction. Services are operating from 06.00 to 22.00 each day, and tramway's independent power supply network includes four substations with a total rating of 160 MW [8].

Figure 2.3 Legehar train station

2.4 Related literatures about the stated problem

2.4.1 Introduction to wheel flange

Wheel flange are the most critical component of rolling stock, and they need the most attention because they are the most stressed components of railway vehicles. The primary function of wheel flange in the operation of rolling stock is to guide the train on the tracks through straights, curves, and switches, so it is reasonable to conclude that wheels are subjected to a constant wear process. Figure 1.4 depicts the various components of a railway wheel flange.

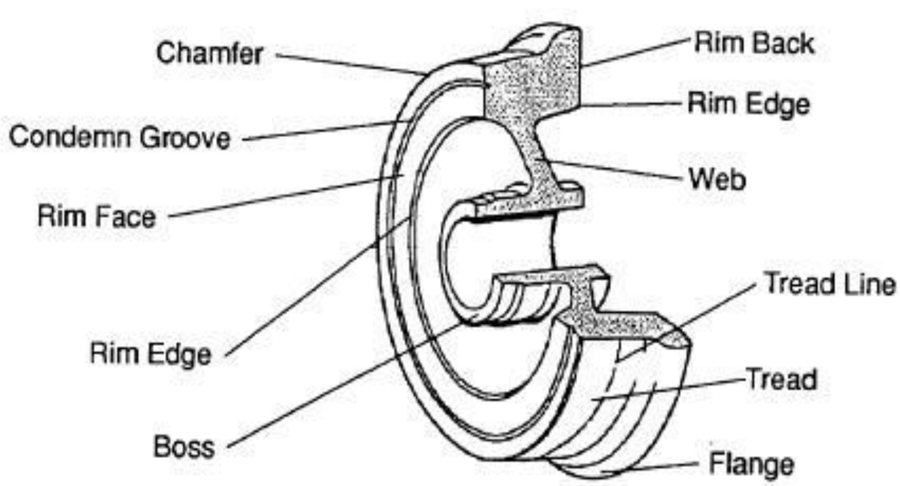


Figure 2.4 Basic wheel components

Railway wheels are usually made of unalloyed or low alloyed steels with a high degree of purity. Standard wheels mainly consist up to 0.6wt% of carbon, up to 8wt% of manganese and up to 0.4wt% silicon.

2.4.2 Wear mechanisms

The loss or displacement of material from a contacting surface is referred to as wear. Debris is one type of material loss. Material displacement can occur as a result of adhesion or local plastic deformation of material from one surface to another. There are numerous wear mechanisms that can occur between contacting bodies, each of which produces a different rate of wear. The most basic classification of the various types of wear that result in varying wear rates is “mild wear” and “severe wear.” Mild wear produces a smooth surface, which is often smoother than the original surface. Severe wear, on the other hand, results in a rough surface that is frequently rougher than the original surface [9]. Mild wear is characterized by the removal of materials in extremely small fragments. Mild wear is beneficial to contact wear life in many cases because it results in a smooth run-in of the contacting surfaces. However, it has been observed in some cases that it worsens the contact condition and that mild wear can change the form of the contacting surfaces in an unfavorable way [6]. Another wear process that results in a smooth surface is the oxidative wear processes characterized by the removal of the oxide layer on the contacting surfaces. In this case the contact temperature and asperity level influence the wear rate [8]. Abrasive wear caused by hard particles between the contacting surfaces can also cause significant wear and reduce the life of the contacting bodies [6].

The basic concept for adhesive mechanisms is that actual contact between surfaces occurs at discrete points within the apparent area of contact. At these spots, called junctions, bonding occurs between surface asperities (see Figure 1.5). When the surfaces move relative to each other, these junctions are broken and new ones formed. Usually the tip is plucked off the softer asperity leaving them adhering to the harder surface. This can be via a ductile or brittle fracture. Subsequently the tips become loose and give rise to wear debris. Severe damage can sometimes result in the tearing away of macroscopic chunks of material and this situation is known as *galling*. If adhesive wear results from the breakdown of lubrication in a contact, then the term *scuffing* is used to describe the onset of wear.

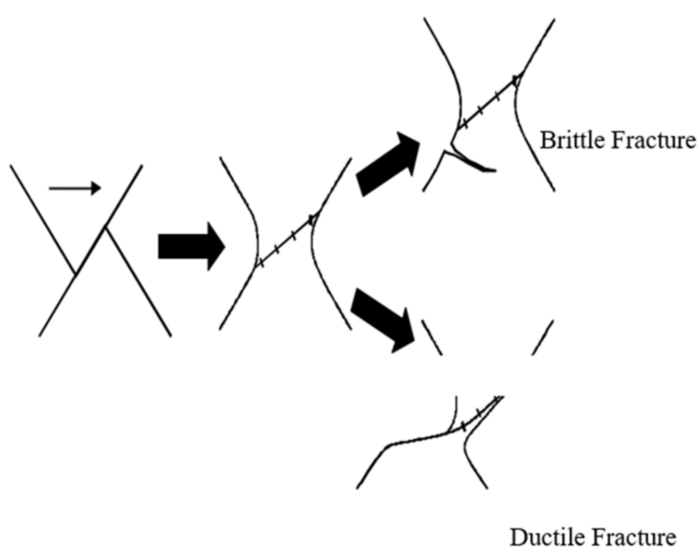


Figure 2.5 Adhesive wear mechanisms

Abrasive wear is damage to a component surface, which arises because of the motion relative to that surface of either harder asperities (*two-body abrasive wear*) or because of hard particles trapped between the surfaces (*three-body abrasive wear*) (see Figure 1.6). Such particles may be introduced between the two softer surfaces as a contaminant from the outside environment, or they may have been formed *in situ* by oxidation or by some other chemical or mechanical process.

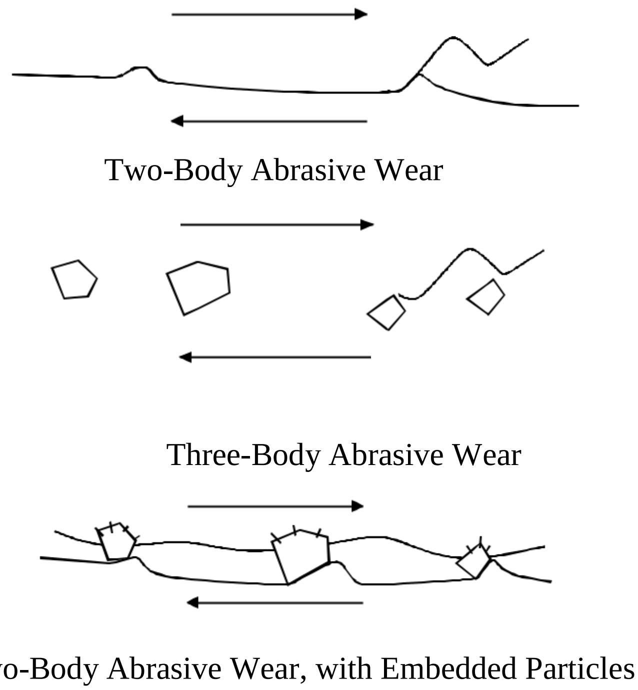


Figure 2.6 Abrasive wear mechanisms [10]

The rate of damage is relatively insensitive to the hardness of the particles in a three-body situation, as long as they are at least 20% harder than the surface itself. The most commonly occurring contaminant in industrial machinery is that from quartz or silica (these minerals make up about 60% of the Earth's crust) (silica sand is either used on its own as a friction enhancer in the wheel-rail contact or mixed with water and viscosity enhancer in traction gels such as Sandite or Alleviate [11].

Many factors influence the type of wheel profile that an operator may choose to use on their trains. These include the curvature of the infrastructure, the design speed, lubrication type and the type of rail. Generally, for light rail applications, coned wheels are used in order to navigate tight curves.

Coned wheels connected by a rigid axle allow rail vehicles to steer around curves by creating a differential in rolling radius. When in a curve, the inside wheel rotates with a smaller radius, and travels a shorter distance, than the outside wheel. This differential reduces friction and flange contact, reducing wear on the wheels and the rails.

Addis Ababa Light rail vehicles contain double-articulation using a short center trailer. To achieve a low-floor design in the middle of the train, the axle is removed, allowing the wheels to turn independently from one another. Without an axle, the self-steering mechanism that stabilizes the vehicle is removed. Coned or not, the wheels are free to rotate independently of one another, which means it no longer self-steers towards the center of the track.

In some situations, such as tight curves, turnouts or even when travelling at higher speeds on straight tracks with unevenness, the trailer may be guided by the flanges of the wheels rather than the rolling radius differential. This contact increases friction, wear and sometimes noise.

NJ Transit reported "higher wheel wear on the center trucks of its lower floor light rail vehicle (LFLRV) fleet than on the wheels of the motor trucks" and "very high rail wear on sharp curves."

Portland Trimet came to a similar conclusion, reporting that "Portland MAX has experienced higher LFLRV wheel flange wear on the center vehicle than on the motor vehicles."

At its worst, the forces generated through this increased flange contact may be high enough to let the wheel climb over the tracks and cause a derailment, and the report notes:

As with any engineering issue, there are methods for mitigation, including modification of infrastructure for better wheel-rail interfaces and maintenance. Wear and noise can be mitigated using several methods, including lubrication, which Sound Transit has done. Additional protection through curves could also be provided by restraining rails. Operationally, the report also suggests that curves should be taken at constant speeds, with acceleration only after the curve has passed. Finally, improved vehicle and infrastructure design can also reduce these negative effects. However, the need for these mitigation measures demonstrates that for light rail, "track standards have to be tighter than might be acceptable with more conventional vehicles. It is also generally recognized that the management of the wheel/rail interface is even more critical."

Generally, this means that it is more difficult for light rail to achieve the same performance (speed, acceleration, curving capabilities, etc.) compared to a conventional train.

Parameters that have an influence on the wheel wear at different levels:

- Vehicle characteristics (Axle load, Primary suspension stiffness and geometry, Carbody / Bogie rotational stiffness, Motor or trailer axle, Traction / Braking forces & characteristics)
- Wheel / Rail contact (Wheel & Rail Profiles and rail cant, Wheel/Rail friction coefficient, lubricator device, Wheel material)
- Operating conditions: Curve radius and track cant in curve distribution, Mission profile
- Type of lubrication system (side rail lubrication, onboard lubrication and etc.)

2.4.3 Wheel-Rail Wear Processes

Rails and wheels are subjected to a variety of conditions and wear modes or processes, which are mitigated by lubrication. Presented a suitable method of representing the conditions under which each of these wear processes can occur [12].

[12] Groups wear modes into four broad categories: seizure, melt wear, oxidation-dominated wear, and plasticity-dominated wear. All of the wear process modes occurrences are possible in a rail/wheel system.

2.4.4 Wheel-Rail Wear Particles

Wear particles from rails and wheels are classified based on their wear modes. The tread contact experiences rolling and micro-slip, whereas sliding becomes more dominant closer to the flange due to the conical wheel profile. In the work of [12] the wear debris from rolling processes is classified into three types. Thin, small oxidized wear particles characterize Type I wear. Type II wear is considered as a range of wear particle sizes with agglomerated particles. Type III wear is known by high wear rates, large particle size and extremely rough surface.

By using wear mapping technique (see Figure 2.2) [7] also define three modes of wear depending on surface appearance, wear particles, and wear rate. Each researcher defines the wear modes with a different. A researcher in **[14]** also wrote similar findings about wear particles and similar wear processes.

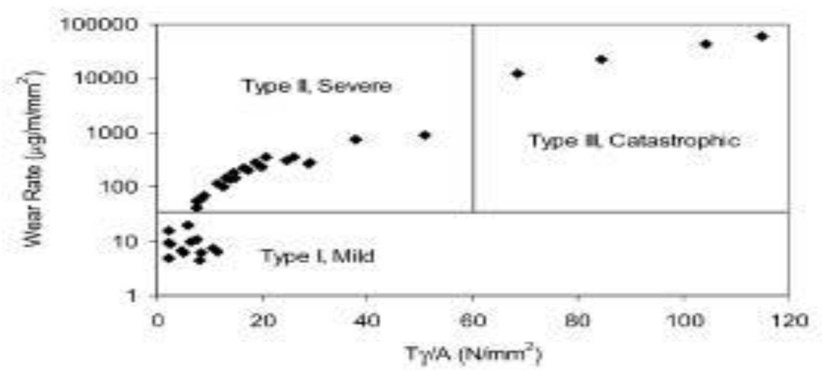


Figure 2.7 Wear map showing defined wearmodes [7]

2.5 Wheel Rail Lubricant Characteristics

To control the effects of wear in the flange contact, railway systems use a wide range of lubricants. These are divided into three types: oil, grease, and water. Railway systems frequently use a combination of lubricants. Some European railway use wayside lubricators for half of the year and depend on snow (water) for the remaining months [4] but in Australia, greasing through wayside lubricators and onboard lubricators are the most common. But still now it is not clear what parameters form a 'good' lubricant.

To ensure best lubrication practice, the parameters of amount and location are generally agreed. If the lubricant is not applied properly, it can spread to the wheel tread, resulting in a dangerous loss of traction and brake forces. Similarly, if the lubricant is applied correctly but in excess, the lubricant can migrate to the tread contact area, which is dangerous. As a result, the focus for industry is on the right amount and the right location.

According to [12], the benefits of wheel rail lubrication can be including lower fuel consumption, less wheel wear, and less rail wear. In these studies, three types of the lubricant applicators are considered: wayside, onboard, and high rail. Each lubricator preferred a different type of lubricant: wayside and high rail applicators preferred grease, while onboard lubricators preferred liquids like oil sprayed onto the contacting surfaces.

Generally, we can use lubrication for two reasons, both are economic in nature. The first one is lubrication reduces rolling friction and energy lost due to friction, lowering the operating costs of a rail network. Secondly, reduced wear means less maintenance for rail infrastructure and rolling stock. Due to the relative ease of measuring performance, research has focused on the first reason [13].

Oil is widely used in Australia and the United States because grease is considered unsuitable [13]. The fact that oil will remain adhered to a surface is advantageous because lubricant waste is both an environmental and a safety concern. Oil is also more resistant to environmental factors like temperature and rain. It is also much easier to add solid lubricants to oil; graphite or molybdenum disulfide.

2.6 Specifications of wheel flange and rail curve lubricating oil

Lubricants are produced to meet the requirements of a tribological system. Railway companies specify lubricant properties that may directly related to the wear processes encountered at the interface [14]. The following table shows the specification of wheel flange lubricant.

Table 2.1 wheel flange lubrication oil specification

Application	Product	Characteristics
Wheel flange lubrication	WF BiorNaturWF68 Oil	Biodegradable lubricant for lubrication of on-board system

Lubricant oil benefits

- Operations optimized over wide working temperature ranges
- Costs savings
- Approved by Rebs and Bijur Delimont for on-board lubrication systems
- Low re-oiling interventions
- Limits wear and friction on wheel flanges
- Reduction of noise disturbance

2.7 Literature about lubricant application method

The distance of lubrication from the application point is used to calculate lubricator efficiency. The modeling of the lubricant transport process is inadequate in the body of literature [15].

There has been research in this area to determine lubricant placement algorithms. According to the findings of [16], more efficient lubricator placement can be achieved through direct measurement of lubricator effectiveness. Lubricators have evolved through a series of iterations, beginning with mechanical devices and progressing to hydraulic and electronic devices. The lubricant applicator methodology has evolved to address the shortcomings of wayside lubricators, specifically to increase device reliability. Lubricants are a commercial product, so the research that went into their development is not available for review. More research is needed to determine the performance of rail curve lubricants [17][13][4].

In actual contacts, geometric and physical considerations change rapidly, so there are a plethora of variables to consider. It is difficult to draw comparisons between field and laboratory results, and no direct comparisons have been made from scaled simulation results [4][13]. Full-scale testing facilities have yet to publish significant results on optimal lubricant and lubrication strategies. Due to the sheer number of variables that must be recorded, from the weather to axle loading, in-service equipment is nearly impossible to manage. Another challenge in all types of testing is the time required to collect data for wear rates.

American researchers attempted to overcome the simulation challenges by building a full-scale test facility. The FAST (Facility for Accelerated Service Testing) track has yet to yield definitive research results in rail/wheel tribology. Another full-scale test facility exists in Sweden and is used by Chalmers University, but no publications on lubricant performance have been published at the time of writing. The value of testing at full scale facilities will be determined by the volume of results that will be analyzed once the wheel-rail interface is better understood.

Laboratory simulation is regarded as a useful tool in other tribological systems, and its development is critical. Due to a lack of recent publications, the review of laboratory lubricant testing devices is limited. Three groups [4][17]have published in the field of rail lubrication, with the most recent work being that of [4]. [4] examined the relationship between laboratory and field lubrication. Beginning in 1997, field testing of rail curve lubricants has investigated the influence of mineral oil based oils, such as the ones tested in this thesis, environmentally adapted oils, and the influence of solid lubricant additives to these oils. The Plint and Partner High Frequency Apparatus with a "cylinder on flat" arrangement was used in Waara's laboratory testing. The cylinder is pushed against the flat and then slid in an oscillating motion. This apparatus contrasts sharply with the three other groups of researchers, each of whom used a different variant of a twin disk apparatus. The field and laboratory studies on [4] using the cylinder on flat device have similarities and differences.

As trains travel in both directions, the cylinder sliding forwards and backwards corresponds to gauge face contact. Heavy haul lines are an exception in the field, with trains traveling loaded in one direction and unloaded in the other, resulting in primarily unidirectional loading. The cylinder sliding back and forth differs from the field contact in that it lacks the rolling component of the field contact.

The sliding section of the cylinder (the contact patch) remains in a constant state of stress, with no time for stress relaxation to occur. The loading situation in the field is cyclic, with a single point on the wheel compressed once per revolution. The fatigue component of wear processes is reduced when there is no cyclic loading. The shape and stress distribution of the contact are similar to that of the field, but the contact area is much smaller. Surface roughness has a greater impact on simulators as the contact area decreases. The wear processes in this situation may differ from the wear processes in the field.

Lubricant spread is accomplished by sliding the cylinder across the flat, whereas the field process is primarily a rolling motion. When it is considered that the process is more damaging to the lubricant and forces more lubricant from the contact, the spread of lubricant by sliding is desirable. However, sliding to spread the lubricant does not reflect the rolling and sliding that occurs in the field.

According to the findings of [18], there is a need for a “simple inexpensive laboratory test method” for characterizing the performance of rail curve lubricants. [19]reviewed the tribological issues in rail wheel contact as a follow-up to his previous research [18]. This review identified a need for a laboratory test device capable of measuring lubricant performance in the presence of a lubricant film that has been depleted of its lubricant. To address this shortcoming in rail curve lubricant research, the work presented later in this thesis represents a method of predicting the decay or half life of the starved lubricant film

The research in [18] measured the lubricant performance as the number of revolutions to lubricant film failure and the wear rate. The number of revolutions is representative of the number of axles or strain history and was defined as retentively. The variability between tests was larger than the range of presented results for comparison between lubricants. [18]did not make clear if the variability was from the accuracy and resolution of measurements of the device or the test method itself. Under fully lubricated conditions the wear rate was reduced by 1400 times as compared to the unlubricated case. According to the work in [18], research was required to determine the lubricant film thickness and the decay of this thickness. This thesis addresses a research gap by presenting a performance criterion to address the issue of film decay, namely half-life. [13] Emphasizes the importance of three test parameters for the success of laboratory simulation: contact stress, creep or slip, and lubricant quantity. The fact that they emphasize lubricant quantity as an important test parameter indicates that the volume of lubricant was insufficient to the point of excess in any of their tests.

2.8 Rail and wheel flange lubrication researches

It is critical to consider the lubricant application system in order to improve the effect of wear between the wheel and rail. There are three main methods for applying lubricant to the gauge corner on the railway and wheel flange [13]:

- Wayside lubricators, see Figure 2.8
- On-board lubricators, see Figure 2.9
- High rail lubricators, see Figure 2.10

Figure 2.8 Wayside lubrication device

Figure 2.9 On-board lubrication that mounted on bogie.

Figure 2.10 Hi-rail lubrication vehicle

Wayside (trackside) lubrication research has primarily focused on determining the effectiveness of lubrication on the cost-involved aspects of rail infrastructure and rolling stock. The research in [20] looked into the rail system and the effect of lubrication on it. Their study focuses on reducing wear and energy consumption (tractive effort) associated with flange/gauge face contact..

Due to the low demand for new systems, commercial research into wayside lubricators has been slow. Following a major breakthrough, new systems are implemented, or existing system maintenance costs exceed the cost of replacement systems. These new systems are frequently developed commercially, with the results remaining unpublished..

In [19], the efficiency of lubrication strategies was measured in Australia's Hunter Valley by obtaining friction coefficients at the head of the rail. The projects altered the system parameters of lubricator location in terms of direction, loading, and whether it was on hi-rail, low-rail, or both. [21] Does not provide precise location information. There is also no indication that an analytical algorithm was used to determine the location of the lubricator.

[21] Discovered that increased contact pressure between the rail gauge face and the flange reduces the efficiency of the lubricator system. Because of the high flange forces, the lubricant sprayed out of the contact zone. As a result, the lubricant is wasted into the ballast material or onto the rail's running surface. Large compressive forces, such as those described in [21], were found to have a similar effect on lubricant response in the rail/wheel simulator. The problem of lubricator location in relation to a

predetermined level of flange force or shearing force could be investigated in order to provide a design that improves lubricant transport.

2.9 Prediction and modeling of lubricant application

The body of knowledge in wheel-rail lubrication provides general lubrication principles rather than specific lubrication regimes. General principles obstruct accurate simulation of industry practice, a critical simulation parameter. Field experience and measurement are typically used to develop these lubrication systems. The literature does not adequately define the large number of variables in a lubrication system and their interactions. Despite this scarcity, there are ‘rules of thumb' that provide guidance for appropriate lubricant application strategies..

According to [15], the lubrication device should be placed at the point on the curve where flange contact wear is observed, as shown in Figure 2.6. This location is easily measured and, as a result, track personnel can find it. The implication is that only after wear occurs and the location for lubrication can be determined will it be possible to lubricate.

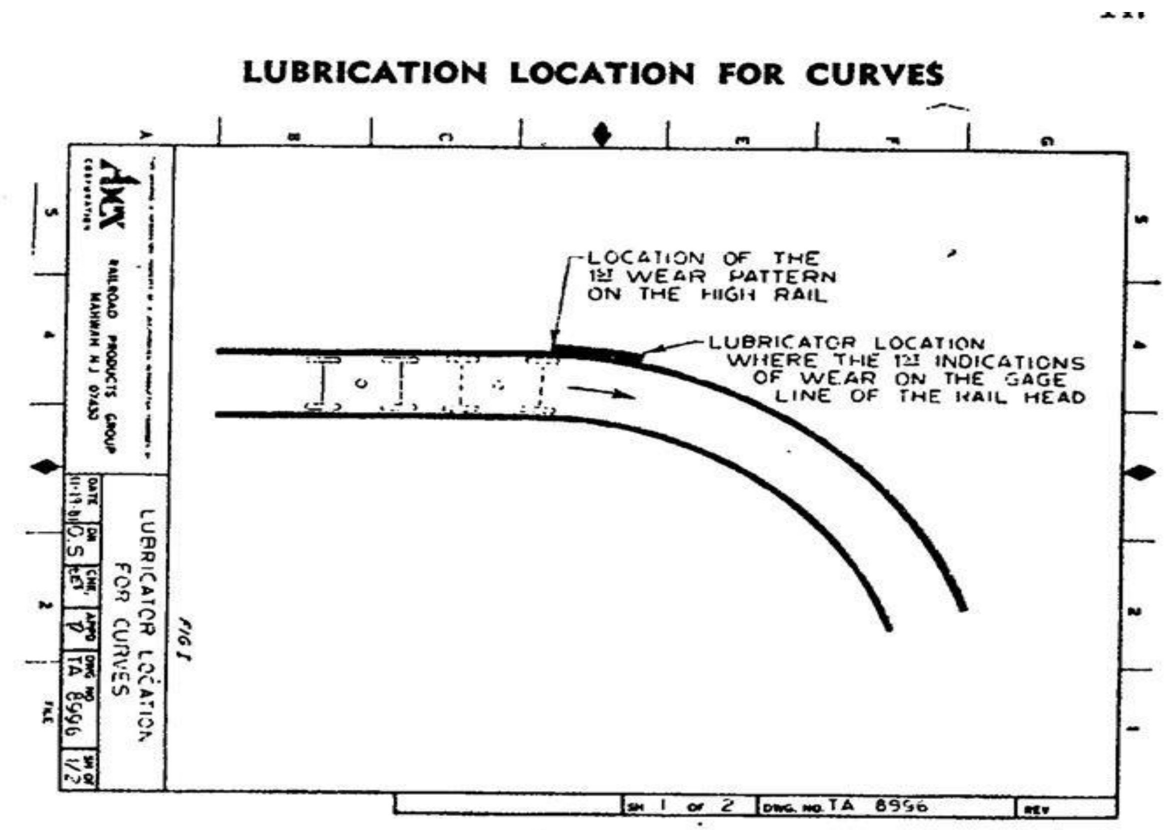


Figure 2.11 Wayside lubricator position

Lubricant spread may not occur using [15] method, as contact pressures may be high enough to force the lubricant away from the desired location. In contrast, if the contact pressure is insufficient, the wheel can transport excessive amounts of lubricant to locations other than the rail face (fling off). In the case of excess applied lubricant, the actuation system has a direct impact on lubricant waste. If the flange does not come into contact with each passing axle, the system will continue to pump lubricant to the application point, resulting in large pools of lubricant.

[15] Also proposed that the length of the lubricator delivery system be equal to that of the wheel's circumference in case of onboard system. This length ensures that the entire flange receives lubricant. In the event that wheel contact is not maintained over the length of the lubricator, excess lubricant (puddles) can again occur. The proposed application methodology of [15] was employed in the lubricated testing of the rail/wheel simulator.

Figure 2.6 is from the work of [15] and shows the work they did to determine the effective range of lubricants. The downstream lubricated distance can be seen to be proportional to the radius of the curve. This curve radius determines how fast a train can negotiate a corner and has a direct impact on the contact conditions at the flange. The relationship in this table is empirical and only takes into account the variable of curve radius. Maintaining a constant flange force and corresponding lubricant shear force could be used to generate additional tables like those shown in [15]. This thesis' design onboard lubrication system so that no need to measure the spray force

2.10 Research Gap

There has been a variety of research about wheel flange rail wear analysis and wheel flange lubrication, but most studies have focused either on wheel-rail wear analysis and importance of lubrication on wheel rail contact surface. These studies overlooked the cause of wheel flange wear regarding due to lack of lubrication. From reviewed different literatures, the research focusing on cause analysis of AALRT train wheel flange wear analysis and designing appropriate lubrication system is less studied. Therefore, more comprehensive research is required to investigate why AALRT train wheel flange is worn out before expected lifetime and design suitable spray type wheel flange lubrication system.

CHAPTER THREE

AALRT Operational Characteristics and Current Lubrication Methods

3.1 Infrastructure Network and Environment Conditions

The total length of the AALRT two lines is 31.025km. The East-West main line is approximately 16.99 kilometers long, while the North-South main line is approximately 16.689 kilometers long. Both lines share a 2.662km section and five train stations from stadium to lideta. AALRT uses double track dedicated to passenger service for both lines, with a track gauge of 1435mm. The minimum radius of horizontal curve for mainlines between sections is 50m, and the radius for yard lines is 30m. The minimum radius of the vertical curve for the lines is 1000m, and the maximum gradient is 55%. Rails for main lines and depots are 50kg/m, with a maximum super-elevation of 120mm and an inclination at rail bottom of 1/40. The train axle load is 11t (1+3%).

Table 3.1 Weather condition in Addis Ababa city

Altitude above sea level	2355m
Ambient temperature	0℃～+29.7℃
Average daily highest temperature in years	26℃
Average daily lowest temperature in years	6℃
Average relative humidity in years	95%
Average annual rainfall	1000-1450mm
Maximum daily rainfall	42mm

In the East-West line (Ayat-Torhayloch), there are 21 trains allocated for operation, standby and maintenance, which are green in color while North-South (Kaliti- Menilik II Square) line, there are 20 trains allocated in the same way which are blue in color. It should be noted that all t trains that are in operation are the same vehicle type and specifications. The trains operating in each route are identified by their vehicle number; trains operating in the East-West line start by vehicle number 1YY and trains operating in the North-South line start by vehicle number 2YY. In the East-West line, there are 22 stations and also in the North-South line, there are 22 stations. These routes share stations at five locations with shared track, which are stations at Stadium, Legehar, Mexico, Tegbaret and St. Lideta as shown on Fig 3.1.

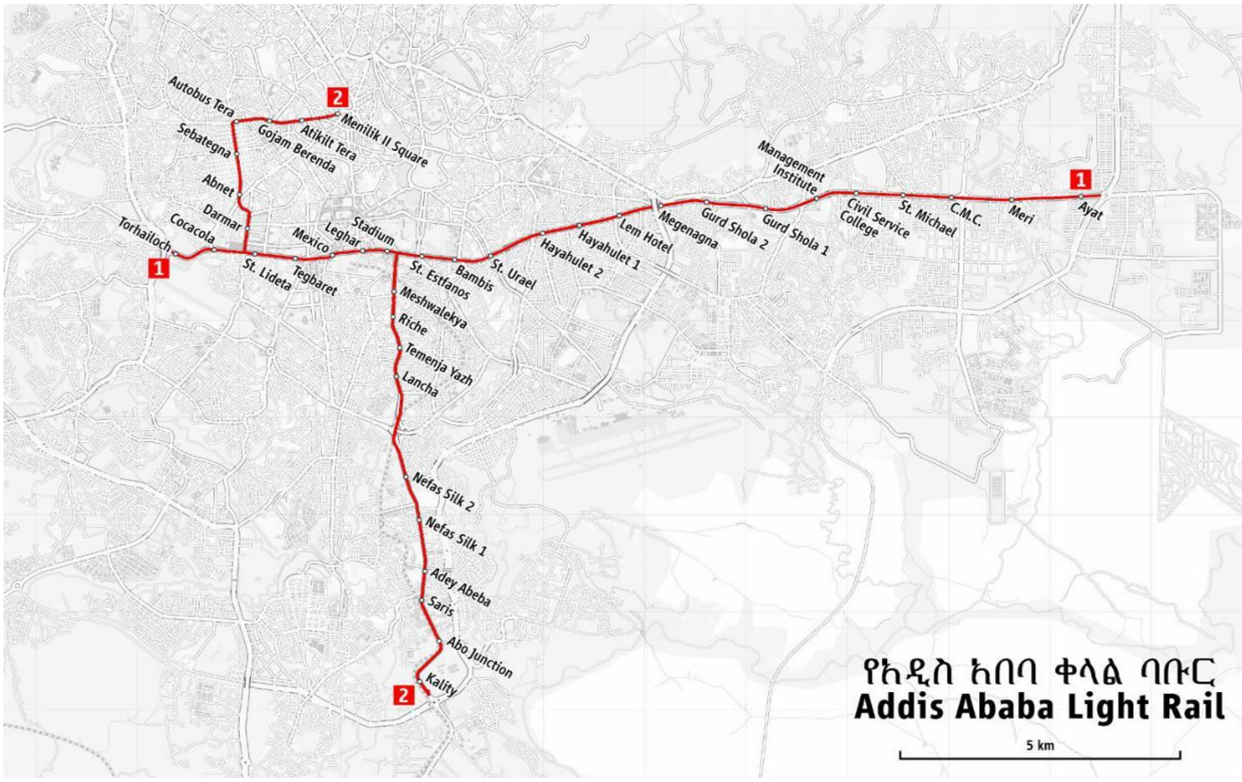


Figure 3.1 Map of AALRT line showing all stations in both routes

Table 3.2 Stations of AALRT (East-West and North-South lines)

East-West line stations (Ayat-Torhayloch)	**North-South line stations (Menilik II Square-Kality)**
Ayat	Kality
Meri	Abo Junction
CMC	Saris
St. Michael Church	Adey Abeba
Civil Service College	Nifas Silk 1
Management Institute	Nifas Silk 2
Gurd Shola 1	Lancha
Gurd Shola 2	Temenja Yazh
Megenagna	Riche
Lem Hotel	Meshwalekiya
Hayahulet 1	Stadium
Hayahulet 2	Legahar
St. Urael	Mexico
Bambis	Tegbared
St. Estifanos	St Lideta
Stadium	Darmar
Legahar	Abinet
Mexico	Sebategna
Tegbared	Autobus Tera
St Lideta	Gojam Berenda
Cocacola	Atikilt Tera
Torhayloch	Menilik II Square

3.2 AALRT Rolling Stock Characteristics

The AALRT vehicles are 70% low-floor articulated 6-axle modern trams with two motor cars and one trailer car that are able to operate with double heading.

Train formation: -Mc+Tp+Mc-

Mc module: motor car with driver's cab

Tp module: trailer without driver's cab and with pantograph

+: articulation device

-: hidden folding coupler

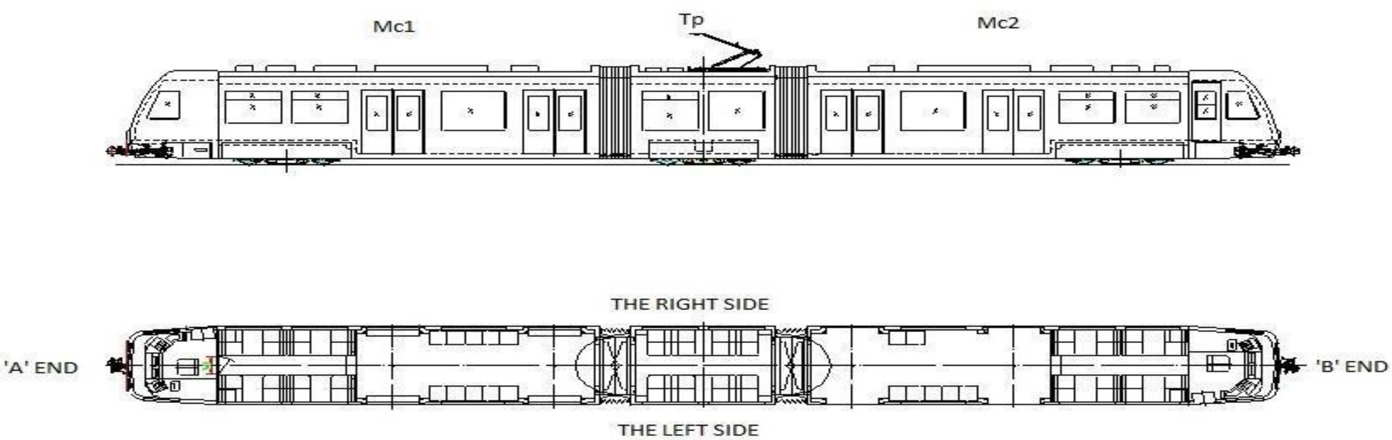


Figure 3.2 Train formation of AALRT vehicle

3.2.1 Dimensions of AALRT vehicles

The following table shows the basic vehicle dimensions that AALRT vehicles have.

Table 3.3 Dimensions of AALRT vehicles

Length of the vehicle	28800 mm
Height of vehicle roof from top of rail (excluding pantograph)	3610 mm
Maximum width of car body	2650mm
Height of vehicle floor from top of rail (low floor area, new wheels and empty load)	380 mm
Height of vehicle floor from top of rail (exit and entry areas, new wheels and empty load)	350 mm
Height of vehicle floor from top of rail (raised floor area, new wheels and empty load)	655 mm
Axle distance of the motor unit (motor bogie)	1900 mm
Axle distance of the trailer unit (trailer bogie)	1800 mm
Clear height of passenger compartment at high-floor area	1980 mm
Clear height of passenger compartment at low-floor area	2255mm
Wheel diameter (new wheel)	660 mm
Minimum limit of wheel diameter (Max wear)	580 mm
Side doors of passengers' compartment	8 doors
Clear opening of passenger compartment door (width x height)	1300×1860 mm

3.2.2 Carrying capacity of vehicles

The vehicle is designed to carry a large number of passengers at once, so it is spacious and designed for more people to stand to maximize carrying capacity for serving more people at once.

Table 3.4 Carrying capacity of AALRT train

Number of passengers (persons)	Seating capacity	Standing capacity	Total(person)
AW0	0	0	0
Seats (AW_1)	65	0	65
Seating capacity (AW_2) (standing: 6 persons/m^2)	65	189	254
Overload capacity (AW_3) (standing: 8 persons/m^2)	65	252	317

3.2.3 Vehicle weight

Weights of vehicles are given in table 3.5 with axle load of ≤11（1+3%）t and taking 60 kg as average weight of each passenger

Table 3.5 Vehicle weight of AALRT vehicle

	Loads condition	Train weight (t)	Passenger weight (t)	Total train weight (t)
AW0	Empty vehicle	44	0	44
AW1	Seating capacity	44	3.9	47.9
AW2	Seating and standing capacity (AW_2) (standing: 6 persons/m^2)	44	15.24	59.24
AW3	Overload capacity (AW_3) (standing: 8 persons/m^2)	44	19.02	63.02

3.2.4 Main Technical Parameters of the Vehicle

The maximum operation speed of the vehicle is 70 km/hr with average speed of 25 km/hr average dwelling time of 30 seconds at each station. The average acceleration of the vehicle under rated load and rated voltage on straight and dry track, with half-worn wheels is given as follows.

1. for speed from 0km/h to 40 km/h $\geq$1 m/s^2
2. for speed from 0km/h to 70 km/h $\geq$0.5 m/s^2

The average braking acceleration under rated load on straight and dry track, with half-worn wheels from maximum vehicle operation speed of 70 km/h is as below:

3. maximum service brake deceleration: $\geq$ 1.1 m/ s^2
4. emergency brake deceleration: $\geq$ 2.0 m/ s^2

The ride quality of vehicle is $\leq$ 2.5, coefficient of derailment of the vehicle is $\leq$ 0.8. The longitudinal vehicle jerk rate is $\leq$ 1.0 m/s^3.

3.2.5 Vehicle bogie

The vehicle bogie is constructed of a high-strength cast steel frame that, under normal operating conditions, should have a lifetime of at least 30 years. The bogie is equipped with two suspension systems: a primary suspension of rubber springs and a secondary suspension of steel springs. The secondary lateral oil damper and secondary vertical oil damper provide damping action to the bogie. The table below shows additional technical parameters of the vehicle bogie used by AALRT.

Table 3.6 Specifications of AALRT vehicle bogie

Maximum operation speed	60 km/hr
Maximum test speed	70 km/hr
Axle load	11 (1+3%) t
Track gauge	1435mm
Fixed wheelbase of motor bogie	1900mm
Wheel diameter	Φ660mm(New wheel), Φ580mm(Fully worn wear)
Axle box bearing type	Tapper roller bearing unit
Motor car drive mode	Double reduction gear
Installed brake type	Disk brake + Magnetic track brake

The AALRT vehicle consists of two types of bogie which are motor and trailer bogies.

i) Motor bogie

This bogie is attached to the car at both ends, underneath module Mc. This bogie's structure consists of a bolster, full side bearing, outer-side axle box, and fixed axle wheelset. This bogie is made up of the following components: frame, wheelset, primary/secondary suspension, traction assembly, driving unit, brake unit, and auxiliary devices. The details of the bogie's structure are shown in Figure 3.3.

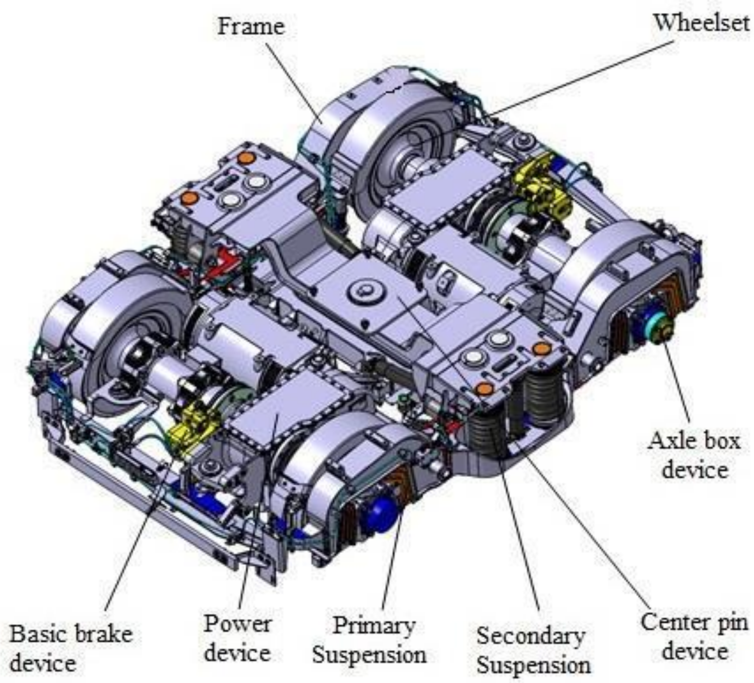


Figure 3.3 Powered (motor) bogie of AALRTS

a. Frame and wheel set

The powered bogie has welded structure which includes steel plates and cast steel parts. These parts are side sill, cross beam and end sill. This bogie is designed to have improved frame strength and reduced welds through monobloc casting of the critical bearing area. This frame is designed according to UIC615-4, EN13749 and VDV152. The bogie wheelset consists of resilient wheel, axle, axle box and bearing unit.

b. Primary and secondary suspension

The primary suspension is of metal rubber spring and is mounted between frame and axle box, with primary hanger link that enables the wheelset to be lifted up along with bogie. The secondary suspension is located at side bearing so that it handles weight of car body and it includes bolster, secondary spring, vertical damper, lateral damper, side bearing, lateral rubber stop, secondary hanger link and load sensor.

c. Traction assembly

This assembly transfers longitudinal force and lateral force between bogie and car body

d. Driving and Brake unit

The driving unit includes traction motor, gear box, hollow shaft and star coupling. The gear box is of two gears which are double reduction and parallel-axe gears. The traction motor is incorporated with gear box on one side and suspended on cross beam of bogie frame. The other end is suspended on end sill. The brake unit consists of hydraulic disk brake and magnetic track brake.

e. Auxiliary devices

There are all sorts other devices which are of significant importance. These include flange lubrication unit, rail cleaner, fender, hydraulic pipe, sanding and others. Flange lubrication, which is dry type, is of great importance because it is used to reduce flange wear and extend wheel re-profiling interval. It is located on each one axle of end bogies.

ii) Trailer bogie

This bogie is mounted underneath Tp module in middle of car. Similar to the powered bogie, the trailer bogie also consists of frame, independently rotated wheelset, primary suspension, secondary suspension, traction assembly, brake unit and auxiliary devices. The figure below shows the structure of the unpowered bogie.

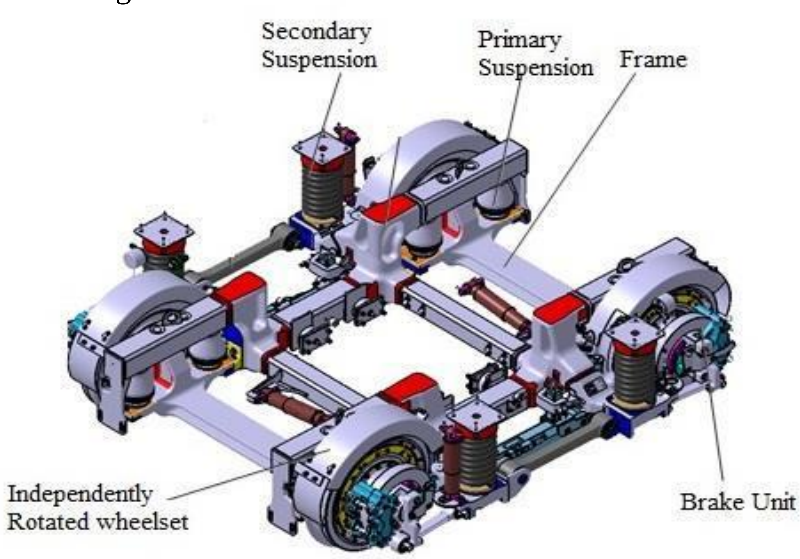


Figure 3.4 Unpowered (trailer) bogie

a. Frame

The frame of this bogie is an H shaped welded structure, and is welded of casting and square boxes. Like the powered bogie, same calculation and criterion is used for the design and weld of this bogie.

b. Secondary Suspension and traction assembly

The secondary spring supports the car body having similar structure as the suspension of the powered bogie. Similar with the powered bogie, the traction assembly consists of double traction bars arranged at both sides of bogie.

c. Brake unit and auxiliary devices

The trailer car brake unit mainly consists of only hydraulic. While the auxiliary devices include the wheel fender, ground device and speed sensor.

3.3 Analysis of AALRT train wheel wear

3.3.1 Comparison between AALRT vehicles of East-West and North-South

Wheel data measurements of AALRT vehicles from both lines, as recorded by AALRT workshop personnel, are shown in Appendix 1 of this design. Vehicles with nearly equivalent mileage have their measurements taken from wheel-lathe machining data at their respective depots. The analysis's goal is to determine which routes are the most affected, as well as the cause and solution for the AALRT train wheel. Table 3.7 displays vehicles from both routes that were chosen based on total average mileage run similarity for comparison of flange thickness and tread diameter. The new wheel diameter is 660mm, the worn limit is 580mm, the new wheel flange thickness is 22mm, and the minimum worn wheel flange limit is 15mm.

Table 3.7 Train selected from the two routes for comparison

N-S line Vehicle No.	Mileage run, km	E-W line Vehicle No.	Mileage run (km)
212	44025	115	45541
205	49030	114	45550
215	47318	108	40410
208	43451	111	45551
218	54475	110	54808
206	75029	109	76431
216	66528	115	69043
210	51664	108	52733
Average run, km	**53937.88**	Average run, km	**53758.75**

The flange thicknesses of vehicles from both routes are summarized in Tables 3.8 and 3.9, which are taken from Appendix 1. For each route, the average flange thicknesses per wheel and per bogie are computed..

Table 3.8 East-West train flange thickness (Sd)

Vehicle No.	**Flange thickness (Sd) in mm for respective wheels**											
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
115	20.62	19.75	20.39	20.28	19.2	15.13	19.77	14.08	20.71	20.59	20.45	19.91
114	19.6	20.48	20.29	20.47	18.52	19.71	18.4	19.63	19.68	20.34	21.11	19.99
108	20.44	20.4	19.94	19.66	18.59	17.81	17.9	16.94	19.64	19.67	20.05	20.08
111	18.52	18.79	18.05	18.59	17.14	13.11	17.26	13.04	19.68	20.34	21.11	19.99
110	18.71	19.11	18.86	18.64	17.13	14.58	17.02	13.09	19.71	18.67	18.97	18.06
109	18.71	18.59	19.16	18.28	12.45	17.42	13.68	16.42	18.65	18.27	19.18	18.24
115	21.41	19.37	21.15	19.99	19.34	15.24	18.52	14.09	21.45	20.51	20.98	19.82
108	21.29	20.63	20.87	19.87	18.78	18.65	18.6	18.04	20.71	19.97	20.98	20.43
Average	**19.91**	**19.64**	**19.84**	**19.47**	**17.64**	**16.46**	**17.64**	**15.67**	**20.03**	**19.80**	**20.35**	**19.57**
Average Sd/ bogie	**19.72**				**16.85**				**19.94**			

Table 3.9 North-South train wheel flange thickness (Sd)

Vehicle No.	Flange thickness (Sd) in mm for respective wheels											
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
212	16.06	17.5	17.02	13.66	16.49	17.69	17.48	17.62	16.63	19.38	16.41	16.93
205	16.71	16.54	17.48	13.48	17.38	18.24	16.38	17.37	16.48	16.59	17.59	18.51
215	17.07	17.93	15.46	13.46	18.05	16.75	17.09	15.45	16.54	16.65	16.17	16.03
208	16.34	17.53	13.45	18.34	17.05	15.44	17.28	14.47	18.68	16.96	17.09	15.99
218	13.7	16.65	14.16	13.86	17.08	16.14	14.11	12.83	18.38	18.06	16.02	15.26
206	17.08	16.77	16.57	15.74	15.41	15.38	14.6	14.34	16.52	16.09	16.07	15.47
216	16.52	16.1	15.96	15.02	17.86	16.84	18.15	17.53	18.47	16.75	16.6	14.75
210	16.12	16.36	16.3	14.39	15.52	14.21	17.51	17.45	16.4	16.93	16.38	14.98
Average Sd/wheel	**16.20**	**16.92**	**15.80**	**14.74**	**16.86**	**16.34**	**16.58**	**15.88**	**17.26**	**17.18**	**16.54**	**15.99**
Average Sd/bogie	**15.92**				**16.41**				**16.25**			

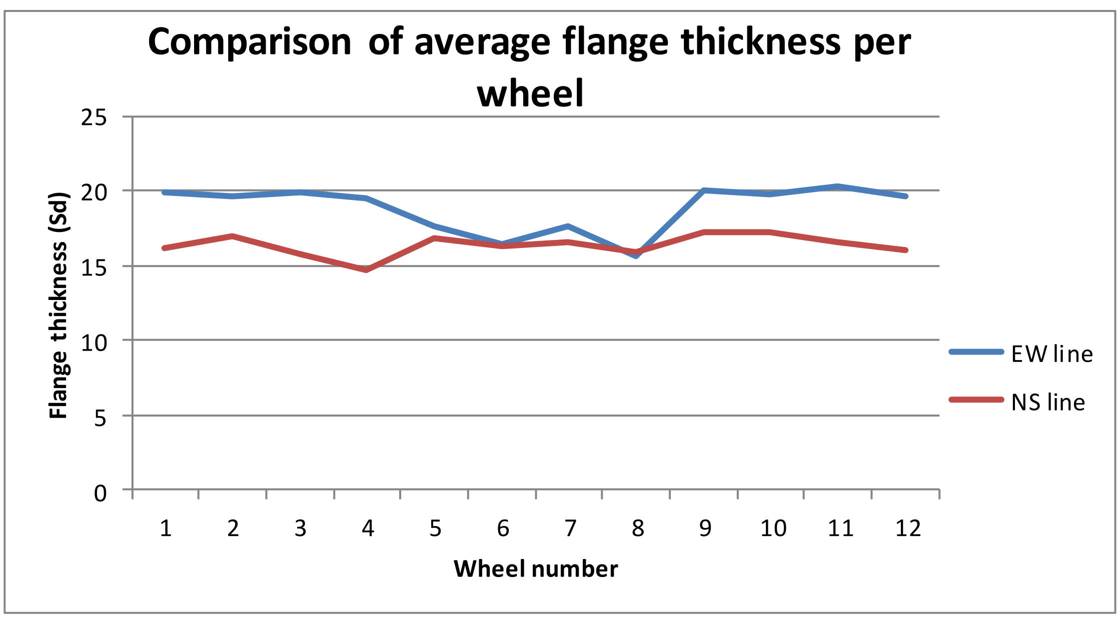


Figure 3.5 Comparison of NS and EW line train average flange thickness (Sd) per wheel

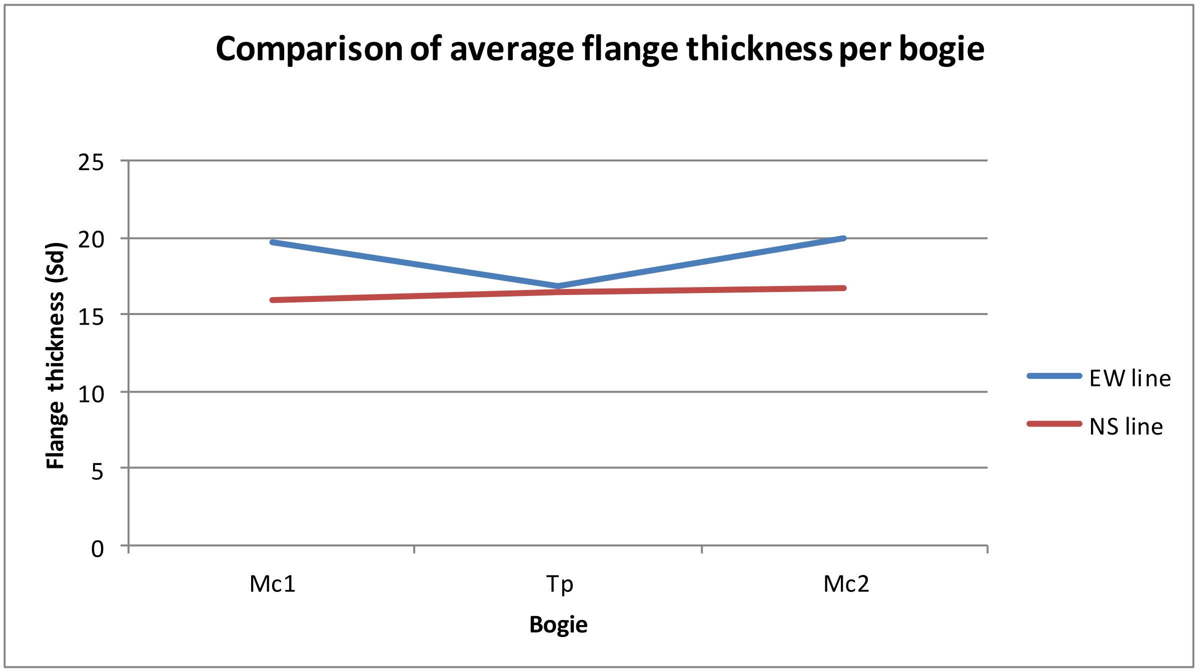


Figure 3.6 Comparison of NS and EW line train average flange thickness (Sd) per bogie

Total average flange thickness of Ayat vehicles = 18.83 mm

Total loss = New wheel – Worn wheel = 22- 18.83 = 3.17 mm, Percentage loss = 14.4 %

Total average flange thickness of Kality vehicles = 16.36 mm

Total loss = New wheel – Worn wheel = 22- 16.36 = 5.64mm, Percentage loss = 25.6 %

Figures 3.5 and 3.6 compare the average flange thickness of selected Ayat and Kality vehicles. Figure 3.6 shows that the average flange thickness per wheel of Kality vehicles is significantly smaller than that of Ayat's vehicle. Kality vehicles have a total percentage loss of 25.9 percent in flange thickness when compared to Ayat vehicles, which have an average flange thickness of 18.83 mm and a percentage loss of 14.4 percent. The flange thicknesses of the trailer (bogie 2) bogies are significantly worn when compared to the other two motor bogies. One of the characteristics of trailer bogies is that it do not promote self-steering through curves, increasing flange forces and angle of attack, which leads to flange wear and noise, and thus the wheel life of trailer bogies is less than that of motored bogies. Because of the adverse conditions of the line’s sharper curves, this is especially the cause of wheel flange wear for Kality vehicles. The tables 3.10 and 3.11 summarize the tread diameters of vehicles from both routes and are taken from Appendix 1. For each route, the average tread diameters per wheel and per bogie are calculated.

Table 3.10 East-West train wheel tread diameter (Td)

Vehicle No.	**Tread diameter (Td) in mm for respective wheels**											
	1	2	3	4	5	6	7	8	9	10	11	12
115	659.7	659.5	659.8	659.7	659.9	660.3	659.9	660.3	659.9	659.7	659.6	659.4
114	659.9	659.7	659.9	660.0	660.3	660.1	660.3	660.0	659.9	659.8	659.8	659.7
108	659.9	659.5	659.7	659.6	660.5	660.3	660.2	660.3	659.9	659.6	659.9	659.5
111	659.2	658.7	658.9	658.7	659.8	660.4	659.7	660.3	659.9	659.8	659.8	659.7
110	659.3	659.1	659.4	659.2	660.0	660.3	659.8	660.4	659.8	659.3	659.2	659.0
109	658.8	658.7	658.9	658.8	660.4	659.9	660.2	659.9	659.2	659.0	658.9	658.8
115	659.1	658.8	659.1	659.1	635.1	635.9	634.9	635.4	659.3	659.0	658.8	658.7
108	659.7	659.2	659.3	659.3	654.4	655.1	653.7	654.0	659.5	659.2	659.5	659.2
Average Td/wheel	**659.4**	**659.2**	**659.4**	**659.3**	**656.3**	**656.5**	**656.1**	**656.3**	**659.7**	**659.4**	**659.4**	**659.2**
Average Td/bogie	**659.3**				**656.3**				**659.4**			

Table 3.11 North-South (Kality) vehicles tread diameter (Td)

Vehicle No.	**Tread diameter (Td) in mm for respective wheels**											
	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*
212	659.7	659.6	659.7	659.4	660.1	660.1	660.1	660.2	659.3	659.9	659.6	659.5
205	659.4	659.5	659.6	659.6	660.2	660.2	660.0	660.0	659.6	659.6	659.6	659.7
215	659.6	660.0	659.8	659.7	660.3	660.4	660.1	660.3	659.8	659.8	659.8	659.6
208	659.4	659.5	659.6	659.8	660.1	660.3	660.2	660.1	659.7	659.6	659.4	659.6
218	659.3	659.6	659.3	659.4	660.2	660.2	660.1	659.9	659.1	659.7	658.9	659.3
206	648.5	648.5	647.4	647.5	638.8	638.9	637.3	637.6	652.6	652.7	652.4	652.6
216	648.9	649.1	645.6	645.5	660.0	660.0	660.0	659.8	647.3	647.2	647.2	647.3
210	659.0	659.3	659.4	659.2	660.1	660.3	650.7	650.9	659.3	659.5	659.2	659.2
Average Td/wheel	**656.7**	**656.9**	**656.3**	**656.3**	**657.5**	**657.6**	**656.1**	**656.1**	**657.1**	**657.2**	**657.0**	**657.1**
Average Td/bogie	**656.5**				**656.8**				**657.1**			

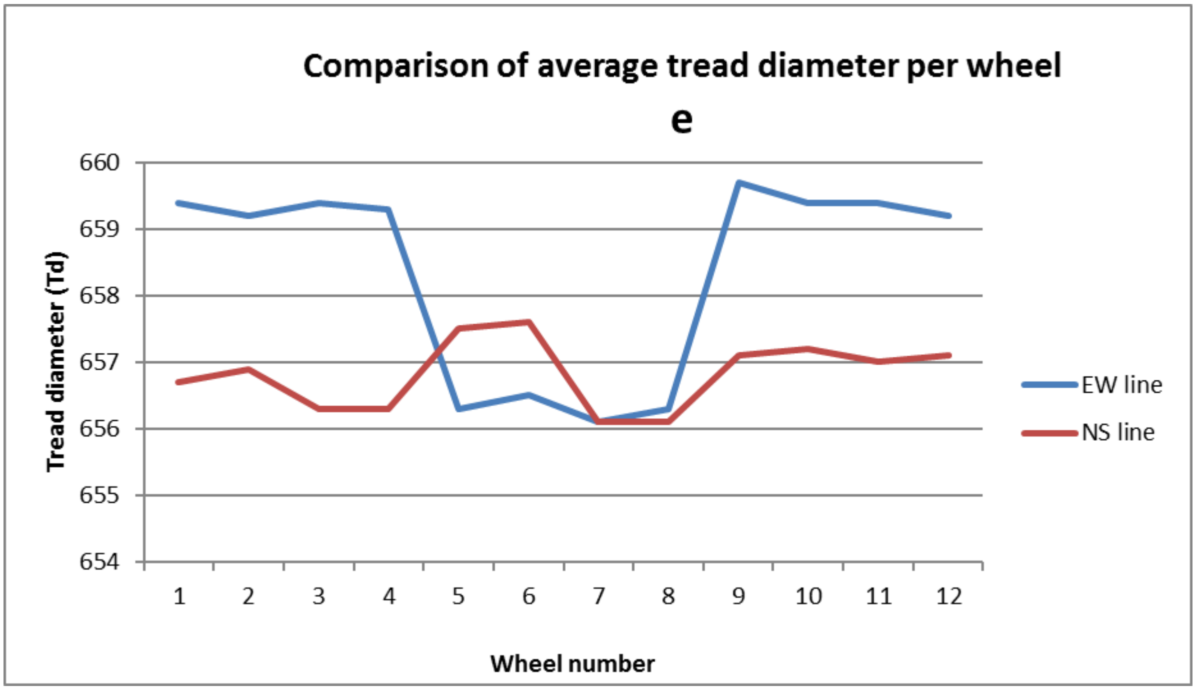


Figure 3.7 Comparison of NS and EW line train in average tread diameter (Td) Per wheel

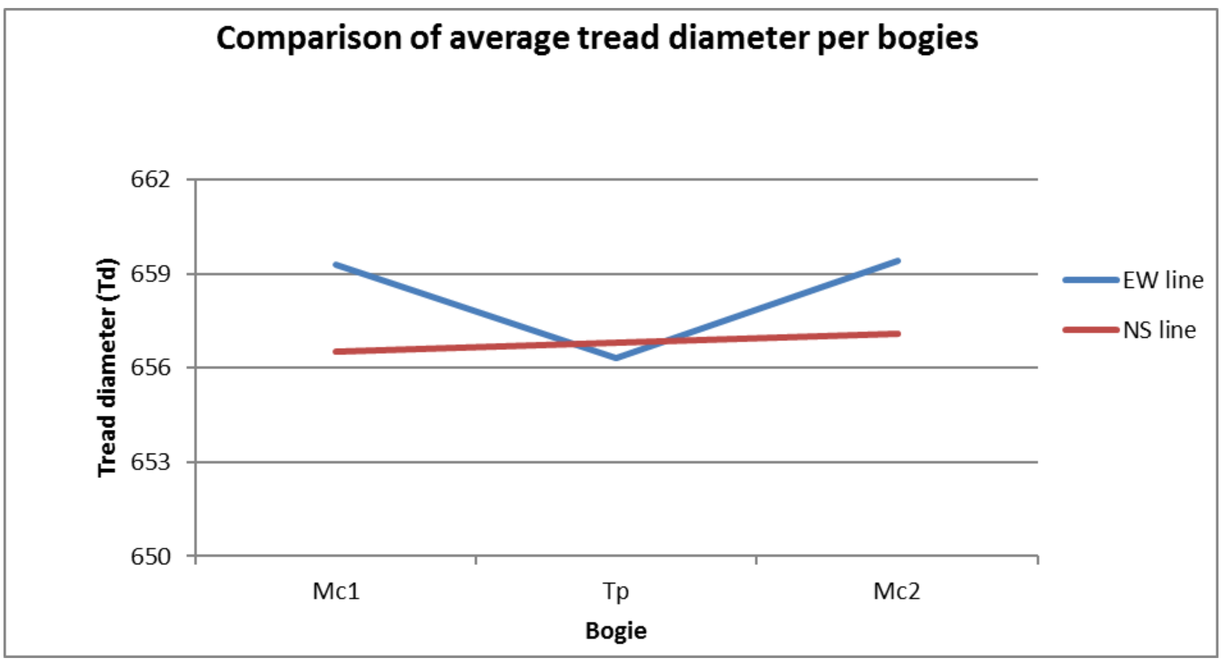


Figure 3.8 Comparison of NS and EW line train in tread diameter (Td) per bogie

**Total average tread diameter of Ayat vehicles* = 658.3 mm

Total loss = New wheel – Worn wheel = 660 – 658.3 = 1.7 mm, Percentage loss = 0.25 %

Total average tread diameter of Kality vehicles = 656.82 mm

Total loss = New wheel – Worn wheel = 660 – 656.82 = 3.19 mm, Percentage loss = 0.48 %.

Figures 3.7 and 3.8 compare the average tread of selected Ayat and Kality vehicles. Figure 3.8 shows that the average tread diameter loss per wheel of Kality trains is significantly greater than that of Ayat's trains. Kality vehicles with an average tread diameter of 656.2 mm show a total percentage loss of 0.48% in tread diameter when compared to Ayat vehicles with an average wheel diameter of 658.3 mm and a percentage loss of 0.25% in flange thickness. The average tread diameter of the trailer bogies for Ayat vehicles is much smaller than the other two bogies. This is due to the fact that trailer bogies wear at a faster rate than the other two bogies due to increased forces at contact because these bogies do not allow self-steering.

3.3.2 Summary from actual wheel data of AALRT vehicles

a. Similar travel mileage vehicles from the two lines are compared, and the results show that the wheels of vehicles operating in the North-South line are more worn than vehicles operating in the East-West line. This is because vehicles on the North-South route travel in relatively sharper curves. The flange and tread wear of the route's wheels are much worse. The tread is primarily worn as a result of machining to increase the thickness of flanges thickness.

b. Vehicles in the North-South line had their wheel hubs replaced after 2018 due to wheel displacement, so this comparison used wheel profile data prior to 2018.

c. Because of the sharper curves encountered on the North-South route, the flanges of the wheels are severely worn. Some wheels have worn past their flange thickness limit. It is also observed that trailer bogies of AALRT vehicles are much more worn than the motorized bogies due to behaviors of trailer bogies of not allowing self-steering motion while curving and higher lateral forces on straight track also which make it even more difficult when vehicles operate on irregularly constructed tracks and sharp curves

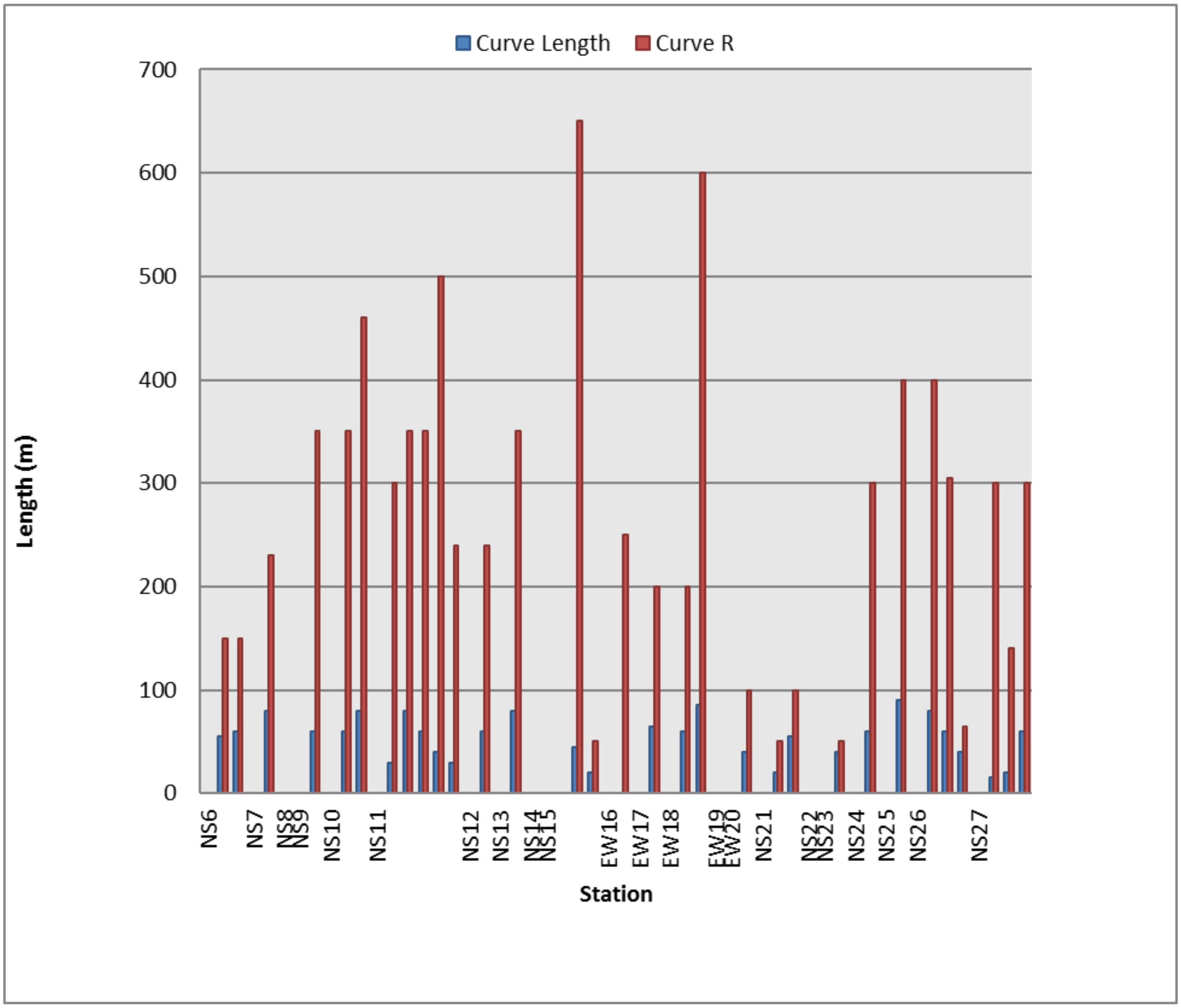


Figure 3.9 NS line curve radius and curve length

As we seen from figure 3.9 above the curve radius is very small at between NS15-EW16 and also EW20-NS21. Wheel flange will be worn out more when the curve radius is too small. The lubricant should be applied on the place where the radius is very small to resist the effect of the curve on the wheel flange and rail.

3.4 AALRT current lubrication system

Wear has a significant impact on rail and wheel life and increases maintenance costs. The AALRT incurs additional costs each year as a result of wear rail and wheel defects, breaks, and derailments, including cancelled and delayed traffic, emergency maintenance, asset loss, revenue loss, and so on. One of the most effective maintenance programs for reducing wear, energy consumption, and noise is lubrication. There are various lubrication systems available to provide uniform film thickness at the wheel-rail interface. It is critical to select the proper lubricant, lubricator, and placement model by considering track characteristics, lubricant type, and maintenance activities. Furthermore, we should consider that lubricant additives and lubricant amount are influencing factors on wear control. A direct lubrication method is to lubricate the gauge corner at the rail.

However, it is still heavily influenced by a number of parameters that can reduce the maximum effect of lubrication, such as the frequency of trains and lubrication passes, as well as the amount of lubricant used.

3.4.1 Effect of designed wheel flange lubrication on rail-wheel contact

Every wheel flange or rail lubrication system lubricates the surface contact between the rail head and the wheel flange. Lubrication is known to have a significant impact on reducing rail-wheel wear. Since the lubrication system was implemented, many companies have realized significant savings as a result of reduced rail wheel wear.

These are the benefits to use new lubrication systems at AALRT;

- Its lubricant is easily available on local market and also cheaper.
- Increased rail and wheel life
- Reduced risk of new or recently profiled wheel flanges to climb the gauge face of the rail.
- Reduced workman as result of avoiding manpower lubrication
- Reduced material cost due to wheel maintenance or wheel flange reprofiling
- Reduced number of installations and removal of the wheels from the train and locomotives.
- Reduce wear rates in tight curves when compared to dry unlubricated contact
- Limit track gauge corner cracking.
- Its use lubricant properly (it spray on the curved track only).

Economic aspect Improved wheel/rail friction control has significant, positive benefits for the railway industry, according to effective lubrication studies. It was discovered that by improving lubrication techniques and lubrication system maintenance, a substantial benefit could be gained. These advantages are primarily due to increased rail/wheel life and fuel/lubricant consumption. Rail life increased as a result of reduced wear on rails, and maintenance time decreased.

3.4.2 Type of Lubrication system and Current AALRT lubrication

3.4.2.1 Type of Lubrication system in railway industry

Railways around the world use three types of lubrication methods: wayside, on-board, and hi-rail lubrication.

3.4.2.1.1 Wayside lubrication

Wayside lubrication is a popular method of lubrication. Both the gauge face and the top of the rail can be lubricated. The lubricant is transferred to the rail via the applicator bars, but it is also possible to transfer the lubricant inside rail holes. A wayside lubrication system consists of a reservoir tank, oil pump unit, controller, connecting hoses, power supply unit, applicator bars, wheel–axle sensor unit or plunger, and sometimes a telemetry or remote condition monitoring system such as RPM (remote performance monitoring).

3. 4.2.1.2 High-rail lubrication

Hi-rail lubrication is the controlled application of a bead of oil directly to the wear face of the rail from a vehicle traveling on the track. The high rail vehicle is typically a modified delivery vehicle outfitted with a specialized storage and application system..

3.4.2.1.3 On-board/ Mobile Lubrication

Onboard lubrication is a method where the lubricator is mounted on the train, and the lubricant is applied to the vehicle wheel flange. There are two different application types of onboard lubrication. The first one is by using spray systems and the other one is solid sticks.

But onboard systems have a number of advantages over wayside lubricators;

- Can be inspect and maintain easier (carried out under more controlled conditions)
- Lower risk exposure to staff during installation, inspection, and maintenance
- It can be inspected when the vehicle or train is being checked.

3. 4.3.2 Current AALRT lubrication system discussion

AALRT trains have onboard lubrication systems that use solid stick as a lubricant. The procedure for lubricating a solid stick-based wheel flange is straightforward: a carbon-based dry lubricant minimizes frictional forces between the wheel flange and rail. The applicator assembly is attached to the rail vehicle's bogie frame. The lubricant, which is usually rectangular in shape, comes in the form of a stick or hollow 'tips' that slot into each other. A spring presses the stick against the wheel flange, ensuring continuous lubrication in straight or curved trucks. As a result, there is a significant reduction in running noise and wear, resulting in a longer wheel and rail service life.

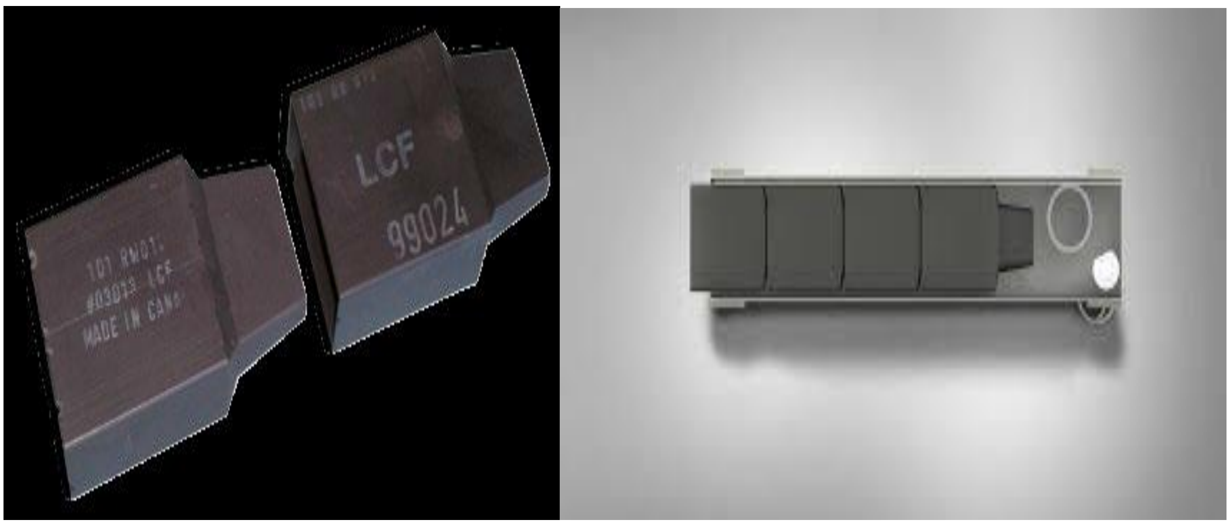


Figure 3.10 Slotted solid stick

Disadvantages of installed (old) AALRT wheel flange solid lubricants:

- Higher coefficient of friction and wear
- Low stability of the lubrication film.
- Less convenient system of the lubricant delivery to the friction surfaces.
- Solid lubricants are continuously supplied, couldn’t lubricate only curved track.
- The lubricant is not available on local market.
- The price of lubricant does not match with company income

Figure 3.11 Old or existing AALRT train lubrication system

But on the downside, there are two inconveniences the stick remains in permanent contact, which means that large quantities are used, plus it is impossible (or difficult) to adjust the lubricating parameters to meet traffic conditions. This continuous lubrication may inhibit railway industry by extra usage of lubricant on un-curved line. But oil-based lubrication system characterizes with lower wearing at steel wheel surfaces than the graphite sticks.

CHAPTER FOUR

Spray Type Wheel Flange Lubrication System: Modeling, Simulation and Analysis

4.1 Calculations of design parameters

Standard input calculation for system simulation

- C_w=circumferential of the wheel
- L_c=length of the curve
- Nr=revolution of one wheel in one second
- Vt=train speed
- t=average time to finish curve
- V=Volume of lubricant needed for four trains
- Q_{1t}=flow rate for one train
- A= area of the pipe
- v= speed of lubricant in the pipe
- d=diameter of the pipe

4.1.1 Calculation of lubricant flow rate

The following table includes the data which are used to calculate the flow rate.

To find the flow rate we should determine the time for the train to finish running the curve

Wheel circumference: Cw=$2\pi r$=2*3.14*330mm=2071.2mm/rev=2.071m

Train speed: V_t=20km/hr(average speed on curve)=5.555m/s

$$t=\frac{L_c}{V_t} \tag{1}$$

Time required running the curve: $t=\frac{L_c}{V_t}$(let's say curve length is 30m)

$t=\frac{30m}{Vt}=\frac{30}{5.555}$=5.4s, this is the time for one stroke

$$Nr=\frac{Vt}{Cw} \tag{2}$$

By using equation (2)

$\frac{Vt}{Cw}Nr=\frac{Vt}{Cw} = \frac{5.55}{2.071m}=2.61\frac{rad}{s}$

$V=0.002m^3$ (practical data from lubricator)

$Q=V \times Nr=0.002m^3 * 2.61 rad/s$

$Q=0.0013 m^3/sec$ (for 24 wheels) (for 4 trains)

To find how much lubricant needed for one train at left/right side or 6 wheels we should divide total flow rate by 4

$Q_{1t}=\frac{Q}{4}=\frac{0.0013m^3/s}{4}=0.000326m^3/sec$

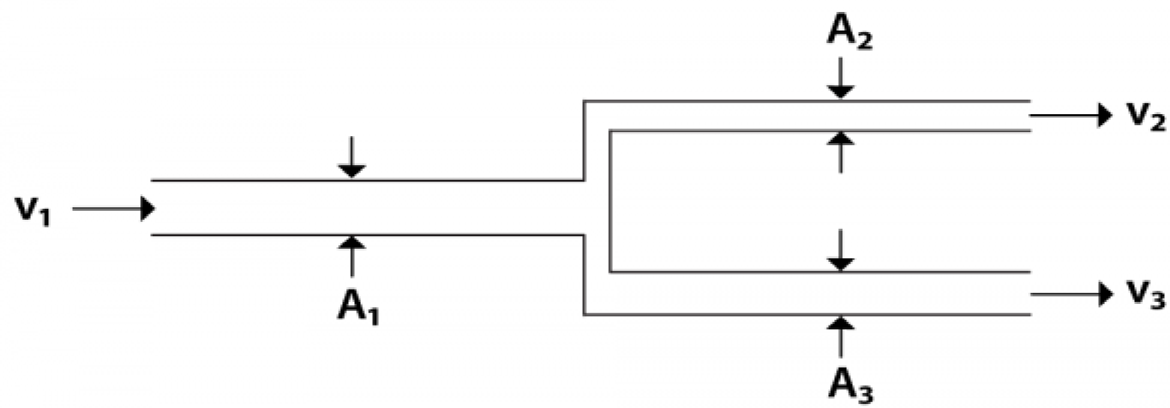


Figure 4.1 principle of flow rate diagram

$$V_1 A_1=V_2 A_2+V_3 A_3 \quad (3)$$

From equation 3

$V_1 A_1=V_2 A_2+V_3 A_3$

$Q_{1t}=Q_{1tl}+Q_{1tr}$

Note: - (Q_{1tl} -Total flow rate for one train at left side)

(Q_{1tr} -Total flow rate for one train at right side)

(Q_{1t} -Total flow rate for one train)

$Q_{1t}= 0.000326\frac{m^3}{sec}=0.000163\frac{m^3}{sec}=+0.000163\frac{m^3}{sec}=$

$Q_{1t}=0.000326\frac{m^3}{sec}$=(for lubricating both right and left side)

Hose sizes indicate the inside diameter of the plumbing. A 1/2" diameter hose has an internal diameter of 0.50 inches, regardless of the hose pressure rating.

Suggested Piping Sizes:

Pump suction lines should be sized so the fluid velocity is between 2 and 4 feet per second (0.61-1.22m/s).

Oil return lines should be sized so the fluid velocity is between 10 and 15 feet per second (3.048-4.572m/s).

Medium pressure supply lines should be sized so the fluid velocity is between 15 and 20 feet per second (4.572-6.096m/s).

High pressure supply lines should be sized so the fluid velocity is below 30 feet per second (9.144m/s).

From the above result, we can select the average of second sentences which is identify the return line 3.048-4.572m/s

Speed of return oil will be average of 3.048 and 4.572m/s

$V=\frac{3.048+4.572}{2}= 3.81m/s$

$$Q_{1t}=v*A \qquad (4)$$

$Q_{1t}=v*A$

$A=\frac{Q1t}{v}=0.000326m^3/sec/3.81m/s=0.00008556m^2$

$A=3.14*r^2$

$r^2=0.00002725m2$

r=0.00522m

r=5.22mm

d=2r=10.44mm

Most Oil pipelines are made from steel or plastic tubes with inner diameter typically from 4 to 48 inches (100 to 1,220 mm).

So the calculated pipe diameter is correct.

Therefore, Hydraulic cylinder sizing, Parameter of cylinder, Cylinder piston, Piston stroke, Piston diameter and piston speed will be calculated

To find the above parameter we have $Q=0.000326m^3/sec$ and we can take speed of train as piston speed So piston speed can be calculated from the train 4.16m/s

Now we calculate area of cylinder

Q=Av~

A=$\frac{Q}{v}$=$\frac{0.000326m^3/sec}{4.16m/s}$=0.00007837m^2

$A = \pi r^2$

0.0072=πr^2

r^2=$\frac{0.0072}{3.14}$=0.00229667m^2

r=0.004995m=4.995mm

4.1.2 Calculation of the diameter of cylinder

One train can pass the 30m curve within 5.4s so we can use this time to calculate volume of cylinder by taking value of stroke 0.4m.

Speed v=stroke/time

v=$\frac{0.4m}{5.4s}$=0.1852m/s

Q=Av

A=$\frac{Q}{v}$=$\frac{0.000326m^3/sec}{0.1852m/s}$=0.00176m2

$A = \pi r^2$

$r^2 = \frac{A}{\pi} = \frac{0.00176}{3.14}$=0.000561m

r =0.02367m=23.67mm

From calculated radius, we can get diameter of cylinder

d=47.35mm

4.1.3 Motor and pump sizing

First we should calculate displacement from the flow rate

Flow rate=volume of cylinder x time for one stroke

Or flow rate = displacement x speed of pump

Q=0.000326$\frac{m^3}{sec}$

Let's say 0.000326$\frac{m^3}{sec}$ = 0.000326$\frac{m^3}{rev}$*$\frac{rev}{sec}$=0.000326$\frac{m^3}{rev}$*$\frac{60rev}{min}$

Most of hydraulic pump run at 1200RPM

So can multiply denominator and nominator by 20

$0.000326\frac{m^3}{rev}*\frac{60rev}{min}=0.000326\frac{m^3}{20rev}*60*\frac{20rev}{min}=0.0000163\frac{m^3}{rev}*1200RPM$

We can take d=0.0000163$\frac{m^3}{rev}$ pump displacement

So pump speed will be V=1200RPM

Table 4.1 Input parameters and calculation results

No	Symbol	Definition	Unit	Calculation result
1	C_w	Circumferential of the wheel	m	2.07
2	L_c	Length of the curve	m	30
3	Nr	Revolution of one wheel in one second	rad/s	2.61
4	V_t	Train speed	m/s	5.55
5	t	Average time to finish curve	s	5.4
6	V	Volume of lubricant needed for four trains	m^3	0.002
7	Q	Total flow rate	m^3/s	0.0013
8	Q_{1t}	Flow rate for one train	m^3/s	0.000326
9	Ap	Area of the pipe	m^2	0.00008556
10	v	Speed of lubricant in the pipe	m/s	3.81
11	d	Diameter of the pipe	mm	10.44
12	Ac	Area of hydraulic cylinder	m^2	0.00007837

Then the above Table 4.1 summarizes all numerically calculated parameters.

4.2 Development of the new wheel flange lubrication system

Wheel flange lubrication is a much more challenging area, which needs constant attention. The proposed wheel flange lubrication system provides a solution to reduce wear problem at AALRT.A new wheel flange lubrication systemis desired to achieve the goal of reduced wheel wear and increase in life of wheelsets and tracks, and reduced maintenance costs.. The new wheel flange lubrication use local lubricant that can reduce foreign currency. This new machine consists of a piston pump with a reservoir used to store the lubricant to use it repeatedly for long time before refilling. From reservoir, the lubricant (oil) feeds the pump unit.

4.2.1 Components of hydraulics

1. Rod-less Hydraulic cylinder

Rodless cylinders differ from conventional rod-style cylinders in several ways that offer distinct advantages for certain types of applications. The two main benefits may seem contradictory.

- Rodless cylinders conserve space, but they also allow for a longer stroke within the same space as a conventional cylinder. They save space because the stroke is contained within the envelope of the cylinder body.
- They move in both directions with the same force. This differs from rod-style cylinders that produce maximum force for extension, and a lower force for retraction

2. Fixed-Displacement Hydraulic Pump

Hydraulic pump is a mechanical device that converts mechanical power into hydraulic energy. It generates flow with enough power to overcome pressure induced by the load. Second, its mechanical action delivers this liquid to the pump outlet and forces it into the hydraulic system. When choosing a hydraulic pump solution, it is essential to determine the type of work to be performed and the amount of pressure required. All hydraulic systems rely upon pressurized fluid to create force in order to perform work, such as lifting materials using a forklift. Furthermore, systems can either be “closed-loop” or “open-loop”. In a “closed-loop” system, the fluid passes from the pump directly to the motor before returning to the pump. In an “open-loop” system, the pump draws fluid from a reservoir / tank then pumps it to a control valve from where it is directed to the services being operated before returning to tank. For an open loop system, a fixed-displacement hydraulic pump is one type of pump solution.

It has several key benefits over variable displacement pumps, including:

- Easier to Maintain
- Less Expensive
- Simpler Design
- Flow rates directly proportional to pump drive speed.

Fixed-displacement pumps are well suited for a wide range of functions where the amount of pressure required to perform work is the same each and every time. Two common types of fixed-displacement pumps are the bent axis piston pump and the gear pump. The bent axis piston pump provides the added benefit of normally having a higher pressure capability than a gear pump. Since this machine is simple process, we can select gear type fixed displacement pump.

3. Hydraulic reservoirs

A hydraulic system is closed, and the oil used is in a tank or reservoir to which it is returned after use and also reused by using fixed or variable pump. The volume of fluid in a tank varies according to temperature and the state of the actuators in the system, being minimum at low temperature with all cylinders extended, and maximum at high temperature with all cylinders retracted. Normally the tank volume is set at the larger of four times the pump draw per minute or twice the external system volume.

4. Filters

Metal particles, Dirt in a hydraulic system causes blocking of valves, failure of seals and early wear. Evenparticles of dirt as small as 20/x can cause damage, 1 micron is one millionth of a meter; the naked eye is just able toresolve 40/x). Filters in the hydraulic system are used to prevent metal particles, dirt entering in the parts of the hydraulic system, and are generally specified in microns or meshes per linear inch.

5. Fixed-displacement pumps

Fixed displacement pumps are well suited for a wide range of functions where the amount of pressure required to perform work is the same each and every time. Two common types of fixed-displacement pumps are the bent axis piston pump and the gear pump. The bent axis piston pump provides the added benefit of normally having a higher pressure capability than a gear pump. So for this paper gear type fixed displacement pump more suitable.

6. Directional Control Valve

The direction valve can control the start, stop, and change in direction of flow of a pressure of fluid, this case, the hydraulic oil. It can be installed directly at the pump reservoir or externally. With this option, both directions of travel can be supplied with one pump. Directional control valve (DCV) used in this system has four ways and three positions for controlling the direction of motion of hydraulic cylinders. A 4/3 DCVs are used to start, stops, or change the direction of fluid flow.

7. Throttle Valve

The throttle valve is used to restrict the fluid flow in both directions. For setting the pump supplying pressure.

8. Check Valve

The check valve is generally used to allow for free flow in one direction, and obstruct the fluid flow in the opposite direction.

9. Hydraulic Actuator

The hydraulic cylinders convert the hydraulic power into mechanical power, performing rectilinear motion. The pressure of input oil is converted into force acting on the piston. The hydraulic cylinder used in the test rig is double acting universal cylinders. It can lift the load up, down, or hold it into the required position. A mathematical model of a double-acting hydraulic cylinder is analysis by Heinze. Basically, the resulting force of a double-acting cylinder is determined by the difference of the chamber's product of pressure and cross-sectional area. To pump out the oil from cylinder, the pressure applied to the piston side should be higher than pressure at rod side.

10. Wheel flange lubrication oil

Railway companies specify lubricant properties that may directly related to the wear processes encountered at the wheel rail interface [14]. The table 4.2 summarize property of new AALRT train wheel flange lubrication system oil which shows service temperature from -40c^0 to 80c^0. This wheel flange lubrication oil also satisfies weather condition in Addis Ababa city that shown in Table 3.1.

Table 4.2 Wheel flange lubrication oil property

WF Biornatur WF68 oil	
Color	Dark grey
Service temperature	-40c^0-80c^0
Base oil viscosity (at 40c^0)	35mm2/sec
Pour point of base oil	<-40 c^0
Stirring properties (at -30c^0)	Good
Water Resistance	1-60 value step
Oil separation (40 c^0 .18H)	<2%

11. Curve sensor

As curves increase friction and wear of wheel and rail, this equipment can detect when the train enters a curves. It is used to control wheel flange lubrication system for optimizing the sprayed lubricant quantity. Lubrication is triggered after a certain number of previously specified pulses are received. In the case of curve-dependent lubrication, this paper, it is possible to specify whether lubrication is to take place on both side or only on the respective outside curve, depending on the direction of travel. The optional curve sensor enables the system to be activated in response to a curve. LCG2-Axx (24VDC design) and LCG2-Bxx (72VDC to 110VDC design) curve sensor controls unit are used solely for the control of lubrication system in railway application. LCG2-A03 curve sensor spray both sides simultaneously (outer and inner curve side) of the wheels, whereas LCG2-B06 controls only the outer-curve wheel side according to curve direction. Since some of AALRT track radius are less than 100 meter and the AALRT train battery output voltage is 24V DC, LCG2-A03 curve sensor is appropriate curve sensor for this lubrication system.

12. Spray nozzle

The spray nozzles ensure that the wheel flanges are lubricated even at high speeds, without fouling other components such as the brakes. The spray nozzles' design is determined by the lubricant used.

13. Variable flow control valve

Variable flow control valve is used to regulate the volumetric flow rate in both directions.

4.2.2 Components of pneumatic

The compressor fitted on AALRT train designed to supplies compressed air for operation of air brakes, sanding system, horns, wipers and other pneumatically controlled equipment like lubrication system. But only sanding system controlled by using compressed air whereas another system are uses electrical control system on AALRT train.

Table 4.3 AALRT train compressor capacity

Maximum operating pressure	10bar
Nominal pressure	8bar
Ambient temperature range	-35℃～+50℃
Altitude	≤3000 m
Working voltage	DC24V±30%

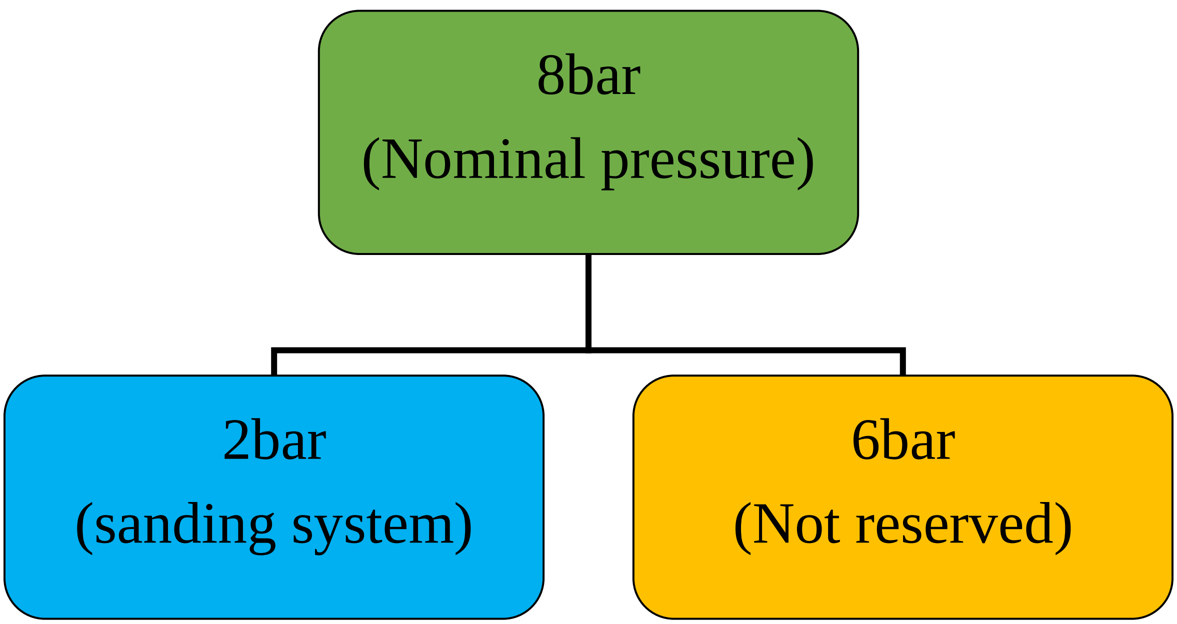


Figure 4.2 AALRT train air compressor capacity diagram

According to AALRT train maintenance manual, when the air pressure is less than 5bar, the compressor is automatically started and when the pressure is 8bar, the compressor stops operating. The role of the safety valve is that it will be opened to exhaust the pressure air when the air pressure in the pipeline is more than 10bar. When the pressure in the pipeline is 8bar, the safety valve is closed so as to assure that the pressure in the system shall not exceed 10bar. Pressure regulating valve: because the normal operating range of the air supply system is 5-8bar and the pressure needed by the sanding system is 2bar and for new lubrication system is 1bar or 0.1mpa as shown on Figure 4.2. The pressure regulating valve shall be needed to regulate the pressure from the higher pressure to 2bar and 1bar.

Pneumatic cylinder Working Principle

The gas receives piston compression in the compressor cylinder to boost the pressure, and the air transfers thermal energy into mechanical energy through expansion in the engine cylinder. There is a rod-cavity exhaust when compressed air is input from the rod-less cavity; the pressure differential between the two chambers of the cylinder acts on the piston to drive the piston movement, causing the piston rod to expand.

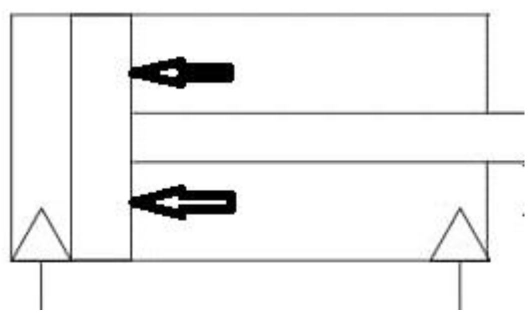


Figure 4.2 Piston retraction time

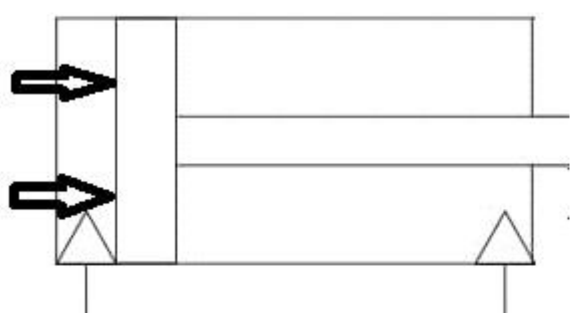


Figure 4.3 Piston extend time

Proximity Sensor

By sensing the presence of close items without making physical contact, a proximity sensor is used to identify the position of a pneumatic cylinder. The proximity sensor's target is the thing that is being detected. A proximity sensor frequently generates an electromagnetic field or a beam of electromagnetic radiation and monitors changes in the field. Different sensors are required for different proximity sensor targets. A capacitive photoelectric sensor, for example, may work with a plastic target, whereas an inductive proximity sensor requires a metal target

4.2.3 Control circuit and simulation using automation studio

4.2.3.1 Introduction

For fluid power systems and electrical projects, Automation Studio is a circuit design, simulation, and project documentation program. It can be utilized to create hydraulic machines that are fully automated. Its software aids in hydraulic circuit simulation, automation, and design. Hydraulic, digital electrical, and electronic technologies are all supported. If a corporation wants to thrive in today's highly competitive industrial environment, it must be adaptable, cost-effective, and efficient. The use of control systems and information technology to lessen the demand for human power is known as automation. Figure 4.1 shows the linear speed of a double-acting cylinder at various loads utilizing a 3/2-way directional valve and a proportional pressure relief valve. However, to regulate the variable flow control, the appropriate setting pressure is provided. The cylinder's dynamic behavior improves as a result of the avoidance of a large oscillation.

4.2.3.2 Working principle of the new system

- A spray type lubrication system for onboard wheel flanges is installed under the vehicle or train's bogie.
- An on-board lubricator consisting of a lubricant supply tank positioned on the locomotive's first and last axles for applying lubrication to the wheel flange behind the locomotive's last axle.
- A pipe connects the lubrication supply tank to a hydraulic pump, which is installed on the system and directs a lubricant jet into the hydraulic cylinder.
- The fluid is delivered to the first and second nozzles, which are placed to send a jet of lubricant onto the wheel flanges on the left and right sides, via a pair of hoses attached to a variable flow control valve.
- Both nozzles are mounted such that the jet of lubricant is disposed at an angle of between 0 degrees and 80 degrees to the vertical, with the angle increasing in the direction opposite to the direction of train travel.
- Curve sensor is responsible for measuring the degree of curvature of the rails, and a controller for governing the flow of the lubricant from the supply tank to the nozzles. The curve sensor for controlling the flow of lubricant includes a means for stopping the flow of lubricant from the lubricant storage tank and triggering a signal for activating the lubricating system.
- The curve sensor for controlling the flow of lubricant includes a means for stopping the flow of lubricant from the lubricant storage tank and triggering a signal for activating the lubricating system.
- The sanding system, which includes a pipe leading to a pneumatic control valve for applying compressed air activated by the control system, is installed on the first and last trains. After that, the hydraulic system kicks in, and the pump system pushes lubricant from the lubricant supply tank to a spray nozzle aimed at the point of contact between the vehicle wheel and rail.

4.2.3.3 Simulation of the system

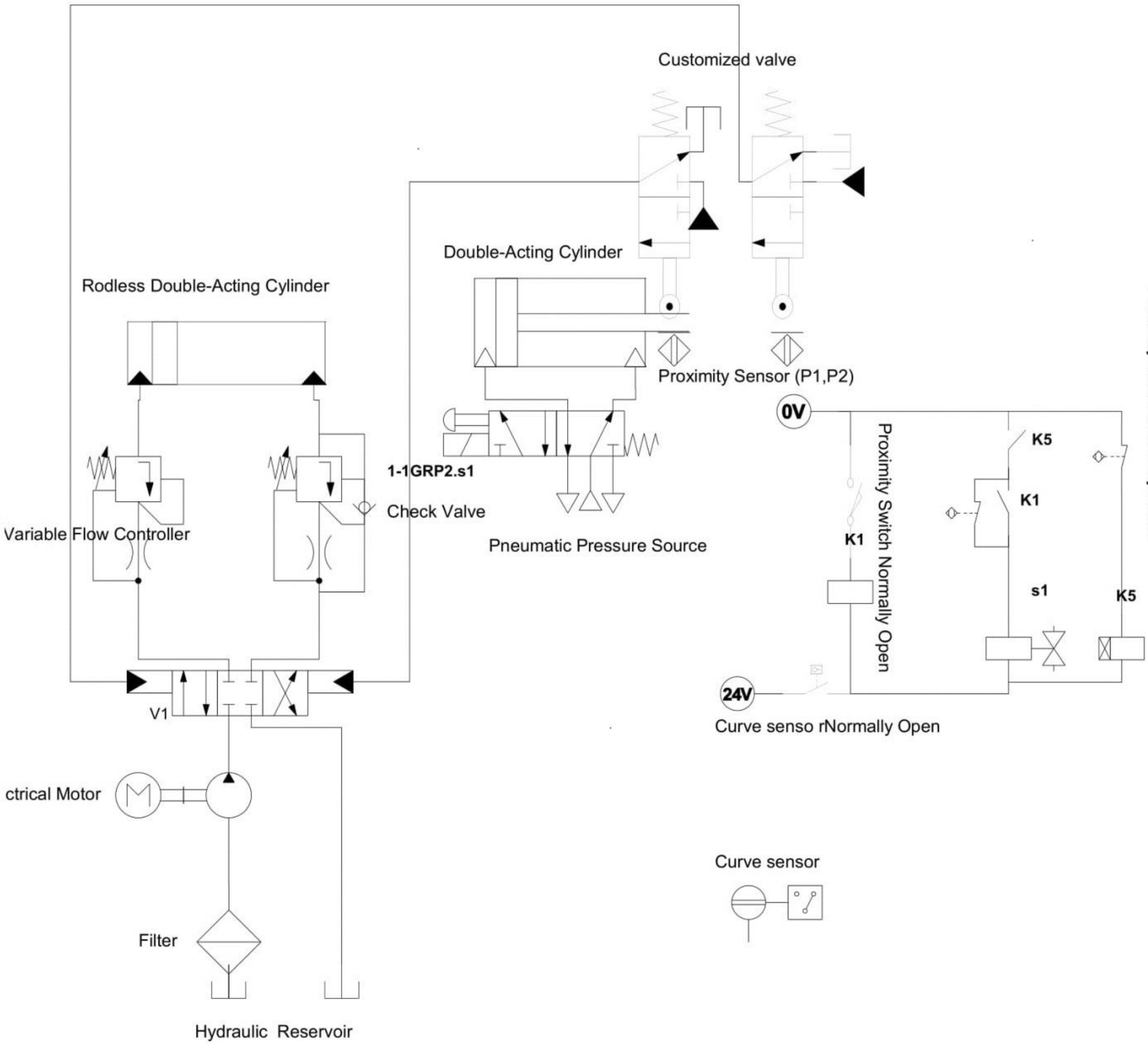


Figure 4.4 Design of electro-hydraulic circuit on AS 5.2.0.6

The hydraulic circuit is made up of two proximity sensors, p1 and p2, that are attached to the cylinder's end. In the electric circuit, there are two normally closed proximity switches and one normally open proximity switch. At operate the electric circuit, the electric input is set to 24 volts. A solenoid valve is an electromechanically driven valve that is controlled by an electric current through a solenoid, with the flow being switched on or off in the case of a two-port valve. One solenoid valve is controlled serially by a proximity switch.

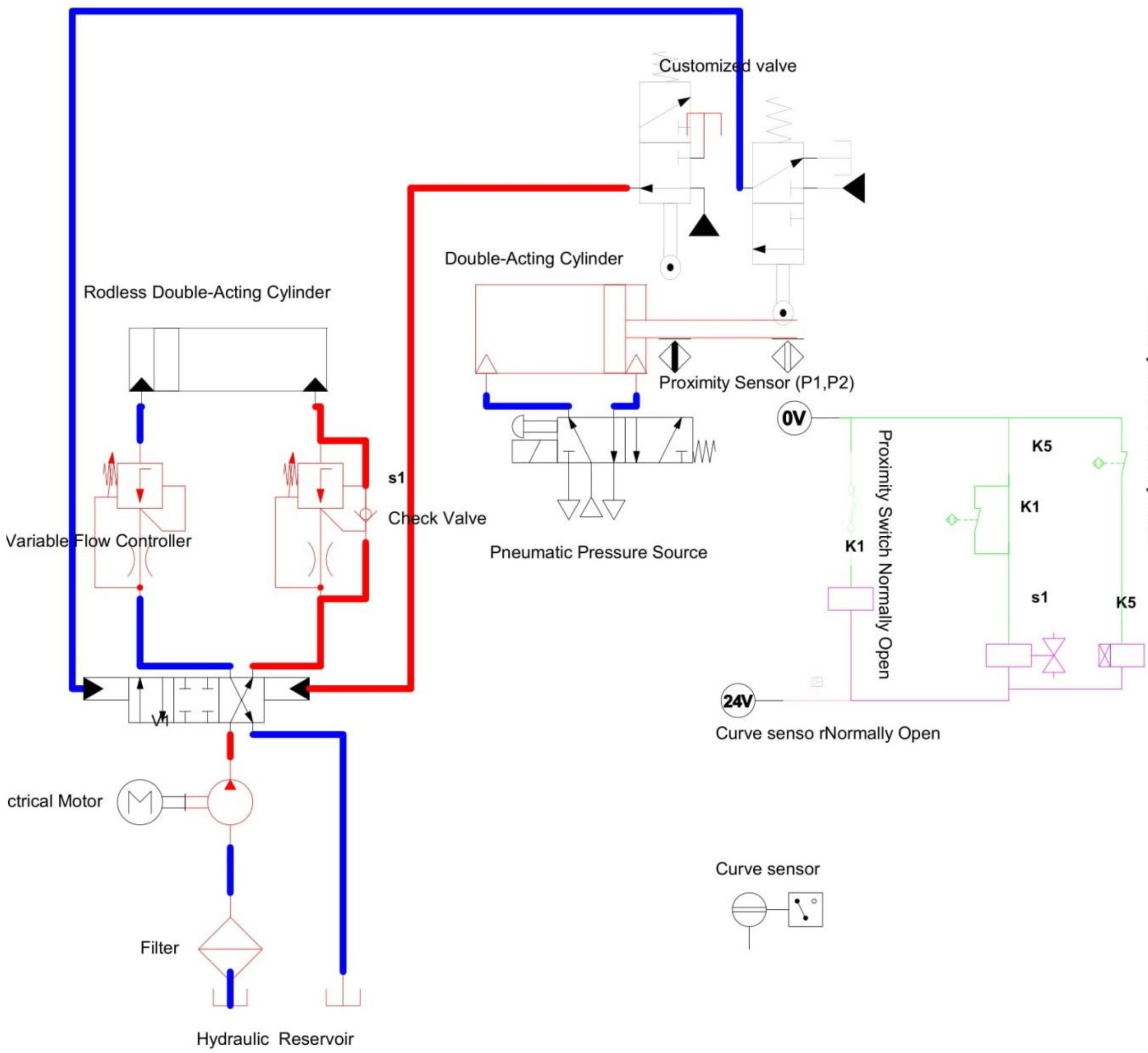


Figure 4.5 Working principle of wheel flange lubrication system circuit on AS 5.2.0.6

4.2.3.4 Simulation control circuit

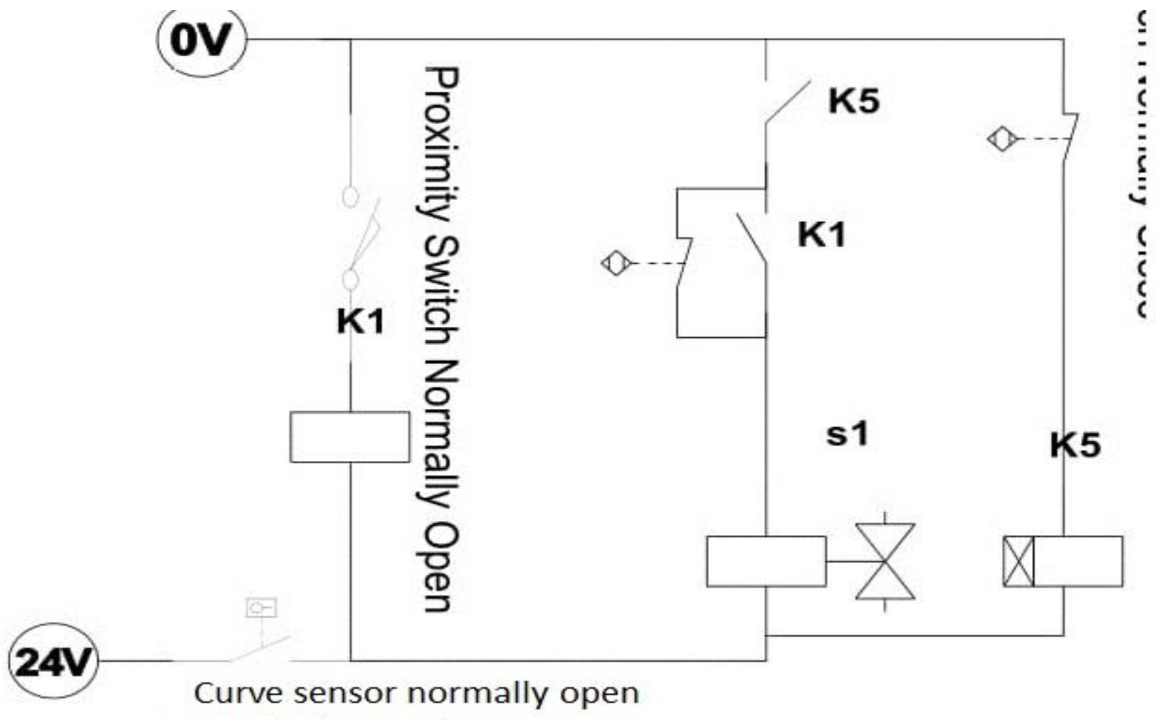


Figure 4.6 Control circuit of the wheel flange lubrication system

This circuit is responsible for activating the onboard wheel flange lubrication system. The curve sensor detects the train traveling through the curve when the vehicle approaches it. The normally open switch is then automatically closed by the curve sensor. After a delay, the coil receives power as the curve sensor switch is closed, causing K5 to close after 0.16 seconds.

CHAPTER FIVE

Results Analysis and Discussion

5.1 Effect of new system lubrication on reducing wheel flange wear

Rail and wheel are capital-intensive assets for any railway, and correct maintenance practices will affect the asset's life and maintenance costs. As wear rates rise, the expense of maintaining rails and wheels rises as well. Another benefit of adjusting the friction coefficient is that it can save energy and improve train steering performance. Adoption of proper lubricating solutions for rail and wheel should be considered to enable this. Wheel maintenance has a significant impact on railway operations' reliability, availability, maintainability, and safety (RAMS). Due to increased track deterioration and wear, increased axle load and longer train length provide issues in rail and wheel maintenance.

This new lubrication system can:

- Highly reduce wear rates in tight curves when compared to dry unlubricated contact.
- Reduce wheel and also rail wear.
- Reduce the risk of new or recently profiled wheel flanges climbing the gauge face of the rail.
- Reduce traction coefficient and thereby limit the initiation of rolling contact fatigue and gauge corner cracking.
- Save lubricant consumption on straight line because it will be activated on curves.
- Can extend the life of wheel or rail to increase availability of rolling stock.
- Help to improve the steering performance of vehicle and no mechanical contact with wheel or rail.
- Use intelligent controller (sensor).
- Use right quantity of lubricant right in time at the right place.

5.2 Cost analysis of old lubrication system

The test run project monitoring (measurement) of wheel flange lubricant (solid stick) was performed within two weeks. At the beginning, the prepared solid stick had four slotted pieces that are assembled together was 24 cm long. After 787 km journey, the solid sick were measured to be 18.8 cm. Therefore, the wear rate of the solid stick on the train was 5.2 cm per 787 km. According to a case measurement during one train run of a 207train from Kality to Milinik square (NS line) or vise-versa (Kality train) (16.9 km), the 24 cm length graphite stick is estimated to be fully consumed after approximately every 3,154 km run, but it should be noted that there is always about 5 cm graphite scrap remaining. The reason of this is that one graphite stick would never be fully consumed because with gradual lengthwise consumption, ultimately the end part of the stick would definitely fall out of the cartridge end at the open space (about 5 cm) or even some sticks occasionally break and never reach the flange. Regarding the 5 cm graphite stick scrap, the calculation of one train run graphite stick consumption is based on a 19 cm (190 mm) length: i.e. 240 mm (total graphite length) – 50 mm (scrap part) = 190 mm (useful length). Table 5.1 shows the number of kilometers run of train no. 207 and shows that four set of solid stick inserted in installed lubrication system on every 1st and 6th axle are consumed after 3154 km run**.**

Table 5.1 Durability of solid stick test

Solid stick performance check on 207 train				
Date	Train No	Km	Solid stick length(cm)	Remark
2018.5.6	207	140557	24	Fully
2018.5.7	207	140817	-	
2018.5.8	207	141080	-	
2018.5.9	207	141080	-	
2018.5.10	207	141344	18.8	Measured
2018.5.11	207	141607	-	
2018.5.12	207	141607	-	
2018.5.13	207	141870	-	
2018.5.14	207	142396	12.3	Measured
2018.5.15	207	142659	-	
2018.5.16	207	142922	8.8	Measured
2018.5.17	207	143185	-	
2018.5.18	207	143448	-	
2018.5.19	207	143711	5.05	Fully consumed

Table 5.2 Cost analysis of solid stick in AALRT

No	Part name	No of solid stick used for one train in two weeks	Total number AALRT train	Cost of one solid stick(Birr)	Total cost (Birr) in two weeks	Total cost (Birr) in one year
1	Solid stick	16	41	1,300	852,800	20,467,200

We have investigated on June 2017 on train number 207 for two weeks with rolling stock technician and Chinese expert to know how long we can use it. Every AALRT train was equipped with four old lubrication machines brackets, two of them are on the first wheel-set and other two of them are installed on the 6^{th} or the last wheel-set. This lubrication block is arc shaped and spring-forced laterally and radially into the flange. Each of these machines contains four pieces of solid stick. After two weeks we took out the lubrication system to check how long we can use this lubricant. But, these solid sticks were totally consumed. So the result obtained on the Table 5.2 shows that this type of lubrication system can disclose the company for unexpected capital expenditure to purchase solid sticks. So AALRT contract management agrees not to use this type of lubrication system. We state, then, that the introduction of new lubrication system which is called onboard sprays type wheel flange lubrication is of paramount need. For this reason, we are designing a new system that adapts to the need and interest of AALRT.

5.3 Capital expenditure on new lubrication system

Table 5.3 Purchase cost of new lubrication system

S.N	Part name	Model & specification	Quantity of components	Estimated Cost($)	Average cost ($)	Remark
1	Pump with motor		1	59-109	84	
2	Rod-less hydraulic cylinder		1	36-38.5	37.25	
3	Double acting pneumatic cylinder		1	17.4-19	18.2	
4	Oil Filter		1	1.4-2.85	2.125	
5	Oil Reservoir		1	50-60	55	
6	Variable flow controller		2	35-38	36.5	
7	Control Valve & solenoid direction control valve		2	$(11 - 29.1) \times 2$	36.2	For both pneumatic and hydraulic
8	Customized valve		2	41	82	
9	Proximity Sensor two normally and one normally closed		2	43××2	86	
10	Curve sensor with normally open		1	40	40	
11	Coil with on delay time 0.16ms		1	6-7.5	6.75	
12	Solenoid coil		1	5.3-7	6.15	
13	Coil		1	7-8	7.5	
14	Check valve		1	15	15	
Total			**18**		**512.675**	

5.4 Validating wheel flange lubrication flow rate of AALRT train

The modeled AALRT vehicle is simulated on train wheel diameter of 660mm, with a train speed of 20 km/hr, average curve length is 20m, and average time to finish the curve is 5.5s. The results are validated against the flow rate at a curve, and optimum speed of the pump. It is evident from the numerical results in the Table 5.4 that shows flow rate of 0.326e-3m^3/s, resulted in very small different compared to standard flow rate at the curve which is 0.3e-3m^3/s, and thus, it can be concluded that smaller oil flow rate than the standard at the curves decrease the lifetime of wheel flange.

5.4.1Validating numerical and simulation result against standard flow rate

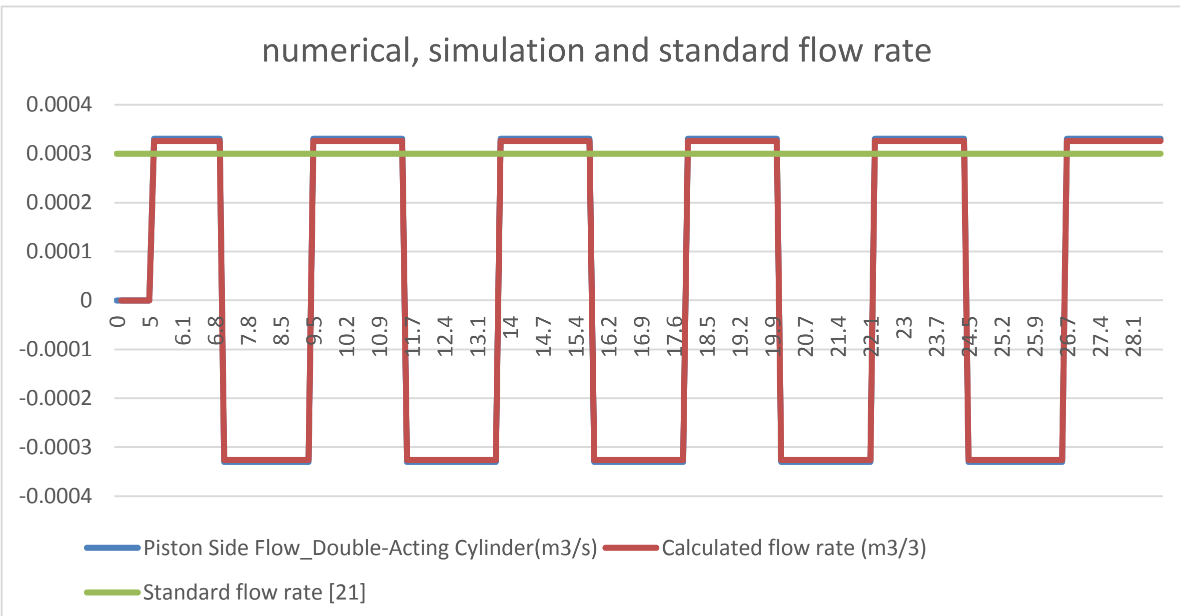


Figure 5.1 Comparison of mathematical and simulation results with standard flowrates

Percentage error=$\frac{\textbf{Approximate error} - \textbf{Exact value}}{\textbf{Exact value}}$ X100

$\%error = \frac{0.326e - \frac{sm^3}{s} - 0.3e-3m^3/s}{0.326e-3m^3/s}$ X100

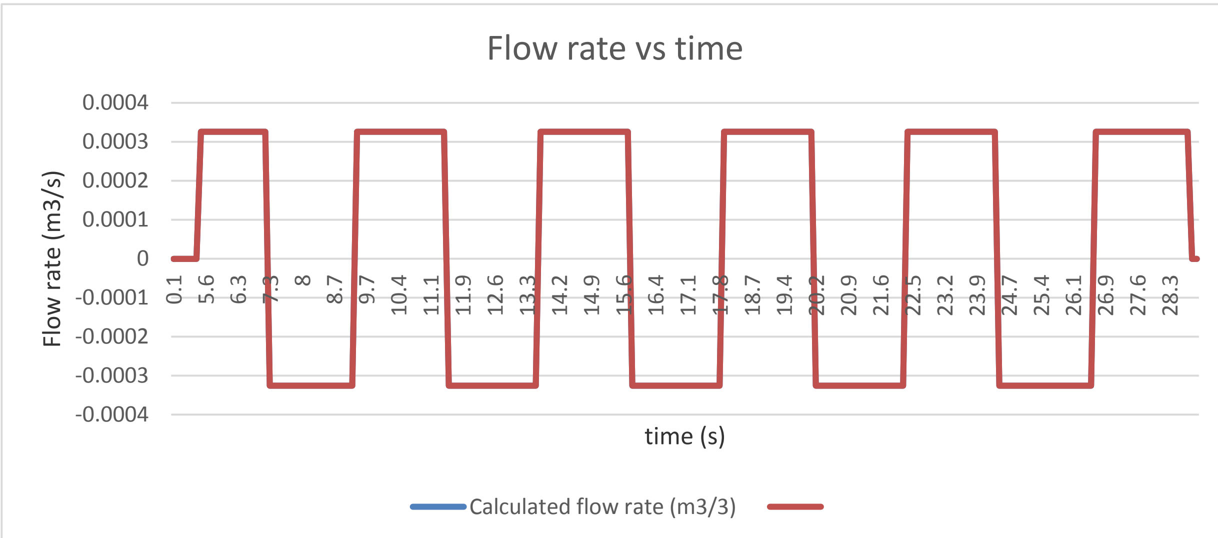
$\%error = \frac{0.026e-3m^3/s}{0.326e-3m^3/s}$ X100

$\%error$ =0.079×100

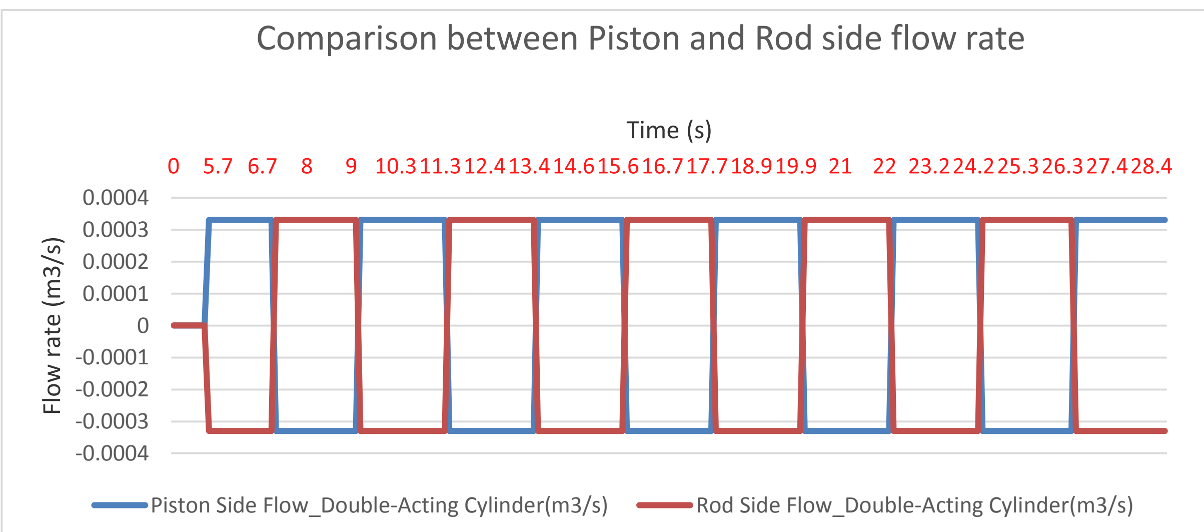
$\%error$ =7.9%

The oil tanks were estimated to be 0.5m^3 while the flow rate through the spray nozzle is calculated to be approximately 0.326e-3m^3/s and the standard flow rate at curve is approximately 0.3e-3m3/s [22] which gives a difference of 0.026e-3m^3/s with a corresponding error of 7.9%. This is a clear indication that the design process met the international standard for the design of such system. Similarly, the oil flow rates at curve track were seen to be at the acceptable limits.

5.4.2 Validating the oil flow rate at both piston and rod side



(a) Flow rate vs. time



(b) Comparison of both side flow rates

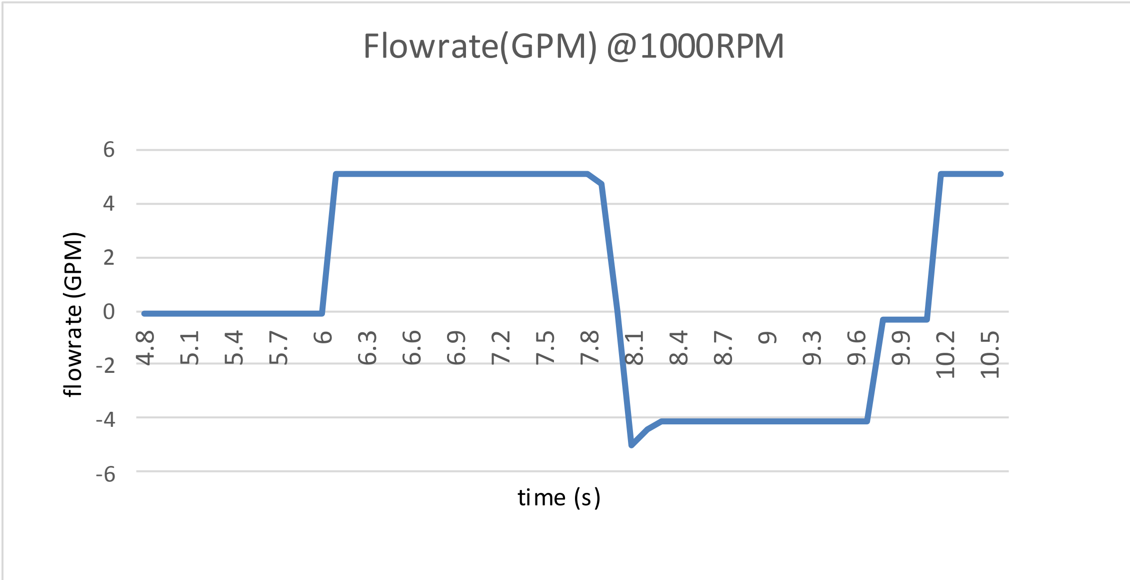
Figure 5.2 (a) Flow rate vs. time and (b) Comparison of both side flow rate

As we seen from Figures 5.2 (a) and (b), the piston side and rod side of the cylinder flow rate are the same, so this is very important for uniformity of the spray oil on the wheel flange. Any point above the time (horizontal) axis is positive velocity, meaning the piston is moving forward. When this line crosses the t-axis, the object has (momentarily) stopped, and is in the process of changing direction. Negative flow rate must mean piston movement in the opposite direction. When the oil flow rate is at maximum for this study 0.326e-3m3/s or -0.326e-3m3/s means the system spraying saturated oil on the wheel flange of the vehicle.

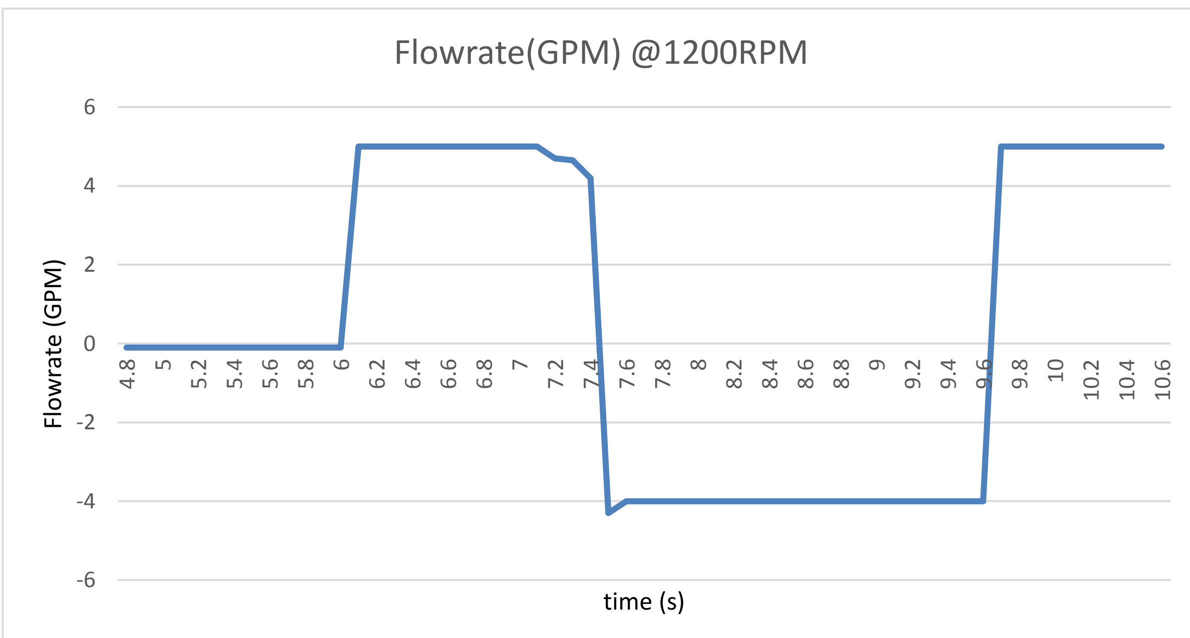
Table 5.4 Numerical result of simulation

Time (s)	Piston Side Flow Double-Acting Cylinder(m3/s)	Calculated flow rate (m3/3)	Time (s)	Piston Side Flow Double-Acting Cylinder(m3/s)	Calculated flow rate (m3/3)
0	0	0	17.2	-0.000330363	-0.000326
1	0	0	18.1	0.000330363	0.000326
5.5	0.000330363	0.000326	18.5	0.000330363	0.000326
5.9	0.000330363	0.000326	18.9	0.000330363	0.000326
6	0.000330363	0.000326	19	0.000330363	0.000326
6.2	0.000330363	0.000326	19.4	0.000330363	0.000326
6.4	0.000330363	0.000326	19.8	0.000330363	0.000326
6.6	0.000330363	0.000326	20	0.000330363	0.000326
6.8	0.000330363	0.000326	20.6	-0.000330363	-0.000326
7.3	-0.000330363	-0.000326	20.9	-0.000330363	-0.000326
7.8	-0.000330363	-0.000326	21	-0.000330363	-0.000326
8.1	-0.000330363	-0.000326	21.5	-0.000330363	-0.000326
8.4	-0.000330363	-0.000326	22	-0.000330363	-0.000326
8.7	-0.000330363	-0.000326	22.5	0.000330363	0.000326
9	-0.000330363	-0.000326	23	0.000330363	0.000326
9.1	-0.000330363	-0.000326	23.5	0.000330363	0.000326
10.2	0.000330363	0.000326	24	0.000330363	0.000326
10.6	0.000330363	0.000326	24.5	-0.000330363	-0.000326
10.9	0.000330363	0.000326	25	-0.000330363	-0.000326
11	0.000330363	0.000326	25.5	-0.000330363	-0.000326
11.1	0.000330363	0.000326	26	-0.000330363	-0.000326
11.4	0.000330363	0.000326	26.5	-0.000330363	-0.000326
11.9	-0.000330363	-0.000326	27	0.000330363	0.000326
12.3	-0.000330363	-0.000326	27.1	0.000330363	0.000326
12.7	-0.000330363	-0.000326	27.2	0.000330363	0.000326
13	-0.000330363	-0.000326	27.4	0.000330363	0.000326
13.5	-0.000330363	-0.000326	27.5	0.000330363	0.000326
14	0.000330363	0.000326	27.7	0.000330363	0.000326
14.5	0.000330363	0.000326	27.9	0.000330363	0.000326
15	0.000330363	0.000326	28	0.000330363	0.000326
15.5	0.000330363	0.000326	28.1	0.000330363	0.000326
15.9	-0.000330363	-0.000326	28.2	0.000330363	0.000326
16.2	-0.000330363	-0.000326	28.3	0.000330363	0.000326
16.7	-0.000330363	-0.000326	28.4	0.000330363	0.000326
17	-0.000330363	-0.000326	28.5	0.000330363	0.000326
17.1	-0.000330363	-0.000326	28.6	0.000330363	0.000326

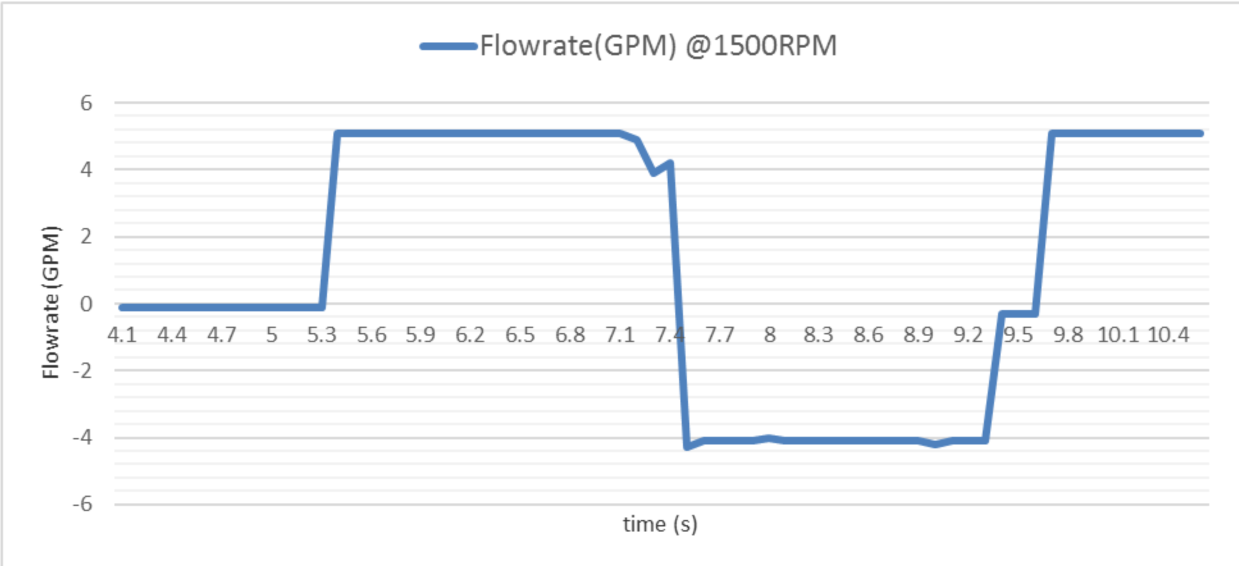
5.4.3 Validating the oil flow rate against different pump speeds



(a)



(b)



(c)

Figure 5.3 Comparison of flowrate at different speed of pump

The above Figure 5.3 shows the oil flow rate calculated for the different pump speed. But the Figure (a)(b) and (c) approximately the same flow rate value. The value of flow rate above the x-axis shows when the cylinder piston is forward and the value of flow rate below the x-axis is when the cylinder piston is reverse direction. In Figure (a)(b)(c), three chart shows approximately the same result but Figure (b) has no any deflection on chart. So the Figure 5.3 (b) at the pump speed of 1200RPM is the more acceptable.

CHAPTER SIX

Recommendation, Future work and Conclusions

6.1 Introduction

The first chapter discussed the rail system, AALRT characteristics, and wheel flange wear, as well as wear solutions. Chapter 2 looked at the challenges surrounding wheel flange lubrication and gave an overview of rail/wheel lubrication approaches for design and simulation. The existing Lubrication System and operational characteristics of AALRT were discussed in Chapter 3. To obtain an understanding of the intelligent simulation and novel wear solution in Chapter 4, these data emphasize the similarities and contrasts between the simulated and current installed lubrication system conditions.. Chapter 4 describes how the simulator, which was previously used to investigate novel wheel flange lubrication system materials, was modified to examine a simulation. The method, measurements, and measurement errors related with the experimental procedure were also covered in Chapter 4 Chapter 5 contrasted the findings received from the simulated new lubrication system to the results acquired from the old carbon-based lubricant. Finally, this chapter summarizes the research findings, offers the conclusions, and considers potential future research possibilities.

6.2 Recommendation

Installed onboard lubrication system of AALRT train is now out of the service due to high cost of lubricant and also it is not appropriate lubrication with the infrastructure with full of small radius like AALT. The highest rate of wear occurs on both wheel flange and rail during past AALRT operation time at minimum curve due to poor lubrication system. This will lead the early wheel wear and can cause early wheel flange profiling and early wheel axle change which cause high cost and even derailment can happen. Since changing constructed curve lines and rail geometry, repeatedly wheel flange re-profiling or changing wheel hub can cause high cost, the author tries to design new machine which can lubricate wheel flange and rail to reduce wear at low price for existing parts.

In addition to design the new system, the author recommends AALRT to purchase the equipment and put it to operation, to use friction modifiers or optimum lubrications at curves.

6.3 Conclusions

A wheel flange lubricator sprays lubricant on the wheel flange which comes into contact with the rail at curves, consequently decreasing the wear rate. Electric Multiple Units (EMUs) of Addis Ababa Light Rail Transit (AALRT) integrated with solid stick wheel flange lubrication mechanism. However, nowadays, AALRT EMUs solid stick lubrication system is not functional because of material cost and lack of availability. In this study a new technology of wheel flange lubrication system is proposed and designed to solve the problem of AALRT maintenance and operational safety. Based on the inspections and wheel data analysis work undertaken for this investigation causes of the wheel wear of AALRT vehicles can be considered as the combination of issues related to inadequate lubrication system and poor track infrastructure. Inadequate friction management at AALRT, in which lack of rolling stock wheel flange lubricant and inadequate manual based track lubrication on the rail, have led to undesired wear due higher friction between wheel and rail. Average tread diameter of North-South line train is 656.2 mm show a total percentage loss of 0.57% when compared to East-West line with an average wheel diameter of 658.3 mm and a percentage loss of 0.25%. The analysis results indicate that North-South line EMU wheel flange wears faster than that of East-West line. It was also found that the trailer car wheels' thicknesses are worn faster than other two motor bogie wheels. Our designed lubrication system replaces the previous lubrication system (solid stick) and is intended to be operated by priority of fast wearing axle wheels and corresponding vehicles. The designed spray type wheel flange lubrication system flow rate through the spray nozzle is calculated to be approximately 0.326e-3m^3/s and the standard flow rate at the curve is approximately 0.3e-m^3/s which gives a difference of 0.026e-3m^3/s with a corresponding error of 7.9%. The tight curves at AALRT, mainly in the North-South line, contribute to high flange wear This work has demonstrated that the simulator is capable of reducing wheel rail contact wear due to friction and generates appropriate lubrication system.

6.4 Future Work

Designing onboard spray type wheel flange lubrication system is a complex research field that requires new ideas and innovative design solutions from day to day. Especially Ethiopia starts a plan to connect regional state and also with other country with railway lines, so the study of wheel flange lubrication will help to face challenges in operation due to lack of lubrication, modify and upgrade her own vehicle types and track lines for better operation. In this paper the author tries to find the solution for fast wheel and rail wear challenges that Addis Ababa Light Rail EMUs has faced. The real design, and results when carried out, will be published as work ancillary to this project. Through this process the author face limitations from different reasons. Further work is required like evaluation of lubrication system performance and calculation of lubrication system mean time between failure (MTBF) to set a final compatible machine to improve wheel flange lubrication system and also to extend wheel and rail life.

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Appendices

Appendix 1

Table 1: Data collected on wheel diameter and wheel flange thickness of both Kality (NS) and Ayat (EW) trains

					pre-measurement					post-measurement					
						diameter		flange thickness			diameter		flange thickness		
No.	Date	Mealage	Train No.	wheelset No.	diameter d/t	left	right	left	right	diameter d/t	left	right	left	right	Total re-profiled wheelset
1	27/5/2019	196283	**101**	1z	0.33	654	654	22.8	22.5	0.55	651	651	22.5	22.1	1
				2z	0.44	654	654	22.9	22.9	0.99	651	652	22.6	22.02	2
				3z	0.43	658	659	21	16.8						
				4z	0.36	658	658	21.8	17.3						
				5z	0.4	654	655	23.6	22.7	0.83	652	653	22.8	22.32	3
				6z	0.57	654	654	22.8	22.1	0.59	651	652	22.6	21.92	4
2	22/1/2020	247130	**101**	1z	0.4	648	648	22.4	22.1						
				2z	0.51	648	648	23.2	22.4						
				3z	0.37	658	658	20.3	14.1	0.17	639	639	17.4	17.11	5
				4z	0.37	657	657	20.9	15.1	0.15	640	640	17.5	17.38	6
				5z	0.8	649	649	22.7	22.6						
				6z	0.21	648	649	22.7	22.2						
3	2/10/2019	205516	102	1z	0.03	648	648	22.9	23.6	0.51	646	646	23	22.56	7
				2z	0.31	647	647	24.3	23.9	0.53	645	646	23	22.59	8
				3z	0.05	652	652	22.2	19.6						
				4z	0.09	652	652	22.3	20.7						
				5z	0.45	646	647	24	24	0.31	645	645	22.9	22.69	9
				6z	0.06	646	646	24.3	23.7	0.32	644	645	23	22.51	10
4	2/12/2019	172039	103	1z	0.3	654	654	20	18.8	0.25	651	651	18.7	18.37	11
				2z	0.58	655	654	20.7	20.6	0.18	652	652	20.8	20.49	12
				3z	0.65	658	659	16.4	15.2	0.42	645	644	17.6	16.94	13
				4z	0.67	658	659	18.6	15.3	0.17	644	645	17.7	17.23	14
				5z	0.31	654	655	21.2	20.9						
				6z	0.27	654	655	20.7	19.9						
5	3-9/2/2016	4888	104	1z	0.08	661	661	23.3	23.3	-	-	-	-	-	
				2z	0.1	661	661	23.2	23.3	-	-	-	-	-	
				3z	0.67	660	661	22.4	23	1.77	650	652	19.8	19.96	15
				4z	0.21	660	661	23	22.5	0.06	653	653	20.6	21.03	16
				5z	0.15	660	661	23.1	23.2	-	-	-	-	-	
				6z	0.06	660	661	23.5	23.4	-	-	-	-	-	
6	6/6/2019	220019	**104**	1z	0.3	654	653	22.9	23.1	0.32	651	651	22.8	22.42	17
				2z	0.31	654	653	24.2	23.4	0.23	649	649	22.9	22.51	18
				3z	0.05	621	621	18.2	18.1						
				4z	0.05	624	624	18.6	18.3						
				5z	0.55	653	654	24.2	23.4	0.03	652	652	23	22.69	19

				6z	0.01	653	653	23.4	23.3	0.36	651	651	23	22.47	20
7	15-18/03/2016	6065	104	1z	0.14	661	660	23.3	23.1	-	-	-	-	-	
				2z	0.04	661	661	23	23.3	-	-	-	-	-	
				3z	0.76	651	652	19.6	19.7	1.36	650	651	19.6	19.75	21
				4z	0.01	652	652	20.3	20.8	0.16	651	651	20.2	20.05	22
				5z	0.13	660	661	23.2	23.3	-	-	-	-	-	
				6z	0.22	661	660	23.4	23.2	-	-	-	-	-	
8	16/01/2017	62254	118	1z	0.45	659	659	20.3	19.8						
				2z	0.23	659	659	21.2	20.9						
				3z	0.47	660	660	15.3	19.5	0.05	635	635	19.4	19.15	23
				4z	0.18	660	660	16.1	19.7	0.42	637	636	19.3	19.49	24
				5z	0.51	659	659	21.7	19.6						
				6z	0.02	659	659	21.1	19.8						
9	25/03/2016 to 11/04/2016	30478	119	1z	0.1	660	660	20.2	21	-	-	-	-	-	
				2Z	0.15	660	660	20.8	20.8	-	-	-	-	-	
				3z	0.01	660	660	19.8	20.4	0.3	655	655	22.3	22.3	25
				4z	0.49	661	660	20.2	19.5	0.39	657	656	19.7	19.71	26
				5z	0.08	660	660	20.8	20.6	-	-	-	-	-	
				6z	0.09	660	660	21.1	20.8	-	-	-	-	-	
10	7/12/2019	303387	119	1z	0.52	651	650	21	22.1						
				2z	0.78	651	650	23.1	22.5						
				3z	0.95	651	652	15.1	15.2	0.06	627	627	18.5	18.19	27
				4z	3.48	650	653	15	14.2	0.11	627	627	18.7	18.4	28
				5z	0.37	650	651	23.2	21.7						
				6z	0.47	650	650	23.1	22						
11	28/5/2019	228529	**120**	1Z	0.17	654	654	21.9	20.8	0.06	651	651	21.1	20.83	29
				2Z	0.03	653	653	21.4	21.5	0.14	651	651	21.6	21.4	30
				3Z	2.76	655	658	18.3	14.5	0.22	635	636	18.4	18.34	31
				4Z	1.45	657	658	17.8	14.3	0.22	636	636	18.6	17.98	32
				5Z	0.57	654	654	21.3	21.6	0.59	651	652	21.8	20.94	33
				6Z	2.03	652	654	21.1	22.4	0.2	651	651	21.4	20.63	34
12	26/9/2019	400915	121	1z	2.49	651	648	21.7	21.7	0.05	645	645	21.7	21.22	35
				2z	0.22	651	651	22.3	21.6	0.11	646	646	21.6	21.46	36
				3z	0.37	638	638	15.5	17.5	0.18	622	623	18.4	18.47	37
				4z	0.63	638	638	16.2	17.7	0.08	624	624	18.5	18.29	38
				5z	0.16	651	651	20.8	22.6	0.08	648	648	20.9	20.53	39
				6z	2.04	649	651	21.8	21.6	0.19	647	647	21.6	21.24	40
13	7-8/5/2016	91086	213	1z	0.53	659	660	16.7	17	0.01	640	640	19.9	19.86	41
				2z	0.84	659	659	17.5	14.6	0.16	635	635	19.4	19.57	42
				3z	-	-	-	-	-	-	-	-	-	-	
				4z	-	-	-	-	-	-	-	-	-	-	
				5z	0.1	660	660	15.7	17.6	-	-	-	-	-	
				6z	0.35	660	659	17.8	15.5	-	-	-	-	-	
14	42799	91086	213	1z	0.37	638	638	18	17						
				2Z	0.67	634	633	18.3	16.4						
				3z	0.08	660	660	18.5	15.6	0.16	644	644	18.6	18.61	43
				4z	0.32	659	660	16.8	15.6	0.3	644	645	18.5	18.54	44

				5z	0.07	659	659	16.3	16.9	0.01	632	632	20.6	20.76	45
				6z	0.88	659	658	18.2	14.4	0.23	630	630	19.1	19.29	46
15	8-10/6/2016	26848	211	1z	0.14	660	660	19.1	19.4	-	-	-	-	-	
				2z	0.32	660	660	17.9	18.3	-	-	-	-	-	
				3z	0.61	651	652	19.1	19	0.01	640	640	18.9	18.31	47
				4z	0.71	661	660	19.1	13.2	0.35	635	635	19.5	18.74	48
				5z	0.21	660	660	19.2	19.4	-	-	-	-	-	
				6z	0.11	660	660	19.5	17	-	-	-	-	-	
16	21/02/2017	80287	211	1Z											
				2Z											
				3Z	0.2	629	629	18.4	18.1	0.92	625	626	81.1	81.03	49
				4Z	0.01	630	630	19.6	18.6	0.23	626	627	18.6	18.32	50
				5Z											
				6Z											
17	11-12/6/2016	56447	209	1z	0.2	659	659	15.3	17.2	0.41	651	651	17.3	17.3	51
				2z	0.09	659	659	16	15.6	0.04	651	651	17.6	17.69	52
				3z	0.16	660	660	17.2	17.5	0.11	649	649	20	20.03	53
				4z	0.08	660	660	15.3	16.3	0.14	648	649	19.1	18.99	54
				5z	0.23	659	660	17.3	17.3	-	-	-	-	-	
				6z	0.02	659	659	16.4	15.2	0.22	654	654	17	16.85	55
18	9/10/2017	85008	209	1z	0.2	650	650	15.7	15.5	0.05	635	635	18.2	18.31	56
				2Z	0.16	650	650	16.3	15.8	0.02	635	635	18.4	18.33	57
				3z	0.09	648	648	18.1	17.8						
				4z	0.05	648	648	16.7	16.4						
				5z	0.37	659	659	17.5	17	0.26	640	639	19.9	19.97	58
				6z	0	653	653	15.7	14.9	0.49	636	637	18.6	18.2	59
19	29/3/2018	119274	209	1z	0.14	634	634	18.5	18.5						
				2z	0.05	634	634	18.8	18.9						
				3z	0.02	648	648	18.3	17.6	0.07	639	639			60
				4z	0.12	647	648	16.9	16.4	0.06	637	637			61
				5z	0.06	638	638	20.4	20.3						
				6z	0.24	635	635	18.9	18.6						
20	2/2/1016	35955	216	1z	0.18	660	660	16.8	17.8	0.4	650	650	19.2	19.16	62
				2z	0.07	660	660	15.3	14.5	0.12	647	647	17.9	17.87	63
				3z	0	660	660	18.1	18	-	-	-	-	-	
				4z	0.07	660	660	18.5	18.5	-	-	-	-	-	
				5z	0.23	660	660	17.5	16.6	0.17	648	648	20.2	19.9	64
				6z	0.02	660	660	18.3	14.8	0.6	648	649	18.6	18.35	65
21	14-16/6/2016	44026	212	1z	0.04	660	660	16.1	17.5	0.03	641	641	19.9	19.7	66
				2Z	0.33	660	659	17	13.7	0.07	638	638	18.4	18.4	67
				3z	0.01	660	660	16.5	17.7	0.38	653	653	18.4	18.6	68
				4z	0.12	660	660	17.5	17.6	0.26	654	653	19.5	19.53	69
				5z	0.54	659	660	16.6	19.4	0.05	654	654	18.4	18.36	70
				6z	0.06	660	659	16.4	16.9	0	653	653	18.1	18.07	71
22	17-18/6/2016	6518	107	1z	0.25	660	659	19.9	20.3	-	-	-	-	-	
				2z	0.04	659	660	19.8	19.7	-	-	-	-	-	
				3z	0.3	660	660	18.2	16.1	0.31	650	650	18.7	18.87	72

				4z	0.32	660	660	18	14.8	0.32	650	650	18	17.86	73
				5z	0.36	660	659	19.3	19.5	-	-	-	-	-	
				6z	0.07	660	659	20.1	20.3	-	-	-	-	-	
23	21/06/2017	82008	107	1z	0.35	659	659	20.7	20.1						
				2z	0.01	659	659	20.5	19.6						
				3z	0.3	650	650	17.8	15.3	0.28	628	627	18.3	18.66	74
				4z	0.23	650	650	17.3	14.3	0.12	627	627	18.4	18.39	75
				5z	0.45	659	659	20.3	19.5						
				6z	0.17	659	659	20.9	20.3						
24	11/1/2020	284396	107	1z	0.15	651	651	22	21.3						
				2z	0.06	651	651	22.1	20.9	0.22	649	649	20.9	20.47	76
				3z	0.04	602	602	17.5	16.2						
				4z	0.25	604	604	17.5	17						
				5z	0.14	651	651	21.7	20.5	0.04	649	649	20.5	20.4	77
				6z	0.12	651	651	22.6	21.5						
25	18-21/06/2016	35568	217	1z	0.13	656	656	16.7	17	0.16	652	652	17.1	17.61	78
				2z	0.06	660	660	17.6	16.8	0.31	655	656	18.3	18.22	79
				3z	0.19	651	651	18	18.5	0.06	641	641	19.6	19.86	80
				4z	0.11	645	645	16.7	16.8	0.05	641	641	17	17.15	81
				5z	0.21	660	660	18.3	18.9	-	-	-	-	-	
				6z	0.05	660	660	17.5	16.4	-	-	-	-	-	
26	1/1/216	43043	217	1z	0.07	624	624	19.4	19.5						
				2Z	0.1	625	625	21	21.2						
				3z	0.05	616	616	19.5	19.5						
				4z	0.38	614	614	18	18.3						
				5z	0.01	642	642	21	20.9						
				6z	0.21	640	641	18.7	18.6						
27	4-24/06/2016	53109	206	1z	0.39	659	659	16.3	17.2	0.16	649	649	19	19.38	82
				2z	0.06	659	659	16.9	15.1	0.16	648	648	18	18.57	83
				3z	0.29	660	660	14	15.1	0.16	639	639	18.6	18.8	84
				4z	0.23	660	660	12.5	14.5	0.16	638	638	17.7	17.94	85
				5z	0.21	659	660	17.4	16.6	0.16	653	654	17.9	18.01	86
				6z	0.02	659	659	15.9	15.4	0.16	653	653	17.6	17.91	87
28	24-26/06/2016	45540	115	1z	0.17	660	659	20.6	19.8	-	-	-	-	-	
				2z	0.18	660	660	20.4	20.3	-	-	-	-	-	
				3z	0.41	660	660	19.2	15.1	0.92	635	636	20	20.79	88
				4z	0.32	660	660	19.8	14.1	0.37	635	636	19.3	19.38	89
				5z	0.22	660	660	20.7	20.6	-	-	-	-	-	
				6z	0.18	660	659	20.5	19.9	-	-	-	-	-	
29	20/06/2018	168776	117	1z	0.33	656	656	22.9	22.4						
				2Z	0.27	656	656	22.9	22.6						
				3z	0.21	659	659	14.2	21.3	0.25	635	635	17.9	18.35	90
				4z	1.68	659	657	15.3	21.3	0.6	634	635	18.0	18.27	91
				5z	0.31	655	656	23.2	22.7						
				6z	0.09	655	655	22.6	22.1						
30	27/6-1/7/2016	49030	205	1z	0.11	659	660	16.7	16.5	0.44	640	640	20.3	20.09	92
				2z	0.02	660	660	17.5	13.5	0.47	637	638	17.6	17.56	93

				3z	0.04	660	660	17.4	18.2	-	-	-	-	-	
				4z	0.08	660	660	16.4	17.4	-	-	-	-	-	
				5z	0.04	660	660	16.5	16.6	-	-	-	-	-	
				6z	0.08	660	660	17.6	18.5	-	-	-	-	-	
31	1/8/2017	111744	205	1z	0.16	638	638	18.1	17.4	0.09	614	614	21.2	21.48	94
				2z	0.1	636	636	16	14.3	0.07	613	613	18.3	18.36	95
				3z	0	659	659	18	17.5	0.23	655	655	18.3	18.27	96
				4z	0.27	659	659	16.7	16.5	0.49	654	655	17	17.41	97
				5z	0.15	658	658	16.9	16.6						
				6z	0.03	658	658	18.1	17.8	1					
32	30/1/2018	95879	204	1z	0.91	628	629	20.2	19						
				2z	0.15	631	630	21.4	19.8						
				3z	0.29	659	659	19.9	19.7	0.35	637	638			98
				4z	0.11	659	659	19.8	19.6	0.09	638	638			99
				5z	0.47	658	658	20.5	19.4	0.09	638	638			100
				6z	0.2	658	658	20.1	19.2	0.18	637	637			101
33	3-7/7/2016	54471	218	1z	0.3	659	660	13.7	16.7	0.24	643	643	17.7	17.59	102
				2z	0.15	659	659	14.2	13.9	0.32	643	643	17.6	17.67	103
				3z	0.01	660	660	17.1	16.1	0.24	637	637	19.6	19.72	104
				4z	0.16	660	660	14.1	12.8	0.32	638	638	17.7	17.78	105
				5z	0.53	659	660	18.4	18.1	0.03	648	648	21.1	20.85	106
				6z	0.41	659	659	16	15.3	0.22	648	648	17.8	17.78	107
34	08-11/07/2016	47312	215	1z	0.44	660	660	17.1	17.9	0.31	641	641	21	21.08	108
				2Z	0.06	660	660	15.5	13.5	0.1	642	642	17.4	17.55	109
				3z	0.09	660	660	18.1	16.8	0.3	645	645	19.7	19.94	110
				4z	0.18	660	660	17.1	15.5	0.21	644	644	18.8	18.81	111
				5z	0.02	660	660	16.5	16.7	-	-	-	-	-	
				6z	0.17	660	660	16.2	16	-	-	-	-	-	
35	/2017	67968	215	1z	0.44	640	640	19.1	18.5	0.12	620	620	21.7	21.96	112
				2z	0.05	641	641	16.2	15.2	0.2	618	618	19.3	19.32	113
				3z	0.18	645	645	18.2	17	0.04	620	620	21	21.33	114
				4z	0.31	644	644	16.9	15.4	0.05	621	621	19	19.27	115
				5z	0.19	659	659	17	15.9	0.001	635	635	19.9	20.01	116
				6z	0.17	659	659	16.3	15.1	0.03	634	634	19.3	19.17	117
36	13-14/07/2016	22282	207	1z	0.19	660	660	18.6	20	0.1	655	655	19.6	19.84	118
				2z	0.08	660	660	18.5	17.5	0.1	655	655	18.9	18.96	119
				3z	0.01	660	660	19.5	19.4	-	-	-	-	-	
				4z	0.06	660	660	18.1	18.1	-	-	-	-	-	
				5z	0.12	660	660	19.4	18.8	-	-	-	-	-	
				6z	0.06	660	660	19.1	17.6	-	-	-	-	-	
37	15-27/07/2016	43452	208	1z	0.07	659	660	16.3	17.5	0.29	638	638	20.1	20.24	120
				2Z	0.22	660	660	13.5	18.3	0.19	635	635	17.4	17.75	121
				3z	0.15	660	660	17.1	15.4	0.1	640	640	18.6	18.78	122
				4z	0.06	660	660	17.3	14.5	0.23	639	639	18.3	18.3	123
				5z	0.12	660	660	18.7	17	0.19	646	646	19.7	19.82	124
				6z	0.2	659	660	17.1	16	0.07	646	646	18.9	18.9	125

38	6/8/2019	195736	208	1z	0.14	658	659	23.3	22.5						
				2z	0.19	658	658	23.4	23						
				3z	0.48	638	639	15.4	16.4	0.12	627	627	17.3	17.05	126
				4z	1.2	636	638	16	16.2	0.14	626	627	17.4	17.83	127
				5z	0.06	659	659	23.6	22.8						
				6z	0.02	659	659	23.4	22.7						
39	17-18/08/2016	45551	114	1z	0.12	660	660	19.6	20.5	-	-	-	-	-	
				2z	0.1	660	660	20.3	20.5	-	-	-	-	-	
				3z	0.25	660	660	18.5	19.7	0.35	656	655	18.7	19.38	128
				4z	0.25	660	660	18.4	19.6	0.58	655	656	19.4	19.26	129
				5z	0.09	660	660	19.7	20.3	-	-	-	-	-	
				6z	0.12	660	660	21.1	20	-	-	-	-	-	
40	6/2/2018	153179	114	1z	0.37	656	657	20.8	21.7						
				2Z	0.12	657	657	21.3	20.7						
				3z	0.59	655	654	19.1	14.6	0.11	632	632	19	17.2	130
				4z	0.35	654	654	19	15.7	0.19	633	633	19	17.5	131
				5z	0.02	657	657	21.6	21						
				6z	0.07	657	657	21.4	20.3						
41	29/11/2019	302681	114	1z	1.08	650	652	21.6	21.9						
				2z	0.53	651	651	22.8	21.9						
				3z	1.11	630	629	18.2	12.9	0.29	**600**	**600**	17.3	17	132
				4z	0.06	630	630	18.9	15.2	0.24	**602**	**602**	19.4	18.85	133
				5z	0.26	651	651	22.1	22						
				6z	1.16	652	650	22.4	20.9						
42	9-22/08/2016	51662	210	1z	0.32	659	659	16.1	16.4	0.29	643	642	19	18.99	134
				2z	0.24	659	659	16.3	14.4	0.61	642	642	17.8	18.09	135
				3z	0.23	660	660	15.5	14.2	0.39	641	641	17.4	17.46	136
				4z	0.21	651	651	17.5	17.5	0.05	643	643	18.1	18.44	137
				5z	0.2	659	659	16.4	16.9	0.15	646	646	18	18.11	138
				6z	0	659	659	16.4	15	0.41	646	646	17.3	17.58	139
43	23-25/08/2016	40415	108	1z	0.42	660	660	20.4	20.4	-	-	-	-	-	
				2Z	0.03	660	660	19.9	19.7	-	-	-	-	-	
				3z	0.21	660	660	18.6	17.8	0.65	655	655	18.5	18.82	140
				4z	0.13	660	660	17.9	16.9	0.23	654	655	18.5	18.87	141
				5z	0.38	660	660	19.6	19.7	-	-	-	-	-	
				6z	0.37	660	660	20.1	20.1	-	-	-	-	-	
44	5/6/2019	242049	**108**	1z	0.43	647	646	22.7	23.1	0.11	644	644	22.6	21.98	142
				2z	0.17	646	646	22.5	22.8	0.47	644	644	22.4	21.88	143
				3z	0.39	653	653	16.6	15.2	0.11	634	634	18.5	18.08	144
				4z	0.32	652	652	16.6	14.7	0.39	633	634	18.3	18.1	145
				5z	0.62	653	653	22.5	21.5	0.33	648	648	21.4	20.89	146
				6z	0.23	653	653	22.1	21.6	0.05	649	649	21.4	21.22	147
45	25-30/08/2016	45551	111	1z	0.44	659	659	18.5	18.8	-	-	-	-	-	
				2z	0.19	**659**	**659**	18.1	18.6	-	-	-	-	-	
				3z	0.53	660	660	17.1	13.1	0.31	636	636	17.9	17.76	148

				4z	0.56	660	660	17.3	13	0.51	635	636	17.2	16.99	149
				5z	0.09	660	660	19.7	20.3	-	-	-	-	-	
				6z	0.12	660	660	21.1	20	-	-	-	-	-	
46	28/02/2018	157409	111	1z	0.69	657	656	20.6	20.4						
				2Z	0.29	**656**	**656**	20.4	20.5						
				3z	0.51	611	612	18.2	18.5	0.12	**605**	**605**			150
				4z	0.32	610	610	18.4	18.4	0.02	**606**	**606**			151
				5z	0.22	656	657	20.6	20.4						
				6z	0.55	657	656	21.7	19.5						
47	05-07/09/2016	54807	110	1z	0.22	659	659	18.7	19.1	-	-	-	-	-	
				2z	0.23	659	659	18.9	18.6	-	-	-	-	-	
				3z	0.31	660	660	17.1	14.6	1.1	637	636	18.3	18.75	152
				4z	0.58	660	660	17	13.1	0.22	637	636	18.2	18.07	153
				5z	0.5	660	659	19.7	18.7	-	-	-	-	-	
				6z	0.25	659	659	19	18.1	-	-	-	-	-	
48	28/3/2019	203768	**110**	1z	0.13	654	654	21.4	21						
				2z	0.53	655	654	21.5	21						
				3z	1.07	636	635	18.4	15.1	0.1	616	616	18.3	18.01	154
				4z	0.11	635	635	18.6	14.4	0.19	616	616	18.2	17.93	155
				5z	0.2	655	655	22.2	20.7						
				6z	0.29	654	654	21.6	19.8						
49	19/6/2019	210456	110	1z	0.15	654	654	21.6	20.9	0.02	651	651	21.9	21.35	156
				2z	0.56	654	654	21.5	21	0.11	649	649	20.8	20.34	157
				3z	0.23	616	616	18.4	17.8						
				4z	0.26	615	616	18.1	18						
				5z	0.21	655	655	22.1	20.4	0.34	650	651	20.6	20.15	158
				6z	0.27	654	654	21.5	19.9	0.08	650	650	19.8	19.33	159
50	09-16/09/2016	61474	219	1z	0.42	659	659	13.8	15.7	0.22	633	633	18.5	18.34	160
				2z	0.11	659	659	14.1	13	0.27	632	632	17.8	17.87	161
				3z	0.26	660	660	14.9	14.2	0.96	631	631	18.8	18.42	162
				4z	0.12	660	660	15	13.2	0.75	631	631	18.3	17.86	163
				5z	0.52	659	660	15	13.2	0.13	634	634	17.9	17.96	164
				6z	0.43	659	659	13.7	12.6	0.19	633	633	17.9	18.11	165
51	14-15/11/2016	76430	109	1z	0.11	659	659	18.7	18.6	-	-	-	-	-	
				2Z	0.05	659	659	19.2	18.3	-	-	-	-	-	
				3z	0.49	660	660	12.5	17.4	0.65	629	629	17.9	18	166
				4z	0.31	660	660	13.7	16.4	0.27	630	629	19.6	19.49	167
				5z	0.19	659	659	18.7	18.3	-	-	-	-	-	
				6z	0.09	659	659	19.2	18.2	-	-	-	-	-	
52	28/06/2018	189515	109	1z	0.04	655	655	21	20.5						
				2z	0.05	655	655	21.7	20						
				3z	1.04	629	628	14.2	19.2	0.12	606	605			168
				4z	0.18	628	628	16.3	20.8	0.28	607	606			169
				5z	0.39	655	656	21.2	20						
				6z	0.2	655	655	21.5	19.9						
53	16-18/11/2016	78624	218	1z	0.26	642	642	13.7	14	0.12	618	618	18.1	18.17	170
				2z	0.12	642	642	14.7	14.1	0.06	617	617	20.4	19.53	171

				3z	0.16	612	612	19.6	19.7	0.16	612	612	19.6	19.74	172
				4z	0.32	638	638	13.3	13.1	0.18	**610**	**610**	17.9	18.05	173
				5z	0.04	627	627	20.9	20.9	0.04	627	627	20.9	20.87	174
				6z	0.13	647	647	14.8	14.3	0.11	626	626	18	17.93	175
54	19to21/11/ 2016	66522	216	1z	0.15	649	649	16.5	16.1	0.3	623	623	20	20.09	176
				2Z	0.07	646	646	16	15	0	622	622	18.5	18.4	177
				3z	0.07	660	660	17.9	16.8	-	-	-	-	-	
				4z	0.15	660	660	18.2	17.5	-	-	-	-	-	
				5z	0.08	647	647	18.5	16.8	0.05	627	627	19.7	19.12	178
				6z	0.06	647	647	16.6	14.8	0.01	625	625	18.4	18.36	179
55	24/11/2016	26848	211	1z											
				2z											
				3z	0.06	640	640	18.9	17.8	0.09	630	630	19.1	19.3	180
				4z	0.42	635	635	19.3	18.2	0.2	629	629	18.2	18.15	181
				5z											
				6z											
56	20/9/2019	246448	211	1z	0.05	623	623	19.8	20						
				2z	0.12	622	621	20	19.9						
				3z	2.5	621	624	15.9	16.4	0.4	613	613	17.4	17.82	182
				4z	0.65	624	625	17.8	16.3	0.13	614	614	18.7	18.16	183
				5z	0.17	659	659	23.5	22.5						
				6z	0.19	659	659	23.4	22.3						
57	12/3/2018	86190	212	1Z	0.35	639	638	18.1	17.3	0.3		633	634		184
				2Z	1.18	636	635	17.2	16.1						
				3Z	0	652	652	16.2	16.2						
				4Z	0.15	653	653	17.4	17						
				5Z	0.77	651	651	17.4	16.6						
				6Z	0.31	651	650	17	16.1						
58	12/2/2019	194009	**212**	1z	0.11	660	660	23.1	22.8						
				2z	0.11	660	659	23.2	22.7						
				3z	0.35	652	652	17.3	16.6						
				4z	0.07	652	652	16	15.4		641	642	17.7	17.49	185
				5z	0.04	660	660	23	22.7						
				6z	0.2	660	660	23	22.6						
59	30/11/2016	69044	115	1z	0.37	659	659	21.4	19.4	-	-	-	-	-	
				2Z	0.06	659	659	21.2	20	-	-	-	-	-	
				3z	4.69	635	636	19.3	15.2	0.32	607	608	19.6	19.55	186
				4z	0.45	635	635	18.5	14.1	0.02	605	605	18.8	18.71	187
				5z	0.23	659	659	21.5	20.5	-	-	-	-	-	
				6z	0.16	659	659	21	19.8	-	-	-	-	-	
60	3/3/1017	79934	115	1z	0.42	659	658	21	19.5						
				2z	0.11	659	659	21.2	20.1						
				3z	0.71	607	607	19.5	19.6	0.47	**605**	**604**	19.2	19.74	188
				4z	0.11	605	605	18.8	18.5	0.11	**603**	**603**	18.5	18.19	189
				5z	0.24	659	659	21.5	20.7						
				6z	0.19	659	658	21.2	19.8						

61	14/8/2019	268801	116	1z	0.61	652	651	23.4	23.2						
				2z	0.91	651	652	23.9	23.5						
				3z	1	657	656	15.2	21.5	0.15	635	635	18.1	18.14	190
				4z	0.62	656	656	15.2	21.3	0.33	634	635	18.4	18.24	191
				5z	0.62	652	651	22.6	23.6						
				6z	2.17	651	654	22.3	23.1						
62	15/8/2019	255863	117	1z	0.18	652	652	23.3	22						
				2z	0.41	652	653	24	22.7						
				3z	0.77	633	632	14.4	18.4	0.3	**607**	**608**	18.4	18.27	192
				4z	0.49	634	633	13	17.9	0.28	**608**	**608**	17.1	17.03	193
				5z	0.5	653	653	23.6	22.7						
				6z	0.69	652	653	23.7	22.4						
63	12/5/2016	57012	220	1z	0	659	659	18.4	17.7	-	-	-	-	-	
				2z	0.03	660	659	17.8	17	-	-	-	-	-	
				3z	0.22	660	660	17.6	15.6	0	636	636	19.7	19.83	194
				4z	0.1	660	660	18.6	18.7	0	636	636	18.6	18.69	195
				5z	0.33	659	659	18.2	17.7	-	-	-	-	-	
				6z	0.02	659	659	18.3	16.6	-	-	-	-	-	
64	13-14/12/2016	61474	219	1z	0.22	633	633	20.2	19.3	-	-	-	-	-	
				2Z	0.23	631	632	19.7	19.2	-	-	-	-	-	
				3z	0.11	631	631	20.4	19.4	0.07	627	627	19.3	19.36	196
				4z	0.16	631	631	19.9	19.9	0.04	628	628	19.4	19.48	197
				5z	0.02	634	634	19.8	18.9	-	-	-	-	-	
				6z	0.45	633	633	19.5	19.2	-	-	-	-	-	
65	15-20/12/2016	52732	108	1z	0.43	660	659	21.3	20.6	0.01	653	653	21.5	21.61	198
				2z	0.04	659	659	20.9	19.9	0.12	653	653	20.7	20.74	199
				3z	0.73	654	655	18.8	18.7	-	-	-	-	-	
				4z	0.43	654	654	18.6	18	-	-	-	-	-	
				5z	0.32	660	659	20.7	20	-	-	-	-	-	
				6z	0.31	659	659	21	20.4	-	-	-	-	-	
66	22-28/12/2016	75028	206	1z	0.07	648	649	17.1	16.8	0.02	625	625	20.5	20.34	200
				2z	0.06	647	647	16.6	15.7	0.05	624	624	19.8	19.69	201
				3z	0.15	639	639	15.4	15.4	0.23	616	615	19.2	19.21	202
				4z	0.23	637	638	14.6	14.3	0.02	615	615	18.4	18.28	203
				5z	0.14	653	653	16.5	16.1	0.0.15	626	626	20.7	20.44	204
				6z	0.23	652	653	16.1	15.5	0.33	625	625	19.9	19.91	205
67	11/10/2017	131579	206	1z	0.04	624	624	19.8	20.6						
				2z	0.1	622	622	20	20.4						
				3z	0.12	615	614	18	19.1	0.04	611	611	18	18.21	206

APPENDIX 2

Table 2: AALRT North-South and East-West line curves

Station No	Curve length	Curve Radius	Comment
NS6			END
	55	150	Small
	60	150	Small
NS7			
	80	230	
NS8			
NS9			
	60	350	
NS10			
	60	350	
	80	460	
NS11			
	0	2000	
	35	300	
	30	350	
	80	350	
	60	1000	
	60	500	
	40	240	
	30	1000	
	25	1300	
NS12			
	80	240	
	60	290	
NS13			
	60	350	
	80	290	
NS14			
NS15			
	25	1000	
	45	650	
	30	1000	
	25	1300	
	0	200	
	20	50	sharp
EW16	STADIUM		
	40	250	
	25	1300	
EW17	0	2000	
	0	2000	
	0	5000	large
	65	200	
EW18			
	60	200	
	85	600	
EW19			
EW20			
	20	50	sharp
NS21			
	40	100	small
	55	100	small
NS22			
	25	1200	
	0	2000	
	25	1300	
NS23	0	2000	
	40	50	sharp
NS24			
	60	300	
NS25			
	90	400	
NS26	20	800	
	80	400	
	60	305	
	40	65	Small
NS27	15	300	
	20	1400	

APPENDIX 3

Main parameters of AALRT rail lines and Vehicle

- Track gauge: 1435mm
- Minimum radius of horizontal curve: Mainlines between sections 50m and Yard line 30m
- Minimum radius of vertical curve: 1000m
- Maximum gradient: 55%
- Type of rails for main lines and depot: 50kg/m; Maximum super elevation: 120mm Inclination at rail bottom: 1/40
- The vehicles adopt right-side running rules.
- Length of MC car 11340mm; Length of T car 3600mm, Max. width of car body : 2650mm and Car body height (to rail top) :3025mm
- Height of vehicle floor from top of rail (exit and entry areas, new wheels and empty load) ≤350 mm
- Wheelbase: unpowered bogie 1800 mm; powered bogie 1900 mm
- Bogie base 10400 mm
- Wheel diameter (new wheel) =660 mm (Max. wear) ≤ 580 mm
- Weights of vehicles: Axle load: ≤11 （1+3%） t

Table 3: Total Car body weight at empty, normal and overload condition

Loads	Carbody weight	Passenger weight	Total weight
Empty vehicle (t) (AW_1)	44	0	44
Seatingcapacity (t) (AW_2)	44	15.24	59.24
Overload capacity (t) (AW_3)	44	19.02	63.02

Note: Take 60kg as average weight of each passenger.

- Maximum operation speed:70km/h
- Maximum test speed:80km/h
- Damping: Secondary lateral oil damper + secondary vertical oil damper
- Suspension: Primary rubber spring;Secondary steel spring

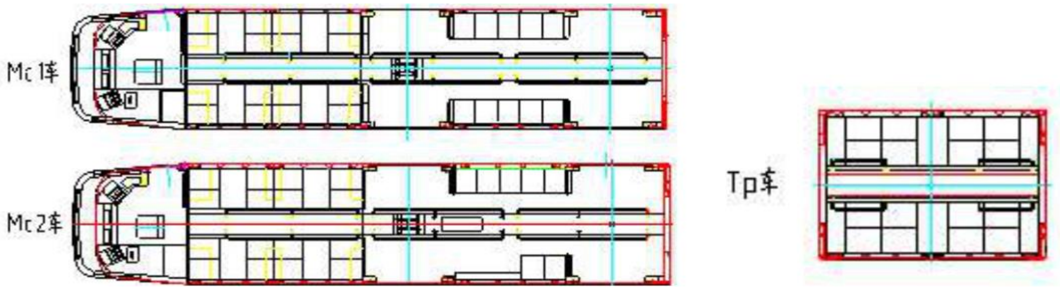

Figure 1. AALRT motor car and trailer car body module

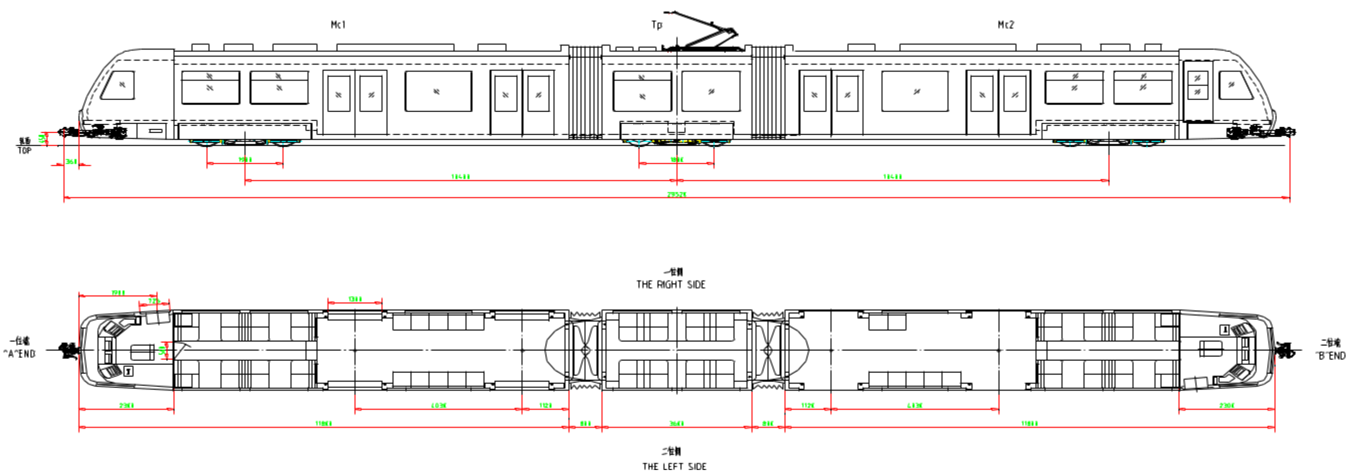

Figure 2. Overall layout of Ethiopia 70% low-floor coupler system which comprised of hinge device

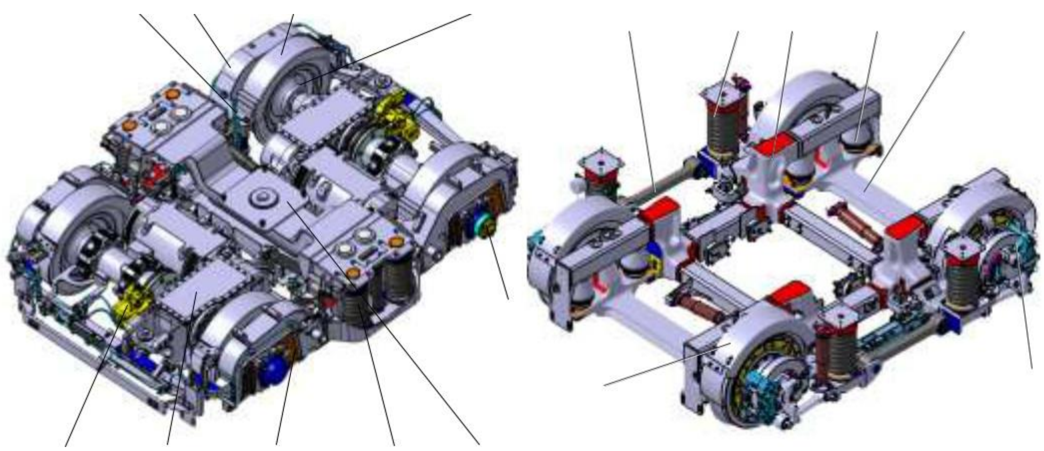

Figure 3. a) Designed structure of power bogie and b) designed structure of trailer bogie of AALRT

Table 4: AALRT train parameters

Parameters	Trailer car (Tp)	Motor car（Mc）
Mass of wheelset（kg）	1360	1587
Inertia of wheelset x/y/z（kgm ^{2}）	410/50/410	440/56/440
Mass of Bogie（kg）	4680	7200
Mass of frame and mounted parts（kg）	1960	4026
Inertia of frame (kgm ^{2}）	660/835/1410	1286/1629/2743
Inetrtia of carbody x/y/z（kgm ^{2}） ,AW0	3.69e4 / 6.84e5 /6.76e5	3.52e4 / 6.53e5 / 6.45e5
Axle load: AW0/AW2/AW3（t）	8.96/12.57 / 13.56	9.75 / 13.86 / 14.98
Diameter of new wheel (mm）	660	
Wheel /Rail profile	S1002(EN13715) /UIC60,(R330)	
Base of wheelset（mm）	2200	
Base between wheel inside planes（mm）	1380±2	
Base of bogie（mm）	12600	
Height of carbody gravity center above top of rail mm）	1428/1664(AW0/AW3,with bogie) ; 1791/1948（AW0/AW3, without bogie）	
Height of frame gravity center above top of rail (mm）	510	
Distance between left and right primary spring（mm）	1930	
Distance of left and right secondary vertical damper (mm）	1860	
Height of seconadary lateray damper,TOR（mm）	485	
Stiffness of per coned primary rubber metal spring（N/m）	9.0e6/6.8e6/1.4e6	
Damping of primary vertical damper（N/m/s）	No damper, but 2000Ns/m is consider as coned element	
Damping of secondary vertical N/m/s) per side of bogie	30000	
Damping of secondary lateral N/m/s） , per bogie	5000/0.1；7000/0.3	
Stiffness of ARB Nm/rad）	Without anti-roll bar	
Clearance of carbody lateral: free + elastic (mm）	10+15	
Stiffness of elastic stop N/m）	5.0e6	

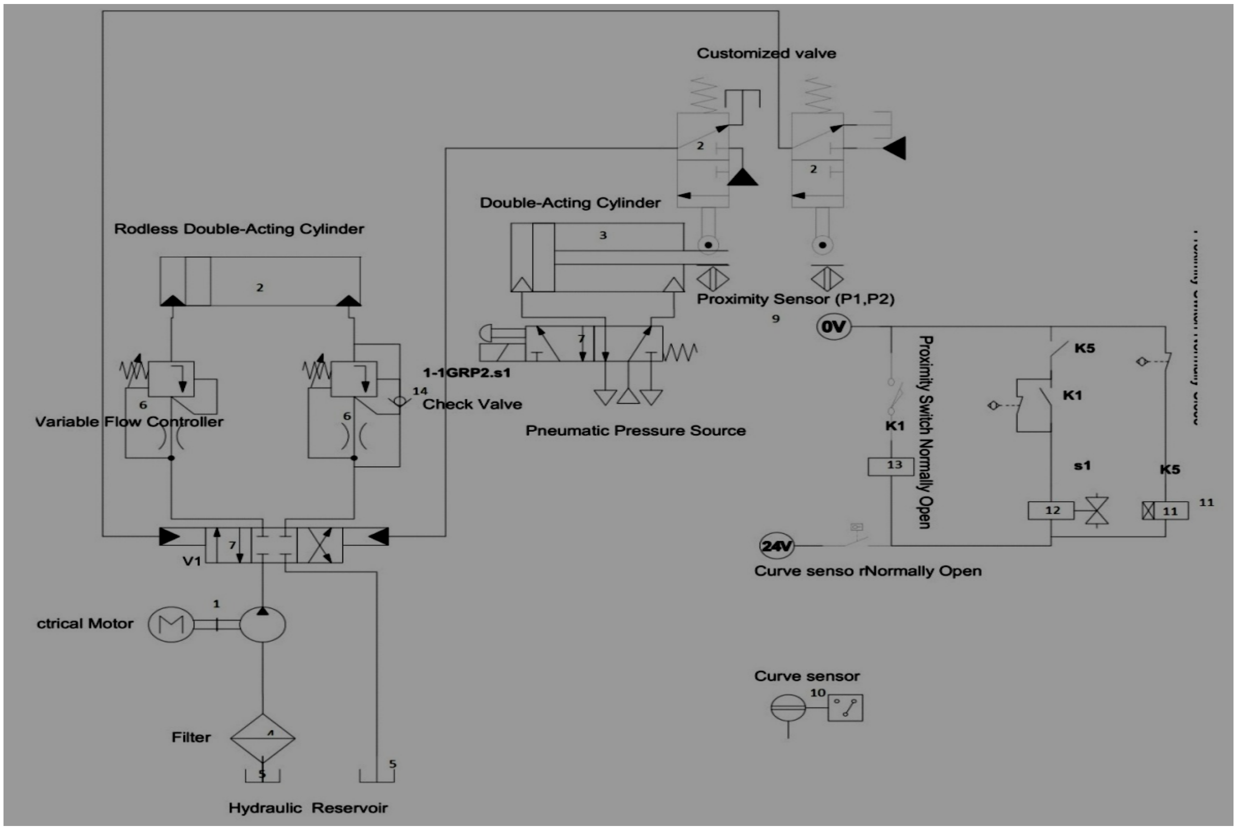

Figure 4. Part name of new lubrication system

APPENDIX 4

Important picture of simulation software

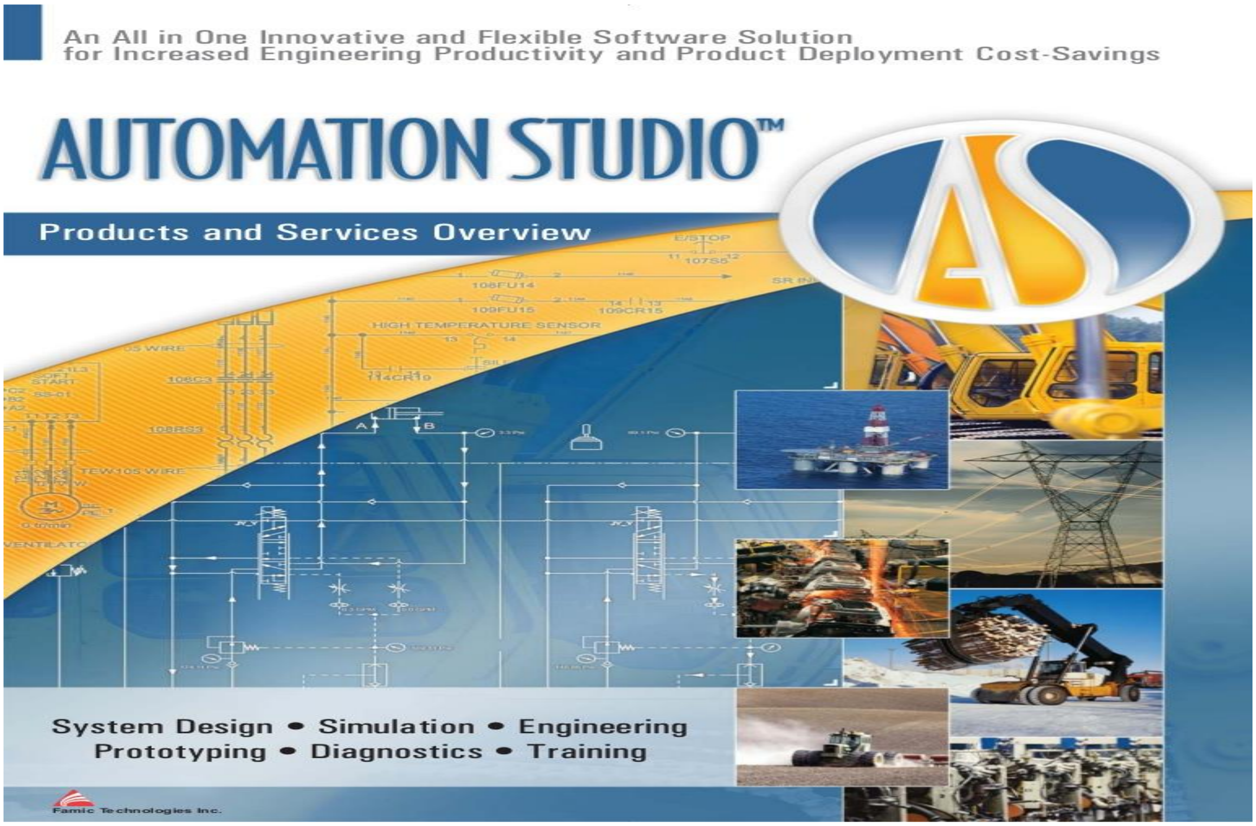

Figure 5. Background of simulation software

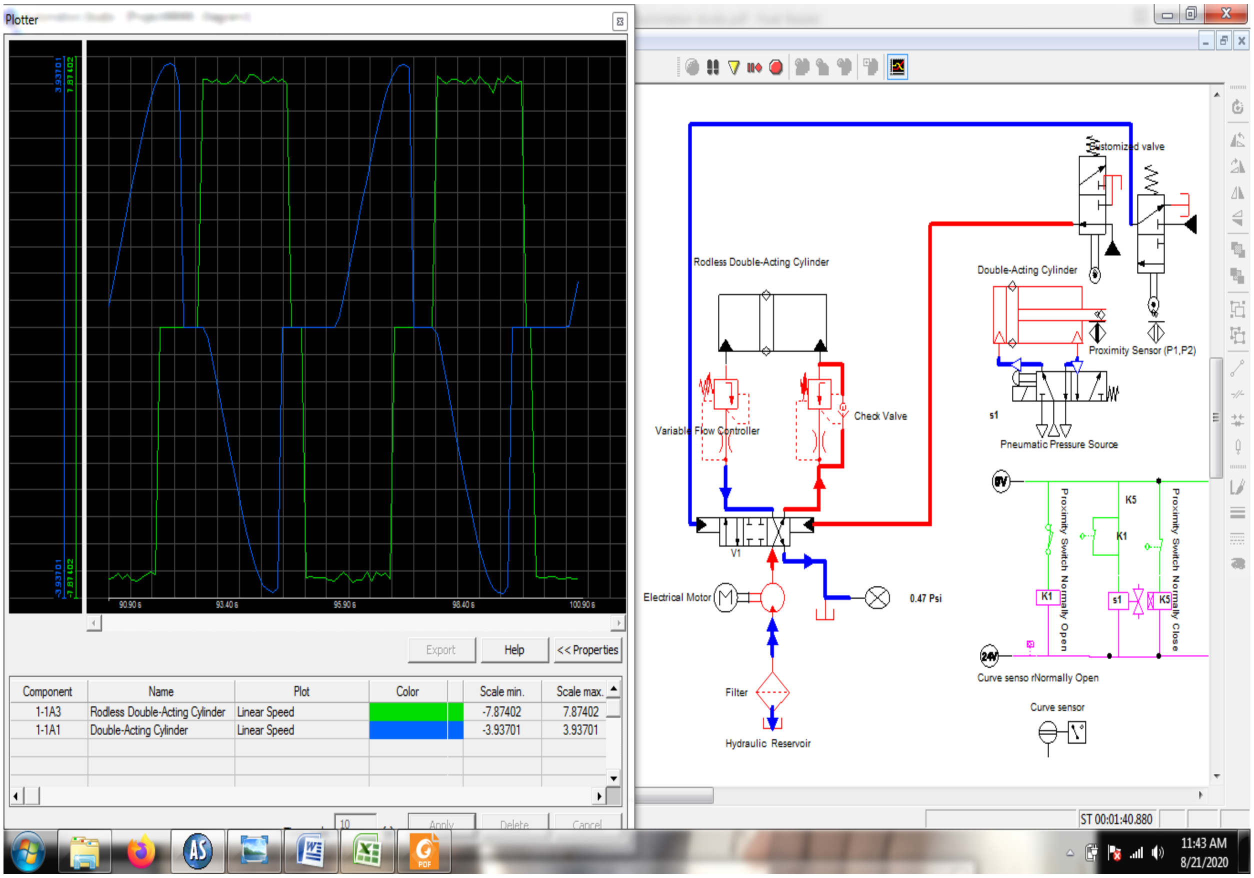

Figure 6. The graph of Pneumatic cylinder and hydraulic cylinder from simulation