Impact Analysis of Autonomous Trams in Depot

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Declaration of Authorship

I hereby affirm that I wrote the master thesis titled "*Impact Analysis of Autonomous Trams in Depot"* on my own without any assistance of third persons and without other resources and sources as denoted in my work. I indicated all parts which I integrated by wording or by meaning. This work was not in part or in all issue of other examination procedures and was not submitted to other examination authorities.

Berlin, 12th day of October 2021

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List of Abbreviations

AStriD:	Autonomous Trams in Depot
BMVI:	Bundesministerium für Verkehr und digitale Infrastruktur (Federal Ministry of Transport and Digital Infrastructure in Germany)
DFStrab:	Straßenbahnsignale in Deutschland (Service instruction manual for the tram service in Germany)
EC:	European Commission
GPS:	Global Positioning System
IKEM:	Institut für Klimaschutz, Energie, und Mobilität (Institute for Climate Protection, Energy, and Mobility)
IT:	Information Technology
ITIV:	Institut für Technik der Informationsverarbeitung (Institute for Information Processing Technology of the KIT)
KIT:	Karlsruher Institut für Technologie (Karlsruhe Institute of Technology)
LiDAR:	Light Detection and Ranging
mFUND:	Modernity Fund by the BMVI
POI:	Points of Interest
Radar:	Radio Detection and Ranging
SAE:	Society of Automotive Engineers
SDG’s:	Sustainable Development Goals
SP:	Service Personnel
ViP:	Verkehrsbetrieb in Potsdam GmbH (Public Transport Company in Potsdam)
WP:	Workshop Personnel

Abstract

As technological innovation in mobility progresses, the importance of efficient systems and economically feasible solutions becomes greater. Developments in autonomous driving technologies along with rapid advancements in artificial intelligence are changing the way current transportation systems are perceived and operated in cars, shuttles, and buses. Trams must also keep up with the present technological trends, else their operating costs and operational flexibility will lose their economic competitiveness. In order for trams to reach the stage of fully autonomous operation, some important milestones must be reached technologically, economically, and legally. An impact analysis of a digitized autonomous tram depot located in the city of Potsdam, Germany, is a stepping-stone to reach that modern vision. The main research lies in the evaluation of the economic aspects of the concept to derive a generic operational method to quantify the efficiency gains in various dimensions. Therefore, the economic analysis compares the time efficiency gains through automation with the conventional depot and provides the economic basis for transferring the concept.

Keywords: Autonomous Driving, Autonomous Trams, Automated Tram Depot, Artificial Intelligence (AI), Time Efficiency Gains, Economic Analysis, Potsdam, Germany

Introduction

1.1 Problem Statement

The world as we know it is suffering an unprecedented climate crisis. For over a century, transportation has been highly dependent on oil and other fossil fuel sources that emit greenhouse gases, which are one of the main drivers responsible for global warming. Over that period, these emissions had significant negative impacts on earth, gradually raising its temperature, increasing its weather irregularity, and hence endangering life for its current and future inhabitants. Considering this global threat, countries around the world gathered in Paris in 2015 and agreed to take strong initiatives to reduce their emission levels. This has come to be known as the Paris Agreement or Agenda 2030, where a legally binding emissions target was drafted to reduce carbon emissions, control climate change, and become more sustainable (European Union, 2015).

Since then, the future of mobility has never been under such immense pressure to transition towards more sustainable solutions. The transportation sector alone accounts for almost a quarter of Europe's greenhouse gas emissions, where 70% of those emissions comes from road transport (European Commission, 2016). Although rail transport is generally more sustainable than road transport, developments must be made to ensure it becomes even more so. Technological innovations derived from the road transport sector must be passed on to the rail sector so it can also improve and remain economically competitive. Autonomous and connected mobility solutions have a big role to play in achieving the SDG's set in the Paris Agreement. This is because they are programmed to operate on the highest safety and energy efficiency levels, which is currently unachievable due to human-error, and hence reduce the overall required danger, energy, and cost of operation.

Furthermore, the COVID-19 pandemic in 2020 has stressed the importance of automation in minimizing the negative economic impact associated with human workforce (Peterson et al., 2021). Stricter hygiene rules and preferred contactless work environments have created a surge in the need for automation, which in turn has accelerated the shift towards driverless operation in the transportation sector. Autonomous mobility solutions create a social dilemma due to the elimination of humans operating the vehicles and machines. However, a successful solution requires ecologic, economic, and social cohesion, and it is the responsibility of both governments and businesses alike to ensure that a balance is made between automation and human workforce.

1.2 AStriD Project

A pilot project named AStriD (Autonomous Trams in Depot), which is sponsored under the mFUND by the BMVI in Germany, focuses on the research and development of autonomous trams in the ViP depot located in the city of Potsdam. The project includes the examination of the necessary hardware and software components required for such operation and outlines the ease of transferability with other depots around Germany, and possibly around the EU. The aim is to correctly analyse and transmit data sets from systems running at specific times and at a certain quality to ensure that a tram can run a service process autonomously within the depot. This type of operation requires a digital map of the depot and a data hub with data integration of all systems, including obstacle detection. A data-based analysis of the entire depot and trams will not only increase efficiency but also enable new business models in the digital economy to emerge.

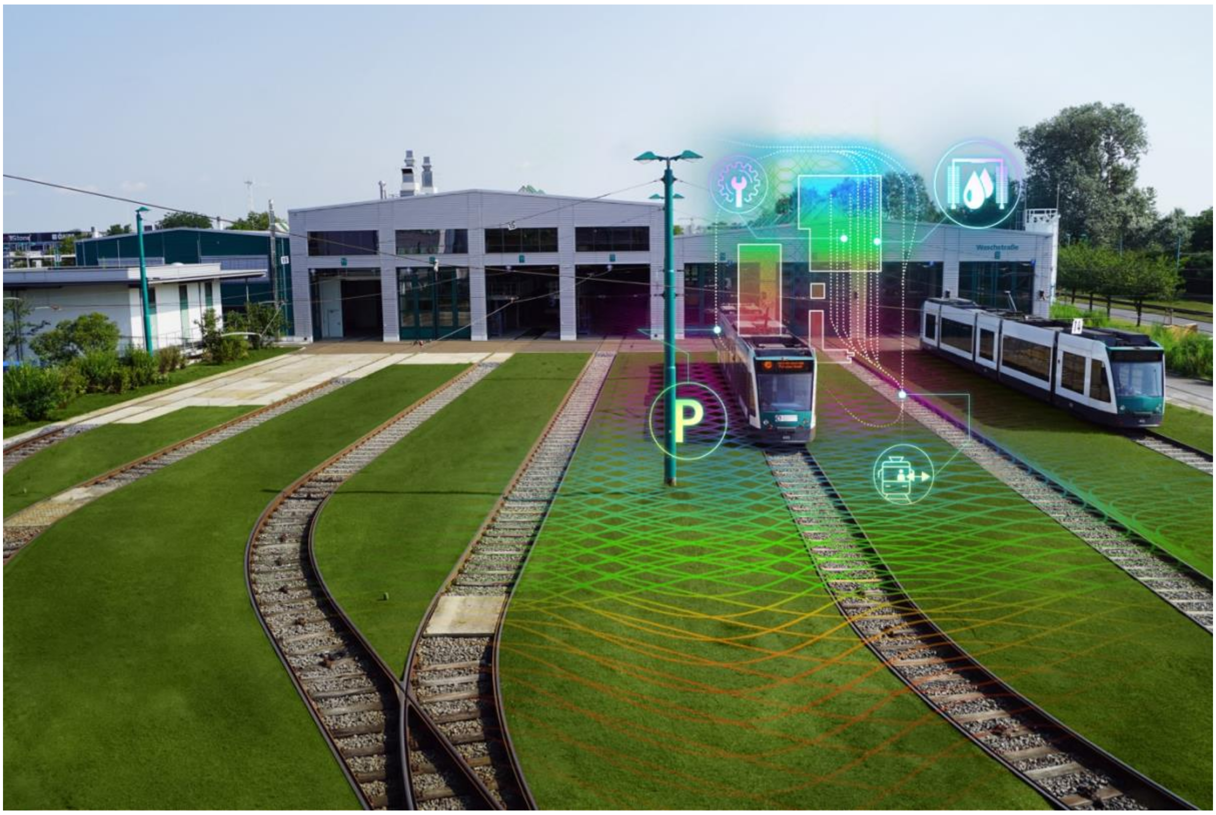


Figure 1 - AStriD Project Illustration (Siemens Mobility, 2020)

While the framework for assistance systems in the case of road vehicles has advanced, the regulations for autonomous driving in the rail sector for depots and public traffic areas has not yet been developed. The funding of this pilot project is intended to contribute to the development of this framework by bundling the competencies of the project partners, who will set the parameters for practical implementation.

The consortium project partners involved with their respective roles are:

Siemens Mobility GmbH: Leading project partner, responsible for implementing the autonomously running tram in the depot, which is integrated into the data and system landscape via the data hub from partner Codewerk and localizes itself based on the digital map from Siemens/KIT.

Verkehrsbetrieb in Potsdam (ViP) GmbH: Operates the depot, responsible for the provision and maintenance of vehicles and infrastructure, support in sharing necessary data on vehicles, infrastructure and processes, personnel support, and the joint evaluation of results.

Codewerk GmbH: Specialises in industrial communication and develops the necessary software for data communication on rail vehicles. Codewerk implements the data hub and the data integration of all systems in the project.

Institute for Information Processing Technology (ITIV) of the Karlsruhe Institute of Technology (KIT): Contributes its expertise in the automation of processes, the identification of required data and the associated machine learning.

Institute for Climate Protection, Energy, and Mobility (IKEM): Analyses and evaluates the legal and economic issues of the project. Research topics include vehicle automation and its interdependencies with data protection and data security as well as the investigation of efficiency gains.

1.3 Thesis Focus and Methodology

The motivation of this thesis, in conjunction with IKEM's work package in the AStriD project consortium, is to conduct an economic analysis on the ViP tram depot that compares the cost and efficiency gains that result from a digital depot with autonomous trams in comparison with conventional tram depots. To do so, it is imperative to recognise the boundaries and limitations of the technology, and be able to distinguish which processes will change, have the potential to change, or remain the same post-automation. The levels of automation that the project aims to reach is automation level four, and once the framework for autonomously driving the trams outside the depot is established, the vision is to reach automation level 5 (Chai et al., 2021). To better understand the differences of the levels of automation, an illustration is shown below (see Figure 2).

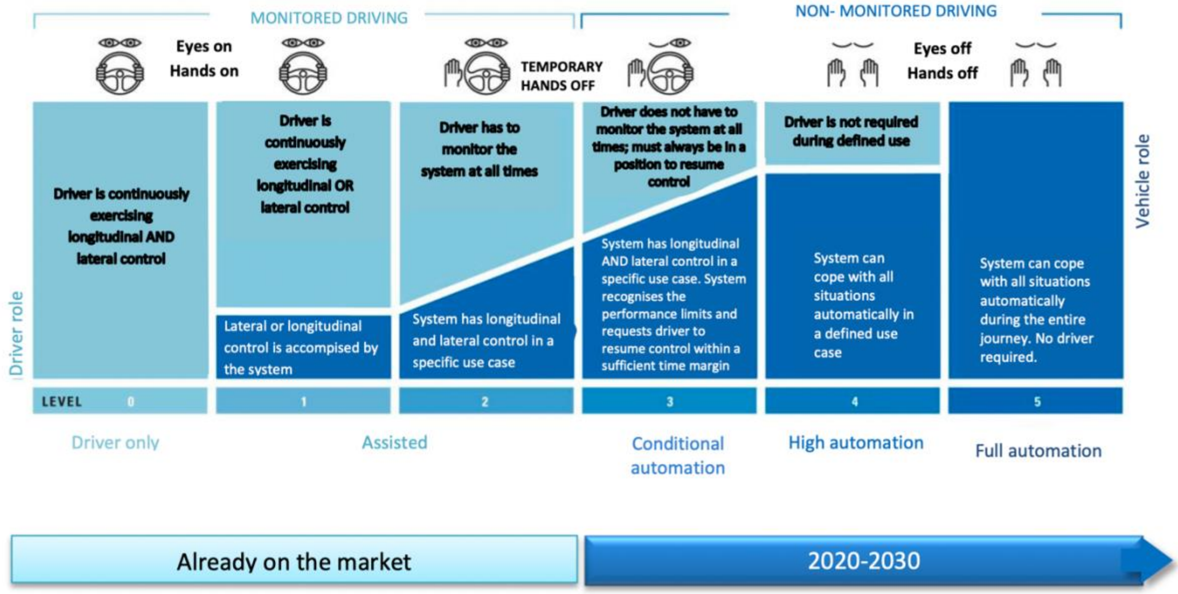


Figure 2 – Different Levels of Automation by the SAE (European Commission, 2018)

The depot must be taken as a closed system and carefully analysed in its current state of operation, where all the significant maintenance processes are documented. This is further substantiated by examining data from previous years that may aid in estimating the future number of occurrences for different processes and their manner of operation. Theories from kinematics, statistical analysis, and work study measurements are key to quantify efficiency gains and create a database that achieves an annual economic analysis. A detailed depiction of the processes post-automation must also be developed for the analysis to take place, where assumptions are made based on the state of technology and innovation reached. Once the depot is analysed, the methods, results, and conclusions will serve as a reference point and guideline, which will yield a generic model that can be transferred to other depots in Germany.

Furthermore, a digital depot with autonomous trams ultimately means improved local public transport. Once the technology has matured and the required legal framework has been established for trams to drive autonomously outside the depot, the cost of operation on the public transport company will significantly be reduced due to the reduction of personnel cost. This results in higher frequencies and availability of trams in the city, higher levels of safety, and reduced fares for passengers. This will in turn attract more people to use public transportation instead of private means, creating a more sustainable modality shift in daily mobility.

Literature Review

2.1 European Commission Strategies

The European Commission (EC) has stressed the critical role of automated and connected vehicles in decarbonizing the transport sector increasing its efficiency both economically and from an energy use perspective. The 'European Strategy for Low-Emission Mobility' discusses the importance of digital mobility solutions in meeting the Paris Agreement commitments and in making transport safer and more inclusive. The strategy emphasises the change in the way mobility is organised, which is caused by emerging business models that depend on digital and automated technology, rapid data transfer, and clearer price signals (European Commission, 2016). These business model concepts are key in promoting and incentivising multi-modality, and hence increasing the use of more sustainable transport modes such as rail or other public transport options. The social dilemma of jobs becoming redundant due to automation is addressed in the strategy by explaining how new skills will be required in technological fields to help in the transition to low-emission mobility. An agenda named 'The Commission's New Skills Agenda for Europe' is aimed at tackling this specific issue (European Commission, 2016).

Further communications from the EC titled 'On the Road to Automated Mobility and 'Europe on the Move' concentrate on establishing the necessary framework for automated and connected vehicles in the EU. The ambition is for the EU to become a pioneer in automated transport technologies and to heavily reduce the number of transport fatalities, congestion, and emission levels across the continent (European Commission, 2018b). Moreover, the EC stresses the motivation to reduce the substantial impact of human error in driving accidents by achieving 'Vison Zero', an EU goal to have zero fatalities on European roads by the year 2050. This sets the discussion on how autonomous and connected vehicles are at the forefront and continues to be the backbone of making this vision a reality (European Commission, 2018b). Further integrating the use of existing car sharing and ride hailing business models with autonomous technology in bringing door-to-door mobility for the disabled and for people who are under served by public transportation.

The strategies further tackle the need and availability for smart infrastructure as an integrative system which utilizes the benefits of 5G networks to make use of innovative technologies. These include examples such as Vehicle to X communication which supports in making transport safer and more sustainable through a higher efficiency of operation (European

Commission, 2018b). There is a potential for autonomous technology to revolutionize urban planning and re-create cities by being added to existing concepts such as car sharing and ride hailing, hence free up existing parking spaces (European Commission, 2018b). Cybersecurity, data protection, and data access are amongst the most important issues that must be tackled to make automation a safe and accessible reality for all. The legal and technical framework is being worked on and will improve drastically in the coming years (European Commission, 2018a). New approaches are also being developed regarding the certification and homologation of automated vehicles, where the methods are revised to focus on the evolutionary nature of the technology.

2.2 State of the Art

The developments made in autonomous transportation technology and their state of research are divided in this section into two parts. The first part (2.2.1 Relative Developments) discusses the international and national projects that are related to this study, whereas the second part (2.2.2 Developments by the AStriD Project Partners) discusses the developments made by the partners in the AStriD project consortium.

2.2.1 Relative Developments

In September 2016, Knorr-Bremse demonstrated self-driving trucks at the depot where a semi-trailer was able to travel from the loading docks to the front gate autonomously. Knorr-Bremse argues that autonomous manoeuvring ensures a higher level of efficiency in transport depots, where drivers can save time and conduct other activities in the depot simultaneously (Knorr-Bremse AG, 2016). The developed assistance systems can stop automatically in case of dangerous events and manoeuvre their way around obstacles back to their driving path. Knorr-Bremse is exhibiting what is technically viable and highlighting the areas that require further development.

Alstom and the French public transport company RATP successfully completed initial testing on the stabilization of an autonomous tram. The testing was conducted over a period of six months at the RATP's T7 depot in Vitry-sur-Seine located in Paris, France. The main objective of the project was to offer wide-ranging system solutions that include maintenance and enable operation within a tram depot. Using LiDAR sensor technology, the tram was able to identify obstacles in its path and react appropriately, which includes emergency braking and speed reduction depending on the presented situation (Alstom, 2017). The outcome supports the use of automated technologies within a depot, in which the tram was able to drive at the required speeds and situate itself in the correct position at POI's. This project was conducted in association with Easymile, which partially provided the necessary technology for the development of the autonomous tram tested in the depot.

In 2017, Bombardier was awarded the Innovation Leader in Rail Transport award by the European Railway Clusters Initiative (ERCI) for its obstacle detection assistance system developed for trams and other light rail vehicles (Florez, 2017). The assistance system is the first to be homologated from its kind, and according to Alexander Ketterl, Bombardier's Head of Light Rail Vehicles, the focus was on developing automated mobility solutions that are safe, cost-efficient, reliable, and sustainable. The obstacle detection assistance system helped during critical situations by warning the drivers of any potential risks ahead of time, which increased safety for all traffic participants. Furthermore, the project found that by reducing the risk of accidents, the trams will require less repairs and spare parts, hence reducing operational cost and increasing the availability of vehicles. Bombardier's obstacle detection assistance system is installed on 78 vehicles in the Verkehrsgesellschaft Frankfurt (VGF) as of 2017 in Frankfurt, Germany (Florez, 2017).

The German automotive supplier ZF is working on the possibility of manoeuvring swap bodies of trucks without drivers. The autonomous driving mode is activated by drivers after they enter the depot (Klamert, 2018). The process includes that the vehicle finds the targeted position autonomously and subsequently the intelligent swap body assistant helps with setting the old body down and swap it with the new one autonomously and without human supervision. By using LiDAR and camera-based sensors along with GPS pairing, the orientation and visibility of the trucks are autonomously accomplished. Several systems within the depot are linked to the vehicle's control system, which allows information to be processed in real-time and converted into the appropriate action or command. While the routing system is dynamic and intelligent, the designated location, tasks, routes, and positions of the vehicles in the depot are also monitored for safety and efficiency of operation.

The Fraunhofer Institute for Transportation and Infrastructure Systems is working on the development of autonomous truck technologies, of which the core is an online control system named 'HelyOS' (Highly Efficient Online Yard Operating System). The concept is aimed at autonomously controlling trucks within controlled automation zones, such as depots, logistics centres, or company premises. The notion is to safely utilize these areas which serve as ideal test fields where the traffic and speed is controllable, road approval is not required, and unauthorized personnel have no right of access (Sahn, 2018). A single operator can control several trucks at once (approximately 30 trucks) by accessing the operating system via the internet, where real-time information of all trucks are continuously updated and monitored, such as status information, charge levels and accurate location (Sahn, 2018). A digital map of the automation zone must be created to take the physical geometry of the trucks into account when they are being autonomously maneuvered.

In 2018, Thales Deutschland and AVG (Albtal-Verkehrs-Gesellschaft) worked together on a research project focused on developing an electric autonomous city train (Thales, 2018). The project consisted of two phases that were segregated into the different levels of automation, which in this project are levels three and four, respectively. In the first phase, during automation level three, the testing was conducted at the Verkehrsbetriebe Karslruhe depot, where the train was driving autonomously, however accompanied by a driver on board in case of emergencies. In the second phase, during automation level four, and in collaboration with KIT, the train was able to drive autonomously without a driver on board outside the depot. For safety reasons, intervention from the control centre over the autonomous driving of the train was possible. AVG's goal is to achieve approval for an extended series of testing on the autonomous train outside the depot and to further develop the tram to be more sustainable and have no contact wire (Thales, 2018).

Deutsche Bahn (DB) and rail companies in the transport industry worked together on a pilot project named 'AuRa' (Automatisiertes Rangieren) that investigates the automation of the shunting process (coupling/decoupling of train trailers). The shunting process requires the physical involvement of personnel in the depot or rail yard and is considered a tedious task that has high potential for automation with current existing technology. AuRa is a central IT control system that controls the mechanical components associated with shunting and controls them automatically. In 2016, testing of the control system was recorded at the Paderborn's maintenance depot, where automated shunting was successfully performed (DB Systel GmbH, 2019). The technology involved in making the automated shunting process possible included sensors and actuators that were controlled through the AuRa central control system.

2.2.2 Developments by the AStriD Project Partners

Prior to 2018, Siemens launched the Tram Assistance System which supported drivers in collision prevention. These systems were already being used on trams in several cities in Germany including Ulm and Bremen. This followed the launch of a prototype of the smart autonomous tram in Potsdam, Germany in 2018. Through this test, the tram was experiencing real-life urban traffic. Over time, data analytics and AI were used to optimise the system and enhance the operation of the autonomous vehicle (Siemens Mobility GmbH, 2020). The data provided from these projects aid in bringing the technology closer to practical feasibility.

In 2019, Siemens launched a mobility research project focused on teaching trams how to drive smart and autonomous (Siemens Mobility GmbH, 2019a). The three main challenges of the project are identifying different variables in the open infrastructure that the tram operates in (among mixed traffic and other traffic participants), achieving optimal vision of the environment it's operating in through sensors (to avoid collision), and analysing the autonomous behaviour of the tram in complex traffic situations without external interference.

The system starts with analysing the traffic environment using several camera sensors, radar, and LiDAR, which create a three-dimensional image that functions as the tram's eyes (Siemens Mobility GmbH, 2019b). The camera sensors are used for object and signal identification, radar is used for radio ranging and detection, and LiDAR is used for light ranging and detection. The sensors feed the tram with data that permit it to make decisions depending on the presented driving situation and the stationary or moving objects around it. Simultaneously, the driving situation is interpreted and evaluated using complex algorithms, leading to foreseeing developments, measuring risk, and triggering required actions. All mentioned types of sensors play a significant role in this project as they provide a consistent base for making high-speed decisions in order to ensure optimal safety in practice.

A study conducted by KIT at SSB demonstrates how cost reduction is achievable by introducing autonomous driving into bus depots (Sax & Rossel, 2021). Buses undergo different activities such as maintenance and inspection, making them one of the costliest transport means within depot operations. By introducing autonomous driving, the cost of personnel can be reduced significantly. This will manage the ratio of task to personnel, as drivers are also still required to move the vehicle from one location to the other on depot grounds prior to automation. This has been studied at the SSB depot in Stuttgart-Gaisburg where results were derived from the 150 buses present daily.

In the study, a total of nine operational steps observed at the Stuttgart-Gaisburg depot are summarized. These steps along with their average implementation times are recorded and shown in graphs and figures. Autonomous driving would be able to eliminate the walking time involved for the drivers or personnel to reach the buses or back from them to other areas in all these steps. However, the entrance to the maintenance area is an exception, as it is required by law for the bus to be driven in by the driver or depot personnel. Therefore, most of the operational procedures could be highly optimised. For the 150 buses entering Stuttgart-

Gaisburg daily, a cost of nearly 100,000 euros per year is approximately saved (Sax & Rossel, 2021). The availability of the employees or drivers to perform higher value services, rather than time spent driving or walking, is considered more significant than reducing the personnel cost. Furthermore, autonomous driving also reduces the number of injuries and damages caused by accidents or collusions. The trial of autonomous buses in Stuttgart-Gaisburg could be scaled to other even larger depots. Adding to that, new depots can be designed and developed using the data and knowledge gained from this project.

The technology developed was aimed at ensuring that the buses were not only driven autonomously in depots but also in public areas. Although the technology on such buses is compatible with the road infrastructure outside the depot and able to follow traffic regulations, the main challenge remains to be the unpredictability of events caused by road users (Lauber et al., 2016). Using radar, camera, GPS, and ultrasonic systems, the challenges of steering, acceleration, and braking are solved.

Methodology of Calculations

3.1 Depot Personnel

The segregation of responsibilities between working personnel in the depot is crucial to identifying how the processes are executed and to understanding the roles responsible for specific tasks. In this research study, three types of working personnel are considered for the analysis: drivers, service personnel (SP), and workshop personnel (WP).

List of responsibilities for drivers:

- Driving the tram outside of the depot (regular tram operation).
- Parking the tram in the depot parking hall or on the bypass track (track 44).
- Starting up the tram in the parking hall or on the bypass track (track 44) and exiting the depot.

List of responsibilities for SP:

- Conducting the sanding and washing processes.
- Manoeuvring the tram around the depot depending on the required process.
- Graffiti removal.
- Placing advertising material.
- Attaching or removing posters that are related to the tram.
- Filling up the tram's windshield reservoir with washing water.
- Tasks related to buses (since it is a mixed depot of trams and buses).

List of responsibilities for WP:

- Planned/scheduled workshop maintenance process.
- Unplanned repairs.
- Manoeuvring the tram around the depot depending on the required process.
- Taking over service personnel activities/tasks if required when they are not available.

3.2 Pre-Automation Operation in the Depot

The AStriD project focuses on the ViP tram depot in Potsdam, where trams are regularly maintained and parked throughout the year. The depot contains four major processes for tram vehicles: sanding, washing, workshop maintenance (both minor and major), and parking. The sanding, washing, and workshop maintenance operations all occur in the maintenance building, while parking is situated in a separate tram parking hall. To better visualize and understand how these processes take place, a flowchart based on the original KIT flowchart is shown (see Figure 3).

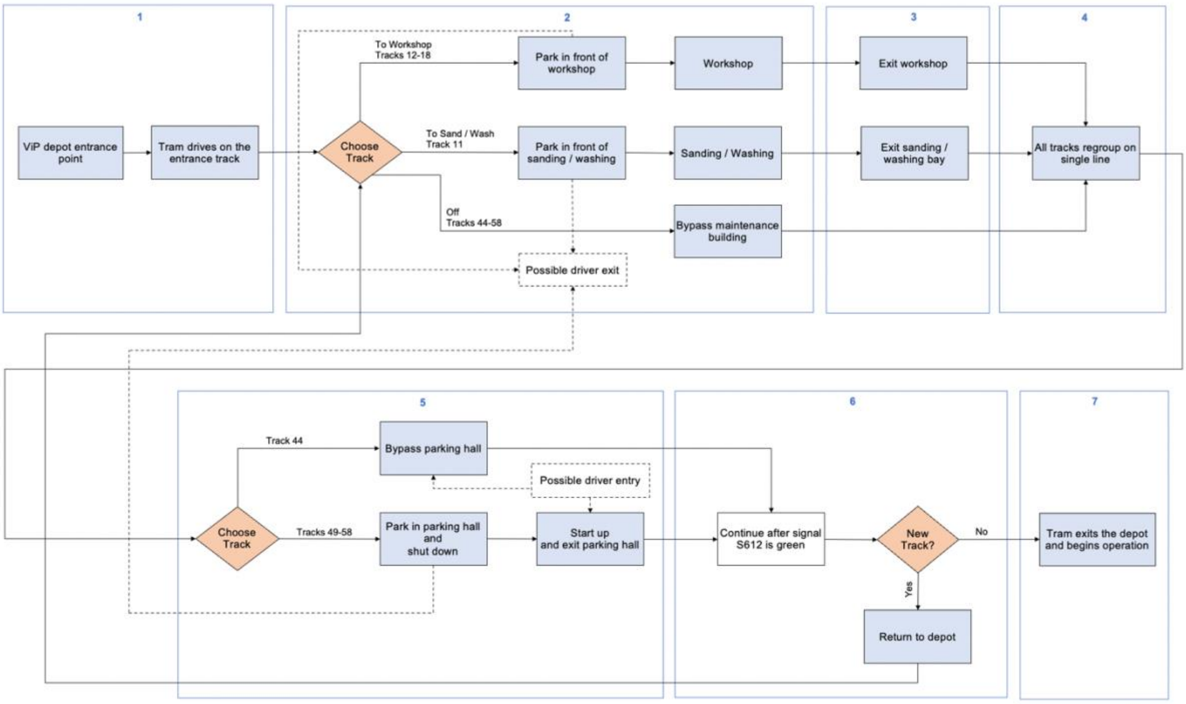


Figure 3 - Pre-Automation Flowchart (KIT, 2020)

From the initial point where the tram enters the depot in box number one until the point where the tram exits in box number seven, all the possible processes are shown in chronological order. The first track decision point occurs as soon as the tram enters the depot and is driven inside on the entrance track. There are three process options here: proceed to sanding/washing on track 11, proceed to workshop maintenance tracks on 12-18, or bypass maintenance building to tracks 44-58. At the second track decision point, the tram must decide whether it will bypass the parking hall via track 44, or if it will enter the parking hall to be parked and shut down. Finally, the third track decision point is either after the tram has started-up and exited the parking hall, or after the tram has bypassed the parking hall on track 44. The tram has two options here: exit the depot and begin tram duty operation or return to the depot for further maintenance and parking processes.

The driver entry and exit points have been added to the flowchart above (shown in dashed lines) because they are of critical importance to conceive an economic analysis. In the pre-automated depot operation, there are three locations where the tram drivers exit the tram after returning the tram to the depot. The first location is in front of the sanding and washing area. If there is a requirement for the tram to be sanded or washed, then the driver is informed upon entering the depot to park the tram in front of the sanding and washing area on track 11. Only the SP are allowed to take the tram into the sanding and washing area, where a switching process is required. When the driver exits the tram, a SP enters and conducts an inspection on the whole tram for any open windows, lost passenger belongings, or missing/used first aid kits, before driving it into the sanding and washing area.

The second location is in front of the workshop maintenance area on tracks 12-18, and similar to the sanding and washing process, the driver also exits and switches with a WP who then inspects the tram before driving into the workshop maintenance area. WP are different to SP since they are strictly responsible for workshop maintenance operations. The third and last driver exit location is in the parking hall, where the tram is driven there to be parked and shut down by the drivers if no further maintenance process is required immediately. Sometimes the drivers are told to park the tram in the parking hall even when some maintenance process is required. This could happen when the depot management schedules the maintenance operations for a later timeframe or simply for the next day.

When the tram is ready to be driven out of the depot to begin its regular operation in the city, there are two locations where the driver accesses the tram. The first location is from the parking hall, where the driver enters the tram, switches it on after conducting the safety check, exits the depot. The second location is on the bypass track called track 44, which is parallel to the parking hall from outside, where the driver also conducts the same safety check before exiting the depot. Trams are usually parked by SP or WP on track 44 after a maintenance operation is carried out so that the drivers can directly enter from there and exit the depot. This is because walking to track 44 from the canteen and office building in the depot requires less time than walking into the parking hall, hence saving time and making it easier and more convenient for the drivers.

3.3 Post-Automation Operation in the Depot

Based on the same flowchart created by KIT for the pre-automation operation in the depot, fixed entry and exit points for the drivers were added in order to directly compare and visualize the differences (see Figure 4). Ideally, for any tram depot that integrates autonomous technology, the best solution would be for the tram drivers to exit and enter the trams outside of the depot, preferably at the trams last stop before returning to the depot. This would be the best case since the drivers would not have to exit or enter from the depot, making the end or beginning of their driving shifts more convenient and efficient in terms of time, and human resource cost. However, the ViP depot entrance and exit points have heavy mixed traffic conditions, making it difficult for the drivers to enter or exit from outside the depot. Due to this reason, the driver entry and exit points post-automation remain inside the depot. The difference compared to the pre-automated operation is that there will only be one driver exit point and one driver entry point. These points have been chosen so that they do not obstruct the movement of other trams inside the depot and ensure the drivers entry or exit points are at an accessible location. The driver entry and exit points post-automation that were added to the post-automation flowchart (see Figure 4) and are in accordance with the depot map (see Figure 5).

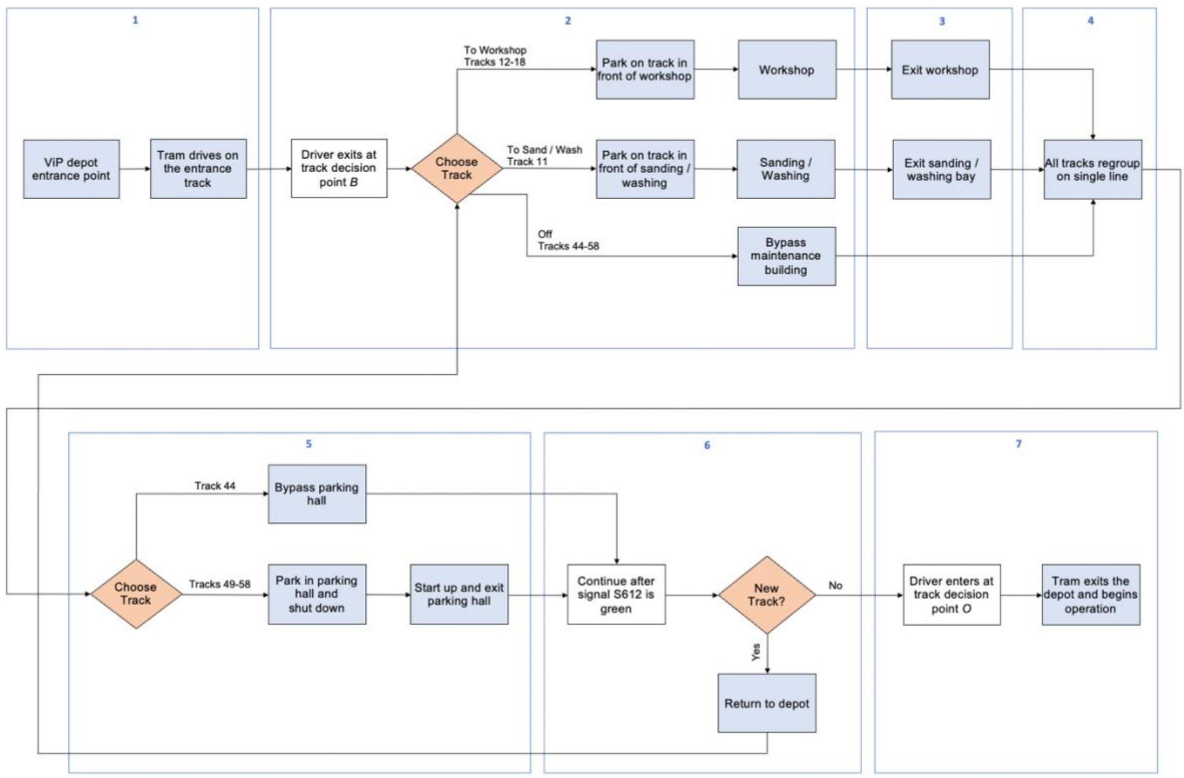


Figure 4 - Post-Automation Flowchart (KIT, 2020)

After the tram enters the depot and is driven through the entrance track, the drivers exit point shown in box number two occurs right before the first track decision point. This ensures that any process or operation that the tram requires can be chosen after the driver exits and will not force the tram to drive a longer distance to reach it, which creates an inefficiency. It is also a suitable exit location for the driver since it is at an accessible walking distance to the canteen and office building and the depot's main exit. As for the driver entry point shown in box number seven, it is located after the third and last track decision point. That way the driver only enters the tram once there are no further processes that are required before beginning regular operation in the city.

3.4 Scenario Planning

To evaluate an economic analysis as well as to compare pre-automated to post-automated tram depot operation, a list of all the possible scenarios that could occur must be generated. Using the mathematical theory of permutation, the total number of possible non-repetitive scenarios is calculated (Nicolaides, 1994). Unlike combinations, order matters in permutations, and since that is particularly important for the depot operations scenario planning, it is therefore used. Since there are only four processes that occur in the depot (sanding, washing, workshop maintenance, and parking), the total number of objects n is a constant equal to *4*. The number of objects selected r is the total number of processes involved in one scenario without repetition. When all the processes are involved in a scenario, then $r = n = 4$, and that will give a total of *24* scenarios without any process being repeated twice per scenario. When $r = 3$, the calculation result shows all possible scenarios involving only three processes, which also results in *24* scenarios. When $r = 2$ there are *12* scenarios, and logically when $r = 1$ then there are only *4* scenarios.

$$ {}_nP_r = \frac{n!}{(n-r)!} $$

Equation 1 - Permutation Formula

${}_nP_r$ = permutation
n = total number of objects
r = number of objects selected

In theory, the total number of possible scenarios for the depot is thus the sum of all these calculations, which is 64. However, to maximize efficiency and reduce the overall time of any scenario operation, important assumptions need to be set. These assumptions will aid in eliminating scenarios which are unfeasible in practice or are considered inefficient. The assumptions are made as a result of the physical limitations of the building layout which govern the order of processes in the depot. After applying the assumptions, 22 scenarios remain in total.

There are four assumptions made for the scenario database to be realised:

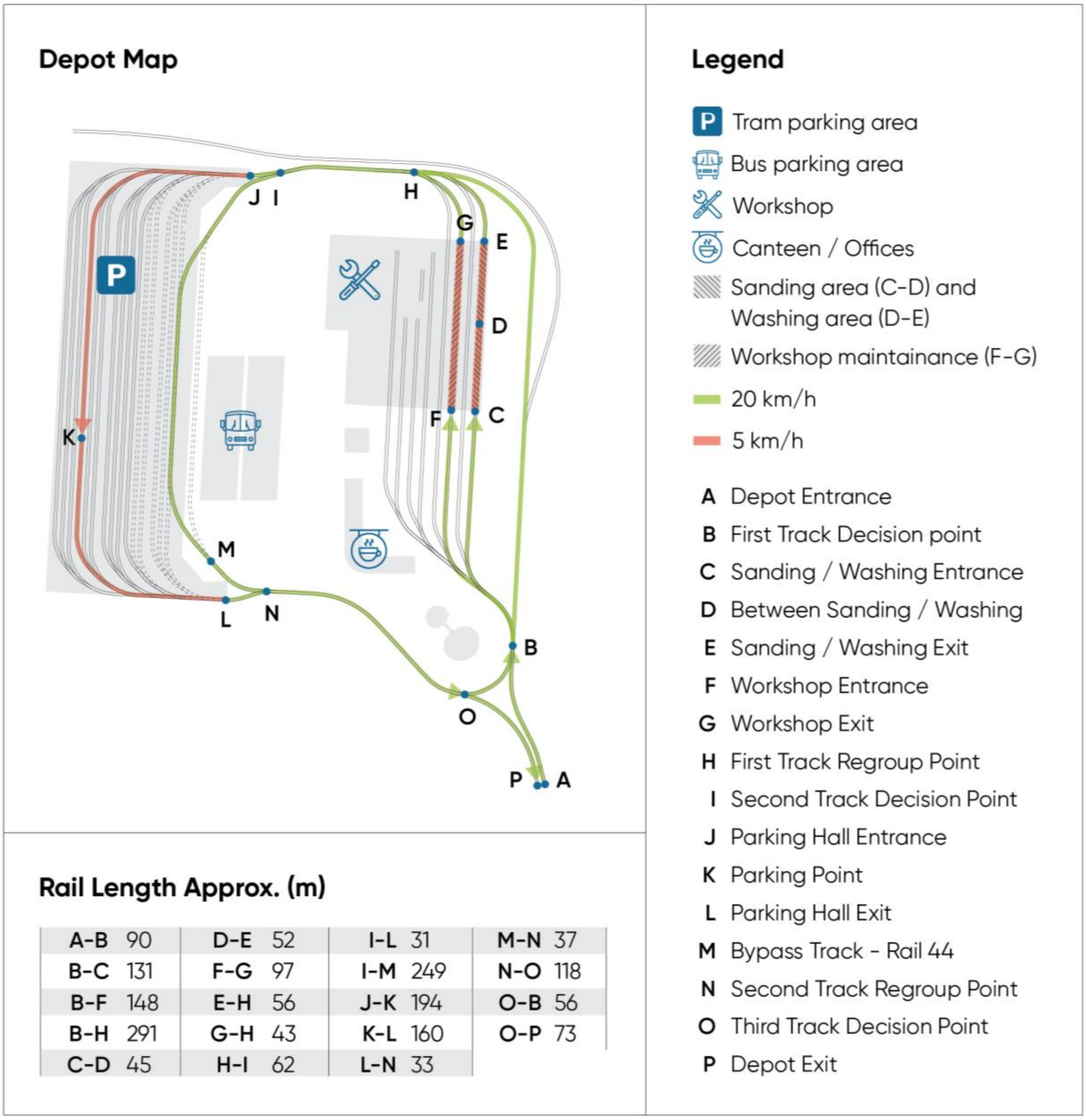
1. There is no repetition of any process in a scenario. Each process can only occur once to ensure maximum efficiency.
2. If both sanding and washing are required in a scenario, then both processes will occur only in that order.
3. If in any scenario, the workshop maintenance process is combined with either a sanding or washing process (or both), then it must only occur before them.
4. If parking is included in a scenario, then it will only take place at the beginning or at the end of that scenario. This is to ensure maximum efficiency and reduce driving time and energy consumption in the depot.

The result of 22 scenarios is split into four different types based on the calculations made above. For one-process scenarios where $r = 1$, all 4 of the scenarios are possible, and hence are included into the scenario database. For two-process scenarios where $r = 2$, only 9 out of the 12 scenarios satisfy the list of assumptions. For three-process scenarios where $r = 3$, only 7 out of the 24 scenarios are included. Finally, for four-process scenarios where $r = 4$, only 2 out of the 24 scenarios are included. The list of all 64 scenarios and the selected 22 can be found in the appendix of this study, where the excluded scenarios are marked in red and the included ones in green.

3.5 Depot Map

After the scenario database is generated and fine-tuned, the next step is to analyse and calculate the travel path and time required of the tram for each of the chosen scenarios in the depot. Once the trams become autonomous, the drivers, SP, and WP, are no longer required to drive the tram in the depot, and hence the required driving time is equal to saved operational cost compared to pre-automation. To calculate this, a map of the depot is required to show all the significant points of interest, the maximum allowed speed in all areas, and the rail length from any point-to-point.

An AutoCAD drawing, originally made by the engineers that constructed the depot, was retrieved from the ViP depot management department. The drawing is a bird's eye view of the depot made to scale, and therefore measuring all the rail lengths correctly was executed via AutoCAD. For simplicity reasons, only one track is outlined in the map for the parking hall and for the workshop maintenance. Realistically the required time and distance differences are considered negligible if the tram travels to any of the other available nearby tracks, and therefore will not affect the results in any way. The depot map shown below along with the pre-and-post automation flowcharts (see Figures 3 and 4) contain the essential information for this research study to be made possible and are the primary illustrative references for all further calculations made.



A-B	90	D-E	52	I-L	31	M-N	37
B-C	131	F-G	97	I-M	249	N-O	118
B-F	148	E-H	56	J-K	194	O-B	56
B-H	291	G-H	43	K-L	160	O-P	73
C-D	45	H-I	62	L-N	33		

Figure 5 - ViP Depot Map (Top View)

The significant points on the map reflect the boxes in the flowcharts shown previously for both pre-and-post automation and can be easily followed when they are cross-checked. The maximum allowed speed in the depot in all areas is 20 km/hr except for three areas where it is 5 km/hr, these areas are: the parking hall on tracks 49-58, sanding and washing on track 11, and the workshop maintenance on tracks 12-18. Since both sanding and washing are on the same track, it is important to note that the sanding process takes place between points *C* and *D*, and the washing process takes place between points *D* and *E*. As for the rail track that exists between points *B* and *H,* it is used as the brake testing area for the trams after a workshop maintenance operation on the brakes is carried out (this is excluded as part of the analysis since it does not have a depot exit point at the end of the track). Using this completed map showing all the rail lengths between different POI's, kinematic equations will be applied to calculate the total required driving time for each of the 22 scenarios that take place.

3.6 Calculating Driving Time for Scenarios

To be able to calculate the total driving time required for a tram in any of the scenarios that were generated, the acceleration and deceleration values of the tram must be obtained. Since there are three types of trams in the ViP depot (KT4DC, Combino, and Variobahn), the acceleration and deceleration values will vary slightly between the models. However, to simplify the approach, the acceleration and deceleration values were retrieved from the ViP depot management as average values for all tram types. Once these values have been attained, the next step is to convert the allowed velocity values in the depot from km/hr to m/s, where 20 km/hr ≈ 5.55 m/s and 5 km/hr ≈ 1.39 m/s respectively. By using the following kinematic equations, the required acceleration and deceleration distances for the tram along with the time to complete any driving route required can be calculated.

Equation 2 - Kinematic Formula

$$v = v_0 + at$$

Equation 3 - Kinematic Formula

$$\Delta x = v_0 t + \frac{1}{2}at^2$$

Equations 2 and 3 will be applied six times in total to replicate the tram's driving behaviour in the depot based on the changes of velocity that occur in any scenario. The first and second calculations yield the distances required for the tram to accelerate from 0 m/s to 5.55 m/s and to decelerate from 5.55 m/s to 0 m/s. The second and third calculations yield the distances required for the tram to accelerate from 1.39 m/s to 5.55 m/s and to decelerate from 5.55 m/s to 1.39 m/s. Finally, the fifth and sixth calculations yield the distances required for the tram to accelerate from 0 m/s to 1.39 m/s and to decelerate from 1.39 m/s to 0 m/s. Once the acceleration and deceleration distances have been attained for all the different cases, the same equations can be used to calculate the driving time required for the tram. In any scenario, each distance travelled and its required time in the depot must be split into three different parts:

1. Distance and time required to accelerate to the desired speed.
2. Time at cruising speed.
3. Distance and time required to accelerate and decelerate from cruising speed to new speed or stop.

If the tram is already at the desired velocity and there is no need to accelerate to a new velocity, then the first step can be eliminated. In the second step, the acceleration and deceleration values are equal to zero since the tram is at cruising velocity, and therefore the distance is a known value, where time is the only unknown. As for the third step, the tram will always undergo a change in velocity or come to a stop and hence both distance and time results are yielded (see Table 1 below for a summary of all the attained values).

Table 1 - Distance and Time Yielded Values

Δ Velocity $(\frac{\mathrm{m}}{\mathrm{s}})$	Acceleration $(\frac{\mathrm{m}}{\mathrm{s}^2})$	Deceleration $(\frac{\mathrm{m}}{\mathrm{s}^2})$	Distance (m)	Time (s)
0 to 5.55	0.6	-	25.7	9.3
5.55 to 0	-	-0.7	22	7.9
1.39 to 5.55	0.6	-	24.1	6.9
5.55 to 1.39	-	-0.7	20.6	5.9
0 to 1.39	0.6	-	1.6	2.3
1.39 to 0	-	-0.7	1.4	2

The distance and time yielded values are then applied to all the scenarios generated to replicate the tram's real driving behaviour for both pre-and-post automation. However, four assumptions must be made for the calculation results to be scientifically sound:

1. The tram's acceleration and deceleration values are constant in all areas around the depot, even when the tram is not travelling on a straight track.
2. The tram will maintain its constant velocity when it is at cruising speed in all areas around the depot, even when it is not travelling on a straight track.

3. The tram will always aim to achieve the maximum allowed speed on all tracks of the depot, ensuring the highest level of efficiency and fastest time possible.
4. The tram will not be driven above or below the allowed speed in all areas of the depot.

Since the tram is always driven at relatively low speeds in the depot, the assumptions made are considered realistic and ensure the highest permissible level of efficiency. In each of the generated scenarios, the number of travel paths analysed will depend on how many times the tram is required to change speed or stop, and the number of processes involved. The complete analysis will be shown in the results (Section 4.3) of this study and will show how much paid personnel time is saved when the tram is autonomously driven in the depot.

3.7 Time Measurements of Processes

The main benefit of having autonomous trams in the depot is to eliminate the running cost associated with personnel driving the trams to conduct the different required processes. The distance and time calculations show exactly how much travel time the tram needs per scenario. However, the time required for each of the processes, along with the required walking time between different locations in the depot is still unknown. To determine the total paid time for any of the scenarios for both pre-and-post automation, time measurements must be made for all the standard processes. It's also important to note that some processes such as shut down or start-up in the parking hall along with the switching time between different personnel exiting and entering the tram will be shortened or eliminated post-automation. Therefore, the total required time for the same scenario post-automation could have significant gains. Furthermore, these measurements enable the analysis of not only the average paid time per process, but also the deviations that occur in each of the required steps in a single process.
This identifies the potential for further automation of several sub-processes and is key in revealing the biggest discrepancies caused by human error or otherwise. This draws a new paradigm for where the future of automation should be.

In this study, the sanding, washing, switching, and inspection processes are each measured a total of ten times. As mentioned above, the processes are further split into sub-processes to be able to identify critical values that will reveal the consistency of performance, such as standard deviation, mean, median, and the minimum/maximum in the set of measurements. The time measurements of the workshop maintenance processes are excluded from this study since the degree of variation is too high and there is no room for further automation of this process in the near future. Moreover, the workshop maintenance operations include two types:

scheduled maintenance and unscheduled maintenance. The scheduled workshop maintenance operations are performed based on the number of kilometres driven by the tram, as for the unscheduled operations, they are performed when there is a need for them (unplanned repairs). For this research study, the generated scenarios include only the scheduled workshop maintenance operations. Since the average number of kilometres driven by the trams annually is acquired by the ViP depot management, the annual number of times the trams are driven into the workshop maintenance area for a scheduled operation is estimated. This means that although the time for the workshop maintenance operation cannot be calculated, the driving time required in any of the scenarios that involve a scheduled maintenance operation is known. Furthermore, the scheduled maintenance operations will continue to be performed manually post-automation, which means that the paid time to do the operation will be the same pre-and-post automation.

3.8 Total Average Annual Paid Time Pre-and-Post Automation

Once the total required time for all the scenarios including their respective processes is completed, the next step is to calculate how many times each scenario takes place in the depot over the course of a year. This will show the annual average driving time in the depot, both pre-and-post automation, which in turn can be reflected as saved cost that is currently paid to drivers, SP, and WP. Moreover, the results can also determine how consistent and efficient the processes can be if they were grouped correctly, as well as the total average distance that the tram travels around the depot annually to conduct all the different processes.

The number of occurrences for the sanding and washing processes is affected by the change in seasonality, whereas processes such as scheduled workshop maintenance and parking are not. Data sets for sanding and washing, which were retrieved from the ViP depot management show how many times these processes occurred in February, June, and November in the years 2019 and 2020. In this study, the available data from February will represent the winter season and is applied over the months of December, January, and February. Subsequently, the available data from June will represent both the spring and summer seasons and is applied over the months of March, April, May, June, July, and August. Finally, the available data from November will represent the autumn season and is applied over the months of September, October, and November. The data used for the annual analysis will be the average number of occurrences between 2019 and 2020 for each of the three months, and then applied across all months based on the seasonality mentioned above.

To find out the total annual number of trips the tram makes in and out of the parking hall in the depot, the average number of trams that operate daily in the city of Potsdam must be realised. This is projected by further retrieved data from the ViP depot management, which shows the average number of trams that leave the depot for operation from Monday to Friday, and on weekends, from Saturday to Sunday, when the demand is reduced. As for the scheduled maintenance operation, it is roughly performed at 5,000 kilometres intervals for each tram, and the average annual kilometres driven for all three types of trams available at the depot (KT4DC, Combino, and Variobahn) is also known from the available data. Since the number of kilometres driven monthly is not affected by the change in seasonality, it is assumed that the total kilometres driven in a year are distributed evenly across all the months.

3.9 Optimisation of Processes

The final step after finding the number of times a process occurs annually is to find out how processes should be grouped to increase operational efficiency. When processes are grouped, the time and distance required to drive around the depot and perform the processes are reduced. This means that the scenarios that combine three to four processes are more efficient in comparison to scenarios with only one or two processes. Therefore, it is important to optimise and group processes whenever possible to ensure the highest operational efficiency in the depot. The acquired data mentioned above provides a precise estimate of the number of occurrences for all the processes, which is explicitly shown in the results section of this study and will govern how many times and which of the 22 scenarios will take place annually.

Finally, an annual calculation is made based on the chosen optimised scenarios to reveal how many hours of paid time is saved due to the implementation of autonomous trams in depot. It is also essential to note that drivers, SP, and WP are all paid differently, where drivers earn the highest and SP earn the least. Hence it is cost-effective to minimize the time that drivers and WP spend driving the tram and maximize the time that SP do. Moreover, the list of generated scenarios and the results from the annual calculation could further be transferred and integrated into a depot tram management system in the future that focuses on the optimisation of different processes.

Results

In this section of the thesis, the objective is to achieve an annual paid personnel cost comparison of the depot operations pre-and-post automation, highlighting the total driving time (manual and autonomous), walking time, and personnel switching time, saved due to autonomous trams. Furthermore, the required average time to perform different processes in the depot are also measured, creating a reference point and performance manual for possible improvements made to these processes in the future. The measurements taken in this section carefully follow the procedure of work study measurements (Kiran, 2020).

First, the time measurements of the processes that take place in the depot must be accurately measured, demonstrating the average process durations, and highlighting the potential for automating specific stages of those processes in the future (Section 4.1). Once the measurements data is completed, two scenario examples are presented with illustrations to help explicitly present the logic of the calculations (Section 4.2). Subsequently, the results of all the 22 scenarios are presented, emphasising the total personnel paid time pre-and-post automation and the delta paid time differences (Section 4.3). The next step is to analyse acquired data from 2019 and 2020 to estimate the annual number of occurrences for each process (Section 4.4). Finally, an annual delta paid time calculation is presented to unveil how many hours of personnel paid time is saved due to the implementation of autonomous trams in the ViP depot (Section 4.5).

4.1 Time Measurements of Processes

To calculate the total required time for the generated scenarios, the average time of each process that takes place in the depot must be measured. Therefore, for this research study and in accordance with the ViP depot management, a total of ten measurements of time were taken with an accurate stopwatch and a designated SP for each process. The measurement parameters and description were documented prior to the depot visit and approved by the respective project partners. Since the SP was informed of the measurements that were being taken and documented, it is important to mention the Hawthorne Effect. The Hawthorne Effect suggests that when workers are aware that they are being observed and/or assessed, their productivity level rises significantly, but falls back down when they know that they are not (Sedgwick & Greenwood, 2015). However, when assessing the impact of autonomous trams in depot and calculating the time differences pre-and-post automation, it is sufficient to assume a high-efficiency level of operation.

4.1.1 Sanding

The time required for the sanding process is measured point-to-point according to the depot map (see Figure 5) in the methodology section. The measurement for the sanding process begins at point *C* when the tram begins driving into the sanding area and ends at point *D* when the tram begins exiting. The sanding process is conducted by one SP and four sandboxes need to be filled for each tram, with two insertion points on each side. As previously mentioned, there are three different types of trams available in the ViP depot, and the ten recorded measurements include all three types, however, the quantity of each type was selected at random to keep the measurements realistic.

Four distinct steps were identified during the sanding process:

A. From the moment the tram begins driving from point *C* on the depot map until the moment the SP exits the tram after parking it in the correct position for sanding.
B. From the moment the SP exits the tram until all four sand guns are inserted.
C. From the moment the fourth sand gun is inserted and until all four sand guns have been removed.
D. From the moment the last sand gun is removed, until the SP re-enters the tram and begins exiting through point *D* on the depot map.

Table 2 - Sanding Process Time Measurements

Measurement	Step A (s)	Step B (s)	Step C (s)	Step D (s)	Total Time (s)
1	35	123	94	23	275
2	30	133	135	21	319
3	32	139	114	26	311
4	33	134	108	15	290
5	31	126	98	22	277
6	36	127	93	13	269
7	31	124	89	16	260
8	39	134	109	21	303
9	38	125	132	18	313
10	33	128	96	18	275

Splitting the sanding process into sub-processes allows us to recognise where the most significant deviation lies in each step, and that ultimately determines which sub-processes have room for further automation in the future. It is important to note that during the sanding process, from when the first sand gun is inserted until the last one is removed, the time is usually consistent. This is because the same SP is responsible for inserting and removing the sand guns. What ultimately occurs is the first sandbox is filled by the time the SP returns to it after circling the tram and inserting all four. This means that regardless of the type of tram being sanded and the size of the sandbox the tram has, the required time in the pre-automated case should be the same. The measurement results for all steps (see Table 3) are reflected into box plots (see Figure 6), which are both shown below. The average time for the sanding process is highlighted in bold and is equal to 289 seconds (4:49 minutes).

Table 3 - Sanding Process Measurement Results

	Step A (s)	Step B (s)	Step C (s)	Step D (s)	Total (s)
Average	34	129	107	19	**289**
SD	3	5	15	4	21
Min	30	123	89	13	260
Q1	31	125	95	17	275
Median	33	128	103	20	284
Q3	36	134	113	22	309
Max	39	139	135	26	319

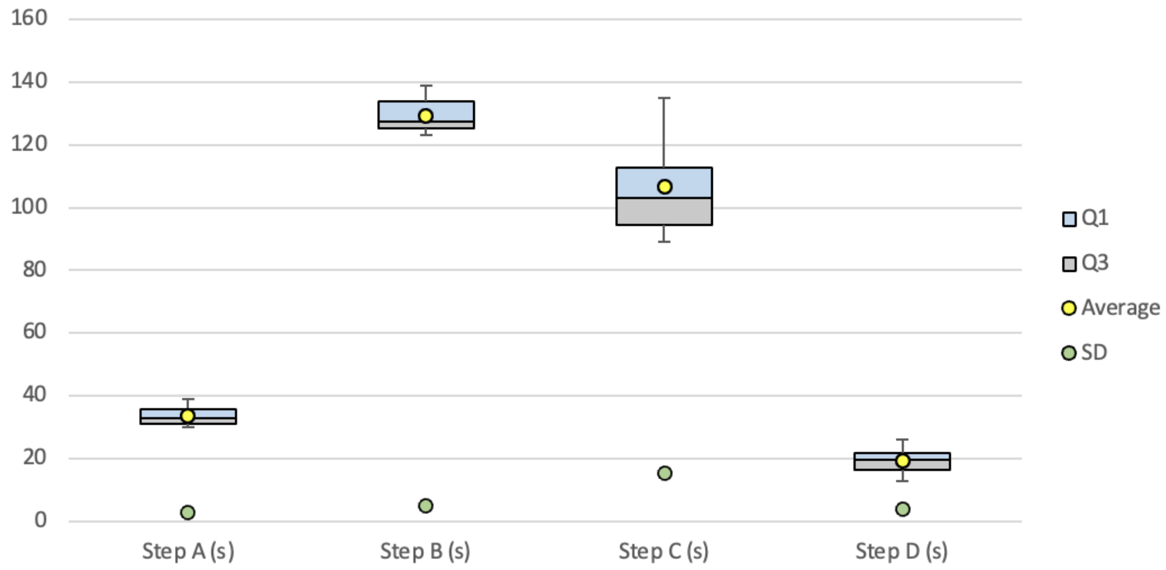


Figure 6 - Sanding Process Box Plots

In Figure 6, the average time and standard deviation are plotted for each of the four steps. The median is the line that separates Q1 and Q3 from each other, whereas the min and max are represented by the top and bottom whiskers and represent the lowest and highest recorded measurement values. These results conclude that Steps A and B are more consistent and have a lower standard deviation when compared to Steps C and D. In Step C, there are 46 seconds between the min and max values, and although Step B has a higher average time, the standard deviation in Step C is three times as much. While Step C is more prone to a higher deviation due to the nature of the process, the human error drawn from the results cannot be disregarded, which can be potentially eliminated if the sanding process becomes automated. As for Steps A and D, the time of each step would be significantly reduced under automation, as the SP does not need to enter or exit the tram before or after conducting the process.

4.1.2 Washing

Like the sanding process, the washing process is also measured point-to-point according to the depot map (see Figure 5) in the methodology section. The measurement for the washing process begins at point *D* when the tram begins driving into the washing area and ends at point *E* when the tram begins to exit after it. The exit clearance is only permissible by the depot management for traffic safety reasons. There is more than one type of washing process that occurs in the depot, however for simplicity reasons the recorded measurements were all done for the 'fast-wash' type. Once the SP parks the tram correctly in the washing area, the SP must exit the tram, shut the door, and select the washing mode via a screen outside. After the fast-washing process is completed, the service person re-enters the tram, shuts the door, and notifies the depot traffic operator that the tram is ready to exit. Only when the exit clearance has been granted, the SP can drive the tram out of the washing area.

Three distinct steps were identified during the washing process:

A. From the moment the tram crosses point *D* on the depot map until the SP exits, after parking it in the correct position for washing.
B. From the moment the SP exits the tram until the SP re-enters the tram after completing washing.
C. From the moment the SP re-enters the tram until the tram begins exiting the washing area through point *E* on the depot map.

Table 4 - Washing Process Time Measurements

Measurement	Step A (s)	Step B (s)	Step C (s)	Total Time (s)
1	54	677	115	846
2	55	700	145	900
3	67	668	73	808
4	45	660	81	786
5	61	668	121	850
6	45	692	125	862
7	44	693	136	873
8	52	696	144	892
9	42	696	106	844
10	57	720	174	951

Unlike the sanding process, the washing process is already semi-automated since the washing is done automatically by a machine. However, as mentioned in the measurement description above, the automatic washing occurs only in Step B, which is also combined with the time required for the SP to exit the tram, select the washing mode, and then re-enter after washing is completed. The measurement results (see Table 5) are reflected into box plots (see Figure 7), which are both shown below. The average time for the washing process is highlighted in bold and is equal to 861 seconds (14:21 minutes).

Table 5 - Washing Process Measurement Results

	Step A (s)	Step B (s)	Step C (s)	Total (s)
Average	52	687	122	**861**
SD	8	18	30	56
Min	42	660	73	775
Q1	45	670	108	823
Median	53	693	123	869
Q3	57	696	142	895
Max	67	720	174	961

The results are plotted into box plots (see Figure 7), where the highest standard deviation clearly occurs in Step C. This is mainly due to the response time from the operator, who is managing the tram traffic in the depot, and allows the safe release of the tram from the washing area. Thus, it is also ordinary that Step C has a higher standard deviation than Steps A and B, and this will continue to be the case post-automation. However, it is imperative to note that the washing process will become entirely automated post-automation (Wenk, 2021). This means that the involvement of the SP will be eliminated throughout the process, which also means that the overall process time will decrease.

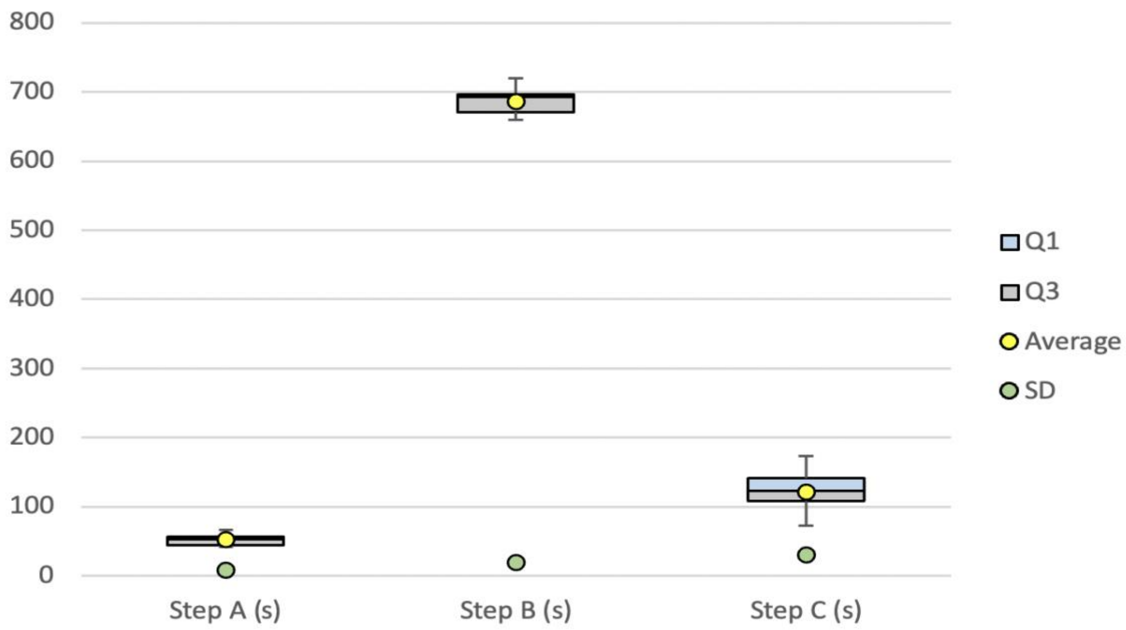


Figure 7 - Washing Process Box Plots

4.1.3 Switching & Inspection

The time required for switching and inspection between the driver and the SP/WP or vice-versa is measured in these three locations: 1. in front of the sanding and washing area at point *C*, 2. in front of the workshop and maintenance area at point *F*, 3. at rail 44 – bypass track at point *M*. It is essential to note that since the walking distance for the service personnel to switch with the driver at points *C* and *F* are similar, the measurements for both will be the same. Similarly, since the switching time at point M on rail 44 requires more walking time, the walking time will be measured on its own. The measurement will begin from the moment the driver or SP/WP exits the tram until the moment when the driver or SP/WP begins driving the tram after entering and conducting the inspection.

Two distinct steps have been identified during the switching and inspection processes:

A. From the moment the driver or SP/WP exit the tram until the driver or SP/WP enter the tram.
B. From the moment the driver or SP/WP enter the tram until the moment the tram begins driving after the tram inspection is conducted.

Table 6 – Switching & Inspection Processes Time Measurements

Measurement	Step A (s)	Step B (s)	Total Time (s)
1	9	60	69
2	13	76	89
3	11	59	70
4	11	52	63
5	11	67	78
6	11	58	69
7	9	52	61
8	13	54	67
9	10	76	86
10	11	55	66

The switching between the driver, SP, and WP can occur multiple times within the same scenario depending on the processes involved. However, the inspection process logically only occurs once per scenario and takes place directly after the first switching process. The inspection is conducted by either the SP or WP, depending on who receives the tram from the driver after the tram enters the depot and is driven to its required process.

Table 7 - Switching & Inspection Processes Measurement Results

	Step A (s)	Step B (s)	Total (s)
Average	**11**	**61**	**72**
SD	1	9	10
Min	9	52	61
Q1	10	54	64
Median	11	59	70
Q3	11	65	76
Max	13	76	89

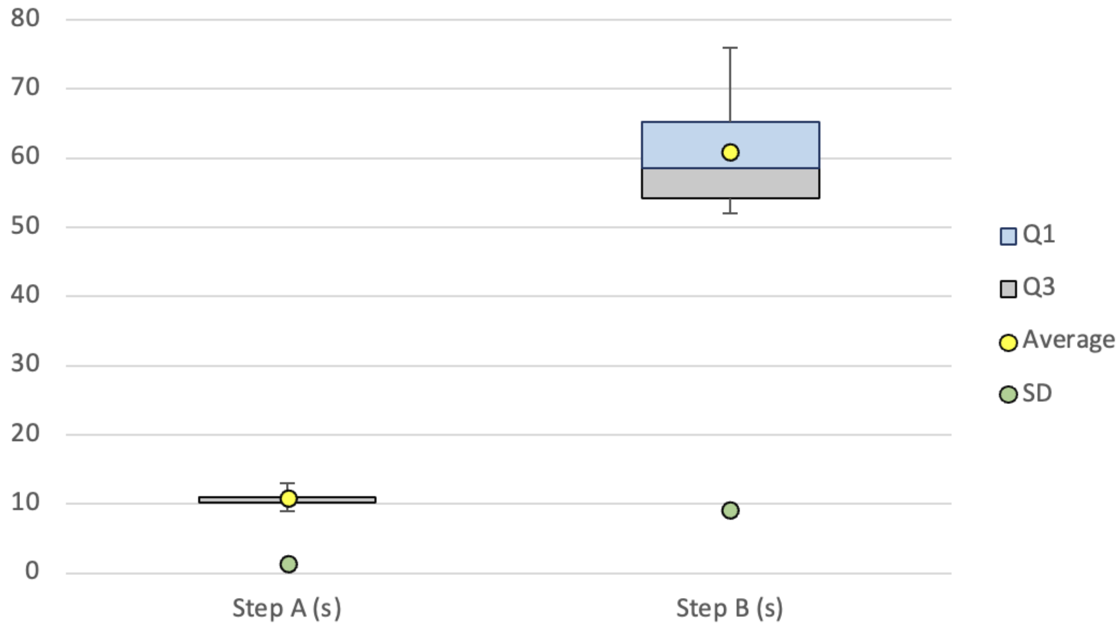


Figure 8 - Switching & Inspection Processes Box Plots

The measurement results (see Table 7) are very coherent overall and within reasonable limits. As it is visually seen in Figure 8, the switching process (represented by Step A), has a negligible standard deviation, with the average value equal to the median. As for the inspection process (represented by Step B), the gap between the min and max values are explained by the different sizes of trams due to the three available types in the depot. The SP or WP enters the tram and inspects it all the way to the end for any open windows, lost items from passengers, or missing first aid kits, which requires more time if the tram length is longer.

Moreover, when the switching process between drivers and SP/WP occurs at point *M*, the SP/WP must also walk the distance from point *M* back to either the sanding and washing area at point *C* or the workshop area at point *F* (see Figure 5). When the SP and WP switch with each other, one of the two must also walk back to their working area, and this is between points *C* and *F*. The walking time is accounted for in all the pre-automated scenarios since it is paid personnel time, and therefore the walking time must be calculated. This calculation is achieved by measuring the distance of the walking path using the given AutoCAD drawing and taking the average walking speed (1.4 m/s) as a constant. Using the kinematic formula (see Equation 3), and assuming that acceleration is equal to zero, the walking time between these points is calculated (see Table 8). The walking time results will be added to all the scenarios that involve walking after or before a switching process at the mentioned points for SP and WP.

Table 8 - Walking Time for Switching Process

Walking Path	Distance (m)	Time (s)
C ⇔ F	13	10
C ⇔ M	186	133
F ⇔ M	173	124

4.1.4 Parking

The time measurements for the parking process were not included in the scope of this research study due to specific limitations in doing so at the depot. However, since the analysis is focused on the paid time of performing a process and not the overall time, the DFStrab states that drivers are compensated for 5 minutes of extra paid time when they park the tram after entering the depot and ending their shift. When drivers end their work shift and return to the depot, there are three locations where they park the tram: 1. in front of the sanding and washing area, 2. in front of the workshop maintenance area, and 3. the parking hall (represented on the depot map in Figure 5 as points *C*, *F*, and *K,* respectively). The paid compensation considers the time required for the driver to shut down the tram, conduct the inspection (if required), and walk to the canteen and office building. It is also important to mention that drivers only conduct the tram inspection when they park in the parking hall at point *K*, otherwise it is conducted by the SP or WP after the switching occurs. A similar paid compensation of 5 minutes is considered when drivers begin their shift at the depot, which reflects the time required for them to walk to the tram from the canteen and office building to either: 1. parking hall, or 2. bypass track 44, which are represented on the depot map (see Figure 5) as points *K* and *M*, respectively. After entering the tram and performing the start-up procedure, the drivers must also do the testing of operational and traffic safety, according to the DFStrab, before exiting the depot and beginning regular tram operation in the city.

Unlike drivers, SP and WP work only in the depot and do not get compensated extra for the parking process since it is part of their work description. However, the walking time required for the SP to walk from the parking hall to the sanding and washing area at point *C,* or the WP to the workshop area at point *F,* or vice-versa, must be calculated and added to the scenarios as paid time. Applying the same logic used to formulate Table 8, the walking time between these points is shown in Table 9 below.

Table 9 - Walking Time for Parking Process

Walking Path	Distance (m)	Time (s)
C ⇔ K	328	235
F ⇔ K	315	225

4.2 Pre-and-Post Automation Scenario Examples

In this section, two scenario examples are visually illustrated to highlight the logic behind the calculations presented in Tables 10, 11, 12, and 13. The illustrations shown reflect the travel routes and transformations pre-and-post automation. The first example is a simple scenario involving only two processes (scenario 5), whereas the second example is a more complex scenario involving all four processes (scenario 21).

The time required to perform any of the mentioned driving routes in the scenario examples is calculated using the yielded values shown in Table 1 and the kinematic equations represented by Equations 2 and 3, which are explicitly discussed in the methodology (Section 3.6). As for the mentioned time for each of the processes, the average recorded time is presented based on the measurements taken in the depot and shown in Tables 3, 5, and 7. Finally, the walking time mentioned for the SP/WP to move around the depot after a switching or parking process occurs is presented in Tables 8 and 9, respectively, which naturally occurs only in the pre-automated part of each scenario.

4.2.1 Two-Process Scenario – Scenario 5

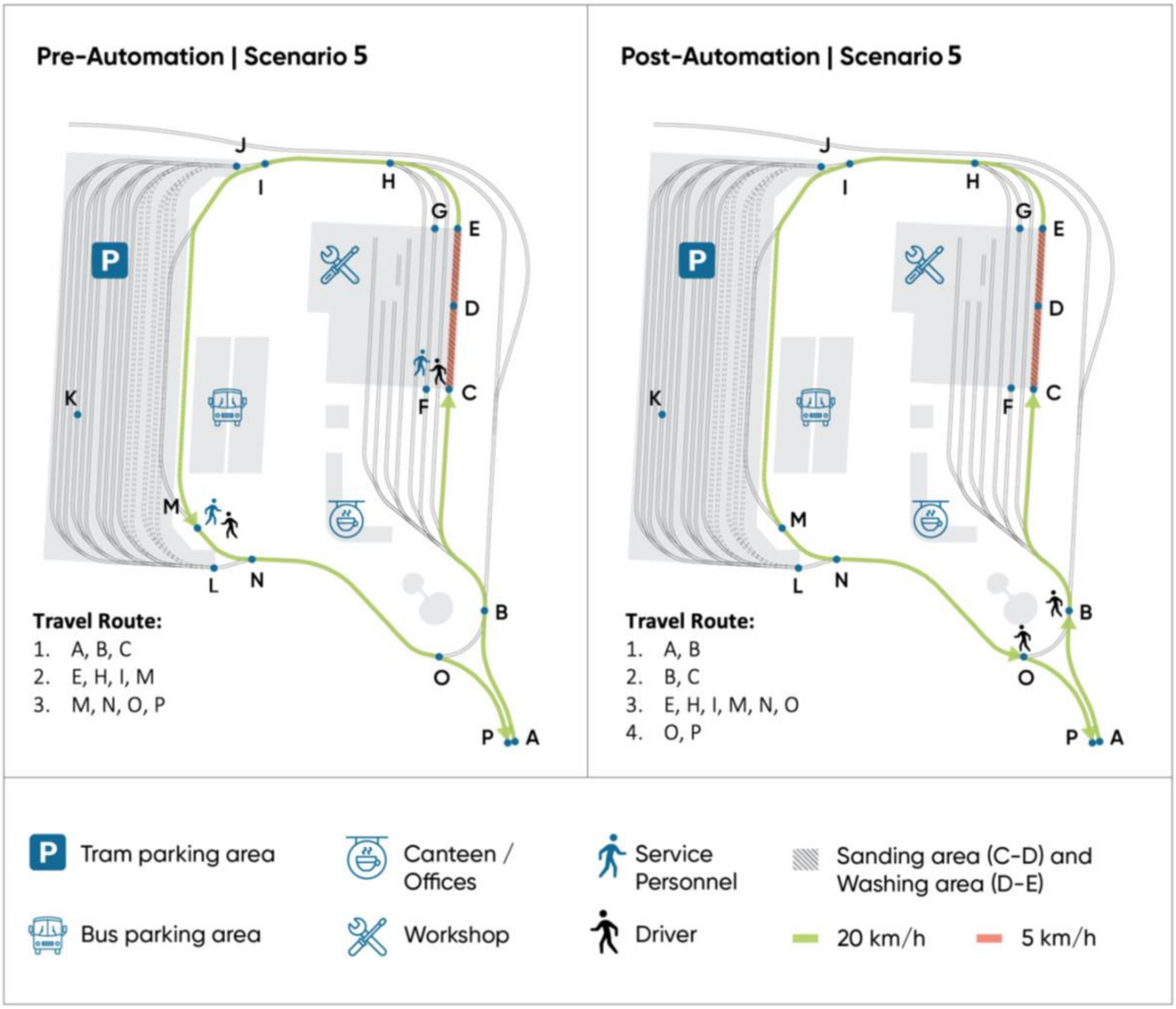


Figure 9 - Scenario 5 Illustration

Pre-Automation:

The tram enters the depot at point *A* at the maximum allowed velocity of 20 km/hr ≈ 5.55 m/s, where the first travel route is through points (*A, B, C)*. Before stopping at point *C*, the tram must decelerate from its cruising velocity to zero. The time required for the tram to drive the first travel route is equal to 43.8 seconds. As shown in Figure 9 at point *C*, the switching occurs next, where the driver exits the tram, and the SP enters, this process has an average measured time of 11 seconds. The driver walks back to the canteen and office building, which according to the DFStrab is compensated 300 seconds of paid time, meanwhile the SP conducts the tram inspection which has an average measured time of 61 seconds.

The SP then performs the sanding process, from points *C* to *D*, followed by the washing process, from points *D* to *E*, which have average measured times of 289 seconds and 861 seconds, respectively. The SP then drives the tram out of the washing area on route (*E, H, I, M)*. In this travel route, the tram must accelerate from zero to 5.55 m/s, cruise at that velocity, and then decelerate back to zero before stopping at point *M*, which in total requires 72.7 seconds. At point *M*, the driver walks from the canteen and office building and switches with the SP. The driver is compensated 300 seconds for this, and the switching process requires 11 seconds. The SP must then walk back to the sanding and washing area (from point *M* to point *C*), which requires 133 seconds. Finally, the driver starts-up the tram and drives on route (*M, N, O, P).* In this travel route, the tram accelerates from zero to 5.55 m/s and cruises at that speed until it exits the depot, which requires 49.7 seconds.

In total, the scenario requires approximately 2,132 seconds (35:32 minutes) to be completed, where all the recorded process and driving time is personnel paid time.

Post-Automation:

In the post-automation scenario, the driver exit and entry points are fixed based on the physical ViP depot layout (see points *B* and *O* in Figure 9, respectively). The tram enters the depot at point *A* at the maximum allowed velocity of 20 km/hr ≈ 5.55 m/s and decelerates before it stops at point *B*, this short travel route requires 20.2 seconds. The driver exits at point *B* and walks to the canteen and office building, which is compensated as 300 seconds of paid time. The tram then autonomously drives on the travel route (*B, C),* where it accelerates from zero to 5.55 m/s, cruises at that speed, and then decelerates back to zero when it reaches point *C*, this requires 32.2 seconds. The SP then conducts the inspection process, which is measured at an average of 61 seconds.

Sanding and washing then require 289 seconds and 861 seconds, respectively, however only the sanding process is considered as paid time since washing occurs autonomously. After the sanding and washing processes are completed, the tram autonomously drives on the travel route (*E, H, I, M, N, O),* where it accelerates to 5.55 m/s, cruises at that velocity, and then decelerates to a stop at point *O*. The driver then walks from the canteen and office building to point *O* and enters the tram, this is compensated as 300 seconds of paid time. Finally, the driver drives the tram on the depot exit travel route (*O, P),* where the tram accelerates to 5.55 m/s and cruises at that speed until it exits the depot, this requires 21.7 seconds.

In total, the scenario requires approximately 1,986 seconds to be completed, however the calculated time that the tram drives autonomously, and the time of the autonomous processes, must be subtracted from the result to attain the delta total paid time. The autonomous driving time for this scenario is 133 seconds, and the autonomous washing process is timed at 861 seconds, making the total personnel paid time 992 seconds (16:32 minutes).

4.2.2 Four-Process Scenario – Scenario 21

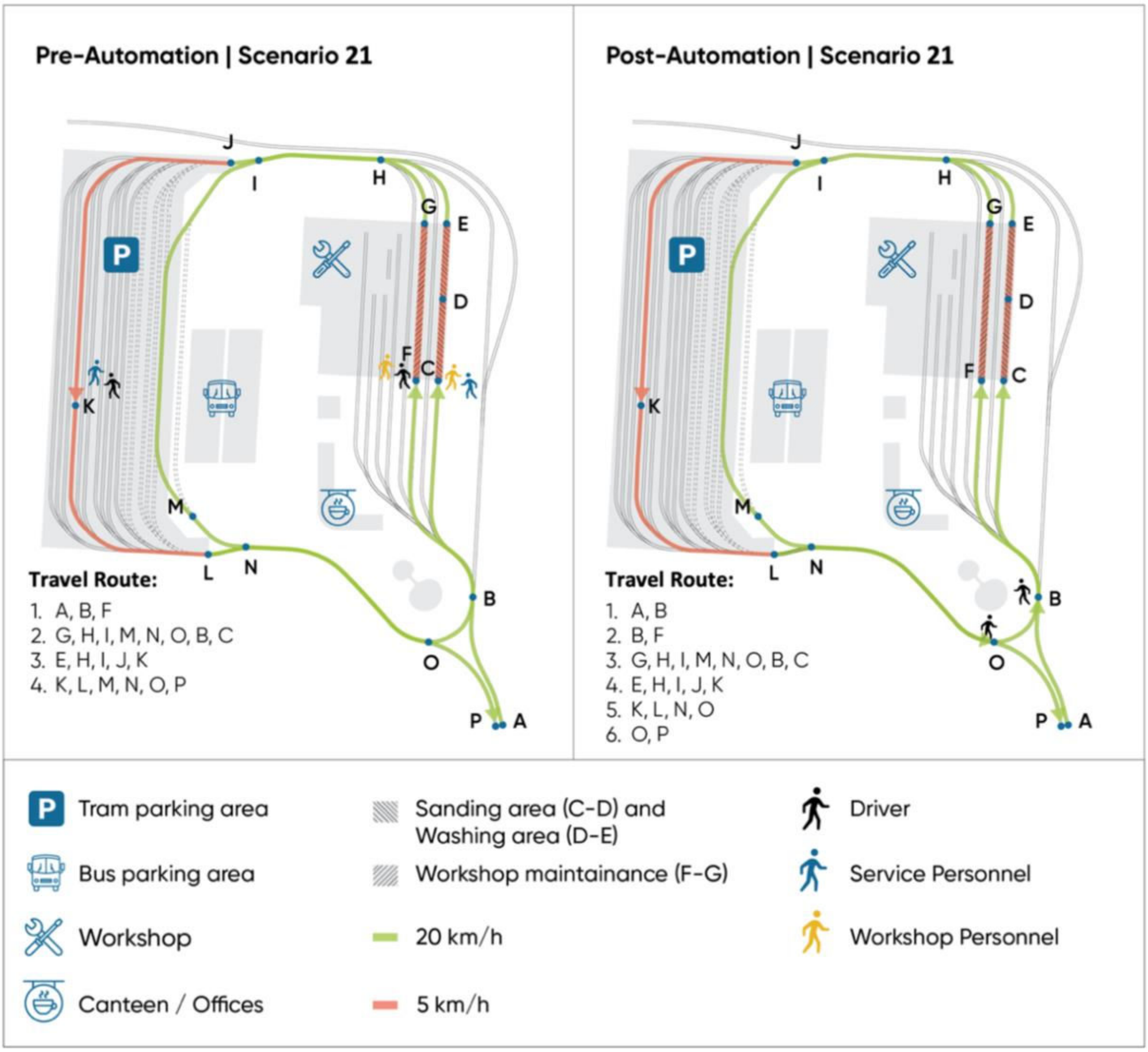


Figure 10 - Scenario 21 Illustration

Pre-Automation:

The tram enters the depot at point *A* at the maximum allowed velocity of 20 km/hr ≈ 5.55 m/s, where the first travel route is through points (*A, B, F*). The tram decelerates from its cruising velocity and comes to a stop at point *F*, this travel route requires 46.8 seconds. The driver switches with the WP, which requires a measured average time of 11 seconds, and then walks to the canteen and office building, which is compensated to the driver as 300 seconds of paid time. The WP then conducts the tram inspection, which requires a measured average time of

61 seconds. After the workshop maintenance operation is completed, the WP enters the tram and drives it to the next required processes, sanding and washing. To get there, the WP drives on the travel route (*G, H, I, M, N, O, B, C),* where the tram accelerates from zero to 5.55 m/s, cruises at that speed, and then decelerates back to zero and stops at point *C*, this requires 132 seconds. The WP switches with the SP, which requires 11 seconds, and then walks back to the workshop (from point *C* to point *F*), which requires 10 seconds. The SP then conducts the sanding and washing processes, which require 289 seconds and 861 seconds, respectively.

The next process is to park the tram in the parking hall for overnight shut down, where the SP drives the tram on the travel route (*E, H, I, J, K).* It is important to note here that this travel route requires a change in speed from 20 km/hr to 5 km/hr when entering the parking hall, since the maximum allowed speed in the parking hall is 5 km/hr $\approx$ 1.39 m/s. Hence, the tram accelerates from a standstill at point *E* to 5.55 m/s, cruises at that speed, then decelerates to 1.39 m/s before entering the parking hall at point *J,* and then cruises at the new speed until it comes to a stop at point *K*, this travel route requires 172.2 seconds. The SP conducts the shut down process which requires 60 seconds and walks back to the sanding and washing area (from point *K* to point *C*), which requires 235 seconds.

The next day, the driver walks from the canteen and office building to the parking hall and enters the tram and conducts the start-up process at point *K*, which is compensated as 300 seconds of paid time. The driver then drives the tram on the final travel route (*K, L, M, N, O, P),* where the tram accelerates from standstill to 1.39 m/s, cruises at that speed until reaching point *L,* and then accelerates again to 5.55 m/s and maintains that constant speed until exiting the depot at point *O*. The final travel route requires 163.2 seconds.

In total, scenario 21 requires approximately 2,652 seconds (44:12 minutes) to be completed, where all the recorded times are paid to the driver, SP, and WP. It is also crucial to note that the workshop maintenance operation time is not recorded due to its high degree of variation, as explained in the methodology section of this study. However, as previously noted, it will not affect the delta paid time pre-and-post automation, since it does not have potential to be automated soon, and hence the process time will be the same in both.

Post-Automation:

The tram enters the depot at point *A* at the maximum allowed velocity of 20 km/hr ≈ 5.55 m/s and then decelerates before it stops at point *B*, this requires 20.2 seconds. The driver then exits at point *B* and walks to the canteen and office building, which is compensated as 300 seconds of paid time. The tram then autonomously drives on the travel route (*B, F),* where it accelerates from zero to 5.55 m/s, cruises at that speed, and then decelerates back to zero when it reaches point *F*, this requires 35.3 seconds. The WP then conducts the inspection process, which is measured at an average of 61 seconds. After the workshop process is completed, the tram autonomously drives to the sanding and washing area, and takes the travel route (*G, H, I, M, N, O, B, C),* where the tram accelerates from zero to 5.55 m/s, cruises at that speed, and then decelerates back to zero and stops at point *C*, this requires 132 seconds. The SP then conducts the sanding and washing processes, which require 289 seconds and 861 seconds, respectively.

The next required process is for the tram to be parked in the parking hall for an overnight shut down. The tram then autonomously drives on the travel route (*E, H, I, J, K),* where it accelerates from zero to 5.55 m/s, cruises at that speed, then decelerates to 5 km/hr ≈ 1.39 m/s before reaching point *J*. The tram then cruises at 1.39 m/s in the parking hall before it decelerates and comes to a stop at the parking location at point *K* and autonomously shuts down, this travel route requires 172.2 seconds.

The next day, the tram autonomously starts up and drives on the travel route (*K, L, N, O),* where it accelerates from zero to 1.39 m/s, cruises at that speed until it reaches point *L*, it then accelerates again to 5.55 m/s, cruises at that speed, and then decelerates before coming to a stop at point *O*. The driver walks from the canteen and office building to the tram and enters at point O, which is also compensated to the driver as 300 seconds of paid time. Finally, the driver drives the tram on the depot exit travel route (*O, P),* where the tram accelerates to 5.55 m/s and cruises at that speed until it exits the depot, this requires 21.7 seconds.

In total, scenario 21 requires approximately 2,342 seconds to be completed. However, like the first example shown in scenario 5, the autonomous driving time, and the autonomous processes time, must be subtracted from the result to attain the delta total paid time. The autonomous driving time for this scenario is 489 seconds, and the autonomous washing time is 861, making the total paid time 992 seconds (16:32 minutes).

4.3 Scenario Results

As illustrated and explained above in the pre-and-post automation scenario examples, the same logic is applied to all the generated 22 scenarios. The scenarios are split into four types: one-, two-, three-, and four-process scenarios (see Tables 10, 11, 12, and 13, respectively). The total paid time pre-and-post automation for all the scenarios are presented along with the delta paid time. The delta paid time result shows how much paid time is saved due to automation of trams in depot per scenario, i.e., the pre-automation paid time minus the post-automation paid time. As previously mentioned, the workshop maintenance process does not have an average time measurement due to its high degree of variation, and it is not added to the total paid time results presented in the tables below. However, since the time required to perform a workshop maintenance process will be the same pre-and-post automation, the delta paid time column will not change, keeping the delta paid time result the same.

Table 10 - One-Process Scenarios

Scenario	Process	Pre-Automation Paid Time (s)	Post-Automation Paid Time (s)	Δ Paid Time (s)
1	Sanding	1,271	992	279
2	Washing	1,843	703	1,140
3	Workshop	974	702	272
4	Parking	991	642	349

Table 11 - Two-Process Scenarios

Scenario	Processes	Pre-Automation Paid Time (s)	Post-Automation Paid Time (s)	Δ Paid Time (s)
5	Sanding, Washing	2,132	992	1,140
6	Sanding, Parking	1,635	992	643
7	Washing, Parking	2,207	703	1,504
8	Workshop, Sanding	1,427	992	435
9	Workshop, Washing	1,999	703	1,296

10	Workshop, Parking	1,337	703	634
11	Parking, Sanding	1,923	992	931
12	Parking, Washing	2,495	703	1,792
13	Parking, Workshop	1,616	703	913

Table 12 - Three-Process Scenarios

Scenario	Processes	Pre-Automation Paid Time (s)	Post-Automation Paid Time (s)	Δ Paid Time (s)
14	Sanding, Washing, Parking	2,496	992	1,504
15	Workshop, Sanding, Washing	2,288	992	1,296
16	Workshop, Sanding, Parking	1,791	992	799
17	Workshop, Washing, Parking	2,603	703	1,900
18	Parking, Sanding, Washing	2,784	992	1,792
19	Parking, Workshop, Sanding	2,069	992	1,077
20	Parking, Workshop, Washing	2,641	703	1,938

Table 13 - Four-Process Scenarios

Scenario	Processes	Pre-Automation Paid Time (s)	Post-Automation Paid Time (s)	Δ Paid Time (s)
21	Workshop, Sanding, Washing, Parking	2,652	992	1,660
22	Parking, Workshop, Sanding, Washing	2,930	992	1,938

Given the results, it was outstanding to notice that when the parking process is involved in pre-automated two, three, or four process scenarios, the order where it occurs makes a difference on the total paid time. When the parking process is combined with other processes and occurs at the beginning of a scenario, that scenario has a higher total paid time when compared to another scenario that has the same processes but has the parking process at the end. This is evident due to the depot design and the extra driving time involved in parking the tram first and conducting the other process/es later, in contrast to doing the opposite, which requires less time. For example, when comparing scenarios 6 and 11 with each other, they are both two-process scenarios that perform the parking and sanding processes. Scenario 6 has a shorter total paid time compared to scenario 11 and hence is a more efficient and cost-effective way of conducting the required processes. Another similar example is comparing scenarios 21 and 22, which have the same processes, but parking occurs at the end of scenario 21 and at the beginning of scenario 22. However, in the post-automation scenarios, the total paid time is the same regardless of the order of processes involved. This is due to the elimination of personnel driving the tram in the depot, switching, and walking. Further proving the advantage of automating the trams since the order of processes no longer affects the overall paid time of operation.

To visually grasp how much paid time is saved due to automation per scenario, the results for all scenarios pre-and-post automation are plotted on a chart shown below (see Figure 11).

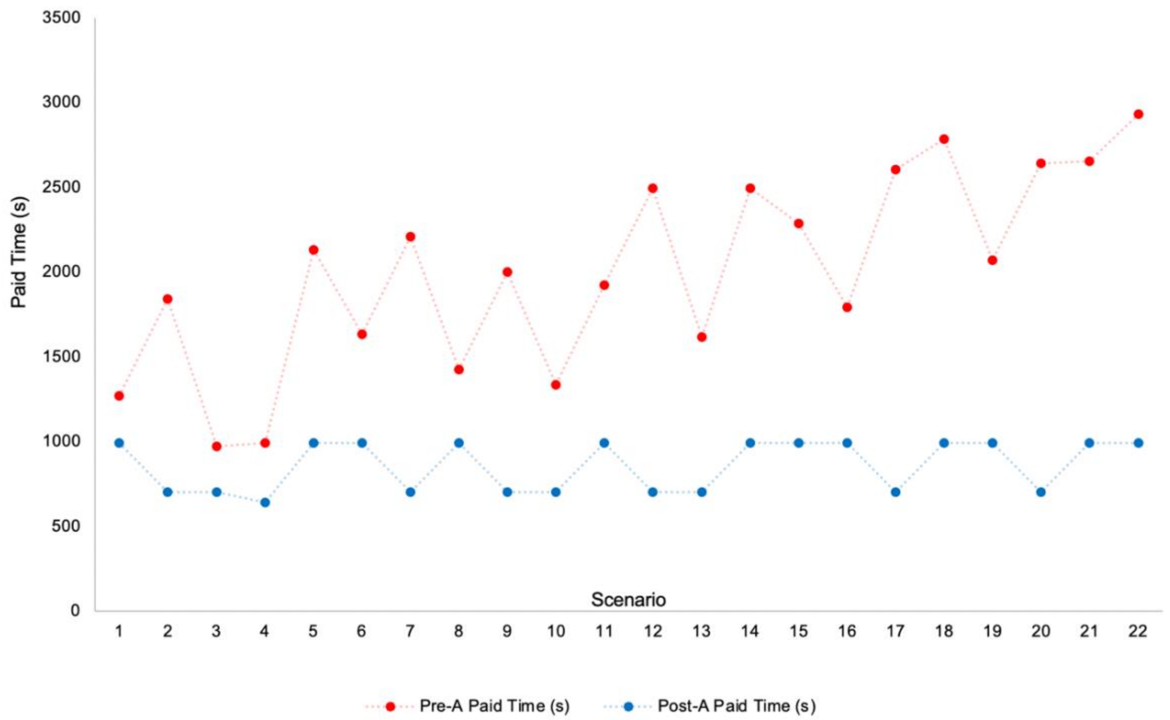


Figure 11 - Pre and Post Automation Paid Time Chart for all Scenarios

4.4 Annual Number of Processes Occurrences

To be able to estimate how many times each of the generated scenarios occur annually, the average number of occurrences for each of the processes must be calculated. As previously mentioned, the number of times the sanding and washing processes occur in a month is affected by the seasonal changes, whereas the workshop maintenance and parking processes are not. In this section of the study, the number of occurrences for each of the four processes will be calculated monthly, which will then be reflected annually.

4.4.1 Sanding and Washing

The number of occurrences for the sanding and washing processes is calculated by using recorded data that the ViP depot management gathered over three months of 2019 and 2020, which represent the different seasons. As mentioned in the methodology section of this study, the recorded data are of February, June, and November. The data for February represents the winter season, the data for June represents both the summer and spring seasons, and the data for November represents the autumn season. By analysing the monthly average numbers shown in Table 14 below, the highest requirement for the sanding and washing processes occurs in the autumn season. In the summer and spring seasons, there is a low requirement for the sanding process and a medium requirement for the washing process. In the winter season, the sanding process has a medium requirement, and the washing process has a low requirement.

The annual total for each of the sanding and washing processes is calculated by multiplying the monthly average by the months that represent the different seasons, which is shown in the last column of Table 14. Hence the monthly average for the winter season is multiplied by three, the monthly average of the summer and spring seasons is multiplied by six, and the monthly average of the autumn season is multiplied by three.

Table 14 - Average Annual Number of Occurrences for Sanding and Washing

Process	Winter (Monthly Average)	Summer/Spring (Monthly Average)	Autumn (Monthly Average)	Annual Total
Sanding	111	91	199	1,476
Washing	65	79	87	930

4.4.2 Scheduled Workshop Maintenance

To accurately estimate how many times a scheduled workshop maintenance operation occurs annually in the depot, the total number of kilometres driven by all the trams must be recorded and then divided by the required maintenance intervals. As seen below in Table 15, the average annual mileage driven for each of the three types of trams (retrieved from the ViP depot management for the year 2019) is multiplied by the number of trams available. Since the trams undergo a workshop maintenance operation approximately every 5,000 km, the annual number of required workshop maintenance operations is calculated for each type. Moreover, since the number of kilometres driven by the tram is generally uniform throughout the whole year, the number of occurrences of the scheduled workshop maintenance operation can be evenly distributed across the months of the year. The result of the applied method reveals that there are approximately 879 required workshop maintenance operations annually for all the trams in the depot.

Table 15 – Average Annual Number of Required Scheduled Workshop Maintenance

Tram Type	No. of Trams	Average Annual Mileage per Tram (km)	Total Average Annual Mileage (km)	Annual No. of Required Workshop Maintenance
KT4DC	18	45,233	814,194	163
Combino	16	107,873	1,725,968	345
Variobahn	18	103,063	1,855,134	371

4.4.3 Parking

To calculate the number of times a tram undergoes a parking process annually, there must be data that confirms the number of trams that operate in the city on an average day or week. Retrieved data from the ViP depot management shows that the average number of trams that exit the parking hall for duty operation from Mondays to Fridays is approximately 44 trams per day. As for weekends, on Saturdays and Sundays, the average number of trams in operation drops down to half at only 22 trams per day. Since the number of trams operating in the city is also not affected by the change of seasons, the number of occurrences for the parking process is evenly spread across all the months of the year. Hence, the average number of times that the tram exits and enters the parking hall per week is approximately 264 times, which reflected over one month is 1,056 times, and 12,672 times annually.

4.5 Annual Delta Paid Time

The annual delta paid time calculation will finally reveal how many hours of paid time is saved due to the implementation of autonomous trams in depot. It is also crucial to note that the scenarios that were chosen to satisfy the annual requirement of processes were selected based on the assumption that the depot operates at the highest level of efficiency pre-automation. To give an example: when four processes are grouped together as shown in Table 13, the paid time in the pre-automated case is different depending on the order of the processes, whereas in the post-automated case, the paid time remains the same regardless of the order of processes. In this calculation, it is assumed that the depot management always chooses the more efficient scenario which requires less paid time pre-automation (scenario 21), and therefore the delta paid time pre-and-post automation is the least amount of paid time saved. This assumption means that the final number of paid hours that is saved due to automation is also the minimum number of paid hours saved, and that in practice, the saved paid time is at least equal to the calculation result or more.

The first step is to create an annual calendar that summarizes the average number of occurrences for each of the processes, which is shown below in Table 16.

Table 16 - Annual List of Required Processes

Month	Sanding	Washing	Scheduled Workshop Maintenance	Parking
January	111	65	73	1,056
February	111	65	73	1,056
March	91	79	73	1,056
April	91	79	73	1,056
May	91	79	73	1,056
June	91	79	74	1,056
July	91	79	74	1,056
August	91	79	74	1,056
September	199	87	73	1,056
October	199	87	73	1,056
November	199	87	73	1,056
December	111	65	73	1,056
Annual Total	1,476	930	879	12,672

The next step is to analyse the processes in each month and group them wherever possible according to the number of occurrences until all are completed, hence optimising the depot operations. For example, the months of December, January, and February in the winter season have similar monthly process requirements. In these months, the washing process has the lowest number of occurrences which is equal to 65 washing processes per month. The idea here is to group four processes 65 times into a scenario that has the total lowest paid time pre-automation, which in this case, is scenario 21 (see Table 13). Then, the scheduled workshop operation would still require 8 processes in that month and is therefore grouped into a three-process scenario 8 times, which is scenario 16 (see Table 12). The remaining processes are then sanding and parking, where sanding now has the lowest number of occurrences at 38 remaining processes to be conducted that month, and the most efficient scenario that satisfies that is scenario 6 (see Table 11). Finally, the remaining number of required parking processes to be performed in one month is 945, and that is reflected as scenario 4 (see Table 10).

The same logic is applied to all the calendar months shown in Table 16, which then shows which are the most efficient scenarios that are chosen, and how many times they occur in a year. Each scenario's delta paid time (shown in Tables 10, 11, 12, and 13) is then multiplied by the number of times the scenario occurs annually, and the total number is the annual delta paid time, or paid time saved.

By adding all the number of hours saved due to automation, the final calculation outcome as shown in Table 17 below is equal to approximately 1,610 hours.

Table 17 - Annual Delta Paid Time Pre-and-Post Automation

Scenario	Δ Paid Time (s)	Annual No. of Occurrences	Annual Δ Paid Time (hours)
4	349	11,196	1,085.4
6	643	522	93.2
14	1,504	75	31.3
16	799	24	5.3
21	1,660	855	394.3
			Total = 1,609.5

Discussion

By analysing Table 17, the most reoccurring process is clearly the parking process (scenario 4), where according to the DFStrab, the driver is compensated a total of 10 minutes of paid time when parking and shutting down the tram in the parking hall, and when starting up and exiting the parking hall. In the calculations made above, the same compensation must be paid to the driver even after the implementation of autonomous trams, due to the mixed traffic restrictions of this specific depot (directly outside points *A* and *P* as seen in Figure 5), which would still require the physical entry and exit of the drivers from inside the depot. As mentioned earlier, the location of the ViP depot in Potsdam currently does not have the potential for the drivers to exit the tram at the last terminal station and have the trams autonomously drive back to the depot. The lack of automation in this process is due to a few critical reasons: there are still legal policies and regulations that must be passed in Germany before the tram is allowed to drive autonomously outside the depot, and especially in areas that have mixed traffic conditions. Moreover, the canteen and office building is situated inside the depot, and therefore entering the depot to begin or end their work shifts is a necessity for the drivers.

Ideally for autonomous trams in the depot to have a more substantial economic impact, some crucial points must be considered. The canteen and office building of the drivers should be located at the closest end station to the tram depot, so that drivers can immediately begin and end their work shifts. By doing so, the 10 minutes compensation can be eliminated, which means that the delta paid time pre-and-post automation will increase from 349 seconds to 991 seconds at the ViP depot. This change alone can make the annual delta paid time increase by almost three times, which has a significant economic impact. Furthermore, the physical designs of depots in the future must take the automation of trams into consideration, meaning that the depot should also be located close to the terminal station and that there is a safe and traffic-free railway connection between them.

Only a few of the generated scenarios were used to calculate the outcome of delta paid time saved due to automation. This is because the result reflects the least number of hours saved and because it assumes the highest degree of efficiency of operations pre-automation. In practice, all the generated scenarios occur throughout the year depending on the immediate requirement and flow of operations in the depot. Since the list of scenarios clearly show which are the most cost-efficient methods of conducting the processes, they can be integrated into a future digital depot management system that manages and optimises all operations in advance. Moreover, since the autonomous trams navigate themselves via a digital map and are monitored in real-time, the scheduling of required maintenance processes or otherwise can be easily implemented via the discussed digital depot management system. Therefore, the scenarios could serve as a foundation on which the scheduling and optimisation systems operate on.

The recorded time measurements of processes performed for this research study allow for further analyses on efficiency and whether it could be economically feasible to automate specific processes or sub-processes in the future. For the sanding process, potential automation is possible and can have a substantial economic gain since it is the most reoccurring maintenance process. As for the washing process, it is already assumed to be fully automated in the post-automation scenarios, since the only missing link to make it so is for the washing system to activate itself after the tram autonomously parks in the correct position, which can be easily done. The switching process along with the required personnel walking time will be eliminated post-automation, but the inspection process will, however, remain the same. It can be argued that cameras placed inside the tram could conduct the inspection, but if there are any open windows, lost passenger items, or missing first aid kits, then depot personnel must physically rectify those issues. The scheduled maintenance process still has no actual potential to be automated in the future and will therefore remain unchanged. According to the depot management, other minor tasks that occur such as shunting, which is when the tram trailers are coupled/decoupled, has a high potential for automation in the future. It is also essential to note that further maintenance operations dedicated to maintaining the autonomous hardware equipment will be added to the depot post-automation, which should be accounted for in terms of required personnel cost and spare parts cost.

One of the main AStriD project deliverables from an economic analysis standpoint is to have a transferable method and approach to other depots around Germany, and perhaps around the European Union. The method created and used in this study satisfies the transferability obligation, on the basis that: the depot is analysed as a closed system, the depot map is available with rail lengths that are correct to scale, the average acceleration and deceleration data of the trams are available, and that the total list of required processes in the depot is fixed. Furthermore, this method could also segregate the amount of delta paid time saved due to automation into categories that represent the different personnel involved in all processes if necessitated.

Conclusion & Future Outlooks

The recorded time measurements of processes mentioned in this study can serve as a reference point and guideline for further efficiency improvements due to automation in the future. Out of all the maintenance processes required, the washing process has the highest potential to become fully automated and is assumed as such post-automation in this study. The sanding process also has potential to be automated, by measuring future sanding technologies under the same parameters used in this research study, a direct comparison with clear results can be achieved. In addition to the maintenance processes that currently exist in the depot, further maintenance operations that are focused specifically on the autonomous packages and technology must be taken into consideration and accounted for, in terms of both hardware and software.

The economic impact success rate from implementing autonomous trams in depot depends on several factors, of which the most significant are: 1. the physical layout, size, and location of the depot, 2. the number of annual required maintenance and parking processes that need to be performed 3. if the tram can autonomously return to the depot once the driver has finished the driving shift, and 4. the location of the canteen and office building for the tram drivers.

Autonomous transportation plays a central role in achieving the Paris Agreement commitments by increasing the overall efficiency (energy use), reducing the number of accidents (less fatalities and repairs), and providing inclusivity in mobility for all. The study further focuses on benefits beyond the economic and sustainable ones highlighted. This includes an evident technological benefit from continuously collecting data and improving the tram's autonomous driving technology, as well as legal benefits from developing the necessary legal framework with the responsible government body. By doing so, this can transition Germany into a leading innovative powerhouse for automated and connected mobility solutions.

Limitations on this study include the analysis and measurements of maintenance processes associated with the autonomous technology itself. By measuring the required time and number of personnel involved in conducting autonomous hardware and software maintenance, a more accurate comparison pre-and-post automation can be achieved.

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Appendix

A1 Scenario Database

Refer to (Section 3.4 Scenario Planning) under the Methodology section.

Assumptions:

1. There is no repetition of any process in a scenario. Each process can only occur once to ensure maximum efficiency.
2. If both sanding and washing are required in a scenario, then both processes will occur only in that order.
3. If in any scenario, the workshop maintenance process is combined with either a sanding or washing process (or both), then it must only occur before them.
4. If parking is included in a scenario, then it will only take place at the beginning or at the end of that scenario. This is of course to ensure maximum efficiency and reduce driving time/energy in the depot.

The list of all 64 scenarios and the chosen 22 are shown below, where the excluded scenarios are marked in red and the included ones in green.

One-Process Scenarios:

Sanding – Scenario 1
Washing – Scenario 2
Workshop – Scenario 3
Parking – Scenario 4

Two-Process Scenarios:

Sanding, Washing – Scenario 5
Sanding, Workshop
Sanding, Parking – Scenario 6
Washing, Sanding

Washing, Workshop

Washing, Parking – Scenario 7

Workshop, Sanding – Scenario 8

Workshop, Washing – Scenario 9

Workshop, Parking – Scenario 10

Parking, Sanding – Scenario 11

Parking, Washing – Scenario 12

Parking, Workshop – Scenario 13

Three-Process Scenarios:

Sanding, Washing, Workshop

Sanding, Washing, Parking – Scenario 14

Sanding, Workshop, Washing

Sanding, Workshop, Parking

Sanding, Parking, Washing

Sanding, Parking, Workshop

Washing, Sanding, Workshop

Washing, Sanding, Parking

Washing, Workshop, Sanding

Washing, Workshop, Parking

Washing, Parking, Sanding

Washing, Parking, Workshop

Workshop, Sanding, Washing – Scenario 15

Workshop, Sanding, Parking – Scenario 16

Workshop, Washing, Sanding

Workshop, Washing, Parking – Scenario 17

Workshop, Parking, Sanding

Workshop, Parking, Washing

Parking, Sanding, Washing – Scenario 18

Parking, Sanding, Workshop

Parking, Washing, Sanding

Parking, Washing, Workshop

Parking, Workshop, Sanding – Scenario 19

Parking, Workshop, Washing – Scenario 20

Four-Process Scenarios:

Sanding, Washing, Workshop, Parking

Washing, Sanding, Workshop, Parking

Workshop, Sanding, Washing, Parking – Scenario 21

Sanding, Workshop, Washing, Parking

Washing, Workshop, Sanding, Parking

Workshop, Washing, Sanding, Parking

Workshop, Washing, Parking, Sanding

Washing, Workshop, Parking, Sanding

Parking, Workshop, Washing, Sanding

Workshop, Parking, Washing, Sanding

Washing, Parking, Workshop, Sanding

Parking, Washing, Workshop, Sanding

Parking, Sanding, Workshop, Washing

Sanding, Parking, Workshop, Washing

Workshop, Parking, Sanding, Washing

Parking, Workshop, Sanding, Washing – Scenario 22

Sanding, Workshop, Parking, Washing

Workshop, Sanding, Parking, Washing

Washing, Sanding, Parking, Workshop

Sanding, Washing, Parking, Workshop

Parking, Washing, Sanding, Workshop

Washing, Parking, Sanding, Workshop

Sanding, Parking, Washing, Workshop

Parking, Sanding, Washing, Workshop

A2 Pre-Automated Scenario List

Refer to Figure 5 (Section 3.4 Dept Map) under the Methodology section.

One-Process Scenarios:

Scenario 1
1. ViP depot entrance point.
2. Tram drives on the entrance track.
3. Track decision point B - proceed to sanding / washing track 11.
4. Park on track in front of sanding / washing.
5. Driver exits and service personnel enters at point C.
6. Only sanding is performed.
7. Exit sanding / washing.
8. All tracks regroup on single line at point H.
9. Track decision point I - proceed to bypass track 44.
10. Bypass parking hall.
11. Service personnel exits and driver enters on rail 44 at point M.
12. Continue after signal S612 is green.
13. Track decision point O - exit depot.
14. Tram exits the depot and resumes operation.

Scenario 2
1. ViP depot entrance point.
2. Tram drives on the entrance track.
3. Track decision point B - proceed to sanding / washing track 11.
4. Park on track in front of sanding / washing.
5. Driver exits and service personnel enters at point C.
6. Only washing is performed.
7. Exit sanding / washing.
8. All tracks regroup on single line at point H.
9. Track decision point I - proceed to bypass track 44.
10. Bypass parking hall.
11. Service personnel exits and driver enters on rail 44 at point M.

12. Continue after signal S612 is green.
13. Track decision point O - exit depot.
14. Tram exits the depot and resumes operation.

Scenario 3
1. ViP depot entrance point.
2. Tram drives on the entrance track.
3. Track decision point B - proceed to workshop tracks 12-18.
4. Park on track in front of workshop.
5. Driver exits and workshop personnel enters at point F.
6. Workshop operation is performed.
7. Exit workshop.
8. All tracks regroup on single line at point H.
9. Track decision point I - proceed to bypass track 44.
10. Bypass parking hall.
11. Workshop personnel exits and driver enters on rail 44 at point M.
12. Continue after signal S612 is green.
13. Track decision point O - exit depot.
14. Tram exits the depot and resumes operation.

Scenario 4
1. ViP depot entrance point.
2. Tram drives on the entrance track.
3. Track decision point B - proceed to off tracks 44-58.
4. Bypass maintenance building.
5. All tracks regroup on single line at point H.
6. Track decision point I - proceed to parking hall tracks 49-58.
7. Driver parks in parking hall and shuts down at point K.
8. Driver starts up and exits the parking hall from point K.
9. Continue after signal S612 is green.
10. Track decision point O - exit depot.
11. Tram exits the depot and resumes operation.

Two-Process Scenarios:

Scenario 5
1. ViP depot entrance point.
2. Tram drives on the entrance track.
3. Track decision point B - proceed to sanding / washing track 11.
4. Park on track in front of sanding / washing.
5. Driver exits and service personnel enters at point C.
6. Both sanding and washing are performed.
7. Exit sanding / washing.
8. All tracks regroup on single line at point H.
9. Track decision point I - proceed to bypass track 44.
10. Bypass parking hall.
11. Service personnel exits and driver enters on rail 44 at point M.
12. Continue after signal S612 is green.
13. Track decision point O - exit depot.
14. Tram exits the depot and resumes operation.

Scenario 6
1. ViP depot entrance point.
2. Tram drives on the entrance track.
3. Track decision point B - proceed to sanding / washing track 11.
4. Park on track in front of sanding / washing.
5. Driver exits and service personnel enters at point C.
6. Only sanding is performed.
7. Exit sanding / washing.
8. All tracks regroup on single line at point H.
9. Track decision point I - proceed to parking hall tracks 49-58.
10. Service personnel parks in parking hall and shuts down.
11. Driver starts up and exits the parking hall from point K.
12. Continue after signal S612 is green.
13. Track decision point O - exit depot.
14. Tram exits the depot and resumes operation.

Scenario 7
1. ViP depot entrance point.
2. Tram drives on the entrance track.
3. Track decision point B - proceed to sanding / washing track 11.
4. Park on track in front of sanding / washing.
5. Driver exits and service personnel enters at point C.
6. Only washing is performed.
7. Exit sanding / washing.
8. All tracks regroup on single line at point H.
9. Track decision point I - proceed to parking hall tracks 49-58.
10. Service personnel parks in parking hall and shuts down.
11. Driver starts up and exits the parking hall from point K.
12. Continue after signal S612 is green.
13. Track decision point O - exit depot.
14. Tram exits the depot and resumes operation.

Scenario 8
1. ViP depot entrance point.
2. Tram drives on the entrance track.
3. Track decision point B - proceed to workshop tracks 12-18.
4. Park on track in front of workshop.
5. Driver exits and workshop personnel enters at point F.
6. Workshop operation is performed.
7. Exit workshop.
8. All tracks regroup on single line at point H.
9. Track decision point I - proceed to bypass track 44.
10. Bypass parking hall.
11. Continue after signal S612 is green.
12. Track decision point O - return to depot.
13. Track decision point B - proceed to sanding / washing track 11.
14. Park on track in front of sanding / washing.
15. Workshop personnel exits and service personnel enters at point C.
16. Only sanding is performed.
17. Exit sanding / washing.

18. All tracks regroup on single line at point H.
19. Track decision point I - proceed to bypass track 44.
20. Bypass parking hall.
21. Service personnel exits and driver enters on rail 44 at point M.
22. Continue after signal S612 is green.
23. Track decision point O - exit depot.
24. Tram exits the depot and resumes operation.

Scenario 9
1. ViP depot entrance point.
2. Tram drives on the entrance track.
3. Track decision point B - proceed to workshop tracks 12-18.
4. Park on track in front of workshop.
5. Driver exits and workshop personnel enters at point F.
6. Workshop operation is performed.
7. Exit workshop.
8. All tracks regroup on single line at point H.
9. Track decision point I - proceed to bypass track 44.
10. Bypass parking hall.
11. Continue after signal S612 is green.
12. Track decision point O - return to depot.
13. Track decision point B - proceed to sanding / washing track 11.
14. Park on track in front of sanding / washing.
15. Workshop personnel exits and service personnel enters at point C.
16. Only washing is performed.
17. Exit sanding / washing.
18. All tracks regroup on single line at point H.
19. Track decision point I - proceed to bypass track 44.
20. Bypass parking hall.
21. Service personnel exits and driver enters on rail 44 at point M.
22. Continue after signal S612 is green.
23. Track decision point O - exit depot.
24. Tram exits the depot and resumes operation.

Scenario 10
1. ViP depot entrance point.
2. Tram drives on the entrance track.
3. Track decision point B - proceed to workshop tracks 12-18.
4. Park on track in front of workshop.
5. Driver exits and workshop personnel enters at point F.
6. Workshop operation is performed.
7. Exit workshop.
8. All tracks regroup on single line at point H.
9. Track decision point I - proceed to parking hall tracks 49-58.
10. Workshop personnel parks in parking hall and shuts down.
11. Driver starts up and exits the parking hall from point K.
12. Continue after signal S612 is green.
13. Track decision point O - exit depot.
14. Tram exits the depot and resumes operation.

Scenario 11
1. ViP depot entrance point.
2. Tram drives on the entrance track.
3. Track decision point B - proceed to off tracks 44-58.
4. Bypass maintenance building.
5. All tracks regroup on single line at point H.
6. Track decision point I - proceed to parking hall tracks 49-58.
7. Driver parks in parking hall and shuts down at point K.
8. Service Personnel starts up and exits the parking hall from point K.
9. Continue after signal S612 is green.
10. Track decision point O - return to depot.
11. Track decision point B - proceed to sanding / washing track 11.
12. Park on track in front of sanding / washing.
13. Only sanding is performed.
14. Exit sanding / washing.
15. All tracks regroup on single line at point H.
16. Track decision point I - proceed to bypass track 44.
17. Bypass parking hall.

18. Service personnel exits and driver enters on rail 44 at point M.
19. Continue after signal S612 is green.
20. Track decision point O - exit depot.
21. Tram exits the depot and resumes operation.

Scenario 12
1. ViP depot entrance point.
2. Tram drives on the entrance track.
3. Track decision point B - proceed to off tracks 44-58.
4. Bypass maintenance building.
5. All tracks regroup on single line at point H.
6. Track decision point I - proceed to parking hall tracks 49-58.
7. Driver parks in parking hall and shuts down at point K.
8. Service Personnel starts up and exits the parking hall from point K.
9. Continue after signal S612 is green.
10. Track decision point O - return to depot.
11. Track decision point B - proceed to sanding / washing track 11.
12. Park on track in front of sanding / washing.
13. Only washing is performed.
14. Exit sanding / washing.
15. All tracks regroup on single line at point H.
16. Track decision point I - proceed to bypass track 44.
17. Bypass parking hall.
18. Service personnel exits and driver enters on rail 44 at point M.
19. Continue after signal S612 is green.
20. Track decision point O - exit depot.
21. Tram exits the depot and resumes operation.

Scenario 13
1. ViP depot entrance point.
2. Tram drives on the entrance track.
3. Track decision point B - proceed to off tracks 44-58.
4. Bypass maintenance building.

5. All tracks regroup on single line at point H.
6. Track decision point I - proceed to parking hall tracks 49-58.
7. Driver parks in parking hall and shuts down at point K.
8. Workshop Personnel starts up and exits the parking hall from point K.
9. Continue after signal S612 is green.
10. Track decision point O - return to depot.
11. Track decision point B - proceed to workshop tracks 12-18.
12. Park on track in front of workshop.
13. Workshop operation is performed.
14. Exit workshop.
15. All tracks regroup on single line at point H.
16. Track decision point I - proceed to bypass track 44.
17. Bypass parking hall.
18. Workshop personnel exits and driver enters on rail 44 at point M.
19. Continue after signal S612 is green.
20. Track decision point O - exit depot.
21. Tram exits the depot and resumes operation.

Three-Process Scenarios:

Scenario 14
1. ViP depot entrance point.
2. Tram drives on the entrance track.
3. Track decision point B - proceed to sanding / washing track 11.
4. Park on track in front of sanding / washing.
5. Driver exits and service personnel enters at point C.
6. Both sanding and washing are performed.
7. Exit sanding / washing.
8. All tracks regroup on single line at point H.
9. Track decision point I - proceed to parking hall tracks 49-58.
10. Service personnel parks in parking hall and shuts down.
11. Driver starts up and exits the parking hall from point K.
12. Continue after signal S612 is green.
13. Track decision point O - exit depot.
14. Tram exits the depot and resumes operation.

Scenario 15
1. ViP depot entrance point.
2. Tram drives on the entrance track.
3. Track decision point B - proceed to workshop tracks 12-18.
4. Park on track in front of workshop.
5. Driver exits and workshop personnel enters at point F.
6. Workshop operation is performed.
7. Exit workshop.
8. All tracks regroup on single line at point H.
9. Track decision point I - proceed to bypass track 44.
10. Bypass parking hall.
11. Continue after signal S612 is green.
12. Track decision point O - return to depot.
13. Track decision point B - proceed to sanding / washing track 11.
14. Park on track in front of sanding / washing.
15. Workshop personnel exits and service personnel enters at point C.
16. Both sanding and washing are performed.
17. Exit sanding / washing.
18. All tracks regroup on single line at point H.
19. Track decision point I - proceed to bypass track 44.
20. Bypass parking hall.
21. Service personnel exits and driver enters on rail 44 at point M.
22. Continue after signal S612 is green.
23. Track decision point O - exit depot.
24. Tram exits the depot and resumes operation.

Scenario 16
1. ViP depot entrance point.
2. Tram drives on the entrance track.
3. Track decision point B - proceed to workshop tracks 12-18.
4. Park on track in front of workshop.
5. Driver exits and workshop personnel enters at point F.
6. Workshop operation is performed.

7. Exit workshop.
8. All tracks regroup on single line at point H.
9. Track decision point I - proceed to bypass track 44.
10. Bypass parking hall.
11. Continue after signal S612 is green.
12. Track decision point O - return to depot.
13. Track decision point B - proceed to sanding / washing track 11.
14. Park on track in front of sanding / washing.
15. Workshop personnel exits and service personnel enters at point C.
16. Only sanding is performed.
17. Exit sanding / washing.
18. All tracks regroup on single line at point H.
19. Track decision point I - proceed to parking hall tracks 49-58.
20. Service personnel parks in parking hall and shuts down.
21. Driver starts up and exits the parking hall from point K.
22. Continue after signal S612 is green.
23. Track decision point O - exit depot.
24. Tram exits the depot and resumes operation.

Scenario 17
1. ViP depot entrance point.
2. Tram drives on the entrance track.
3. Track decision point B - proceed to workshop tracks 12-18.
4. Park on track in front of workshop.
5. Driver exits and workshop personnel enters at point F.
6. Workshop operation is performed.
7. Exit workshop.
8. All tracks regroup on single line at point H.
9. Track decision point I - proceed to bypass track 44.
10. Bypass parking hall.
11. Continue after signal S612 is green.
12. Track decision point O - return to depot.
13. Track decision point B - proceed to sanding / washing track 11.
14. Park on track in front of sanding / washing.

15. Workshop personnel exits and service personnel enters at point C.
16. Only washing is performed.
17. Exit sanding / washing.
18. All tracks regroup on single line at point H.
19. Track decision point I - proceed to bypass track 44.
20. Service personnel parks in parking hall and shuts down.
21. Driver starts up and exits the parking hall from point K.
22. Continue after signal S612 is green.
23. Track decision point O - exit depot.
24. Tram exits the depot and resumes operation.

Scenario 18
1. ViP depot entrance point.
2. Tram drives on the entrance track.
3. Track decision point B - proceed to off tracks 44-58.
4. Bypass maintenance building.
5. All tracks regroup on single line at point H.
6. Track decision point I - proceed to parking hall tracks 49-58.
7. Driver parks in parking hall and shuts down at point K.
8. Service personnel starts up and exits the parking hall from point K.
9. Continue after signal S612 is green.
10. Track decision point O - return to depot.
11. Track decision point B - proceed to sanding / washing track 11.
12. Park on track in front of sanding / washing.
13. Both sanding and washing are performed.
14. Exit sanding / washing.
15. All tracks regroup on single line at point H.
16. Track decision point I - proceed to bypass track 44.
17. Bypass parking hall.
18. Service personnel exits and driver enters on rail 44 at point M.
19. Continue after signal S612 is green.
20. Track decision point O - exit depot.
21. Tram exits the depot and resumes operation.

Scenario 19
1. ViP depot entrance point.
2. Tram drives on the entrance track.
3. Track decision point B - proceed to off tracks 44-58.
4. Bypass maintenance building.
5. All tracks regroup on single line at point H.
6. Track decision point I - proceed to parking hall tracks 49-58.
7. Driver parks in parking hall and shuts down at point K.
8. Workshop personnel starts up and exits the parking hall from point K.
9. Continue after signal S612 is green.
10. Track decision point O - return to depot.
11. Track decision point B - proceed to workshop tracks 12-18.
12. Park on track in front of workshop.
13. Workshop operation is performed.
14. Exit workshop.
15. All tracks regroup on single line at point H.
16. Track decision point I - proceed to bypass track 44.
17. Bypass parking hall.
18. Continue after signal S612 is green.
19. Track decision point O - return to depot.
20. Track decision point B - proceed to sanding / washing track 11.
21. Park on track in front of sanding / washing.
22. Workshop personnel exits and service personnel enters.
23. Only sanding is performed.
24. Exit sanding / washing.
25. All tracks regroup on single line at point H.
26. Track decision point I - proceed to bypass track 44.
27. Bypass parking hall.
28. Service personnel exits and driver enters on rail 44 at point M.
29. Continue after signal S612 is green.
30. Track decision point O - exit depot.
31. Tram exits the depot and resumes operation.

Scenario 20
1. ViP depot entrance point.
2. Tram drives on the entrance track.
3. Track decision point B - proceed to off tracks 44-58.
4. Bypass maintenance building.
5. All tracks regroup on single line at point H.
6. Track decision point I - proceed to parking hall tracks 49-58.
7. Driver parks in parking hall and shuts down at point K.
8. Workshop Personnel starts up and exits the parking hall from point K.
9. Continue after signal S612 is green.
10. Track decision point O - return to depot.
11. Track decision point B - proceed to workshop tracks 12-18.
12. Park on track in front of workshop.
13. Workshop operation is performed.
14. Exit workshop.
15. All tracks regroup on single line at point H.
16. Track decision point I - proceed to bypass track 44.
17. Bypass parking hall.
18. Continue after signal S612 is green.
19. Track decision point O - return to depot.
20. Track decision point B - proceed to sanding / washing track 11.
21. Park on track in front of sanding / washing.
22. Workshop personnel exits and service personnel enters.
23. Only washing is performed.
24. Exit sanding / washing.
25. All tracks regroup on single line at point H.
26. Track decision point I - proceed to bypass track 44.
27. Bypass parking hall.
28. Service personnel exits and driver enters on rail 44 at point M.
29. Continue after signal S612 is green.
30. Track decision point O - exit depot.
31. Tram exits the depot and resumes operation.

Four-Process Scenarios:

Scenario 21
1. ViP depot entrance point.
2. Tram drives on the entrance track.
3. Track decision point B - proceed to workshop tracks 12-18.
4. Park on track in front of workshop.
5. Driver exits and workshop personnel enters at point F.
6. Workshop operation is performed.
7. Exit workshop.
8. All tracks regroup on single line at point H.
9. Track decision point I - proceed to bypass track 44.
10. Bypass parking hall.
11. Continue after signal S612 is green.
12. Track decision point O - return to depot.
13. Track decision point B - proceed to sanding / washing track 11.
14. Park on track in front of sanding / washing.
15. Workshop personnel exits and service personnel enters at point C.
15. Both sanding and washing are performed.
16. Exit sanding / washing.
17. All tracks regroup on single line at point H.
18. Track decision point I - proceed to parking hall tracks 49-58.
19. Service personnel parks in parking hall and shuts down.
20. Driver starts up and exits the parking hall from point K.
21. Continue after signal S612 is green.
22. Track decision point O - exit depot.
23. Tram exits the depot and resumes operation.

Scenario 22
1. ViP depot entrance point.
2. Tram drives on the entrance track.
3. Track decision point B - proceed to off tracks 44-58.
4. Bypass maintenance building.
5. All tracks regroup on single line at point H.
6. Track decision point I - proceed to parking hall tracks 49-58.
7. Driver parks in parking hall and shuts down at point K.
8. Workshop personnel starts up and exits the parking hall from point K.
9. Continue after signal S612 is green.
10. Track decision point O - return to depot.
11. Track decision point B - proceed to workshop tracks 12-18.
12. Park on track in front of workshop.
13. Workshop operation is performed.
14. Exit workshop.
15. All tracks regroup on single line at point H.
16. Track decision point I - proceed to bypass track 44.
17. Bypass parking hall.
18. Continue after signal S612 is green.
19. Track decision point O - return to depot.
20. Track decision point B - proceed to sanding / washing track 11.
21. Park on track in front of sanding / washing.
22. Workshop personnel exits and service personnel enters.
23. Both sanding and washing are performed.
24. Exit sanding / washing.
25. All tracks regroup on single line at point H.
26. Track decision point I - proceed to bypass track 44.
27. Bypass parking hall.
28. Service personnel exits and driver enters on rail 44 at point M.
29. Continue after signal S612 is green.
30. Track decision point O - exit depot.
31. Tram exits the depot and resumes operation.

A3 Post-Automation Scenario List

Refer to Figure 5 (Section 3.4 Dept Map) under the Methodology section.

One-Process Scenarios:

Scenario 1
1. ViP depot entrance point.
2. Tram drives on the entrance track.
3. Driver exits at track decision point B.
4. Track decision point B - proceed to sanding / washing track 11.
5. Park on track in front of sanding / washing.
6. Only sanding is performed.
7. Exit sanding / washing.
8. All tracks regroup on single line at point H.
9. Track decision point I - proceed to bypass track 44.
10. Bypass parking hall.
11. Continue after signal S612 is green.
12. Track decision point O - exit depot.
13. Driver enters at track decision point O.
14. Tram exits the depot and resumes operation.

Scenario 2
1. ViP depot entrance point.
2. Tram drives on the entrance track.
3. Driver exits at track decision point B.
4. Track decision point B - proceed to sanding / washing track 11.
5. Park on track in front of sanding / washing.
6. Only washing is performed.
7. Exit sanding / washing.
8. All tracks regroup on single line at point H.
9. Track decision point I - proceed to bypass track 44.
10. Bypass parking hall.
11. Continue after signal S612 is green.

12. Track decision point O - exit depot.
13. Driver enters at track decision point O.
14. Tram exits the depot and resumes operation.

Scenario 3
1. ViP depot entrance point.
2. Tram drives on the entrance track.
3. Driver exits at track decision point B.
4. Track decision point B - proceed to workshop tracks 12-18.
5. Park on track in front of workshop.
6. Workshop operation is performed.
7. Exit workshop.
8. All tracks regroup on single line at point H.
9. Track decision point I - proceed to bypass track 44.
10. Bypass parking hall.
11. Continue after signal S612 is green.
12. Track decision point O - exit depot.
13. Driver enters at track decision point O.
14. Tram exits the depot and resumes operation.

Scenario 4
1. ViP depot entrance point.
2. Tram drives on the entrance track.
3. Driver exits at track decision point B.
4. Track decision point B - proceed to off tracks 44-58.
5. Bypass maintenance building.
6. All tracks regroup on single line at point H.
7. Track decision point I - proceed to parking hall tracks 49-58.
8. Tram autonomously parks in parking hall and shuts down.
9. Tram autonomously starts up and exits the parking hall.
10. Continue after signal S612 is green.
11. Track decision point O - exit depot.
12. Driver enters at track decision point O.

13. Tram exits the depot and resumes operation.

Two-Process Scenarios:

Scenario 5
1. ViP depot entrance point.
2. Tram drives on the entrance track.
3. Driver exits at track decision point B.
4. Track decision point B - proceed to sanding / washing track 11.
5. Park on track in front of sanding / washing.
6. Both sanding and washing are performed.
7. Exit sanding / washing.
8. All tracks regroup on single line at point H.
9. Track decision point I - proceed to bypass track 44.
10. Bypass parking hall.
11. Continue after signal S612 is green.
12. Track decision point O - exit depot.
13. Driver enters at track decision point O.
14. Tram exits the depot and resumes operation.

Scenario 6
1. ViP depot entrance point.
2. Tram drives on the entrance track.
3. Driver exits at track decision point B.
4. Track decision point B - proceed to sanding / washing track 11.
5. Park on track in front of sanding / washing.
6. Only sanding is performed.
7. Exit sanding / washing.
8. All tracks regroup on single line at point H.
9. Track decision point I - proceed to parking hall tracks 49-58.
10. Tram autonomously parks in parking hall and shuts down.
11. Tram autonomously starts up and exits the parking hall.
12. Continue after signal S612 is green.
13. Track decision point O - exit depot.

14. Driver enters at track decision point O.
15. Tram exits the depot and resumes operation.

Scenario 7
1. ViP depot entrance point.
2. Tram drives on the entrance track.
3. Driver exits at track decision point B.
4. Track decision point B - proceed to sanding / washing track 11.
5. Park on track in front of sanding / washing.
6. Only washing is performed.
7. Exit sanding / washing.
8. All tracks regroup on single line at point H.
9. Track decision point I - proceed to parking hall tracks 49-58.
10. Tram autonomously parks in parking hall and shuts down.
11. Tram autonomously starts up and exits the parking hall.
12. Continue after signal S612 is green.
13. Track decision point O - exit depot.
14. Driver enters at track decision point O.
15. Tram exits the depot and resumes operation.

Scenario 8
1. ViP depot entrance point.
2. Tram drives on the entrance track.
3. Driver exits at track decision point B.
4. Track decision point B - proceed to workshop tracks 12-18.
5. Park on track in front of workshop.
6. Workshop operation is performed.
7. Exit workshop.
8. All tracks regroup on single line at point H.
9. Track decision point I - proceed to bypass track 44.
10. Bypass parking hall.
11. Continue after signal S612 is green.
12. Track decision point O - return to depot.

13. Track decision point B - proceed to sanding / washing track 11.
14. Park on track in front of sanding / washing.
15. Only sanding is performed.
16. Exit sanding / washing.
17. All tracks regroup on single line at point H.
18. Track decision point I - proceed to bypass track 44.
19. Bypass parking hall.
20. Continue after signal S612 is green.
21. Track decision point O - exit depot.
22. Driver enters at track decision point O.
23. Tram exits the depot and resumes operation.

Scenario 9
1. ViP depot entrance point.
2. Tram drives on the entrance track.
3. Driver exits at track decision point B.
4. Track decision point B - proceed to workshop tracks 12-18.
5. Park on track in front of workshop.
6. Workshop operation is performed.
7. Exit workshop.
8. All tracks regroup on single line at point H.
9. Track decision point I - proceed to bypass track 44.
10. Bypass parking hall.
11. Continue after signal S612 is green.
12. Track decision point O - return to depot.
13. Track decision point B - proceed to sanding / washing track 11.
14. Park on track in front of sanding / washing.
15. Only washing is performed.
16. Exit sanding / washing.
17. All tracks regroup on single line at point H.
18. Track decision point I - proceed to bypass track 44.
19. Bypass parking hall.
20. Continue after signal S612 is green.
21. Track decision point O - exit depot.

22. Driver enters at track decision point O.
23. Tram exits the depot and resumes operation.

Scenario 10
1. ViP depot entrance point.
2. Tram drives on the entrance track.
3. Driver exits at track decision point B.
4. Track decision point B - proceed to workshop tracks 12-18.
5. Park on track in front of workshop.
6. Workshop operation is performed.
7. Exit workshop.
8. All tracks regroup on single line at point H.
9. Track decision point I - proceed to parking hall tracks 49-58.
10. Tram autonomously parks in parking hall and shuts down.
11. Tram autonomously starts up and exits the parking hall.
12. Continue after signal S612 is green.
13. Track decision point O - exit depot.
14. Driver enters at track decision point O.
15. Tram exits the depot and resumes operation.

Scenario 11
1. ViP depot entrance point.
2. Tram drives on the entrance track.
3. Driver exits at track decision point B.
4. Track decision point B - proceed to off tracks 44-58.
5. Bypass maintenance building.
6. All tracks regroup on single line at point H.
7. Track decision point I - proceed to parking hall tracks 49-58.
8. Tram autonomously parks in parking hall and shuts down.
9. Tram autonomously starts up and exits the parking hall.
10. Continue after signal S612 is green.
11. Track decision point O - return to depot.
12. Track decision point B - proceed to sanding / washing track 11.

13. Park on track in front of sanding / washing.
14. Only sanding is performed.
15. Exit sanding / washing.
16. All tracks regroup on single line at point H.
17. Track decision point I - proceed to bypass track 44.
18. Bypass parking hall.
19. Continue after signal S612 is green.
20. Track decision point O - exit depot.
21. Driver enters at track decision point O.
22. Tram exits the depot and resumes operation.

Scenario 12
1. ViP depot entrance point.
2. Tram drives on the entrance track.
3. Driver exits at track decision point B.
4. Track decision point B - proceed to off tracks 44-58.
5. Bypass maintenance building.
6. All tracks regroup on single line at point H.
7. Track decision point I - proceed to parking hall tracks 49-58.
8. Tram autonomously parks in parking hall and shuts down.
9. Tram autonomously starts up and exits the parking hall.
10. Continue after signal S612 is green.
11. Track decision point O - return to depot.
12. Track decision point B - proceed to sanding / washing track 11.
13. Park on track in front of sanding / washing.
14. Only washing is performed.
15. Exit sanding / washing.
16. All tracks regroup on single line at point H.
17. Track decision point I - proceed to bypass track 44.
18. Bypass parking hall.
19. Continue after signal S612 is green.
20. Track decision point O - exit depot.
21. Driver enters at track decision point O.
22. Tram exits the depot and resumes operation.

Scenario 13
1. ViP depot entrance point.
2. Tram drives on the entrance track.
3. Driver exits at track decision point B.
4. Track decision point B – proceed to off tracks 44-58.
5. Bypass maintenance building.
6. All tracks regroup on single line at point H.
7. Track decision point I – proceed to parking hall tracks 49-58.
8. Tram autonomously parks in parking hall and shuts down.
9. Tram autonomously starts up and exits the parking hall.
10. Continue after signal S612 is green.
11. Track decision point O – return to depot.
12. Track decision point B – proceed to workshop tracks 12-18.
13. Park on track in front of workshop.
14. Workshop operation is performed.
15. Exit workshop.
16. All tracks regroup on single line at point H.
17. Track decision point I – proceed to bypass track 44.
18. Bypass parking hall.
19. Continue after signal S612 is green.
20. Track decision point O – exit depot.
21. Driver enters at track decision point O.
22. Tram exits the depot and resumes operation.

Three-Process Scenarios:

Scenario 14
1. ViP depot entrance point.
2. Tram drives on the entrance track.
3. Driver exits at track decision point B.
4. Track decision point B – proceed to sanding / washing track 11.
5. Park on track in front of sanding / washing.
6. Both sanding and washing are performed.
7. Exit sanding / washing.
8. All tracks regroup on single line at point H.

9. Track decision point I – proceed to parking hall tracks 49-58.
10. Tram autonomously parks in parking hall and shuts down.
11. Tram autonomously starts up and exits the parking hall.
12. Continue after signal S612 is green.
13. Track decision point O – exit depot.
14. Driver enters at track decision point O.
15. Tram exits the depot and resumes operation.

Scenario 15
1. ViP depot entrance point.
2. Tram drives on the entrance track.
3. Driver exits at track decision point B.
4. Track decision point B – proceed to workshop tracks 12-18.
5. Park on track in front of workshop.
6. Workshop operation is performed.
7. Exit workshop.
8. All tracks regroup on single line at point H.
9. Track decision point I – proceed to bypass track 44.
10. Bypass parking hall.
11. Continue after signal S612 is green.
12. Track decision point O – return to depot.
13. Track decision point B – proceed to sanding / washing track 11.
14. Park on track in front of sanding / washing.
15. Both sanding and washing are performed.
16. Exit sanding / washing.
17. All tracks regroup on single line at point H.
18. Track decision point I – proceed to bypass track 44.
19. Bypass parking hall.
20. Continue after signal S612 is green.
21. Track decision point O – exit depot.
22. Driver enters at track decision point O.
23. Tram exits the depot and resumes operation.

Scenario 16
1. ViP depot entrance point.
2. Tram drives on the entrance track.
3. Driver exits at track decision point B.
4. Track decision point B – proceed to workshop tracks 12-18.
5. Park on track in front of workshop.
6. Workshop operation is performed.
7. Exit workshop.
8. All tracks regroup on single line at point H.
9. Track decision point I – proceed to bypass track 44.
10. Bypass parking hall.
11. Continue after signal S612 is green.
12. Track decision point O – return to depot.
13. Track decision point B – proceed to sanding / washing track 11.
14. Park on track in front of sanding / washing.
15. Only sanding is performed.
16. Exit sanding / washing.
17. All tracks regroup on single line at point H.
18. Track decision point I – proceed to parking hall tracks 49-58.
19. Tram autonomously parks in parking hall and shuts down.
20. Tram autonomously starts up and exits the parking hall.
21. Continue after signal S612 is green.
22. Track decision point O – exit depot.
23. Driver enters at track decision point O.
24. Tram exits the depot and resumes operation.

Scenario 17
1. ViP depot entrance point.
2. Tram drives on the entrance track.
3. Driver exits at track decision point B.
4. Track decision point B – proceed to workshop tracks 12-18.
5. Park on track in front of workshop.
6. Workshop operation is performed.
7. Exit workshop.

8. All tracks regroup on single line at point H.
9. Track decision point I – proceed to bypass track 44.
10. Bypass parking hall.
11. Continue after signal S612 is green.
12. Track decision point O – return to depot.
13. Track decision point B – proceed to sanding / washing track 11.
14. Park on track in front of sanding / washing.
15. Only washing is performed.
16. Exit sanding / washing.
17. All tracks regroup on single line at point H.
18. Track decision point I – proceed to parking hall tracks 49-58.
19. Tram autonomously parks in parking hall and shuts down.
20. Tram autonomously starts up and exits the parking hall.
21. Continue after signal S612 is green.
22. Track decision point O – exit depot.
23. Driver enters at track decision point O.
24. Tram exits the depot and resumes operation.

Scenario 18
1. ViP depot entrance point.
2. Tram drives on the entrance track.
3. Driver exits at track decision point B.
4. Track decision point B - proceed to off tracks 44-58.
5. Bypass maintenance building.
6. All tracks regroup on single line at point H.
7. Track decision point I - proceed to parking hall tracks 49-58.
8. Tram autonomously parks in parking hall and shuts down.
9. Tram autonomously starts up and exits the parking hall.
10. Continue after signal S612 is green.
11. Track decision point O - return to depot.
12. Track decision point B - proceed to sanding / washing track 11.
13. Park on track in front of sanding / washing.
14. Both sanding and washing are performed.
15. Exit sanding / washing.

16. All tracks regroup on single line at point H.
17. Track decision point I - proceed to bypass track 44.
18. Bypass parking hall.
19. Continue after signal S612 is green.
20. Track decision point O - exit depot.
21. Driver enters at track decision point O.
22. Tram exits the depot and resumes operation.

Scenario 19
1. ViP depot entrance point.
2. Tram drives on the entrance track.
3. Driver exits at track decision point B.
4. Track decision point B - proceed to off tracks 44-58.
5. Bypass maintenance building.
6. All tracks regroup on single line at point H.
7. Track decision point I - proceed to parking hall tracks 49-58.
8. Tram autonomously parks in parking hall and shuts down.
9. Tram autonomously starts up and exits the parking hall.
10. Continue after signal S612 is green.
11. Track decision point O - return to depot.
12. Track decision point B - proceed to workshop tracks 12-18.
13. Park on track in front of workshop.
14. Workshop operation is performed.
15. Exit workshop.
16. All tracks regroup on single line at point H.
17. Track decision point I - proceed to bypass track 44.
18. Bypass parking hall.
19. Continue after signal S612 is green.
20. Track decision point O - return to depot.
21. Track decision point B - proceed to sanding / washing track 11.
22. Park on track in front of sanding / washing.
23. Only sanding is performed.
24. Exit sanding / washing.
25. All tracks regroup on single line at point H.

26. Track decision point I - proceed to bypass track 44.
27. Bypass parking hall.
28. Continue after signal S612 is green.
29. Track decision point O - exit depot.
30. Driver enters at track decision point O.
31. Tram exits the depot and resumes operation.

Scenario 20
1. ViP depot entrance point.
2. Tram drives on the entrance track.
3. Driver exits at track decision point B.
4. Track decision point B - proceed to off tracks 44-58.
5. Bypass maintenance building.
6. All tracks regroup on single line at point H.
7. Track decision point I - proceed to parking hall tracks 49-58.
8. Tram autonomously parks in parking hall and shuts down.
9. Tram autonomously starts up and exits the parking hall.
10. Continue after signal S612 is green.
11. Track decision point O - return to depot.
12. Track decision point B - proceed to workshop tracks 12-18.
13. Park on track in front of workshop.
14. Workshop operation is performed.
15. Exit workshop.
16. All tracks regroup on single line at point H.
17. Track decision point I - proceed to bypass track 44.
18. Bypass parking hall.
19. Continue after signal S612 is green.
20. Track decision point O - return to depot.
21. Track decision point B - proceed to sanding / washing track 11.
22. Park on track in front of sanding / washing.
23. Only washing is performed.
24. Exit sanding / washing.
25. All tracks regroup on single line at point H.
26. Track decision point I - proceed to bypass track 44.

27. Bypass parking hall.
28. Continue after signal S612 is green.
29. Track decision point O - exit depot.
30. Driver enters at track decision point O.
31. Tram exits the depot and resumes operation.

Four-Process Scenarios:

Scenario 21
1. ViP depot entrance point.
2. Tram drives on the entrance track.
3. Driver exits at track decision point B.
4. Track decision point B - proceed to workshop tracks 12-18.
5. Park on track in front of workshop.
6. Workshop operation is performed.
7. Exit workshop.
8. All tracks regroup on single line at point H.
9. Track decision point I - proceed to bypass track 44.
10. Bypass parking hall.
11. Continue after signal S612 is green.
12. Track decision point O - return to depot.
13. Track decision point B - proceed to sanding / washing track 11.
14. Park on track in front of sanding / washing.
15. Both sanding and washing are performed.
16. Exit sanding / washing.
17. All tracks regroup on single line at point H.
18. Track decision point I - proceed to parking hall tracks 49-58.
19. Tram autonomously parks in parking hall and shuts down.
20. Tram autonomously starts up and exits the parking hall.
21. Continue after signal S612 is green.
22. Track decision point O - exit depot.
23. Driver enters at track decision point O.
24. Tram exits the depot and resumes operation.

Scenario 22
1. ViP depot entrance point.
2. Tram drives on the entrance track.
3. Driver exits at track decision point B.
4. Track decision point B - proceed to off tracks 44-58.
5. Bypass maintenance building.
6. All tracks regroup on single line at point H.
7. Track decision point I - proceed to parking hall tracks 49-58.
8. Tram autonomously parks in parking hall and shuts down.
9. Tram autonomously starts up and exits the parking hall.
10. Continue after signal S612 is green.
11. Track decision point O - return to depot.
12. Track decision point B - proceed to workshop tracks 12-18.
13. Park on track in front of workshop.
14. Workshop operation is performed.
15. Exit workshop.
16. All tracks regroup on single line at point H.
17. Track decision point I - proceed to bypass track 44.
18. Bypass parking hall.
19. Continue after signal S612 is green.
20. Track decision point O - return to depot.
21. Track decision point B - proceed to sanding / washing track 11.
22. Park on track in front of sanding / washing.
23. Both sanding and washing are performed.
24. Exit sanding / washing.
25. All tracks regroup on single line at point H.
26. Track decision point I - proceed to bypass track 44.
27. Bypass parking hall.
28. Continue after signal S612 is green.
29. Track decision point O - exit depot.
30. Driver enters at track decision point O.
31. Tram exits the depot and resumes operation.