Optimal driving decision based on energy and time costs

SAKINA HUSEYNZADE
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Master Thesis Project
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Abstract

Nowadays the industrial world has a common goal to build environment-friendly transportation and power-train systems. The first step for this aim is electrification of vehicles on the road which has remarkable influence on energy dependency and greenhouse gas emissions. Besides the first aspect the second most important factor is automation of driving technology. Self-driving technology is a significant sight for the industry to develop quality and reduce operation costs. These highlighted tendencies cooperate to enhance the sustainability along with intelligence of the modern transportation world.

VERA is Volvo’s concept for driverless, electric truck technology. It holds the following tremendous advantages: automation, connectivity and electromobility – to accomplish optimal flows in transportation and logistics operations. The control is managed by autonomous electric vehicles equipped with refined systems for autonomous driving. Each vehicle is connected to a control centre. The transport control centre continuously regulates the progress of the transport and keeps an accurate supervision of each vehicle’s position, load content, the batteries’ charge and a number of other parameters.

Despite the improvements performed to refine this technology, heavy batteries, long time charging and the cost of vehicle itself limit the wide usage of electric AV for long distances. The research of this paper illustrates one of the most substantial aspects in autonomous electrified driving which is the charging decision. There are several approaches used to solve this question. It is popular among contributions to provide a data-driven method, i.e by considering constraints from personal daily trips and existing charging infrastructure. As a solution, stochastic energy consumption models are designed within proposed dynamic and multi-stage optimization problems. This paper provides treatment through evaluation and optimization of expenditures for AV involved in a certain road trip.
Sammanfattning


Trots att de förbättringar som gjorts för att förfinna denna teknik, begränsas den bredda användningen av elektriska automatiserade fordon för långa avstånd p g a tunga batterier, att laddning lång tid och kostnaden för fordonet. Undersökningen i detta kommer in på en av de mest väsentliga aspekterna i autonom elektrifierad körning som är laddningsbeslut.

1 Terms and Definitions

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>AV</td>
<td>Autonomous vehicle</td>
</tr>
<tr>
<td>SoC</td>
<td>State of Charge</td>
</tr>
<tr>
<td>VA</td>
<td>Vehicle Automation</td>
</tr>
<tr>
<td>$\eta_{\text{Battery}}$</td>
<td>Battery efficiency</td>
</tr>
<tr>
<td>$\eta_{\text{ElectricMotor}}$</td>
<td>Electric Motor efficiency</td>
</tr>
<tr>
<td>$\eta_{\text{Regeneration}}$</td>
<td>Regeneration efficiency</td>
</tr>
<tr>
<td>$P_{\text{battery}}/P_{\text{ElectricMotor}}/P_{\text{PE}}/P_{\text{Aux}}$</td>
<td>Battery Power/Electric Motor Power/Propulsion Energy Power/Auxiliary Power</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mission</td>
<td>Typically includes a set of activities. An example is a drive.</td>
</tr>
<tr>
<td>Activity</td>
<td>An abstracted type of vehicle command, for instance move from one point to another</td>
</tr>
<tr>
<td>Rolling resistance</td>
<td>Road resistance (one of the aerodynamic forces which resists the motion of a vehicle on a road)</td>
</tr>
</tbody>
</table>
2 Introduction

The purpose of this thesis project is to construct and implement an optimization strategy of optimal driving manner for a fully electric vehicle transporting cargo from point A to point B. The goal is to minimize the energy and operation costs in order to reach the most optimal charging strategy.

To find an optimal driving alternative one also needs a vehicle model describing the behavior of the vehicle in relation to route profile, altitude, speed, acceleration and mass along with power-train data and certain time frames in the transportation process which are considered to be the constraints for the optimization problem. The results show that since the energy cost values were found to be small compared to operational cost. Consequently, the problem is focused on time cost optimization within having higher transportation flow index and lower operational cost values with taking into consideration stochastic disturbance caused by other vehicles.

The thesis will be divided into the corresponding sections. Section 3 Background presents the features of the route and the AV plant model. Section 4 Defining the optimization problem "How should the vehicle be driven" describes the objective functions for cost functions and provides a detailed description Energy model on example when there is 1 VERA on the route. Section 5 Cost of time function when there is 1 VERA on the route shows the time function estimation for 1 VERA only. In Section 6 Expected and actual optimization problem one can find out what the target problem formulation turned out to be. From Section 7 to Section 12 analysis with different numbers of vehicles is discussed. Section 13 provides the summary which makes the final comparison between various alternatives which were analyzed in Sections 7-12.

3 Background

A number of electrified autonomous truck-trailer combinations "VERA" by Volvo GTT will transport goods from a factory A to the nearby harbor B, from where the goods will then be further transported by sea. Up to 6 truck-trailers will be considered in this problem. There is a loading area at the factory and an unloading area at the port. There are two charging stations, one being settled at the factory and combined with a loading spot. The another station is located in the port. Below in Figure 2 there can observed vehicle flow. In this figure A represents the factory and B represents the port. Starting from a parking spot at A, a normal mission would start with going to either a loading spot or a combined loading/charging spot depending on the state-of-charge. The vehicle then goes through Gate A, on the public road stretch, through Gate B, and depending on whether there is a queue to unloading, it goes first to a parking spot or directly to an unloading spot. On the way back to the factory, there is a possibility to stop and charge outside the B gate if needed.

In addition to the normal flow described below, there are a number of possible alternative flows. For instance when the vehicle is fully loaded and charged and ready to leave the factory yard, it may get instructions to go back to a parking spot. The reason may be traffic situation, e.g. traffic jam during rush hours, or road conditions or weather conditions, e.g. snow or too much rain. The most remarkable reason for providing different flows is Vehicle clustering problem(concentration of VERAs at waiting slots of factory and harbor due to the lack of work force, charging and waiting slots).

An approach to the final optimization problem "How VERA should be driven" will be done through defining and implementation of certain sub-tasks.
3.1 Vehicle Flow Topology

The figure below illustrates the flow that each AV follows. This flow contains three loading lanes at factory and three unloading lanes at harbor. It is possible to stop and wait behind each loading spot. This is indicated by the blue Wait squares. So a decision to charge when one other AV is already occupying the charging spot, will not lead to ‘game over’. It will only cause a delay.

![Topology for actual vehicle flow](image)

Figure 2: Topology for actual vehicle flow

3.2 VERA’s plant model

Building of the vehicle plant model is illustrated in Figure 4 below (with possible set of activities and missions set as described in Table 1 and 2 correspondingly ).
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<table>
<thead>
<tr>
<th>Activity</th>
<th>Description</th>
<th>Input/Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drive</td>
<td>Move to destination node</td>
<td>The input destination node is requested. If it is an empty string, the destination is determined by a previous SetDest call.</td>
</tr>
<tr>
<td>SetDest</td>
<td>Set destination node. Logic decision in close relation to Drive activity.</td>
<td>The output is a node, later used as input by Drive activity.</td>
</tr>
<tr>
<td>ManCargoChBatt</td>
<td>Manage cargo and, if possible, charge the battery.</td>
<td>The main input is the reference charging power PowerCh.</td>
</tr>
<tr>
<td>Wait</td>
<td>Wait until 'command flag' is false</td>
<td>Input is from vehicle external command</td>
</tr>
<tr>
<td>Park</td>
<td>Park vehicle until mission is changed</td>
<td>Input is from vehicle external command</td>
</tr>
</tbody>
</table>

Table 1: Possible set of activities

<table>
<thead>
<tr>
<th>Mission</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Work</td>
<td>The productive mission: goods items are moved from nodes [7, 8.9] to nodes [3, 4.5]. It is described in detail in Figure 2.</td>
</tr>
<tr>
<td>UnPark</td>
<td>Activates a parked vehicle, the vehicle will move to State A</td>
</tr>
<tr>
<td>GoPark</td>
<td>Ends a vehicle in Work mission, it will be moved to park node</td>
</tr>
<tr>
<td>ContPark</td>
<td>A vehicle in park mode will persist in this mode</td>
</tr>
</tbody>
</table>

Table 2: Proposed set of missions

In order to see how a certain mission is executed for a vehicle below in Figure 5 the productive work mission is described (mission definition from a graph below will be also given shortly as it is stated in VERA Traffic System modelling).
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Figure 3: VERA’s plant model

This is the only mode where charging power can be non-zero.

When waiting, the system is idling, auxiliary power is consumed.

When parked, the system is shut down, no auxiliary power consumption.

SetDest has another color marking because it does not directly influence the physical states of the vehicle.

The charging cost increases only at charging, it expresses the cost of using external battery charging service.

Figure 4: Work mission description

All mission start the vehicle is located at gate B.
4 Defining the optimization problem ”How should the vehicle be driven”

Based on the Energy+Time price framework an optimal charging decision making model is introduced in the following sections.

4.1 Cost functions for target which compile optimization problem

Assume that there is a limited amount of goods(for this problem there will be considered some cargo with the mass up to 17 tonnes) to be transported from factory to port.

Two cost functions will be considered. Their sum gives a target objective to be minimized :

1. Energy function. Here price of energy is considered and charge decision will be made with corresponding to solution of this optimization problem.
2. Time function (minimize time period for certain number of goods to be transported along the given road). By time, this case also contemplates time in a sense of its cost (price of working hours and VERAs’ price).

Thus, final objective function is the sum of energy and time costs functions which will be described in details in Sections 5 and 6.

4.2 Energy function definition

Propulsion power.

Power of battery depends on the following powers: Propulsion power and Auxiliary power. Here Propulsion power is traffic situation dependent. It requires a specific machine input power which is actually charging power. So, the energy consumed by a vehicle on the route is defined by Propulsion power. Auxiliary power is considered as a sum of all other powers which are not related to Propulsion power (for instance, the energy which is consumed while cooling the VERA motor).

Propulsion power is calculated as propulsion.force * speed. Below one can observe calculation sequence for consumed propulsion energy:

Slope angle and acceleration was calculated throughout provided time profile loop as below:

Calculation of the slope angle:

\[
\text{for } i = 2: \text{length(time)} \\
\text{dh} = \text{altitude}(i) - \text{altitude}(i - 1) \\
\text{dx} = \text{distance}(i) - \text{distance}(i - 1) \\
\text{slopeAngle}(i) = \arctan(\text{dh}/\text{dx})
\]

Calculation of the acceleration:
for i = 2:length(time)
    \[ dt = time(i) - time(i - 1) \]
    \[ acc(i) = (speed(i) - speed(i - 1))/dt \]

\begin{verbatim}
Total force = mass * acceleration;
Gravityforce = mass * g * sin(AngleSlope);
Rollingforce = RollingResistance * mass * g * cos(AngleSlope);
Airforce = 1/2 * airdensity * airResistance * speed^2;
Propulsionforce = Totalforce + Gravityforce + Rollingforce + Airforce;
PropulsionPower = Propulsionforce * speed;
T_{propulsion} = F_{propulsion} * R_{Wheel};
\end{verbatim}
The following equations are showing how the total power of vehicle is calculated. There will be differed equations for Battery Model and Electric Motor Model.

**Battery Model.**

\[
\dot{E}_{\text{battery}} = P_{\text{battery}} \cdot \phi_{\text{battery}} - P_{\text{Regeneration}}
\]

\[
\phi_{\text{battery}} = \begin{cases} 
1/ \eta_{\text{battery}}, & \text{if } P_{\text{battery}} < 0 \\
\eta_{\text{battery}}, & \text{if } P_{\text{battery}} \geq 0 
\end{cases}
\]

\[
P_{\text{Regeneration}} = \begin{cases} 
\text{abs}(P_{\text{battery}}), & \text{if } P_{\text{battery}} < 0 \\
0, & \text{if } P_{\text{battery}} \geq 0 
\end{cases}
\]

\[
P_{\text{battery}} = -P_{\text{PE}} - P_{\text{Aux}}
\]

**Electric Motor Model**

\[
P_{\text{PE}} = P_{\text{ElectricMotor}} \cdot \phi_{\text{ElectricMotor}}
\]

\[
\phi_{\text{ElectricMotor}} = \begin{cases} 
1/ \eta_{\text{ElectricMotor}}, & \text{if } P_{\text{ElectricMotor}} \geq 0 \\
\eta_{\text{ElectricMotor}}, & \text{if } P_{\text{ElectricMotor}} < 0 
\end{cases}
\]

\[
P_{\text{ElectricMotor}} = \begin{cases} 
P_{\text{ElectricMotorMax}}, & \text{if } P_{\text{Propulsion}} > P_{\text{ElectricMotorMax}} \\
P_{\text{Propulsion}}, & \text{if } 0 \leq P_{\text{Propulsion}} \leq P_{\text{ElectricMotorMax}} \\
P_{\text{ElectricMotorMin}}, & \text{if } P_{\text{Propulsion}} < 0 
\end{cases}
\]

\[
P_{\text{ElectricMotorMin}} = \max(P_{\text{Propulsion}} \cdot \eta_{\text{regeneration}}, -P_{\text{ElectricMotorMax}})
\]

**Constraints**

\[
P_{\text{Propulsion}} \leq P_{\text{PropulsionMax}} \cdot \eta_{\text{ElectricMotor}}
\]

\[
P_{\text{Propulsion}} \leq P_{\text{PropulsionMax}} \cdot \eta_{\text{Battery}}
\]

where

\[
P_{\text{PropulsionMax}} \cdot \eta_{\text{ElectricMotor}} = \eta_{\text{ElectricMotor}} \cdot P_{\text{ElectricMotorMax}}
\]

\[
P_{\text{PropulsionMax}} \cdot \eta_{\text{Battery}} = \eta_{\text{ElectricMotor}} \cdot \eta_{\text{Battery}} \cdot P_{\text{BatteryMax}}
\]
With provided Vehicle Powertrain data, time, reference speed and altitude profiles for the wayOUT (from factory to harbor) and wayIN (from harbor to factory) implementation of the described Energy model was performed. (all data is in SI units).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>mass of almost empty VERA (on the return trip)</td>
<td>15000kg</td>
</tr>
<tr>
<td>mass of loaded VERA</td>
<td>32000kg</td>
</tr>
<tr>
<td>rollResistance</td>
<td>0.00576</td>
</tr>
<tr>
<td>airResistance</td>
<td>0.53</td>
</tr>
<tr>
<td>wheelRadius</td>
<td>0.5m</td>
</tr>
<tr>
<td>PropulsionForceMax</td>
<td>147150N;</td>
</tr>
<tr>
<td>$P_{Aux}$</td>
<td>4000Watt</td>
</tr>
<tr>
<td>$P_{PropulsionMax}$</td>
<td>$2 \times 10^5$ Watt</td>
</tr>
<tr>
<td>$P_{PropulsionMin}$</td>
<td>-$10^6$Watt</td>
</tr>
<tr>
<td>$\eta_{Regeneration}$</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Table 3: Vehicle data

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{ElectricMotorMax}$</td>
<td>$2 \times 10^5$ Watt</td>
</tr>
<tr>
<td>$P_{BatteryMax}$</td>
<td>$10^5$ Watt</td>
</tr>
<tr>
<td>$\eta_{ElectricMotor}$</td>
<td>0.9</td>
</tr>
<tr>
<td>$\eta_{Battery}$</td>
<td>0.9</td>
</tr>
</tbody>
</table>

Table 4: Powertrain data
Reference speed profiles behaviour throughout driving time for the way IN (from harbor to factory) and way OUT (from factory to harbor).

The following speed profiles are provided references speeds which were plotted along with provided time profiles.

Figure 5: Reference speed profile behaviour from harbor to factory

Figure 6: Reference speed profile behaviour from factory to harbor
4.3 Energy consumption

Energy consumption constraint

Since the State-of-Charge for VERA during driving should be kept between 15% and 85% and energy storage is 147Kwh (one VERA has 3 batteries that are 49Kwh each) it should be noted that the maximum energy consumption for one VERA on the road is 147*70% which is 3,704,000 * 10^8 Wsec.

Energy consumption depends on a number of variables.

It worth to mention that there will be a number of cars loaded on the wayOUT and no cars loaded on the wayIN, but there are exceptions. Sometimes return cars will be loaded on the wayIN. So, to summarize, there are uncertainties regarding weight (VERA can be loaded by different weights. We assume that almost unloaded VERA’s weight is 15 tonnes which is for the way IN. And at maximum a vehicle can be loaded up till 17 tonnes, i.e maximum weight of VERA will be assumed 32 tonnes for the way OUT).

The calculated total energy is the amount drawn from the battery. The energy drawn from the grid during charging will be more, since there are losses also in the charging process, but that information is not needed in the analysis here.

So, if we consider that the best guess for auxiliary load is 3kW, assumptions regarding energy consumption is then summarized as in the following table:

Energy Consumption with 3 kW of Auxiliary load for 1 full return trip

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Energy kWh</th>
<th>SoC %</th>
<th>Share of recommended SoC range %</th>
<th>Charge time min : s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charge at harbor after driving only from factory</td>
<td>9.4</td>
<td>6.4</td>
<td>7.6</td>
<td>5 : 40</td>
</tr>
<tr>
<td>Charge at factory after driving only from harbor</td>
<td>6.5</td>
<td>4.4</td>
<td>5.2</td>
<td>3 : 20</td>
</tr>
<tr>
<td>Charge after return trip</td>
<td>16.0</td>
<td>10.9</td>
<td>12.8</td>
<td>8 : 60</td>
</tr>
<tr>
<td>Charge from SoC 15% to 85%</td>
<td>102.9</td>
<td>70.0</td>
<td>82.4</td>
<td>51 : 30</td>
</tr>
<tr>
<td>Charge from empty to SoC 85%</td>
<td>125.0</td>
<td>85.0</td>
<td>100.0</td>
<td>62 : 30</td>
</tr>
</tbody>
</table>

Charging current (power) is 120kW.

Charging time is calculated according to the amount of consumed energy and charging current while charging. The table above shows that in order not to be charged, the AV should keep SoC level roughly within 14% , i.e between 71% and 85%. This was done by calculation of Share of recommended SoC range within following strategy of 70% energy range, i.e :

\[
\text{Share of recommended SoC range (\%) } = \frac{\text{SoC}_{use}}{0.7}
\]

where

\[
\text{SoC}_{use}(\%) = \frac{\text{EnergyConsumption}}{\text{MaximumBatteryEnergy (147kWh)}}
\]
4.4 Energy consumption with different auxiliary loads

Since the initial idea is linked to minimization of Energy cost, the energy consumption model had to be implemented to different speed profiles. Since the highest speed profile is provided by project terms, the implementations were done with scaling down of reference speed profile from 90% to 40%. The table below shows energy consumptions of different scenarios with reference and scaled down speed profiles.

There was implemented energy consumption model for reference as well as scaled down speed profiles with different auxiliary loads (0, 1, 2, 3 kW). 3 kW is the best guess for auxiliary load. It will vary due to weather, but 3 kW is an average value.

It should be noted that the weight of VERA for the calculations below is assumed as 15 tonnes since energy consumption model is calculated for the wayIN only. When it comes to the wayOUT, the energy consumption model is the same except that the VERA’s weight is assumed to be 32 tonnes when it is loaded to the maximum and speed profiles, i.e driving times also.

Below in Figures 8-10 one can observe the pattern of change for remarkable magnitudes in the energy model throughout a short frame and also the total energy itself with reference and scaled down by 90% and 40% speed profiles considering 0 kW of auxiliary loads on the harbor to factory route, i.e on the way IN.

It should be noted that auxiliary loading of even 1 kW results as consumption of more energy while driving slowly after a certain deceleration. Thus, having 0 auxiliary load and reference speed scaled down from 90% to 40% ends up by less energy usage throughout the route (less speed means less energy consumption).

However, having auxiliary load leads to consumption of higher amount of total energy for VERA while driving really slowly (if reference speed is down scaled by 50% and 40%, sometimes even by 60%). This feature is shown in Figure 11(a) which is an example of harbor to factory route. The explanation to this is linked with the calculation of battery power as shown in the Battery Model. The addition of auxiliary power to propulsion one changes the behaviour of energy consumption if VERA is driven considerably slowly. However, while the same pattern is observed for the way OUT, it should be noted that for the way OUT scaling down provided reference speed profile by 90% leads to consumption of higher amount of energy compared to energy consumption while driving with reference speed profile. This feature is shown in Figure 11(b).

The table below illustrates data calculated for energy consumption of VERA with provided different auxiliary loads, reference and scaled down speed profiles on both ways.
<table>
<thead>
<tr>
<th>Scenario</th>
<th>Way IN drive time</th>
<th>Energy for Way IN (15 tonnes)</th>
<th>Way OUT drive time</th>
<th>Energy for WayOUT (12 tonnes weight)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>sec</td>
<td>min</td>
<td>kWh</td>
<td>sec</td>
</tr>
<tr>
<td>Aux 0 kW, Reference</td>
<td>698</td>
<td>11.6</td>
<td>5.574</td>
<td>681</td>
</tr>
<tr>
<td>Aux 0, Downscaled</td>
<td>775.56</td>
<td>12.93</td>
<td>5.339</td>
<td>756.67</td>
</tr>
<tr>
<td>90%</td>
<td>872.5</td>
<td>14.34</td>
<td>4.891</td>
<td>852.25</td>
</tr>
<tr>
<td>70%</td>
<td>997.14</td>
<td>16.62</td>
<td>4.550</td>
<td>972.86</td>
</tr>
<tr>
<td>60%</td>
<td>1163.33</td>
<td>19.39</td>
<td>4.283</td>
<td>1135</td>
</tr>
<tr>
<td>50%</td>
<td>1396</td>
<td>23.27</td>
<td>4.086</td>
<td>1382</td>
</tr>
<tr>
<td>40%</td>
<td>1715</td>
<td>29.1</td>
<td>3.955</td>
<td>1702.5</td>
</tr>
<tr>
<td>Aux 1 kW, Reference</td>
<td>5.888</td>
<td></td>
<td>8.462</td>
<td></td>
</tr>
<tr>
<td>Aux 1, Downscaled</td>
<td>5.690</td>
<td></td>
<td>8.682</td>
<td></td>
</tr>
<tr>
<td>90%</td>
<td>5.29</td>
<td></td>
<td>8.663</td>
<td></td>
</tr>
<tr>
<td>70%</td>
<td>5.039</td>
<td></td>
<td>8.355</td>
<td></td>
</tr>
<tr>
<td>60%</td>
<td>4.874</td>
<td></td>
<td>8.078</td>
<td></td>
</tr>
<tr>
<td>50%</td>
<td>4.804</td>
<td></td>
<td>7.915</td>
<td></td>
</tr>
<tr>
<td>40%</td>
<td>4.898</td>
<td></td>
<td>7.842</td>
<td></td>
</tr>
<tr>
<td>Aux 2 kW, Reference</td>
<td>6.214</td>
<td></td>
<td>9.147</td>
<td></td>
</tr>
<tr>
<td>Aux 2, Downscaled</td>
<td>5.959</td>
<td></td>
<td>9.199</td>
<td></td>
</tr>
<tr>
<td>90%</td>
<td>5.719</td>
<td></td>
<td>9.041</td>
<td></td>
</tr>
<tr>
<td>70%</td>
<td>5.539</td>
<td></td>
<td>8.776</td>
<td></td>
</tr>
<tr>
<td>60%</td>
<td>5.462</td>
<td></td>
<td>8.586</td>
<td></td>
</tr>
<tr>
<td>50%</td>
<td>5.388</td>
<td></td>
<td>8.583</td>
<td></td>
</tr>
<tr>
<td>40%</td>
<td>6.079</td>
<td></td>
<td>8.738</td>
<td></td>
</tr>
<tr>
<td>Aux 3 kW, Reference</td>
<td>6.537</td>
<td></td>
<td>9.4369</td>
<td></td>
</tr>
<tr>
<td>Aux 3, Downscaled</td>
<td>6.345</td>
<td></td>
<td>9.3822</td>
<td></td>
</tr>
<tr>
<td>90%</td>
<td>6.161</td>
<td></td>
<td>9.4047</td>
<td></td>
</tr>
<tr>
<td>70%</td>
<td>6.043</td>
<td></td>
<td>9.2192</td>
<td></td>
</tr>
<tr>
<td>60%</td>
<td>6.114</td>
<td></td>
<td>9.1561</td>
<td></td>
</tr>
<tr>
<td>50%</td>
<td>6.441</td>
<td></td>
<td>9.3822</td>
<td></td>
</tr>
<tr>
<td>40%</td>
<td>7.033</td>
<td></td>
<td>9.5547</td>
<td></td>
</tr>
</tbody>
</table>

Figure 7: Consumed total energy amount with various auxiliary loads and speed profiles on the way In and OUT
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(a) Remarkable magnitudes behaviour in 100 sec on the way IN

(b) Energy behaviour on the way IN throughout driving time

Figure 8: Versus with 0 auxiliary load and reference speed on the way IN.
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(a) Remarkable magnitudes behaviour in a short time frame on the way IN

(b) Energy behaviour on the way IN throughout driving time

Figure 9: Versus with 0 auxiliary load and downscaled speed by 90% on the way IN.
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Figure 10: Versus with 0 auxiliary load and downscaled speed by 40% on the way IN.

(a) Remarkable magnitudes behaviour in a short time frame on the way IN

(b) Energy behaviour on the way IN throughout driving time

Figure 10: Versus with 0 auxiliary load and downscaled speed by 40% on the way IN.
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Optimal driving decision based on energy and time costs

Figure 11: Feature of energy consumption dependency on auxiliary loading with several speed profiles on the way IN and OUT.

(a) Feature of energy consumption dependency on auxiliary loading with several speed profiles on the way IN.

(b) Feature of energy consumption dependency on auxiliary loading with several speed profiles on the way OUT.
5 Cost of time function when there is 1 VERA on the route.

When it comes to the time function, here are two aspects which should be taken into account: Personnel cost and VERA’s cost.

The following estimates are true:

**Loading Time:** 14 mins  
**Unloading time:** 9 mins

There are two operators, one is the loading operator at factory, the another is the unloading at harbor. An operator cost: 300 SEK/h, i.e 5 SEK/min.

**Total working time** of both operators is calculated as: **Loading time + unloading time + return trip driving time**.

Therefore, cost of personnel depends on driving time profile, i.e speed profile.

<table>
<thead>
<tr>
<th>Loading+Unloading time</th>
<th>Return driving time</th>
<th>Total working time</th>
<th>Salary per min</th>
<th>Total Personnel cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>23min</td>
<td>23min</td>
<td>46min</td>
<td>5SEK</td>
<td>230SEK</td>
</tr>
<tr>
<td>23min</td>
<td>25.53min</td>
<td>48.53min</td>
<td>5SEK</td>
<td>242.65SEK</td>
</tr>
<tr>
<td>23min</td>
<td>28.74min</td>
<td>51.74min</td>
<td>5SEK</td>
<td>258.7SEK</td>
</tr>
<tr>
<td>23min</td>
<td>32.82min</td>
<td>55.82min</td>
<td>5SEK</td>
<td>279.1SEK</td>
</tr>
<tr>
<td>23min</td>
<td>38.29min</td>
<td>61.29min</td>
<td>5SEK</td>
<td>306.45SEK</td>
</tr>
<tr>
<td>23min</td>
<td>45.97min</td>
<td>68.97min</td>
<td>5SEK</td>
<td>344.85SEK</td>
</tr>
<tr>
<td>23min</td>
<td>57.5min</td>
<td>80.5min</td>
<td>5SEK</td>
<td>402.5SEK</td>
</tr>
</tbody>
</table>

Table 5: Personals cost calculation data for 1 full return trip

The second factor which affects the cost function of time is AV cost.

From the commercial organization we have the following estimates:

**Purchase cost:** 3000000 SEK.  
**Depreciation time:** 4 years.

With such fast depreciation, capital cost will be small in comparison, so we will disregard that and thus can not assume any interest rate and calculate the present value. Cost per time period is calculated by simple division. Table 6 shows cost for certain units of time:

<table>
<thead>
<tr>
<th>Time period</th>
<th>Days of service</th>
<th>Hours of service</th>
<th>Cost per time period</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 years</td>
<td></td>
<td></td>
<td>30000000SEK</td>
</tr>
<tr>
<td>1 year</td>
<td></td>
<td></td>
<td>750000SEK</td>
</tr>
<tr>
<td>1 hour</td>
<td>261</td>
<td>8/5</td>
<td>360SEK/hour</td>
</tr>
</tbody>
</table>

Table 6: Commercial organization provided data for AV service

Therefore, cost of AV will be calculated as following in table below:
Master Thesis Project
Optimal driving decision based on energy and time costs

<table>
<thead>
<tr>
<th>Loading+Unloading time</th>
<th>Return driving time</th>
<th>Total working time</th>
<th>Salary per min</th>
<th>Total Service cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>23min</td>
<td>23min</td>
<td>46min</td>
<td>6SEK</td>
<td>276SEK</td>
</tr>
<tr>
<td>23min</td>
<td>25.53min</td>
<td>48.53min</td>
<td>6SEK</td>
<td>291.18SEK</td>
</tr>
<tr>
<td>23min</td>
<td>28.74min</td>
<td>51.74min</td>
<td>6SEK</td>
<td>310.44SEK</td>
</tr>
<tr>
<td>23min</td>
<td>32.82min</td>
<td>55.82min</td>
<td>6SEK</td>
<td>334.92SEK</td>
</tr>
<tr>
<td>23min</td>
<td>38.29min</td>
<td>61.29min</td>
<td>6SEK</td>
<td>367.74SEK</td>
</tr>
<tr>
<td>23min</td>
<td>45.97min</td>
<td>68.97min</td>
<td>6SEK</td>
<td>413.82SEK</td>
</tr>
<tr>
<td>23min</td>
<td>57.5min</td>
<td>80.5min</td>
<td>6SEK</td>
<td>483SEK</td>
</tr>
</tbody>
</table>

Table 7: AV cost calculation data for 1 full return trip

The figures below illustrate the cost of time and energy function for different round trip time driving time profiles with auxiliary loading of 0 kW and 3 kW. It should be noted that cost of consumed energy is calculated also for 1 round trip by using Energy model with two different weights of VERA (15 tonnes for the way IN and 32 tonnes for the way OUT).

**Note:** Cost for electricity from the grid is assumed to be 0.50 SEK/kWh. Also the efficiency for charging is assumed to be 0.8. Thus, 100 kWh from the battery will cost \( \frac{0.50}{0.8} \times 100 = 62.50\ SEK \)
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(a) Cost for AV service and personnel salary for 1 return trip with Auxiliary load of 0 kW
(b) Energy cost for 1 return trip with Auxiliary load of 0 kW throughout various driving time profiles
(c) Time and Energy Costs behaviour with 0 auxiliary load throughout various driving time profiles
(d) Total Cost function with 0 auxiliary load and security time throughout various driving time profiles

Figure 12: Cost functions behaviours with 0 auxiliary load throughout various driving time profiles
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According to the data collected from simulations carried out by Electro-mobility department of Volvo GTT there was set up “security driving time” for AV which provides information about how much one can scale down/up the speed profile for consuming less energy.

Figures 12(d) and 13(d) illustrate that scalings of reference speed as it was described above in Figure 7 meet the requirements of security driving time, i.e., with described speed profiles AV is always in secure domain of driving. Security driving time of one return trip is 1270 sec, 21 min 17 sec.
6 Expected and actual optimization problem

Calculated operating cost for 1 VERA provides the fact that energy cost is marginal compared to time cost function, i.e. expected optimization problem supposed to look as:

![Expected target optimization problem behavior](image)

Figure 14: Expected target optimization problem behavior

Sum of time and energy objective functions which supposed to compile target objective function was aiming to provide the best optimal reference speed profile that VERA can be driven. However energy consumption and operation cost functions showed the reality which can be seen in Figure 19 below:
Therefore, the task is turned out to be optimization of the operating cost (service fee of VERAs and Personnel cost) in such a way that the total cost will be as least as possible within maximal avoiding vehicle clustering problem on the route.

7 Operating cost optimization for 1 VERA

7.1 Costs share per cycle for 1 VERA

Since there is only one VERA only on the route earlier highlighted charging time and calculated energy amount provides the possibility drive VERA with the reference speed profile to spend as less as time on the route and to have higher productivity flow. One working day is 8 hours. Since each return trip with considered delays for loading/unloading takes 46 minutes in total, 1 VERA manages to finish 10.4 cycles during 8 hours. Therefore, if it is assumed that the process is running in 8 hours cost values are distributed as in the table below:

<table>
<thead>
<tr>
<th>Cost Type</th>
<th>SEK/cycle</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Labor cost</td>
<td>461.54</td>
<td>62</td>
</tr>
<tr>
<td>Equipment cost</td>
<td>276.92</td>
<td>37</td>
</tr>
<tr>
<td>Energy cost</td>
<td>10</td>
<td>1</td>
</tr>
<tr>
<td>Total Cost</td>
<td>748.46</td>
<td>100</td>
</tr>
</tbody>
</table>

Productivity (transport) flow is calculated as the the number of cycles in last return trip duration time in hours, i.e for 1 VERA:

Productivity flow = \( \frac{1}{\frac{46}{60}} \approx 1.3 \)
7.2 Sensitivity analysis for 1 VERA

The risk of running low on battery charge due to some disturbances on the road is investigated. The analysis here will be based on the worst case assumption that the auxiliary load will be 9 kW. The simulation with charging both at factory and harbor on each cycle indicates that without any disturbances SoC level will stay above 80%. This gives a 65% margin down to the lowest recommended SoC level, and 65% corresponds to 0.65 *147 kWh = 96 kWh.

Assuming the worst case with 9 kW of auxiliary power as being the only power consumption when standing still in a traffic jam and starting the first cycle at approximately of 15% SoC there are still 10.6 hours before reaching down to 15% of SoC level at the end of the day. This analysis gives an indication that the VERA should be able to handle some hours in a traffic jam without running low on battery.

![Figure 16: A simulation pattern of SoC behavior for 1 VERA in 8 hour simulation](image)

7.3 Conclusion for 1 VERA on the route

- The absence of the vehicle bunching problem provided the possibility for the charging strategy at harbor and factory every time which is the best due to economy of time (charging is completed at loading and unloading spots).
- There is a significant margin to running low on battery charge.
- Rough calculations indicate that even if the Vera gets stuck for several hours in a traffic jam, it will not run too low on battery charge.
- Energy cost is marginal compared to total operating cost.
8 Optimizing operating cost with 2 VERAs

In the following the two most optimal alternatives when there are 2 VERAs included in the task will be described.

Alternative 1:
1. Both VERAs are charged every time at both factory and harbor. This requires one loading operator at factory and one unloading operator at harbor.
2. VERA1 and VERA2 drive with reference speed profile all the time and both VERAs start driving at factory.

Due to waiting at factory gates for VERA1 loading, VERA2 starts its first cycle 14 minutes later. However this delay for VERA2 with waiting at gates happens only at the first cycle, starting from the second cycle there is no delay for VERAs at gates such as waiting for service. In this case, only at cycle 1 VERA2 spends an hour to complete return trip Factory-Harbor-Factory. The rest of the return trips during the 8 hour work day take 46 minutes to complete for both VERAs.

Therefore, while the 1st VERA manages to finish $(8\,\text{hours}/46\,\text{min}) \approx 10.4\,\text{cycles}$ during a day, VERA2 completes...
1 round trip in the 1st hour and \((7\text{hours}/46\text{min}) \approx 9.1\text{cycles}\) in the rest 7 hours of day. In total VERA2 makes 10.1 cycles during a day. Consequently within the frames of this alternative two VERAs complete 20.5 cycles during a working day. Hence, if it is assumed that the process is running for 8 hours cost values are distributed as in the table below:

<table>
<thead>
<tr>
<th></th>
<th>SEK/cycle</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Labor cost</td>
<td>234.15</td>
<td>45</td>
</tr>
<tr>
<td>Equipment cost</td>
<td>280.97</td>
<td>53</td>
</tr>
<tr>
<td>Energy cost</td>
<td>10</td>
<td>2</td>
</tr>
<tr>
<td>Total Cost</td>
<td>525.12</td>
<td>100</td>
</tr>
</tbody>
</table>

**Productivity (transport) flow** is calculated as the the number of transported VERAs in the last return trip duration time in hours, i.e for 2 VERAs:

**Productivity flow** = \(\frac{2}{46/60} \approx 2.6\)

**Alternative 2:**
1. VERA1 starts at factory at SoC level of 15%, VERA2 starts at harbor at SoC level of 50%. Here we still have 2 operators, one at factory, another at harbor. Charging VERA1 only at factory and VERA2 at only harbor every time.
2. Both VERAs drive with reference speed profile all the time

In this case VERA2 avoids waiting for service at gates of factory since we have different starting points. Therefore there happens no clustering between the two VERAs at any service points during a day while they are driving with the highest provided reference speed profile. Consequently, for the return trip each VERA spends the most optimal time of 46 minutes. In conformity with this circumstance each VERA completes \((8\text{hours}/46\text{minutes}) \approx 10.4\text{cycles}\) which in total gives 20.8 cycles during a working day.

Therefore, for continuous 8 hours running process, cost shares are scattered as following:

<table>
<thead>
<tr>
<th></th>
<th>SEK/cycle</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Labor cost</td>
<td>230.77</td>
<td>45</td>
</tr>
<tr>
<td>Equipment cost</td>
<td>276.92</td>
<td>53</td>
</tr>
<tr>
<td>Energy cost</td>
<td>10</td>
<td>2</td>
</tr>
<tr>
<td>Total Cost</td>
<td>517.69</td>
<td>100</td>
</tr>
</tbody>
</table>

**Productivity flow** = \(\frac{2}{46/60} \approx 2.6\)

**8.1 Conclusion for 2 VERAs on the route**

- With only two VERAs in the loop, and if one gets charged each time at factory and the other one each time at harbor, according to simulations SoC levels for both VERAs will stay roughly within 80 to 85 percent, if no disturbances are assumed.
- If there is a disturbance causing a delay, vehicle can handle some hours (more than 9 according to rough calculation) in a traffic jam without running low on battery charge.
For two VERAs in the loop it is enough with one loading operator and one unloading operator. We have a significant margin to running low on battery charge. Rough calculations indicate that even if the AV gets stuck for several hours in a traffic jam, it will not run too low on battery charge. Energy cost is marginal compared to total operating cost. The main difference when stepping up from one to two VERAs in the loop is that the labor force consisting of one loading operator and one unloading operator are better utilized, so labor cost goes down. Equipment cost and energy cost therefore relatively go up. Energy cost is still marginal, but this does not mean that energy consumption is unimportant. The cost for running out of charge will be high and must be avoided at all time. Also, when we introduce more VERAs in the loop and they will run longer between chargings, energy optimization and monitoring of SoC may become important to get the most out of the system. In this set-up with the two VERAs each has its own dedicated charge station, and also loading and unloading may be done in parallel, vehicle position balancing will still not be an issue.

9 Optimizing operating cost with 3 AV on the route

9.1 Mission Strategy.

In the Figure 19 the vehicle flow when there are three vehicles in the cycle is illustrated.
1. VERA1 and VERA2 start at factory, VERA3 starts at harbor. Here we have 3 operators, 2 at factory, another at harbor. Charging VERA1 and VERA2 only at factory and VERA 3 only at harbor every time.

2. VERA1 and VERA3 drive with reference speed profiles while VERA2 drives with scaled down by 70% speed profile on the way Factory-Harbor and reference speed profile on the Harbor-Factory route.

While VERA1 is loading at the factory slot and charging at the same time, VERA2 is at second loading slot for the first 14 minutes. After finishing loading service VERA1 is starting way OUT journey while VERA2 is heading to the charging slot of the factory to be charged for 3.20 minutes to start trip afterwards. In this time period VERA3 after finishing unloading and charging at harbor lane is heading to factory in 11.6 minutes, where in slot 2 it will be loaded.

VERA2 after 16.2 minutes on the route factory-harbor is arriving to the harbor gates and waits here for 1 minute for VERA1 to finish its unloading process. Afterwards, VERA1 is staring return trip to the first loading and charging lane of factory, followed by VERA2 with time gap of 2.6 minutes which is coming to the second loading slot of the factory. VERA3 in this time period after the loading process at factory is heading to harbor for unloading procedure.

While one full cycle in this mission for VERA1 and VERA2 is finished at factory gates, for VERA3 one full trip is Harbor-Factory-Harbor.

As one can notice while for VERA1 and VERA3 for one return trip there is performed the most optimal operating time in 46 minutes, VERA2 spends longer time due to scaling down of speed profile and short waiting for charging at the 1st spot of factory (3.20 minutes) and 1 minute waiting at unloading slot of harbor. Thus, while VERA1 and VERA3 carry out \((8\text{ hours/46min}) \approx 10.4\) cycles, VERA2 manages to finish the 1st cycle in 52.20 min due to delay. The next cycles VERA2 manages to finish with the optimal duration in 46 min. So, for VERA2 we have in total \((8\text{ hours} - 52.20/(14 + 16.2 + 1 + 9 + 11.6)\text{min}) + 1\) (from the 1st cycle) \(\approx 10.3\) cycles. Consequently, in total three VERAs with the described strategy complete 31.1 cycles.

In continuous 8 hour simulation manner 3 VERAs have the following cost shares:

<table>
<thead>
<tr>
<th>Cost Type</th>
<th>SEK/cycle</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Labor cost</td>
<td>231.51</td>
<td>45</td>
</tr>
<tr>
<td>Equipment cost</td>
<td>277.81</td>
<td>53</td>
</tr>
<tr>
<td>Energy cost</td>
<td>10</td>
<td>2</td>
</tr>
<tr>
<td><strong>Total Cost</strong></td>
<td><strong>519.32</strong></td>
<td><strong>100</strong></td>
</tr>
</tbody>
</table>
Since the very last cycle is completed by VERA2 then we have Productivity flow = $\frac{346}{60} \approx 3.9$.

9.2 Summary for 3 AV on the route

With three VERAs in the loop, and if two gets charged each time at factory and the others each time at harbor, SoC levels will stay roughly within 75 to 85 percent, if no disturbances are assumed.

- If there is a disturbance causing a delay, the Vera can handle some hours (almost 10 according to rough calculation) in a traffic jam without running low on battery charge.
- One can have three VERAs in the process keeping the same pace as only one VERA would, assuming two of them are charged at factory and the another one at factory.
- We have a significant margin to running low on battery charge.
- Energy cost is marginal compared to total operating cost.
- Compared to the 2 VERAs most optimal case by adding 1 more working force at one of the gates we get relatively higher transport flow with just 19 SEK of difference.

10 Optimizing operating cost with addition of the 4th vehicle

For 4 VERAs we will consider the following 2 most optimal alternatives.

1. Two VERAs are charged every other time at factory, and the other two are charged every other time at harbor.
2. Two VERAs are charged every time at factory, and the other two are charged every time at harbor.

Alternative 1.

If a charging station is expensive and can be regarded as a scarce resource, then it could make sense to do charging only every other cycle instead of every cycle. In our case however, as in alternative 2 above that you can do charging every cycle without the VERAs having to wait for each other, so there is nothing to gain by choosing charging less often.

In fact, what will happen is that one will use all three loading lanes and all three unloading lanes, even though there are never more than two VERAs at the same time at factory or harbor. So, either one will need two to three personnel at each end or two operators will serve three lanes.

What will also happen is that since two vehicles which are charging at harbor will get down to a lower SoC level before charging, then charging will take longer, estimated 11.20 minutes exceeding 9 minutes of unloading time at harbor slot. Thus, on every other cycle, the stay at harbor will be a few minutes longer, adding to the total cycle time.

For alternative 1, first one would get slightly higher cost for both labor and energy, because unloading would every other time get slowed down by the charging process. If you also consider having three personnel instead of two in each yard, then labor cost goes up by 50%. Adding time to charging at harbor increases total travel time, therefore equipment service cost is becoming higher.

Alternative 2.

We assume VERA1 and VERA2 starts at the same time from factory and VERA3 and VERA4 starts at the same time from harbor. We also assume that VERA1 and VERA3 are the ones that are charged at factory and VERA2 and VERA4 are the ones charged at harbor.

For this alternative, as long as there are no external disturbances, the VERAs will not disturb each other. If the VERAs are very different on SoC levels, there may be some waiting for each other until they have all come
up on charge levels, but after that it will run smoothly.
An eight hour simulation was implemented when the VERAs start at the same time with SoC levels 85%, 70%, 85% and 65% respectively.

10.1 Full cycle description within Alternative 2 frames.

VERA1 starting at loading+charging slot 1 of factory after finishing 14 minutes process is heading to harbor with reference speed profile, i.e. after 25.4 min VERA1 is reaching harbor unloading slot 2 (since for VERA1 it’s only required to be unloaded at harbor). After 9 minutes of unloading and 11.6 minutes of the driving with optimal velocity into the factory it reaches the lane 1 of factory at 46th minute of trip to be charged and loaded for the next cycle.

VERA2 after finishing 14 minutes loading at factory slot 2 is heading to harbor with reference speed profile, i.e. after 25.4 minutes VERA2 is coming to be unloaded+charged to slot 1 of harbor. After 9 minutes of unloading+charging and 11.6 minutes of the driving with optimal velocity into the factory it reaches lane 2 of factory at 46th minute of the trip to be loaded for the next cycle.

VERA3 starts its cycle at harbor slot 2 where it is unloaded and after driving with reference speed profile it comes to the first lane of factory at 20.6th minute of the trip to be charged and loaded for 14 minutes. Afterwards, the vehicle drives OUT with reference speed to harbor slot 2 for unloading process to start the next cycle.

VERA4 initiates a cycle at 1st (unloading+charging) lane of harbor. Then it drives to the 2nd slot of factory with reference speed profile to be loaded. After 14 minutes of loading procedure VERA4 drives OUT to harbor slot 1 to be charged and unloaded for the next return trip.

Hence, one can observe that in this alternative each cycle for every of four VERAs requires 46 minutes. While the full cycle for VERA 1 and VERA 2 looks like - Factory-Harbor-Factory, for VERA3 and VERA4 it is Harbor-Factory-Harbor. Therefore, the total number of cycles by 4 VERAs is \(4 \times (480\text{min}/46\text{min}) \approx 41.6\text{cycles}\).

Below one can detect cost shares for 4 VERAs within Alternative 2 conditions:
In last 46 minutes there are in total four cycles are carried out, that’s why Productivity flow = $\frac{4}{\frac{46}{60}} \approx 5.2$.

### 10.2 Sensitivity to delays

The analysis here will be based on the worst case assumption that auxiliary load will be 9 kW. The simulation result of SoC behavior indicates that without any disturbances SoC level will stay above 75%. This gives us a 60% margin down to the lowest recommended SoC level, and 60% corresponds to $0.60 \times 147 \text{ kWh} \approx 88 \text{ kWh}$.

Assuming the 9 kW auxiliary power as being the only power consumption when standing still in a traffic jam, this gives us 9.8 hours before reaching down to 15% of SoC level. The simulation indicates that the SoC level will cycle roughly between 75 to 85 percent.

![Figure 20: A simulation pattern of SoC behavior in Alternative 2 frames in 8 hour simulation](image)

### 10.3 Conclusions for 4 AVs in the cycle

- One can have four VERAs in the process keeping the same pace as only one Vera would, assuming two of them are charged at factory and the other two at harbor.
- There is a significant margin to running low on battery charge.
- Calculations based on SoC behavior indicate that even if the VERA gets stuck for several hours in a traffic jam, it will not run too low on battery charge.
- Energy cost is still marginal compared to total operating cost within frames of both alternatives.
- In a process with four VERAs, if one charges every second cycle instead of every cycle, there will be no gain in efficiency.
11 Optimization of driving with 5 vehicles in the system

As it was shown for 4 vehicles charging strategy which is not considered to be every time at one of the stations is disadvantageous due to higher service and travel time which is linked to charging duration. Therefore, afterwards there will be reflected versions with charging at every cycle. By keeping four operators, 2 at each gates of factory and harbor 5 VERAs perform relatively high transport flow within lower operation cost.

11.1 Full cycle mission control for 5 VERAs

VERA1 and VERA2 start cycle at factory with SoC of 60% and 75% respectively while VERA3, VERA4 and VERA5 start at harbor gates with SoC of 65%, 70% and 85% respectively. VERA1, VERA3 and VERA5 are charged at factory while VERA2 and VERA4 are charging at harbor station. All the VERAs drive with the highest possible, i.e. reference speed profile all the time, excepted VERA5 which is driving with 70% scaled down speed profile on the way IN by spending 17.02 minutes. This down scaling is performed in order to avoid waiting at gates of factory for free spot to be loaded.

VERA1 after 25.4 minutes of loading+charging and driving OUT reaches unloading slot 2 of harbor. VERA2 in the same period comes for charging+unloading to the 1st lane of harbor.

VERA3 after 20.6 minutes of unloading+charging and driving into factory reached the 2nd lane of loading. VERA4 in the same time gap reaches the 1st loading+charging lane of the factory.

When it comes to VERA5 after 9 minutes of waiting for the unloading+charging slot, it is heading to unloading spot 1 of harbor. Then it drives IN afterwards and reaches factory gates in 17.02 minutes. By driving in this manner VERA5 avoids waiting for VERA3 which still is in loading process at 2nd spot of factory.

VERA1 and VERA2 after 34.4 minutes drive into the factory slot 1 and 2 respectively in 11.6 minutes completing their full cycles.

VERA3 and VERA4 after 34.6 minutes of finishing loading procedures in factory drive OUT to the harbor in 11.4 minutes, into unloading lane 1 and 2 respectively finishing their full cycles.

VERA5 only after 46.42 minutes reaches the gate of harbor and comes directly into the unloading lane 1 of harbor and accomplishing its full return trip.

Here a full trip for VERA1 and VERA2 is Factory-Harbor-Factory, but for the rest three VERAs it is Harbor-Factory-Harbor.
Since during the 1st cycle there is a delay of 9 minutes for VERA5 due to lack of operator of unloading at harbor slot 3 and afterwards scaling down speed profile for VERA5 the first cycle is tend to be carried out in 60.42 minutes. However, starting from the second cycle the delay at harbor gates is not an issue anymore. Thus, VERA5 as the rest four VERAs manages to complete 1 full cycle in the minimum optimal 46 minutes time gap.

Hence the total number of cycles are done by 5 VERAs is calculated as sum number of cycles for four VERAs and number of cycles by VERA5 in 8 hours time frame: \((4 \times \frac{480\text{min}}{46\text{min}}) + (480\text{min} - 60.42)/46\text{min} + 1 \approx 51.5\text{cycles}\).

Below one can find cost shares with 5 VERAs attracted into the route:

<table>
<thead>
<tr>
<th></th>
<th>SEK/cycle</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Labor cost</td>
<td>186.41</td>
<td>39</td>
</tr>
<tr>
<td>Equipment cost</td>
<td>279.61</td>
<td>59</td>
</tr>
<tr>
<td>Energy cost</td>
<td>10</td>
<td>2</td>
</tr>
<tr>
<td>Total Cost</td>
<td>476.02</td>
<td>100</td>
</tr>
</tbody>
</table>

In last 46 minutes 5 cycles are accomplished, that’s why \(\text{Productivity flow} = \frac{5}{36/60} \approx 6.5\).

### 11.2 Main Conclusions for the system with 5 vehicles

- Assuming the worst case with 9 kW auxiliary power as being the only power consumption when standing still in a traffic jam, this gives us 8.9 hours before reaching down to 15% of SoC level. Since there is charging on each cycle either after driving from harbor or factory charging times do not exceed loading and unloading times,
- One can have five VERAs in the process keeping the same pace as only one Vera would, assuming two of them are charged at factory and the other three at harbor.
• We have a significant margin to running low on battery charge.
• Energy cost is marginal compared to total operating cost.

12 Optimal decision with the maximum 6 VERAs in the route

12.1 Mission decision
1. There are 5 operators in total with 3 being located at factory lanes and 2 being located at harbor spots.
   One can wonder about placement of 5th personnel at factory gates, not harbor, this is linked to unloading and loading time. Since loading requires 5 minutes more than loading, in order to avoid waiting for VERA highlighted placement was chosen.
2. VERA1, VERA3, VERA5 are charging at factory station, VERA2, VERA4, VERA6 charge at harbor.
3. All the VERAs except VERA3 drive with corresponding reference speed profiles on the way IN and way OUT.
   VERA3 in the first cycle has to drive with 70% scaled down speed on the way to harbor.

12.2 Full cycle description
VERA1 starts from the first slot of factory with charging and loading for 14 min. Then it drives in 11.4 minutes to the second harbor slot to be unloaded for 9 minutes.

VERA2 starts the first cycle at second slot of factory with loading. Afterwards it drives to slot 1 of harbor to be unloaded and charged for 9 min.

VERA3 starts the trip from the third slot of factory and after 14 minutes of loading it is heading to the charging station of factory to get charged for 3.20min. Then in order to avoid waiting at the harbor gates for 5.40 min for VERA1 to finish its unloading, VERA 3 drives OUT with 70% scaled down speed profile. Thus, it reaches harbor gates at slot 2 of unloading after 16.2 minutes. In this case waiting time for VERA1 is minimized to 1 minute.

During this time period VERA4 after 9 min of unloading and charging at slot 1 of harbor drives into slot 2 of factory in 11.6 minutes with reference speed profile to be loaded for 14 minutes.

VERA5 after 9 min of unloading at the second slot of harbor drives for 11.6 min into slot 1 of factory for charging and loading.

VERA6 after 9 min of waiting to be charged and unloaded at harbor slot 1 drives with reference speed profile into slot 3 of factory for loading.

The first cycle for VERA 1 and VERA2 are finished after 46 minutes in harbor slots 2 and 1 respectively. For VERA3 due to delays the first cycle is completed after 54 minutes in waiting slot 3 of harbor. Since VERA3 every time is loaded at slot 3 of factory and also need to be charged in factory station starting from the second cycle we get delay in 3.20 minutes for each cycle. Thus, VERA3 has to have 49.20 minutes for each return trip starting from the second one.
VERA4 and VERA5 after finishing loading procedure at factory drive OUT with reference speed to harbor to slot 1 and 2 respectively and finish their first cycles in 46 minutes. VERA6 due to delay at the beginning of cycle reaches harbor slot after 55 minutes. That’s why it does not need to wait at slot 3 of harbor for 9 minutes for unloading and charging. VERA6 directly drives into slot 1 or 2 of harbor for unloading.

Starting from this location there can be 2 alternatives for VERA6:

Alternative 1. Assuming worse situation that VERA6 can always drive to slot 2 of harbor for unloading and only after it drives to slot 1 of harbor to be charged for 5.40 minutes to start its next cycle we will get delay for 5.40 minutes for each next cycle. Hence, VERA 6 will consume 51.40 minutes for each cycle starting from the 2nd cycle.

Alternative 2. However, if VERA6 drives directly to slot 1 of harbor where it can finish charging with unloading at the same time we avoid delay of 5.40 min for each cycle starting from the second trip. Therefore, VERA 6 will spend the most optimal time gap in 46 minutes for each cycle starting from the 2nd cycle.

Here a full trip for VERA1, VERA2 and VERA3 is Factory-Harbor-Factory, but for the rest three VERAs it is Harbor-Factory-Harbor.

Figure 22: Cycle flow with 6 VERAs in the system

12.3 Costs share for 6 VERAs in Alternative 1 frames

The total number of cycles are done by 6 VERAs is calculated as sum of all cycles in 8 hours simulation:

\[(4 \times \frac{480\text{min}}{46\text{min}}) \times (\text{VERA1, VERA2, VERA4, VERA5}) + (\frac{480\text{min}-54}{49.20\text{min}}+1) \times (\text{VERA3}) + (\frac{480-55}{51.40\text{min}}+1) \times (\text{VERA6}) \approx 60.6 \text{ cycles.} \]

Below one can find cost shares with 5 VERAs attracted into the route:
In last 51.40 minutes 6 cycles are completed, that’s why Productivity flow = \( \frac{6}{51.40/60} \approx 7 \).

12.4 Costs share for 6 VERAs in Alternative 2 frames

The total number of cycles are done by 6 VERAs is calculated as sum of all cycles in 8 hours simulation:

\[
(4 \times 480\text{min}/46\text{min}) \text{(VERA1, VERA2, VERA4, VERA5)} + (480\text{min}-54)/49.20\text{min}+1 \text{(VERA3)} + (480-55)/46\text{min} +1 \text{(VERA6)} \approx 61.6 \text{ cycles.}
\]

Below one can find cost shares with 6 VERAs attracted into the route:

<table>
<thead>
<tr>
<th></th>
<th>SEK/cycle</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Labor cost</td>
<td>198</td>
<td>40</td>
</tr>
<tr>
<td>Equipment cost</td>
<td>285.15</td>
<td>58</td>
</tr>
<tr>
<td>Energy cost</td>
<td>10</td>
<td>2</td>
</tr>
<tr>
<td>Total Cost</td>
<td>493</td>
<td>100</td>
</tr>
</tbody>
</table>

In last 49.20 minutes 6 cycles are completed, that’s why Productivity flow = \( \frac{6}{49.20/60} \approx 7.3 \).

12.5 Main conclusions:

- One can have six VERAs in the process keeping the same pace as only one VERA would, assuming 3 of them are charged at factory and the other 3 at harbor.
- We have a significant margin to running low on battery charge.
- Since each VERA is getting to be charged each time at of the stations of harbor or factory even if the VERA gets stuck for several hours in a traffic jam, it will not run too low on battery charge.
- Energy cost is marginal compared to total operating cost.
13 Summary on comparison of different vehicles numbers

The table below provides the results collected from analysis with optimal decisions for different numbers of VERAs in the system.

Summary of cost share and production flow:

<table>
<thead>
<tr>
<th>No. of loading/unloading operators</th>
<th>Operating cost [SEK/cycle]</th>
<th>Production flow</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Labor</td>
<td>Equipment</td>
</tr>
<tr>
<td>1 Vera</td>
<td>2</td>
<td>461.6</td>
</tr>
<tr>
<td>2 Veras</td>
<td>2</td>
<td>234.2</td>
</tr>
<tr>
<td>2 Veras</td>
<td>2</td>
<td>230.8</td>
</tr>
<tr>
<td>3 Vera</td>
<td>3</td>
<td>231.5</td>
</tr>
<tr>
<td>4 Veras</td>
<td>4</td>
<td>230.8</td>
</tr>
<tr>
<td>5 Veras</td>
<td>4</td>
<td>186.4</td>
</tr>
<tr>
<td>6 Veras</td>
<td>5</td>
<td>198</td>
</tr>
<tr>
<td>6 Veras</td>
<td>5</td>
<td>194.8</td>
</tr>
</tbody>
</table>

One the most significant indicators while optimizing operational cost for various numbers of VERAs which we are leaning on is transportation (production) flow per cycle.

The figure below shows behavior of production flow for different numbers of VERAs.

![Figure 23: Relation between total costs and productivity index per cycle](image)

There is no fixed, desired index for production flow defined by the terms of project which could lead to obtain.
Hence, one can notice the fact that although higher number of VERAs as a rule provide higher value for transportation flow depending on different circumstance the target is not always having a big production flow. Because at some points it is unavoidable to have less service fee for per cycle when there are more VERAs included in the task. Thus, a slightly higher transportation flow can be not enough for paying higher amount in that case. As a result one can prefer slightly lower transportation flow with paying considerably less for less amount of VERAs in the route. For instance, if one compares productivity flow for 6 VERAs’ most optimal case and 5 VERAs’ it is distinguishable that 17 SEK of difference with provides just a slight increase in production flow from 6.5 to 7. It can be quite reasonable to prefer to use in that day 5 VERAs instead of 6.

14 Simulink structure on example of one VERA

As it was mentioned before 8 hours simulation was implemented in Simulink. There are 3 main blocks: Mission control, Vera, Performance are performing certain tasks to get final feedback at the end of simulation.

14.1 Mission control block

This block is responsible for vehicle driving and charging control. Boolean blocks are in charge whether VERA is loaded(unloaded), arrived to Factory(Harbor), charged depending on SoC levels.
14.2 Vera block

This second block has more objectives than the rest two. It consists of the next sub-blocks: **Loading and unloading processes**, **Driving Block**, **Power Consumption Block**, **Energy Consumption and Energy Storage Blocks**. In **Loading and Unloading processes** block specific time frames for processed are marked. Let’s see what is going on in the other blocks.
14.3 Driving block

Here vehicle receives the required speed profiles at the beginning and distances (4684m and 4763m) which it should complete on the return way. At the end block checks if AV reached its destination (Factory or Harbour).
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14.4 Power Consumption block

By marking here energy amount provided by energy model for the way IN and OUT in this block there is calculated Propulsion Power amount and included Auxiliary load. Sum of this powers is output of block.

Figure 27: Driving block

Figure 28: Power Consumption block
14.5 Energy Storage block

One of the blocks which is linked to Power Consumption block is this block. Here charging process is performed. The condition of charging up till 120 kW at the station with the rest constraints of Energy model are taken into consideration and battery energy with SoC is received as output from this block.

![Energy Storage block](image)

Figure 29: Energy Storage block

14.6 Energy consumption block

This is the second block which Power Consumption block is combined with. Here is integration operation of calculated final Power is accomplished to have final Energy amount.

![Energy Consumption block](image)

Figure 30: Energy Consumption block

14.7 Performance block

The last block consists of two main sub-blocks which are Cost SEK calculating price of Energy, Operation costs and Productivity measures sub-block which provides the final indicators of optimal driving decision.
14.8 Cost SEK block

All required costs are calculated here. For energy consumption price as input block receives energy consumption. Labor and VERA service costs are calculated according to highlighted above numbers established by project.

14.9 Productivity block

Here the total number of cycles is calculated at the beginning. Consequently, indicators as cycles per hour and corresponding costs per cycle are outputs of the block.
15 Future work and improvements

The most important improvement should be made with analysis of adding into the cycle more number of VERAs. Since the scope of the project was considered within only 6 vehicles making transport topology and constraints were defined correspondingly with them. It is not excluded that adding even 1 more AV into the task can be end up by building new charging stations or waiting lane depending on profit and payments attracted into the case.

The analysis will be adapted to the new scope with shorter route, shorter loading and unloading times.

Vehicle speed and power consumption are modeled in a very simplified way at the moment. One idea has been to use the model that exists within GSP (Global simulation Platform). This may be the most accurate alternative, but it seems to be difficult to run this model outside of the GSP environment. Another idea is to use a simpler model and to get some help from Electro-mobility department to set parameter values.

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Inventors: Dylan Saloner, PaloAlto, CA (US); Yiguang Xuan, Berkeley, CA 1US); Juan Argote, Berkeley, CA 1US); Carlo Daganzo, Berkeley, CA 1US)


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