CUSTOMER REPORT

Feasibility of electric buses in Tromsø

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Confidentiality: Open

Report's title

Feasibility of electric buses in Tromsø

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Project name	**Project number/Short name**
eBus Tromsø	

Summary

Electric buses are being fast deployed in different demonstration and pilot projects across Europe. Also competitive tendering processes on vehicle systems are emerging. The subject of the present work is to study the feasibility of electric buses in Tromsø area in northern Norway. The special conditions in Tromsø include topography with steep hills, relatively high humidity and precipitation, and icing on the roads wintertime. All these make electric bus operation in Tromsø area more demanding than in an average town. The bus network and characteristics of the bus lines was analysed using a geographic information systems (GIS) interface, which enabled the construction of the most relevant bus lines for simulation. Bus lines 26, 32, 33, 34, 37 and 40 in Tromsø were constructed and bus timetables and vehicle rotations on those lines were analysed. The study was carried out by analysing a 12 metre fully electric bus on each of the lines. The electric buses were either with a large 250 kWh battery and charged over night at the bus depot (with an intermediate shorter charging forced in the middle of the day), and opportunity charged buses with a downsized 80 kWh battery and capability for fast high power charging of 1 – 3 minutes at 300 – 500 kW. The total cost of ownership of a 12-metre electric bus fleet was analysed, taking into account necessary charging infrastructure, capital and operational costs over vehicle hold time of 14 years, and compared with diesel buses. Also the environmental impacts (emissions) when changing from diesel to electric buses were analysed. The study concludes that electric buses are feasible in Tromsø as long as the demanding conditions are taken into account in the design phase. Opportunity charged electrical buses appear as the most cost-efficient alternative and also competitive compared to diesel buses, provided that sufficient charging time can be provided for the buses in the vehicle rotation no extra buses are needed in service. A proposal is made for an electric bus pilot in the city of Tromsø.

Espoo 30.9.2016

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Contents

1. Description and objectives

Mobility and transport, both private and commercial, are in the process of transformation. The key challenges faced in today's traffic systems are carbon footprint of the vehicles, local emissions and noise, and congestion. The technosocietal change is moving traffic systems from non-smart and non-ecological mobility towards ecological smart mobility with increasing amount of clean vehicles, shared use and information and communications technology (ICT) services. [1]

Fully electric city buses have the potential to dramatically reduce the carbon footprint (prerequisite: low-carbon electricity), local emissions and noise of public city transport. Combined with smart ICT systems providing accurate timetables and options for the consumers, fully electric city buses can accomplish, in their part, an affordable and ecological inner city smart mobility. For example, the Finnish Helsinki Regional Transport Authority (HSL) responsible for organising public transport in the Helsinki area announced that they are ramping up fully electric bus share being 1% in 2015, 10% in 2020 and 30% in 2025. Similar targets are being set in various major European cities such as Oslo. The feasibility of electric buses is being demonstrated within the Zero Emission Urban Bus System (ZeEUS) project funded by 7th Framework Programme (EU's research and innovation funding programme, FP7) and coordinated by the International Association of Public Transport (L'Union internationale des transports publics, UITP) [2]. An electric bus pilot and living lab development is also on-going in the Helsinki region [3].

The context and purpose of the present work is to contribute to this context through a concrete feasibility study placed in the very north of Europe, Tromsø in northern Norway. The task given has been to study in concrete terms the feasibility and alternatives for an electric bus pilot and strategy in the area. This task has been approached through a set of tools: line network analysis through construction of the relevant line data using a geographic information system (GIS) tool and simulation of the operation on different bus lines, analysis of the operation patterns and timetables, analysis of the total cost of ownership of the fleets, and analysis of the emission impacts compared to conventional diesel buses.

The report discusses the different options and alternatives for an electric bus pilot and operation in Tromsø, and comes with a proposal for an electric bus pilot.

2. Methods and realisation

2.1 Resources and project organisation

Project manager: Mikko Pihlatie (VTT)

Project members: Mikaela Ranta (VTT), Pavel Ponomarev (VTT), Pekka Rahkola (VTT), Christian Weber (TOI), Astrid Amundsen (TOI), Rolf Hagman (TOI)

Project's steering group: Troms fylkeskommune (PL), Troms fylkestrafikk, Nobina, Universitetet I Tromsø and Troms kraft

Subcontractors and other outsourced services: -

2.2 Schedule and project's main events

The project was carried out according to the public tender by Troms Fylkeskommune and subsequent contract with VTT. The project period was July – September 2016. A workshop in Tromsø was held on the 23rd of August. The project will also have an open dissemination conference on the 7th of October in Tromsø.

2.3 Methodology, input data and tools

2.3.1 Bus model

The simulation model of the bus depicts longitudinal dynamics of the bus, which enables performance and energy efficiency studies. The longitudinal dynamic model includes resistive forces rolling resistance, aerodynamic drag, and climbing force. The bus mass is defined using chassis mass, passenger load, and the inertia of the rotational masses. The mechanical driveline is given a constant efficiency factor. The friction between tires and road is taken into account and also the number of driven axles.

The electric system includes the traction motor and battery. The battery has power limits for charge and discharge directions and efficiency factor. The traction motor is characterized by the nominal operating point, which determines the nominal rotational speed and nominal power, maximum torque and maximum rotating speed. The field weakening is modelled using a constant power output after the nominal speed. The efficiency of the traction motor is defined as a function of motor speed and torque. The power converter is given a constant efficiency factor.

The bus driving is managed via a speed controller. Torque of the traction motor is defined based on the speed set value and actual speed of the bus. Bus deceleration is done primarily using regenerative braking and using wheel brakes if regenerative braking effort is not enough.

2.3.2 Bus specifications

Two different buses are defined: one for opportunity charging and one for depot charging. Mass values for the buses are shown in Table 1 (page 7). The total mass of the bus is defined using equations

$$m = m_{chassis} + m_{battery} + m_{load}$$

$$m_{battery} = 20\frac{kg}{kWh} \cdot E_{battery}$$

The nominal mass of the vehicle chassis is $10000\ kg$ in both cases. The mass of the battery pack is assumed to be $20\ kg/kWh$, which gives the total battery mass $1600\ kg$ for the opportunity charged bus and $5000\ kg$ for the depot charged. In the simulations, the passenger load varies in the range 0 – 6120 kg in both cases. Please note that due to the high total mass, the depot charged bus might not be able to offer the same loading capacity in reality, due to high total mass of the vehicle. This would be equal to less passenger capacity available.

Table 1 Bus masses for opportunity and depot charged buses.

Bus type	**Opportunity charged**	**Depot charged**
Chassis weight (kg)	10000	10000
Battery capacity (kWh)	80	250
Bus mass (kg)	11600	15000
Passenger load (kg)	0 - 6120	0 - 6120

Parameters for the bus powertrain and driveline are shown in Table 2 (page 8). The parameters for the powertrain and driveline dimensioning and efficiencies present typical values for electric city buses. The driveline parameters for the opportunity and depot charged buses are the same except the electric motor power and the final drive ratio. For the depot charged bus, the electric motor power and the final drive ratio are slightly increased. These parameters are defined based on the fact that the bus has to be able to climb a 20% slope. The final drive ratio is rather high for both buses, which means that the maximum speeds of the buses are rather low, (70-75 km/h). As there is no gearbox in the bus, the maximum speed has to be limited in order to obtain enough torque for the steep hills. Another option would be to use a heavier and more powerful motor. A more detailed presentation of the bus performance is given in APP. A (page 37).

Table 2. Bus powertrain and driveline parameters for opportunity and depot-charged buses.

Bus parameters	**Opportunity charged**	**Depot charged**
Motor power (kw)	170	190
Motor nominal speed (rpm)	1500	1500
Battery discharge power (kw)	180	200
Battery charge power (kw)	300	300
Inverter efficiency	0.98	0.98
Battery efficiency	0.97	0.97
Inertia coefficient (-)	1.1	1.1
Final drive ratio (-)	8.84	9.42
Tire radius (m)	0.5	0.5
Driveline efficiency (-)	0.85	0.85
Rolling resistance coefficient (-)	0.01	0.01
Rolling resistance coefficient with snow chains (-)	0.014	0.014
Aerodynamic drag C_dA (m^2)	3.5	3.5
Vehicle driven mass ratio	0.55	0.55

2.3.3 Bus parameter study

Sensitivity of some bus parameters relative to the energy consumption was studied. Figure 1 (page 9) shows the energy consumption as a function of the final drive ratio. This analysis is done using Troms line 37 and opportunity charged bus with the total mass of $11600\ kg$. The optimum final drive ratio in this case seems to be around 9.42 which corresponds to a vehicle speed of $30\ km/h$ at motor nominal speed. When the final drive ratio gets lower, the bus maximum speed increases. When the final drive ratio gets low enough, the bus won't succeed to climb the steep hills anymore.

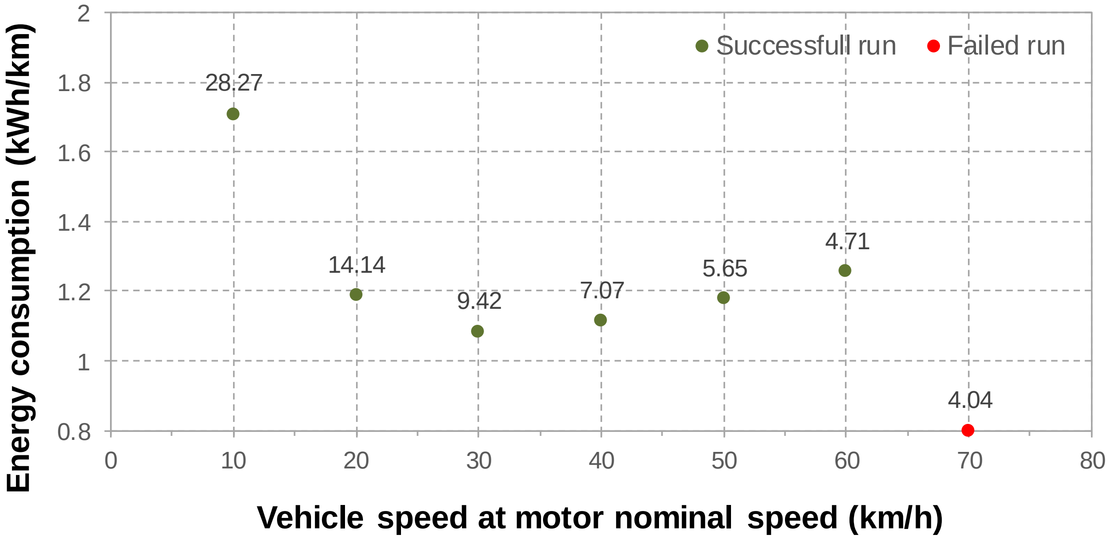


Figure 1. Energy consumption as a function of bus speed at electric motor nominal speed for the opportunity charged bus.

The second parameter study shows energy consumption as a function of the friction coefficient between the tire and the road in Figure 2. The energy consumption is steady until the friction coefficient falls below 0.4. After that regeneration has to be limited which increases energy consumption. When the friction coefficient is low enough the bus cannot succeed the bus line anymore. Four wheel drive helps the situation in the friction coefficient range of 0.2 – 0.4, but if the friction coefficient falls below 0.2, snow chains should be applied on this bus line.

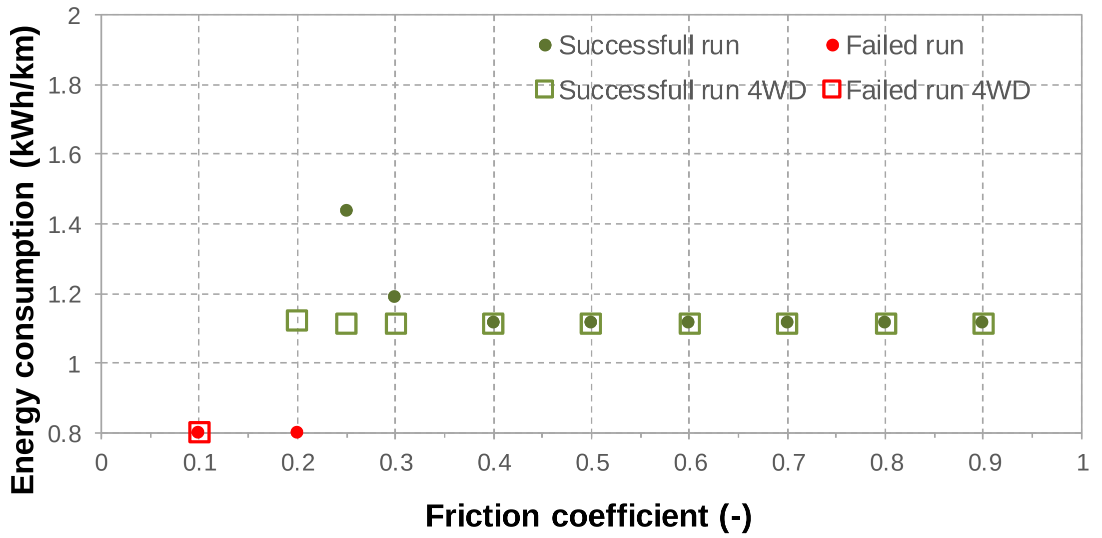


Figure 2. Energy consumption as a function of the friction coefficient between tire and road for the opportunity charged bus.

2.3.4 Construction of the bus lines

Based on discussion with the client, analysis of the bus line network and schedules, as well as the field visit in Tromsø on the 23rd of August, the following bus lines were selected for analysis: 26, 28, 32, 33-34, 37 and 40. The bus lines were constructed using GIS tool interface. The information on the location of each stop of each line was obtained from the travel planner application at http://rp.tromskortet.no/. Each stop was entered manually and the coordinates of each point on the path between the stops were obtained using GIS tool WebAPI from open sources at OpenStreetMap, Google Maps and HERE Maps. The path was verified manually and corrected if needed locally.

Then, for each point along the path the elevation and legal speed limit data was fetched automatically using GIS tool WebAPI. This data was filtered to get rid of artefacts and glitches to represent the real smooth road surface without sharp changes in the elevation.

For several regions, such as bridges and tunnels, the elevation and speed limit data was not available. Those regions were treated manually using open data about construction of those bridges and tunnels found from internet.

2.3.5 Validation of the bus lines GIS data

The speed of the hybrid buses currently used in Tromsø was measured on lines 26 and 37 for validation of the simulation model. No passengers were on the bus, and the bus did not stop at bus stops, except for a few bus stops at line 26, where the bus had to stop due to another bus. The measured speed is shown in Figure 3 and Figure 4 (page 11) together with the simulated speed and the speed limit. Due to random traffic events, the speed profiles are not exactly the same, but they have similar characteristics.

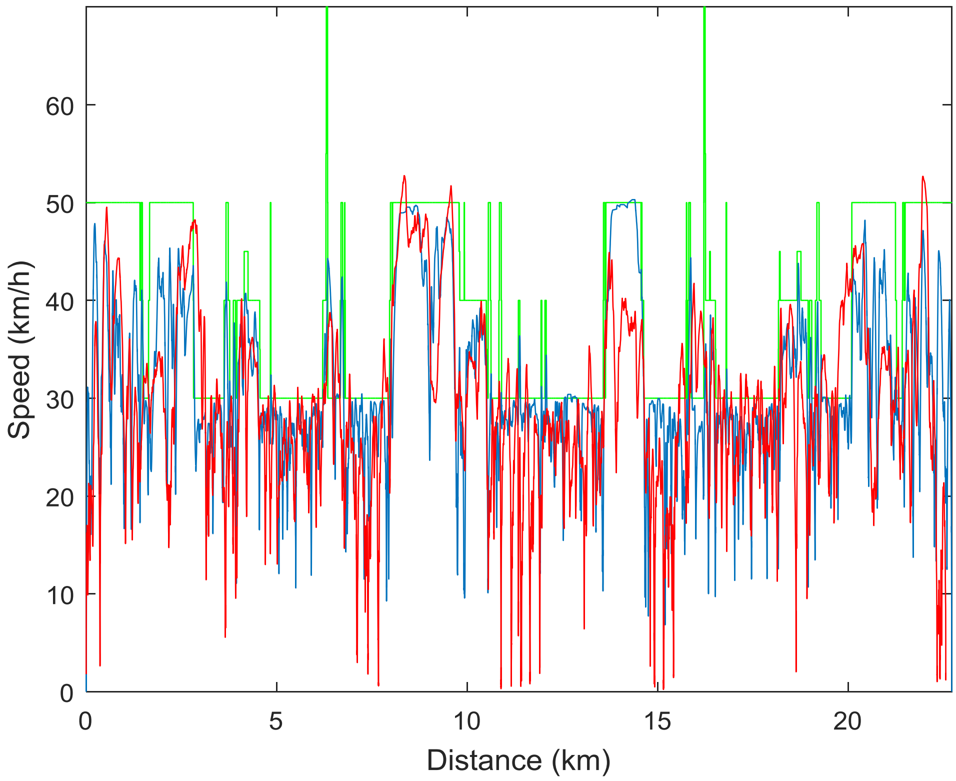


Figure 3. Validation of bus line modelling, line 26. Simulated speed profile is denoted by a blue curve, and measured speed profile by a red curve. The speed limit is shown by the orange curve.

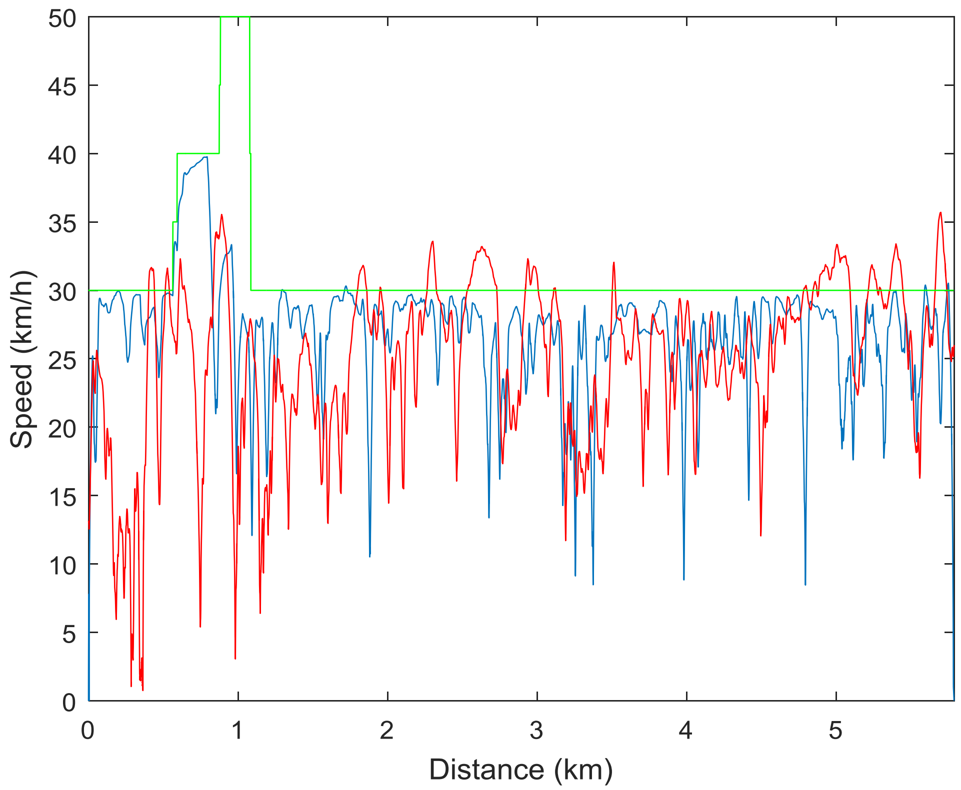


Figure 4. Validation of bus line modelling, line 37. Simulated speed profile is denoted by a blue curve, and measured speed profile by a red curve. The speed limit is shown by the orange curve.

2.3.6 System simulation using the GIS tool

The energy consumption of the buses was studied by means of simulations in the GIS tool. The GIS tool uses the information obtained from the bus line construction as a basis for the simulations. The speed profile is created dynamically during the simulation. The bus follows the speed limits, and slows down in curves. Traffic events are modelled by forcing the bus to slow down at randomly chosen locations. The acceleration and deceleration were in all cases limited.

Various simulations were carried out on each bus line and with both bus types. The number of passengers was varied in the range 0 to 90, corresponding to a load of 0 and 6120 kg. The stopping frequency was also varied from every second bus stop to every bus stop. The simulations were performed both without snow chains and with snow chains. An average power consumption of 5 kW in total for auxiliary systems and heating and air conditioning was assumed. Every case was simulated 5 times in order to take into account the variation produced by the random traffic events. In the results, the mean value of these 5 simulations for every case is presented.

2.3.7 Total cost of ownership tool

Analysing the total cost of ownership (TCO) of owning and operating a bus fleet is a necessary step in assessing how viable a certain technology or solution is in real use. It combines most of the technical aspects regarding the electric bus solutions, but also operational and energy management aspects play a role. For example, the productivity of the electric bus system collapses if the traction battery is empty before reaching the next charging station. A TCO analysis comprises relevant capital costs arising from owning a bus fleet: purchase of the bus, battery and charging infrastructure. The operational costs arise from energy as well as service and maintenance. Furthermore, each of the components (vehicle, battery, chargers) have their own service life (depreciation time) that has to be taken into account. VTT has developed a TCO tool that can be used to analyse an electric vehicle system when sufficient input parameters are known.

The TCO of an electric bus was analysed for a fleet of totally 27 fully electric 12 meter buses, and compared to a fleet of similar size consisting of Euro VI diesel buses. The fleet size of 27 buses was selected because it was the actual number of buses that currently operate on the six Tromsø bus lines analysed in this project: 26, 32, 33, 34, 37, and 40. For these buses, a proper data set existed so that the TCO analysis can be placed on a firmer ground.

The methodology and approach is in more detail described in reference [4].

2.3.8 Special conditions to be taken into account

Geographically, Tromsø is situated in the northern part (69 ºN) of Norway. The population is about 72 000, of which approximately 36 000 is living on Tromsøya (the city centre of Troms). In addition to this, a number of students are also living in the county. The city is located by the ocean, and surrounded by tall mountains.

Tromsø has a subarctic climate, but with quite mild winter temperature considering the altitude. The mild winters result from the warming effect of the Gulf Stream. The mean temperature in Tromsø is 2.5 ºC (ranging from about -17 ºC to 27 ºC), see Figure 5. The average daily temperature in December – February (2014/15) is -0.4 to -3.8 ºC.

During the winter season the temperatures are often around the freezing point, causing difficult driving conditions on the roads. The relatively warm winter days and colder nights causes surface water, this water will freeze on the roads and on the vehicles. In 2015, Tromsø had about 239 days with precipitation. The normal amount of precipitation in a year is 1 031 mm (met.no). A large amount of the precipitation falls as snow. Due to the slippery road surface and deep snow, the operation of buses is sometimes extremely demanding as shown in Figure 6 (page 13).

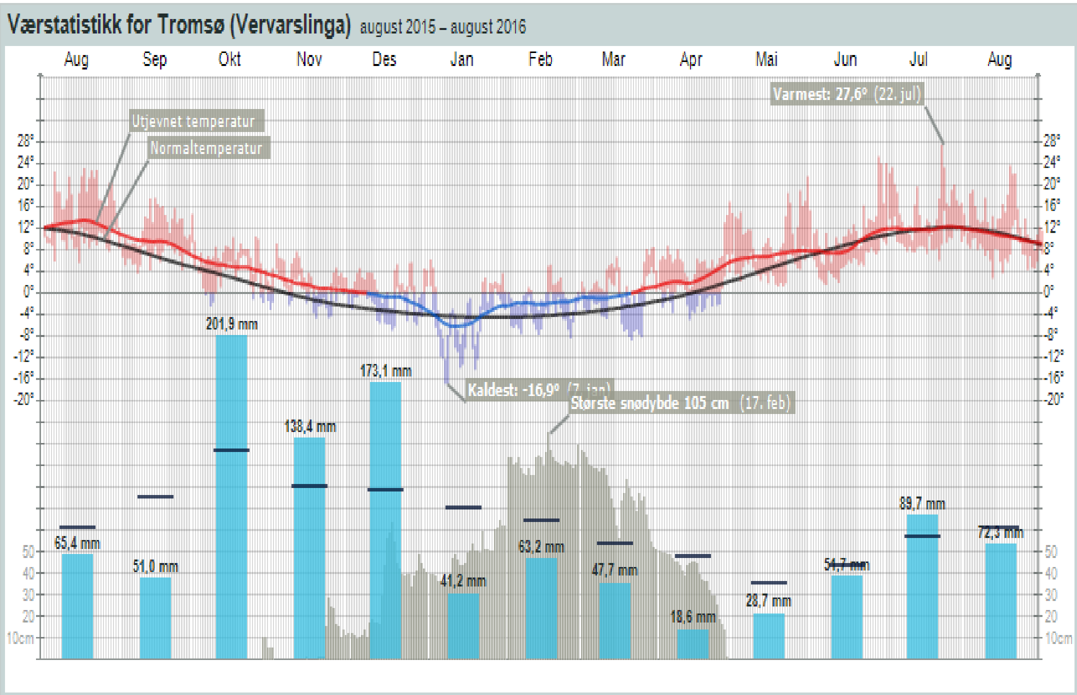


Figure 5. Weather statistics for Tromsø, August 2015 – August 2016. Temperature (ºC), precipitation (mm) and amount of snow (cm). Source: Met.no

Figure 6. Example of demanding winter conditions in Tromsø. Icing and extreme slipperiness necessitates occasional use of snow chains.

3. Results

3.1 Results from simulations

Each of the six bus lines (26, 32, 33, 34, 37 and 40) were simulated using the line and vehicle specific data and two operation concepts. Based on initial simulations on line 28, it was seen that the electric bus is not suitable for the line as such. Due to the length of the line (35 km), the energy consumption is too high for the opportunity charged bus. The performance of the depot charged bus would not be good enough, either. A detailed study on this line was, therefore, omitted.

3.1.1 Depot charged bus

The energy consumption for the depot charged bus on the simulated lines is shown in Table 3 (page 14). The energy consumption varies depending on the passenger load and the number of stops. More detailed diagrams on the energy consumption for each line are presented in the appendix.

3.1.1.1 Line 26

The energy consumption of the bus per round trip varies from 25.9 kWh to 33.2 kWh in good weather conditions when half of the bus stops are omitted and from 27.5 kWh to 35.6 kWh when the bus stops at all bus stops. When snow chains are used, the corresponding energy consumption is between 30.3 kWh and 39.5 kWh when omitting half of the bus stops, and between 32.0 kWh and 41.7 kWh when stopping at all bus stops. Assuming an average consumption of 29.5 kWh per round (corresponding to 45 passengers and omitting half of the bus stops), the range of the bus would be approximately 192 km. Line 26 is 23 km long, and the bus would, thus, be able to complete 8 rounds. In harsh winter conditions using snow chains, the range of the bus decreases to 162 km, resulting in only 7 rounds with a very small margin. In extreme conditions, with a large passenger load, the range could be as small as 136 km. As a comparison, the diesel buses make approximately 12 round trips per day.

3.1.1.2 Line 32

The energy consumption per round trip varies from 20.5 kWh to 26.9 kWh depending on the passenger load when the bus stops at half of the bus stops and the weather is good. When the bus stops at all bus stops, the energy consumption increases to 21.7 kWh – 28.8 kWh. When snow chains are used, the energy consumption is 24.3 kWh – 32.3 kWh when half of the bus stops are omitted, and 25.5 kWh to 34.1 kWh when the bus stops at every stop. In good weather conditions with 45 passengers on average, the maximum range of the bus would be 172 km which would result in 8 round trips. In extreme weather conditions with a high load, the maximum range decreases to 142 km, which corresponds to 7 round trips. As comparison, diesel buses complete approximately 14 round trips per day.

Table 3 Energy consumption of depot charged bus.

Line	Energy used for driving (kWh/km)	Energy used for auxiliary systems and heating (kWh/km)	Energy use due to snow chains (kWh/km)
26	0.91 – 1.28	0.23 – 0.29	0.19 – 0.28
32	0.87 – 1.25	0.20 – 0.24	0.20 – 0.28
33	0.92 – 1.31	0.22 – 0.26	0.20 – 0.27
34	0.88 – 1.24	0.22 – 0.26	0.19 – 0.27
37	0.90 – 1.32	0.28 – 0.34	0.19 – 0.27
40	1.04 – 1.39	0.20 – 0.24	0.15 – 0.27

3.1.1.3 Line 33

The energy consumption of the bus per round trip varies in the range 20.3 kWh to 26.5 kWh when half of the bus stops are omitted and the weather conditions are good. When stopping at all stops, the energy consumption lies in the range 21.4 kWh to 28.1 kWh, and when using snow chains 24.8 kWh – 32.8 kWh. In normal conditions with 45 passengers, the maximum range is expected to be about 190 km, corresponding to 10 round trips. In extreme conditions, the range could be as low as 135 km resulting in only 7 round trips. For comparison, diesel buses complete approximately 18 round trips per day.

3.1.1.4 Line 34

Line 34 is practically the same as line 33, only the direction is different. The energy consumption on line 34 is slightly smaller than on line 33, though. This is due to differences in the speed profiles of the buses. Long and steep segments with a positive slope on line 33 will correspond to long and steep segments with a negative slope on line 34. These differences result in slightly different speed profiles, and different efficiency levels of the motor. The difference in the energy consumption is 2-5%, and the maximum range of the bus is practically the same as on line 33.

3.1.1.5 Line 37

The energy consumption of the bus per round trip varies between 6.8 kWh and 9.1 kWh depending on the passenger load when half of the bus stops are omitted. When using snow chains, the corresponding energy consumption is 8.0 kWh and 10.7 kWh. When stopping at all bus stops, the energy consumption is in the range 7.3 kWh – 9.6 kWh in good weather conditions, and in the range 8.4 kWh – 11.2 kWh when snow chains are used. Assuming an average passenger load of 45 passengers, the range of the bus is 183 km in good weather conditions, which corresponds to 31 rounds. When snow chains are used, the range is approximately 155 km, and 26 rounds can be completed. In extreme cases, with a large passenger load and harsh conditions, the range goes down to 129 km, corresponding to 22 rounds. For comparison, diesel buses complete approximately 34 round trips per day.

3.1.1.6 Line 40

In good weather conditions, the energy consumption per round trip varies between 26.7 kWh and 33.5 kWh when half of the stops are omitted. When stopping at all stops, the energy consumption is in the range 27.4 kWh to 35.2 kWh. When snow chains are used, the energy consumption varies between 30.7 kWh and 39.4 kWh when half of the bus stops are omitted and in the range 31.8 kWh to 40.5 kWh when the bus stops at all stops. Assuming 45 passengers on average, the range of the bus is 179 km in good weather conditions. The bus can, thus, complete 8 rounds. When snow chains are used, the range decreases to 154 km, corresponding to 7 rounds. In very harsh conditions with a large passenger load, the range could be as small as 136 km, which would result in only 6 rounds. For comparison, diesel buses complete approximately 16 round trips per day.

3.1.1.7 Summary of all lines with depot charging

The depot charged bus is rather heavy due to the big battery. This results in high energy consumption. The capacity of the bus is much lower as compared to diesel buses. The bus cannot be used all day without intermediate charging. This is a clear drawback in terms of operability of the bus. A bigger battery would increase the total energy available, but the energy consumption would also increase due to the weight of the battery.

3.1.2 Opportunity charged bus

The energy consumption for the opportunity charged bus is shown in Table 4.

Table 4. Energy consumption of opportunity charged bus.

Line	Energy used for driving (kWh/km)	Energy used for auxiliary systems and heating (kWh/km)	Energy used due to snow chains (kWh/km)
26	0.71 – 1.1	0.23 – 0.29	0.15 – 0.23
32	0.66 – 1.04	0.19 – 0.24	0.15 – 0.22
33	0.72 – 1.1	0.22 – 0.26	0.15 – 0.23
34	0.70 – 1.05	0.22 – 0.26	0.15 – 0.23
37	0.70 – 1.11	0.28 – 0.34	0.15 – 0.22
40	0.81 – 1.17	0.20 – 0.24	0.14 – 0.22

3.1.2.1 Line 26

The energy consumption per round trip varies in the range 21.5 kWh to 28.9 kWh when half of the bus stops are omitted and the weather is good. If snow chains are used, the energy consumption lies in the range 24.7 kWh to 34.2 kWh. When the bus stops at all stops, the energy consumption is 22.8 kWh to 31.1 kWh in good weather conditions and 26.2 kWh to 36.0 kWh when snow chains are used. The battery state of charge (SOC) as the bus completes one round trip is shown in Figure 7 (page 16).

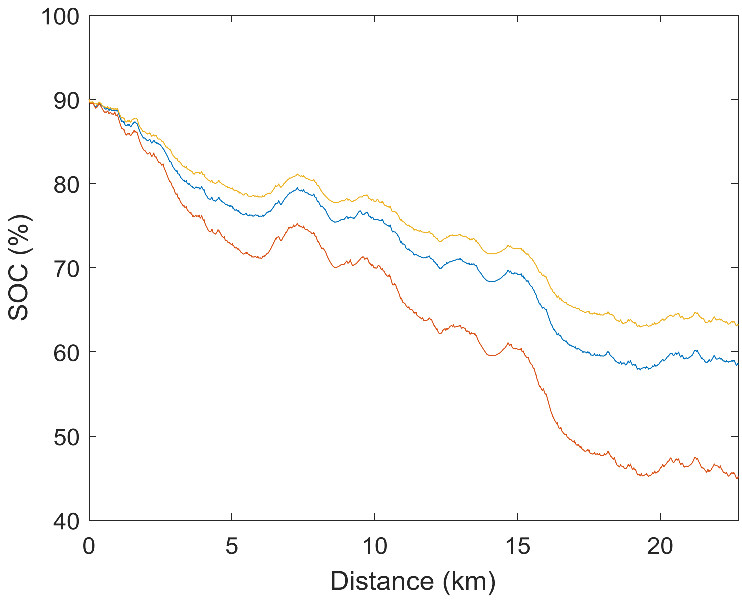


Figure 7. Battery state of charge (SOC) as bus runs on line 26 from the beginning to the end starting at a charging level of 90%. The blue curve shows a typical case with 45 passengers and good weather. The red curve shows the worst case with 90 passengers and snow chains. The yellow curve shows the easiest case without passengers.

3.1.2.2 Line 32

The energy consumption per round trip varies in the range 16.5 kWh – 22.9 kWh in good weather when stopping at half of bus stops. When stopping at all bus stops, the energy consumption is 17.6 kWh- 24.7. When snow chains are used, the corresponding energy consumption is 19.5 kWh – 27.4 kWh, and 20.5 kWh – 29.0 kWh. The battery state of charge as the bus completes one round trip is shown in Figure 8.

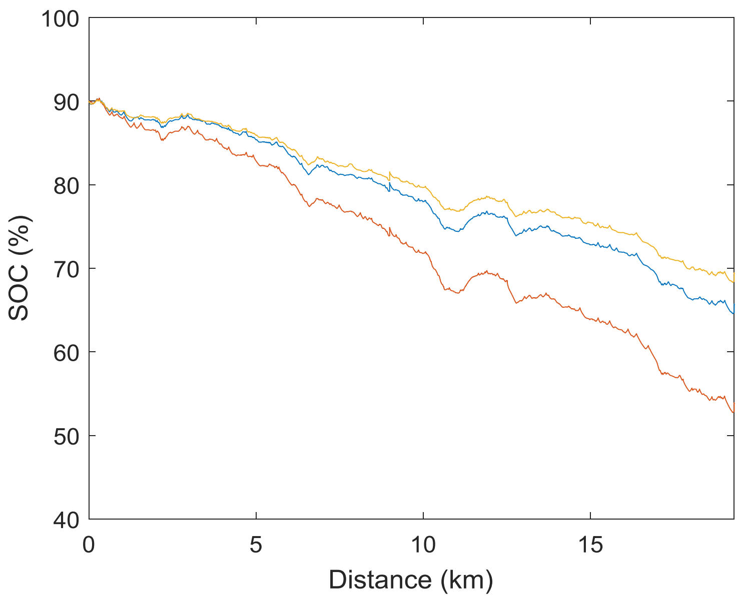


Figure 8. Battery state of charge as bus runs on line 32 from the beginning to the end starting at a charging level of 90%. The blue curve shows a typical case with 45 passengers and good weather. The red curve shows the worst case with 90 passengers and snow chains. The yellow curve shows the easiest case without passengers

3.1.2.3 Line 33 and 34

The energy consumption per round trip in good weather conditions is in the range 16.8 kWh to 23.0 kWh when stopping at half of bus stops and 17.6 kWh to 24.3 kWh when stopping at all bus stops. When snow chains are used, the corresponding energy consumption is in the range 19.3 kWh to 26.8 kWh when stopping at half of bus stops, and 20.2 kWh to 28.2 kWh when stopping at all bus stops. The battery state of charge as the bus completes one round trip is shown in Figure 9. The energy consumption on line 34 is slightly lower than on line 33 due to different speed profiles. The battery state of charge for line 34 is shown in Figure 10.

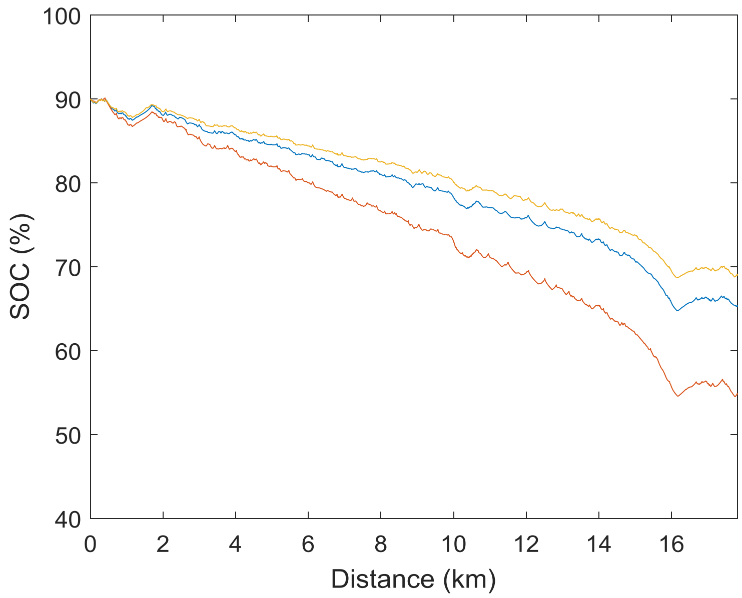


Figure 9. Battery state of charge as bus runs on line 33 from the beginning to the end starting at a charging level of 90%. The blue curve shows a typical case with 45 passengers and good weather. The red curve shows the worst case with 90 passengers and snow chains. The yellow curve shows the easiest case without passengers.

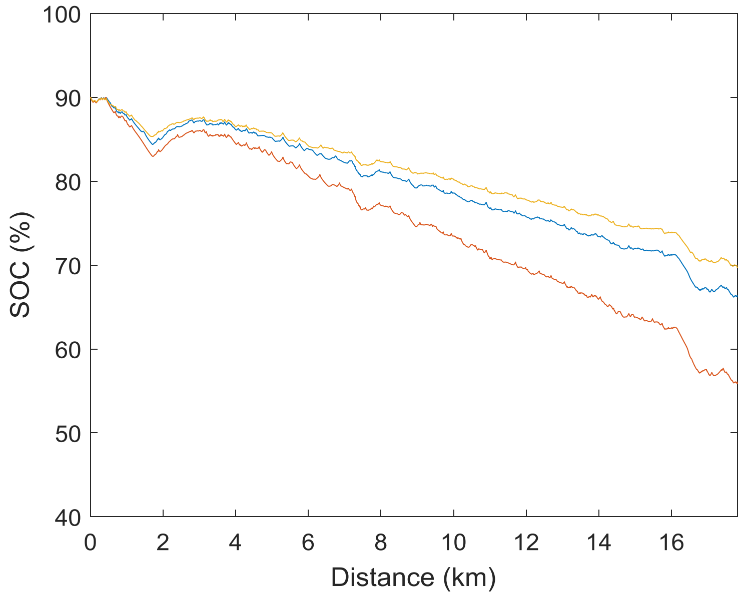


Figure 10. Battery state of charge as bus runs on line 34 from the beginning to the end starting at a charging level of 90%. Curve explanations as in Figure 9.

3.1.2.4 Line 37

The energy consumption of the bus is in the range 5.7 kWh to 7.9 kWh when half of the bus stops are omitted, and 6.1 kWh to 8.4 kWh when the bus stops at all bus stops. When using snow chains, the energy consumption increases to 6.5 kWh – 9.2 kWh when half of the bus stops are omitted, and to 6.9 kWh - 9.7 kWh when the bus stops at all bus stops. The battery state of charge as the bus completes one round trip is shown in Figure 11.

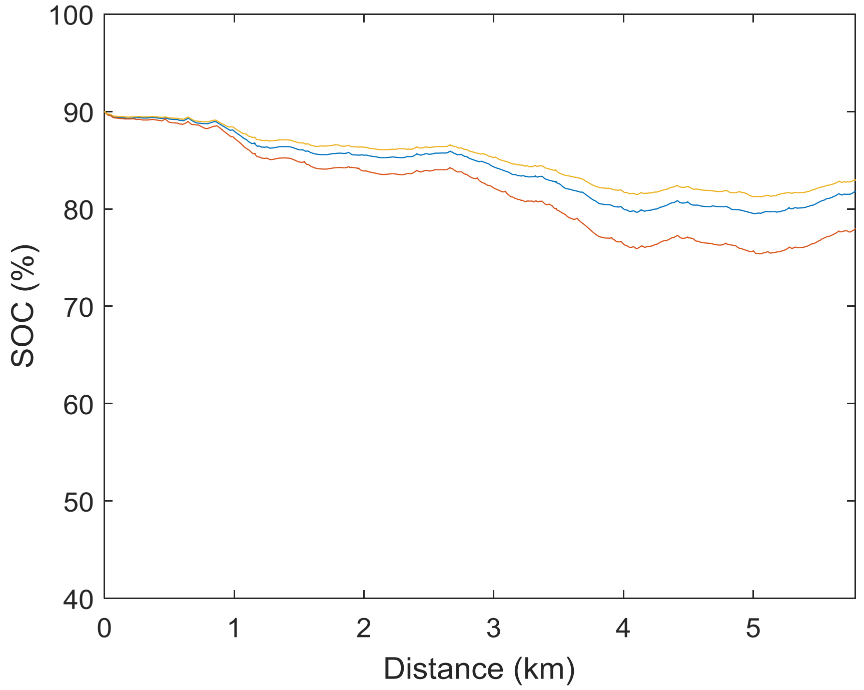


Figure 11. Battery state of charge as bus runs on line 37 from the beginning to the end starting at a charging level of 90%. The blue curve shows a typical case with 45 passengers and good weather. The red curve shows the worst case with 90 passengers and snow chains. The yellow curve shows the easiest case without passengers.

3.1.2.5 Line 40

The energy consumption per round trip lies in the range 21.7 kWh to 29 kWh depending on the passenger load when half of the bus stops are omitted, and no snow chains are used. When the bus stops at all bus stops, the energy consumption is 22.6 kWh to 30 kWh. In winter conditions, as snow chains are used, the energy consumption is 24.8 kWh – 33.7 kWh when half of the bus stops are omitted, and 25.8 kWh – 35.0 kWh when the bus stops at all bus stops. The battery state of charge as the bus completes one round trip is shown in Figure 12 (page 19).

3.1.2.6 Summary of all lines with opportunity charging

The opportunity charged bus has lower energy consumption as compared to the depot charged bus. The variation in the battery state of charge when completing one round trip varies depending on the line from approximately 8.5% to 31.8% in a typical case. Line 37 is the shortest and has the lowest total energy consumption. Lines 26 and 40 are long, and show the largest total energy consumption.

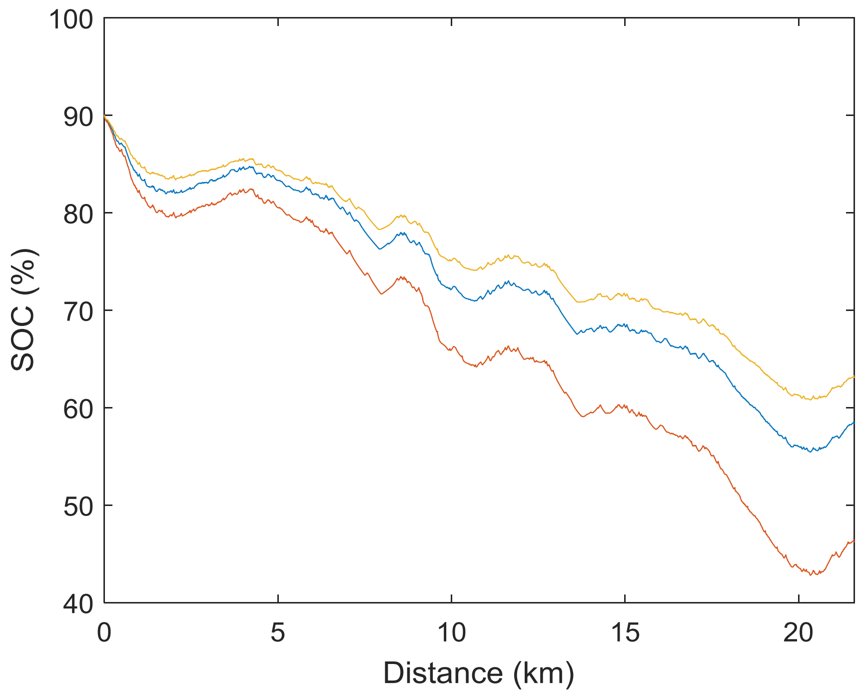


Figure 12. Battery state of charge as bus runs on line 40 from the beginning to the end starting at a charging level of 90%. The blue curve shows a typical case with 45 passengers and good weather. The red curve shows the worst case with 90 passengers and snow chains. The yellow curve shows the easiest case without passengers.

3.2 Special conditions and sensitivity of opportunity charged bus

In order to analyse the performance of the bus during one day, the charging time available for the bus has to be taken into account. It is assumed, that the chargers are placed on the end bus stops, i.e. Giæverbukta for bus line 26, Fr. Langes gate for bus line 37 and 40, and the university area for bus line 32 and 33-34. Currently, the same bus is used on several lines during the day. In this study, however, the lines are analysed one by one. Therefore, the information of several buses in the vehicle specific timetable is combined in order to see how long the time spent at the end bus stop would be if one vehicle would be used on a single line all day. It is assumed that the bus can use all available time at the end stop for charging, but 3 minutes is reduced from the time available in order to account for possible delays. The time necessary for connecting and disconnecting the pantograph is not included in the analysis. This time is short, though. 30 seconds in total should be enough. The charging power used in the analysis is 300 – 400 kW.

3.2.1 Line 26

Assuming an average energy consumption of 25.3 kWh (corresponding to 45 passengers and half of bus stops omitted), the necessary charging time is 5 minutes with a charging power of 300 kW. As seen in Figure 13 (page 20), the available charging time on this line is, according to the current timetables, shorter than 5 minutes in the early morning. The short charging time is compensated later, and the bus can run all day without interruption, see Figure 14 (page 20). However, in extreme weather conditions with delays over 3 minutes, the bus might be further delayed due to charging, as the battery is almost fully discharged (Figure 15, page 21). With a charging power of 400 kW, slightly bigger margins are obtained.

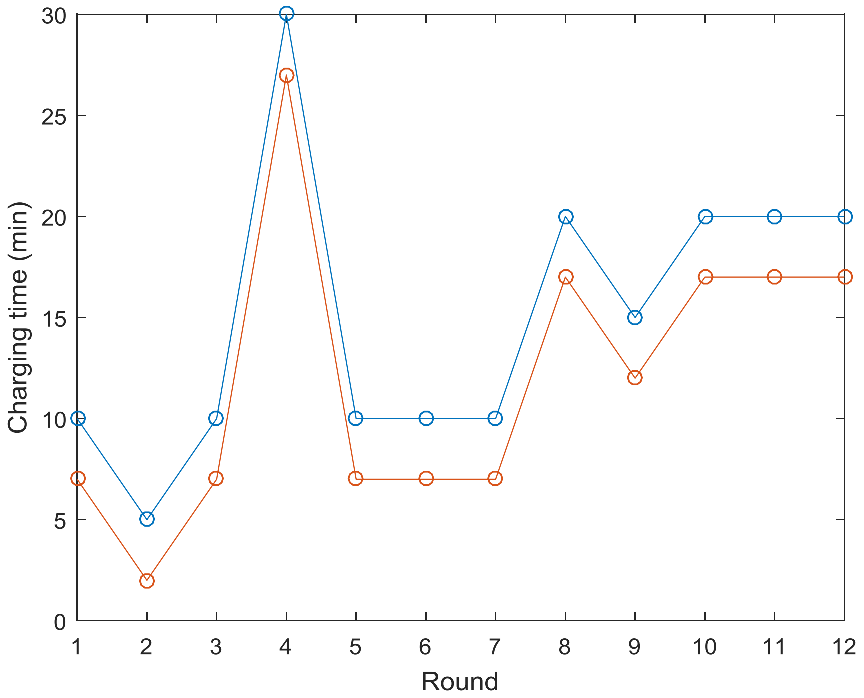


Figure 13. Example of charging times for one vehicle operating on line 26 all day. The blue curve shows the time spent at the end bus stop according to the timetable. The red curve shows the time reserved for charging in the analysis. The time is calculated based on a combination of several vehicles in the vehicle specific timetables.

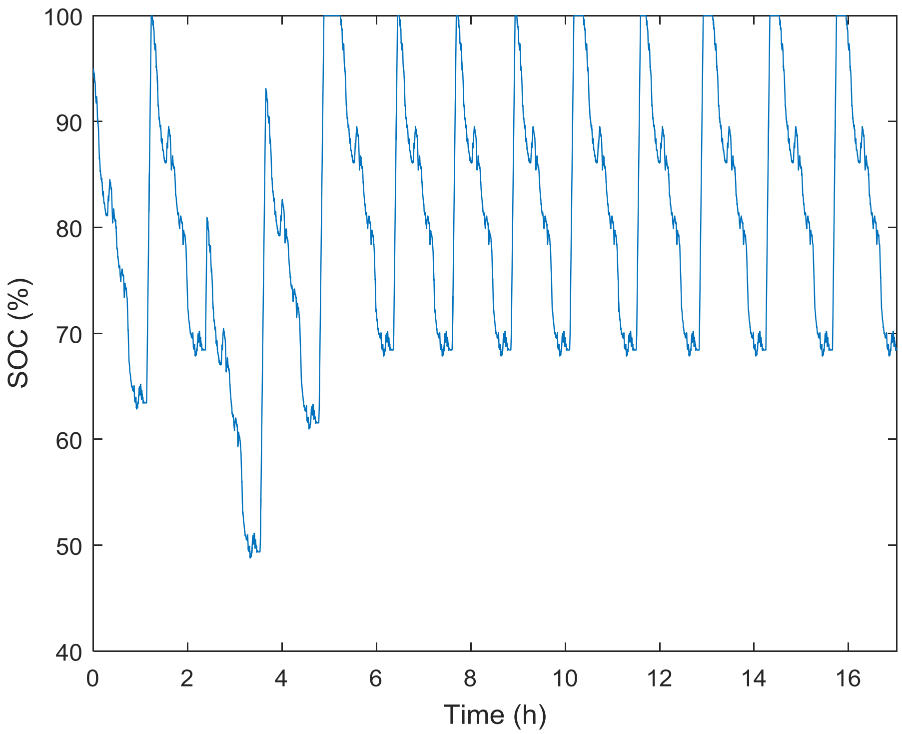


Figure 14. Example of battery state of charge for one day with 45 passengers on line 26. The charging power is 300 kW.

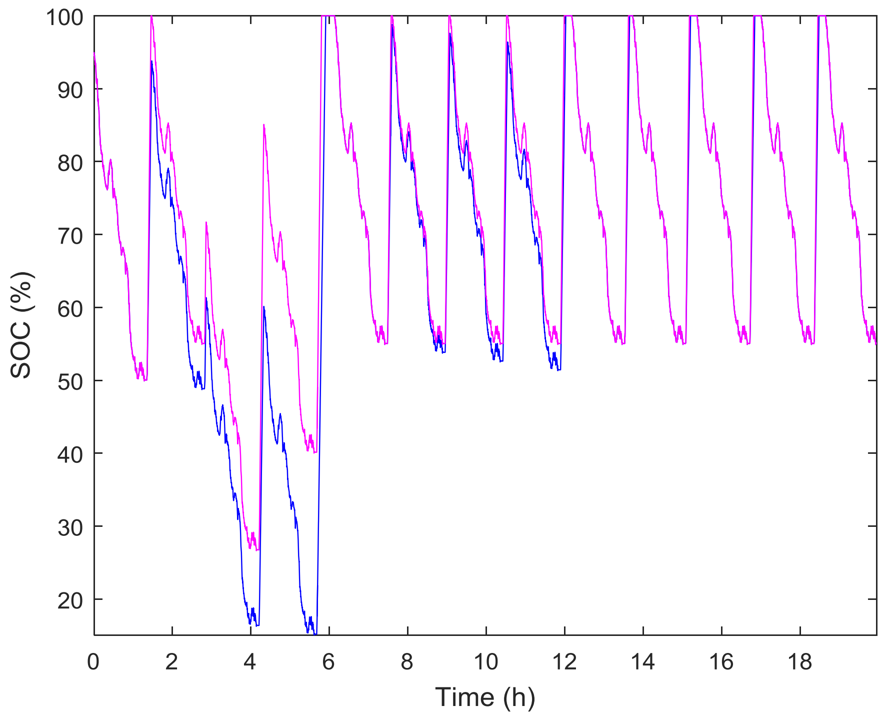


Figure 15. Example of battery state of charge for one day with 90 passengers and snow chains. The charging power is 300 kW (blue) and 400 kW (purple)

3.2.2 Line 32

With 45 passengers and good weather, the necessary charging time per round trip is on average almost 4 minutes. As seen in Figure 16 (page 22), the charging time available varies rather much. The bus can operate on the line without charging after every round trip, but as the charging time is very limited for several consecutive round trips, the battery state of charge level becomes very low (see Figure 17, page 22). In extreme cases, the bus cannot operate without additional delays due to charging (see Figure 18, page 23).

3.2.3 Line 33 and 34

The lines 33 and 34 are combined in the sensitivity analysis, as these are practically the same lines, and the same bus normally runs in both directions. The charging time available is shown in Figure 19 (page 23). The charging time necessary per round trip is on average 4 minutes with a charging power of 300 kW. If the charging power is 400 kW, the charging time is reduced to 3 minutes. The available charging time is on average enough, but the bus repeatedly has to complete two round trips without charging in order to avoid delays. This might be problematic in bad winter weather. The battery state of charge in good weather is shown in Figure 20 (page 24) and in extreme conditions in Figure 21 (page 24).

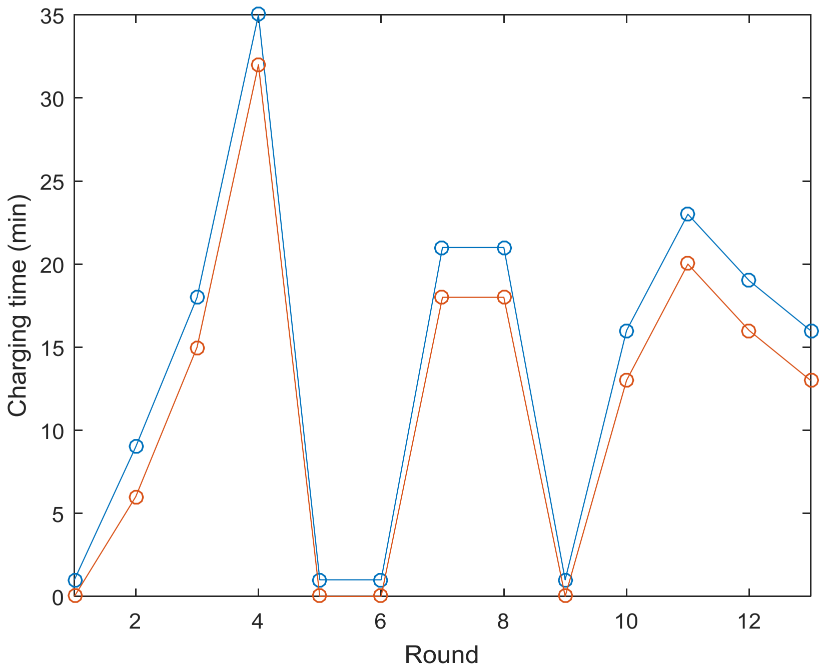


Figure 16. Example of charging times for one vehicle operating on line 32 all day. The blue curve shows the time spent at the end bus stop according to the timetable. The red curve shows the time reserved for charging in the analysis. The time is calculated based on a combination of several vehicles in the vehicle specific timetables.

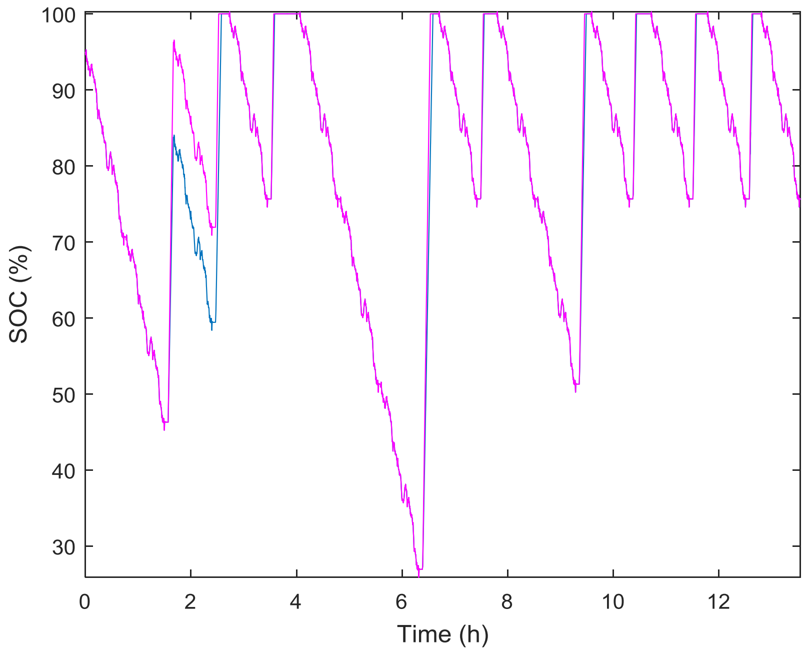


Figure 17. Example of battery state of charge for one day with 45 passengers in good weather conditions on line 32.The charging power is 300 kW (blue) and 400 kW (purple).

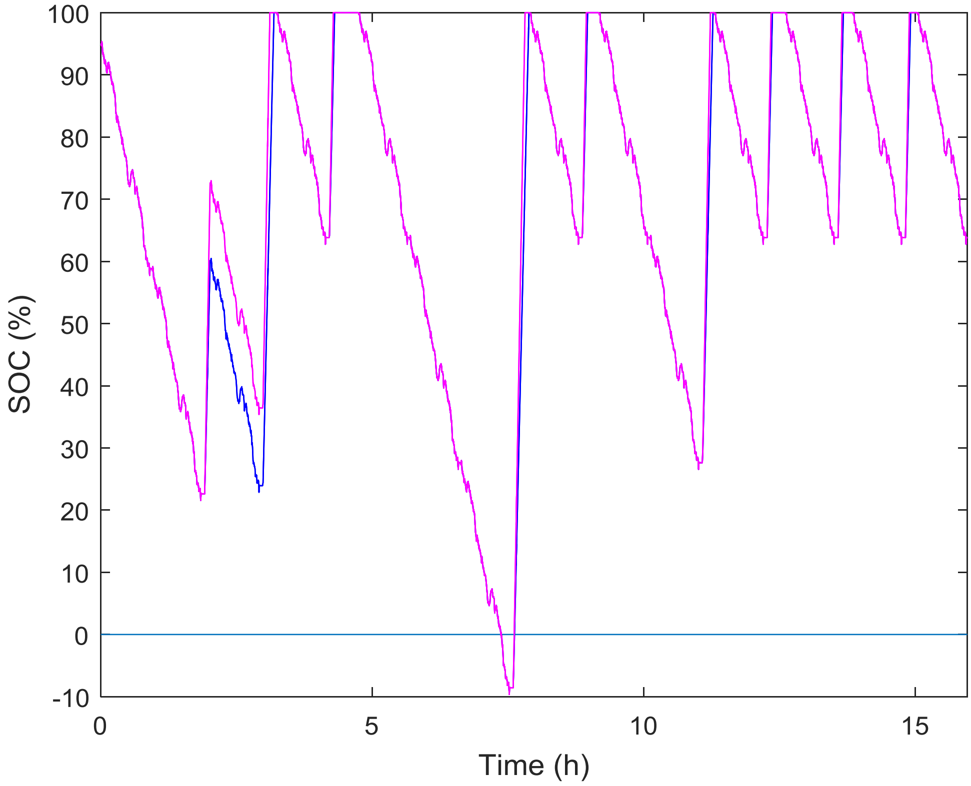


Figure 18. Example of battery state of charge for one day in extreme conditions on line 32. The passenger load is 90 passengers and snow chains are used. The charging power is 300 kW (blue) and 400 kW (purple).

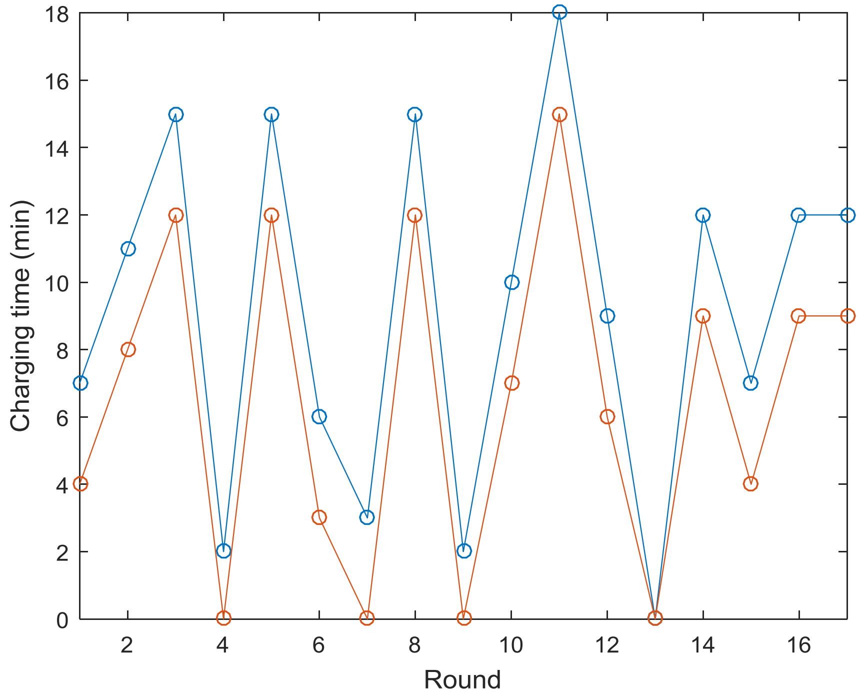


Figure 19. Example of charging times on lines 33-34. The blue curve shows the time spent at the end bus stop according to the timetable. The red curve shows the time reserved for charging in the analysis. The time is calculated based on a combination of several vehicles in the vehicle specific timetables.

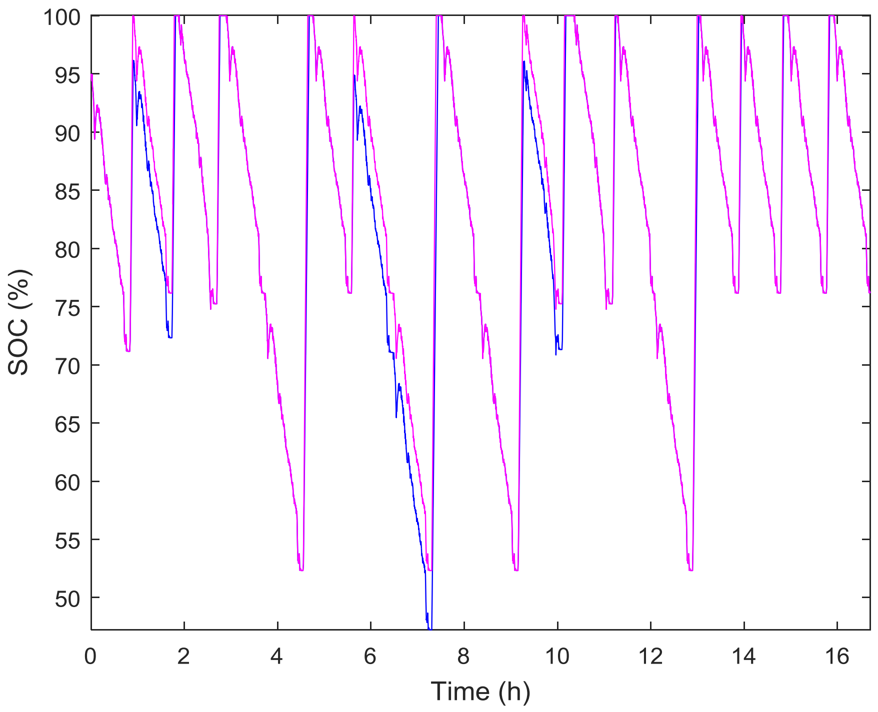


Figure 20. Battery state of charge on line 33-34 with 45 passengers in good weather as the bus runs from early morning to late night. The charging power is 300 kW (blue) and 400 kW (purple).

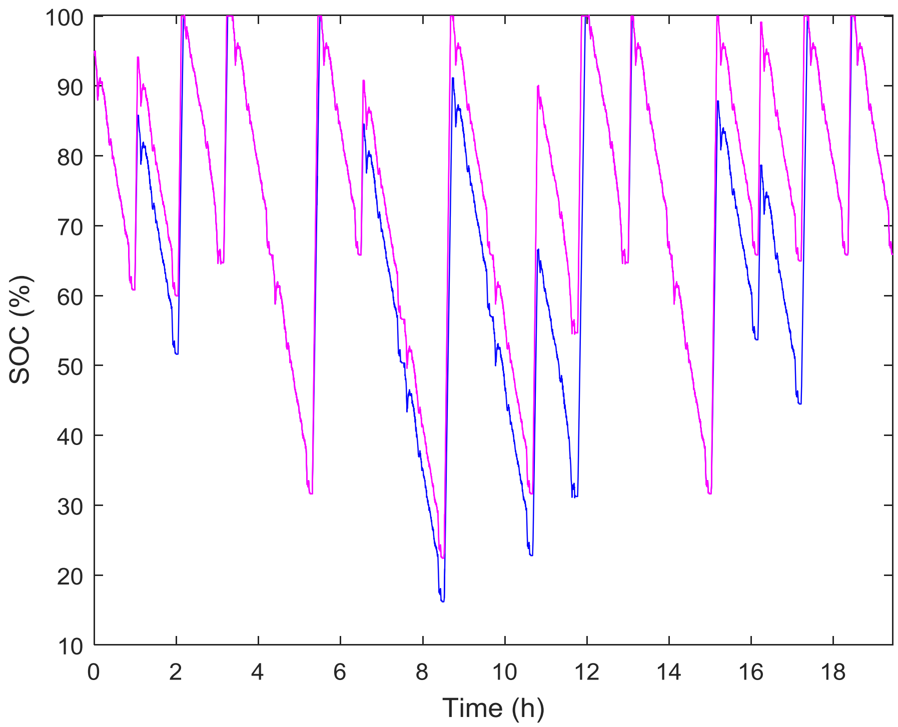


Figure 21. Battery state of charge on line 33-34 with 90 passengers and snow chains as the bus runs from early morning to late night. The charging power is 300 kW (blue) and 400 kW (purple).

3.2.4 Line 37

The available charging time is shown in Figure 22. In a basic case, having 45 passengers in good weather conditions, the necessary charging time is 1 minute and 20 seconds with a charging power of 300 kW. During the morning rush hours, the available time at the end stop is shorter, but the route is short and the bus can easily complete a few rounds even without charging if enough charging time is available (see Figure 23, page 26) later on. Also in harsh winter conditions, the battery capacity is enough for completing several rounds without charging as seen in Figure 24 (page 26).

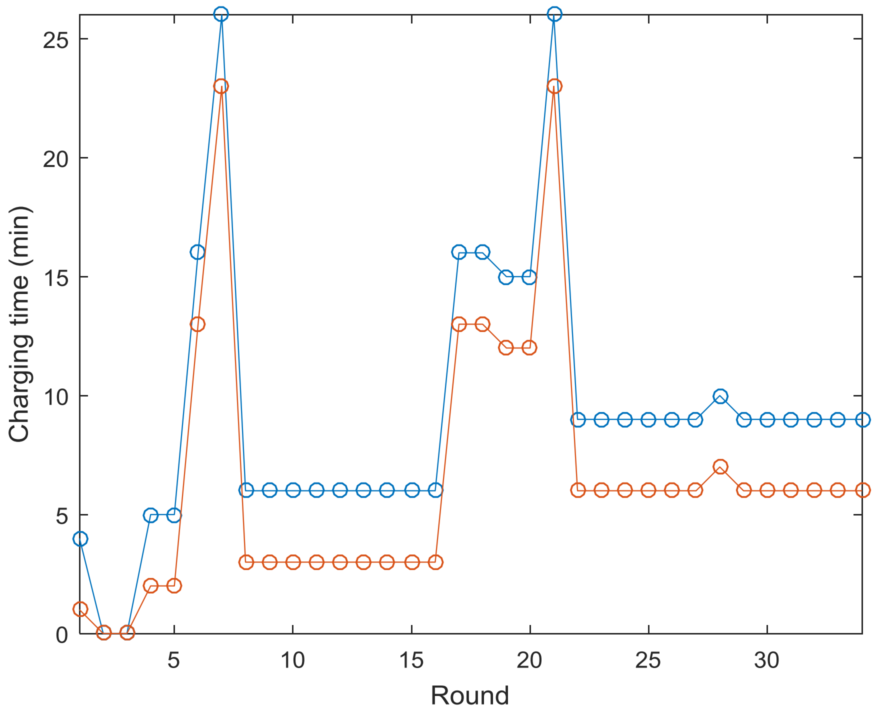


Figure 22. Example of charging times for one vehicle operating on line 37 all day. The blue curve shows the time spent at the end bus stop according to the timetable. The red curve shows the time reserved for charging in the analysis. The time is calculated based on a combination of several vehicles in the vehicle specific timetables.

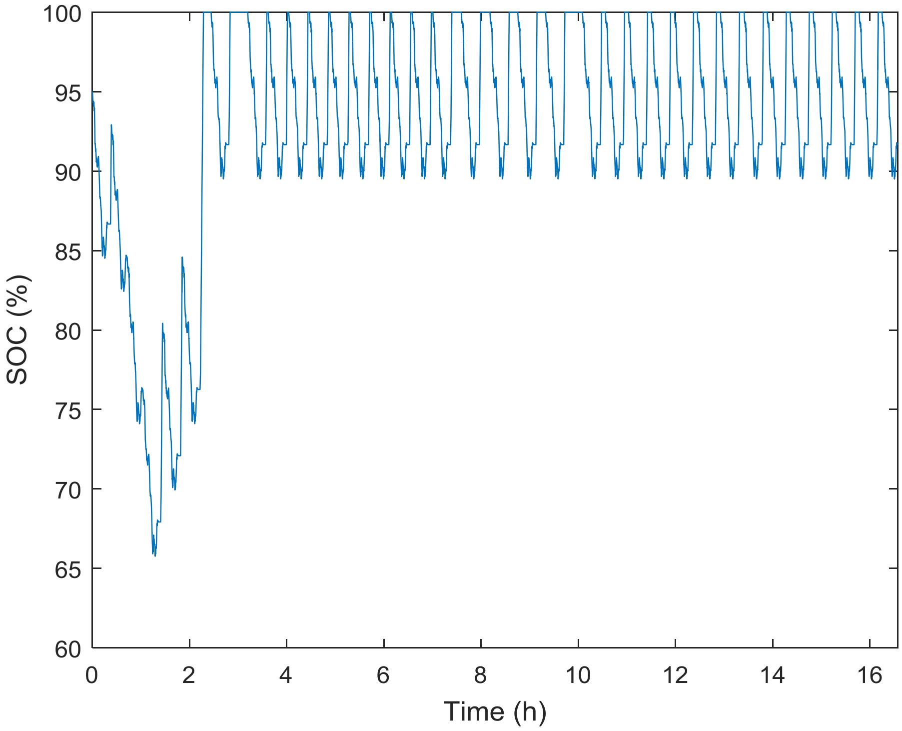


Figure 23. Battery state of charge as bus runs on line 37 from early morning to late night with 45 passengers in good weather. The charging power is 300 kW.

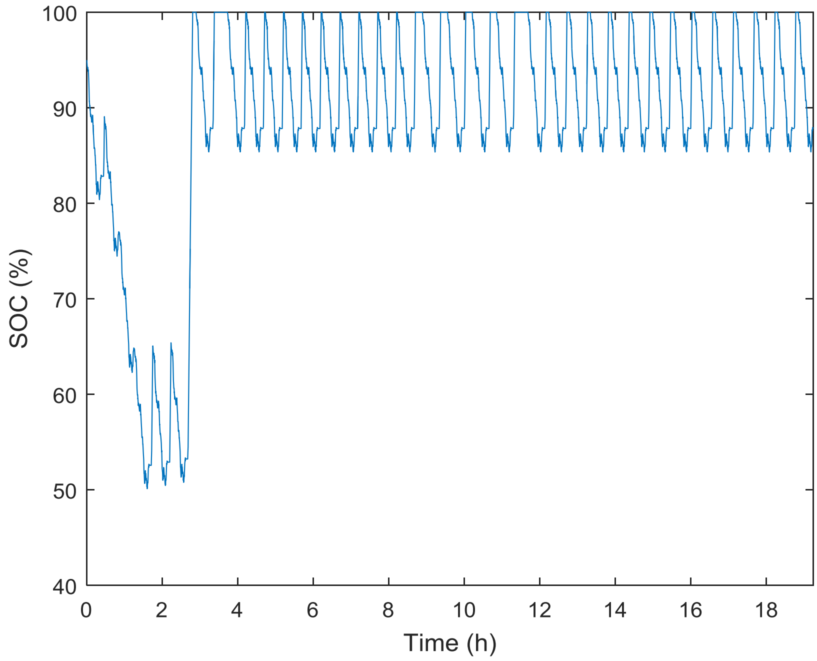


Figure 24. Battery state of charge as bus runs on line 37 from early morning to late night with 90 passengers and snow chains. The charging power is 300 kW.

3.2.5 Line 40

With 45 passengers and good weather conditions, the energy consumption of the bus is 25.4 kWh. This corresponds to a charging time of 5 minutes in average per round with a charging power of 300 kW. According to the schedule, the time at the end bus stop is only 6 minutes in the morning, and during the day even shorter (see Figure 25, page 27). When reserving 3 minutes for possible delays, it can be seen that the charging time is too short. The battery state of charge becomes negative after 5 hours of operation, which in practise is not possible (see Figure 26, page 28). With this schedule, the bus is allowed to be only 1.5 minute late after each round, in order to have enough time for charging in good weather conditions (see Figure 27, page 28). The margin is still very small, and during the winter as snow chains are used, 6-7 minutes should be reserved for charging. If the charging power is increased to 400 kW, less time is necessary for the charging, but there is still not enough time according to the bus schedule.

Currently, some vehicles operate on both lines 37 and 40. As an example, the battery state of charge for vehicle 1501 running on these lines from early morning to afternoon is shown in Figure 28 (page 29). As line 37 is very short, the combination of these two lines results in a much more reliable operation than operating on only line 40.

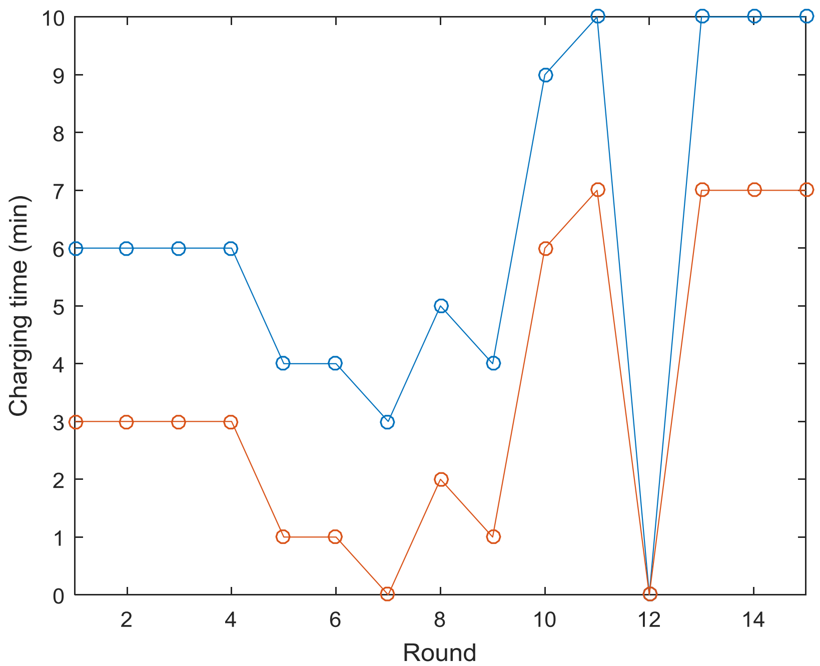


Figure 25. Example of charging times for one vehicle operating on line 40 all day. The blue curve shows the time spent at the end bus stop according to the timetable. The red curve shows the time reserved for charging in the analysis. The time is calculated based on a combination of several vehicles in the vehicle specific timetables.

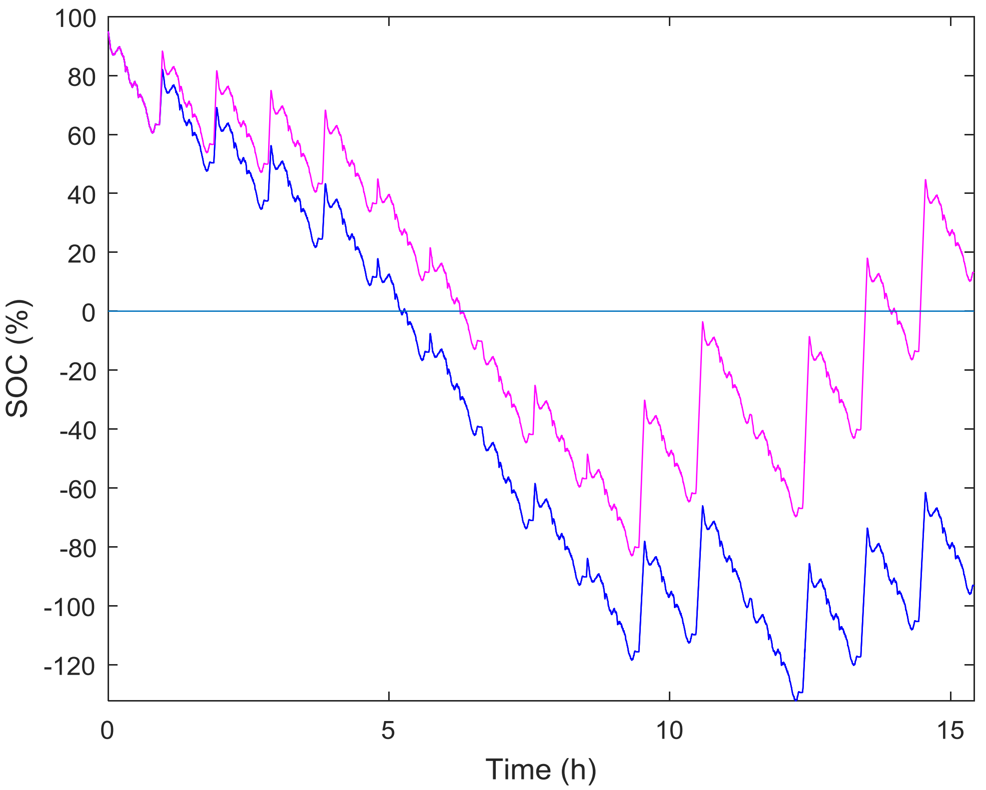


Figure 26. Battery state of charge as bus runs on line 40 from morning to late night with 45 passengers. The charging power is 300 kW (blue) and 400 kW (purple), and the bus is assumed to be delayed by 3 minutes every round.

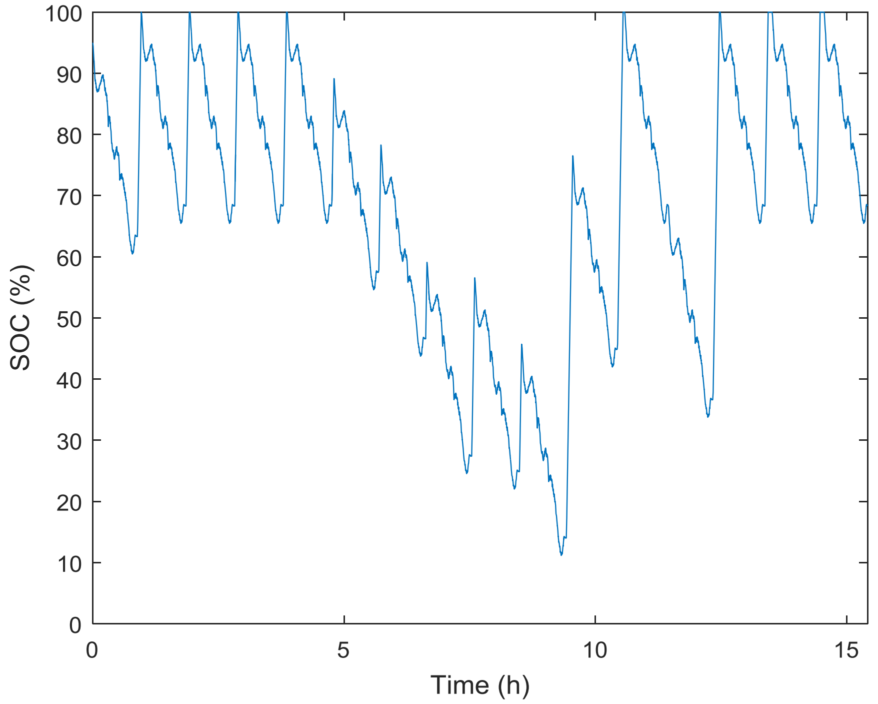


Figure 27. Battery state of charge as bus runs on line 40 from morning to late night with 45 passengers. The charging power is 300 kW, and the delay is only 1 minute and 30 seconds.

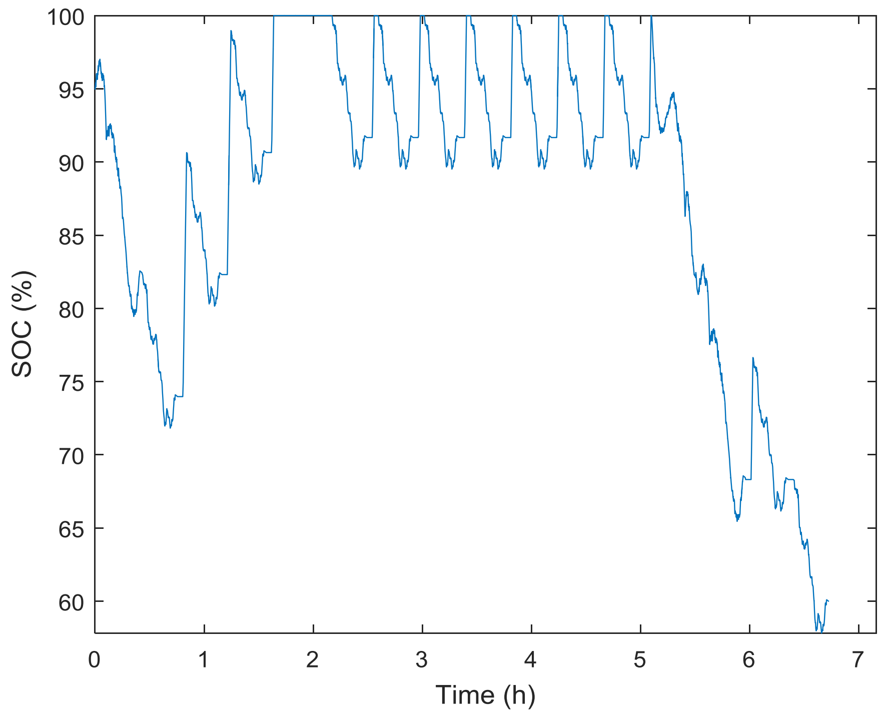


Figure 28. Battery state of charge for vehicle 1501 in the vehicle specific timetable operating on both lines 37 and 40 from morning to afternoon. The passenger load is 45 and the weather conditions are good.

3.2.5.1 Summary of all lines

The easiest line for an opportunity charged bus is line 37. As it is less than 6 km long, occasional lack of charging time on the end bus stop is not a problem even in extreme conditions. The longer lines are more challenging, but operation on lines 26, 33 and 34 should be successful in typical conditions. The margins on line 32 are quite small, and this line might be sensitive to delays, especially in extreme winter weather. The charging time on line 40 seems to be too short for successful operation. However, a combination where the same bus operates on both line 37 and 40 gives better results.

3.3 TCO analysis of electric bus operation

Total cost of ownership of fully electric buses as compared to Euro VI diesel buses was carried out for a fleet of 27 buses of 12 metres. This choice deviates somewhat from the original task to analyse 40 buses. The reason to limit to 27 is because there was a plausible data set analysed and simulated in detail during the on-going project on lines 26, 32, 33, 34, 37 and 40. These six bus lines host together a vehicle fleet of 27 buses. Lines 33-34 are currently operated with 15 metre buses, but the analysis and comparison here has been made using 12 metre buses.

The specifics of the lines and input to the TCO analysis are shown in Table 6 (page 30). The buses are grouped in two groups based on operational synergies with a view to the opportunity charging concept. The first group is lines 26, 37 and 40, which can be charged either at Fr. Langes gate or at Giæverbukta. The second group of lines is 32, 33 and 34, which can be opportunity charged at the University hospital or UiT. Each of the groups has two chargers in the analysis, therefore one fast charger serves 6 or 7 buses. Each depot charged bus has its own charger at the depot. The annual driving (km) per line has been estimated from the vehicle operation data and the number of round trips per day.

Table 6. Specifics of the six analysed lines and summary of the parameters.

Bus line No	N of buses	Charging node	Average kWh/round trip opportunity	Average kWh/round trip depot	Km/ round trip	Round trips /day	Daily driving time (h)	Annual driving (km)
26	6	Giæverbukta	28.8	33.8	22.7	12	18/17/15	99426
32	2	UiT/Planetariet	22.6	27.3	19.3	14	12/0/0	90958
33	6	Universitetssykehuset	22.5	26.6	17.8	18	19/17/16	116946
34	6	Universitetssykehuset	21.9	26.6	17.8	18	19/17/16	116946
37	2	Fr. Langes gate	7.7	9	5.8	34	18/17/15	71978
40	5	Fr. Langes gate	28.4	33.6	21.6	16	18/17/15	126144

The most important technical input data to the analysis are shown in Table 7. Relevant bus-specific data were already given in tables 1 and 2 (pages 7 and 8). The price of a Euro VI bus was taken as 220.000 €. Fuel consumption of diesel 40 l/100 km, price of diesel 1 €/l, electricity price including transmission 0.1 €/kWh, vehicle service and maintenance (S&M) for electric bus 0.04 €/km and for diesel 0.18 €/km. It is worth noticing that we estimate significantly lower service and maintenance cost for the electric buses; no real open data on this is as of yet available.

The results obtained for each of the four groups are shown in figures 29 to 32 (pages 31-32). The TCO is given as a cumulative TCO €/km per bus where the capital costs (CAP) are for vehicle, battery and charger, and the operative costs (OP) are related to energy (fuel or diesel, service & maintenance). Additionally, a cost evaluation is also given for the emissions, using the price for emissions of CO_2, NO_x and PM. Noise has not been evaluated.

Table 7. Summary of the main input parameters to the TCO calculation.

	Depot 26-37-40	Opportunity 26-37-40	Depot 32-33-34	Opportunity 32-33-34
Av. operation km per year	105479	105479	113233	113233
Av. Energy consumption kWh/km	1.5	1.3	1.5	1.2
Vehicle depreciation time (years)	14	14	14	14
Charger depreciation time (years)	14	14	14	14
Battery type	Lithium Iron Phosphate (LFP)	Lithium Titanate (LTO)	Lithium Iron Phosphate (LFP)	Lithium Titanate (LTO)
Battery capacity	250	80	250	80
Battery price (€/kWh)	500	1200	500	1200
Vehicle price (without battery, €)	360.000	360.000	360.000	360.000
Charger power (kW)	80	300-400	80	300-400
Charger price (€)	50.000	300.000	50.000	300.000

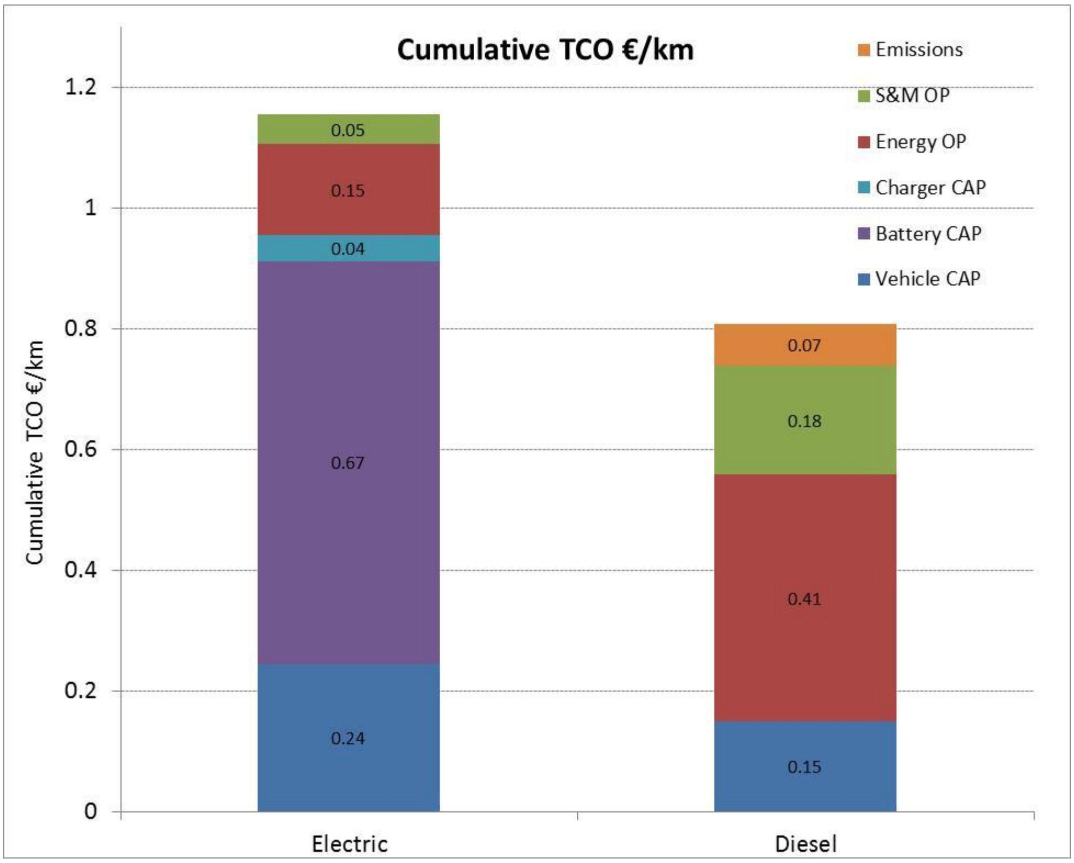


Figure 29. TCO of an average bus in group 26-37-40, depot charged electric bus.

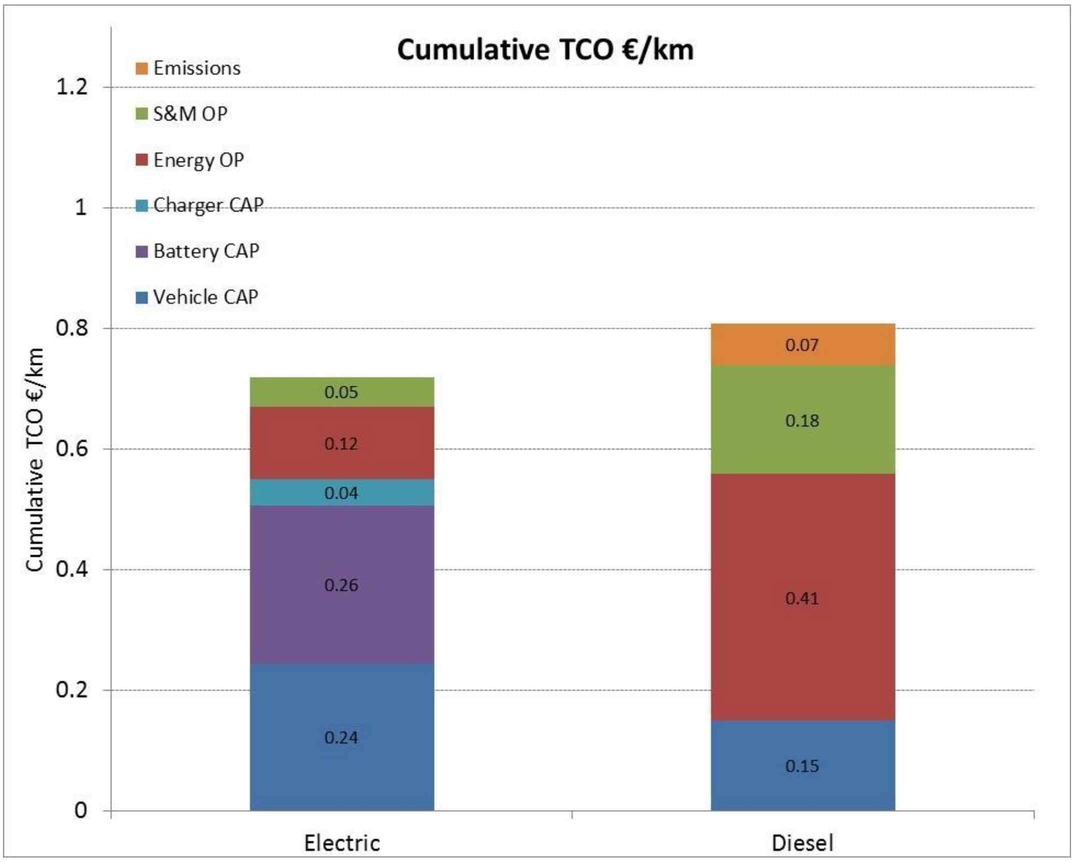


Figure 30. TCO of an average bus in group 26-37-40, opportunity charged electric bus.

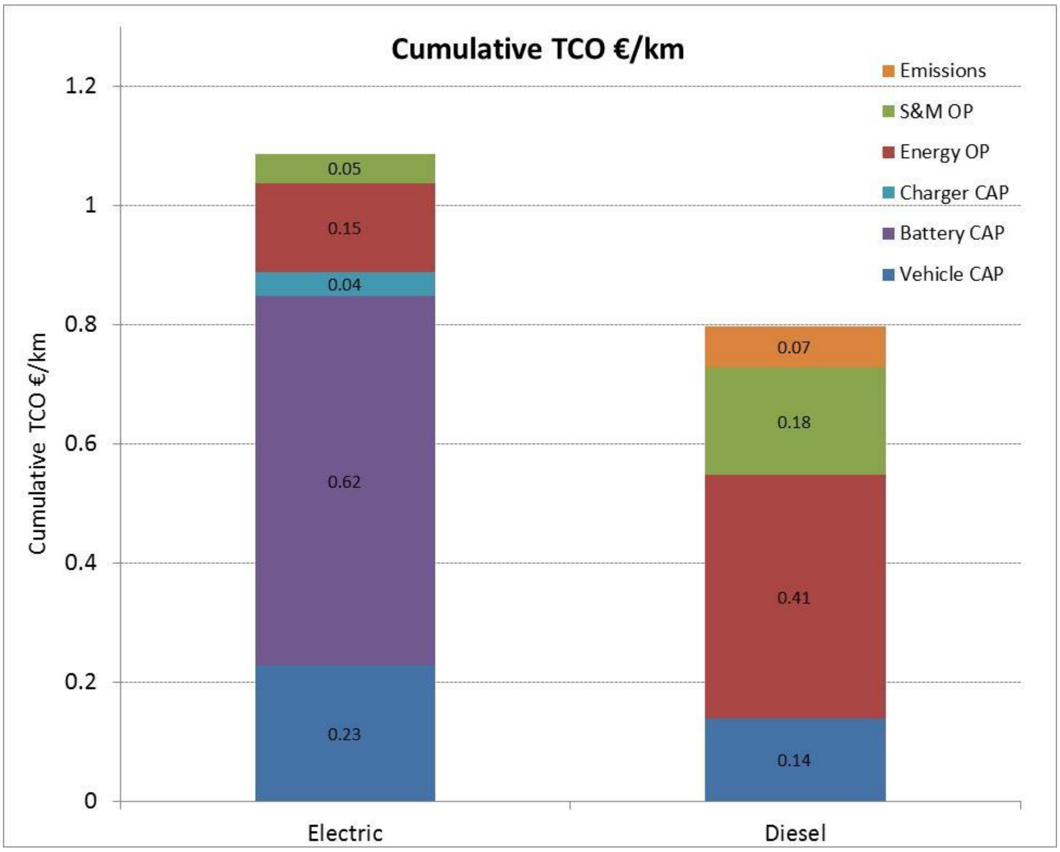


Figure 31. TCO of an average bus in group 32-33-34, depot charged electric bus.

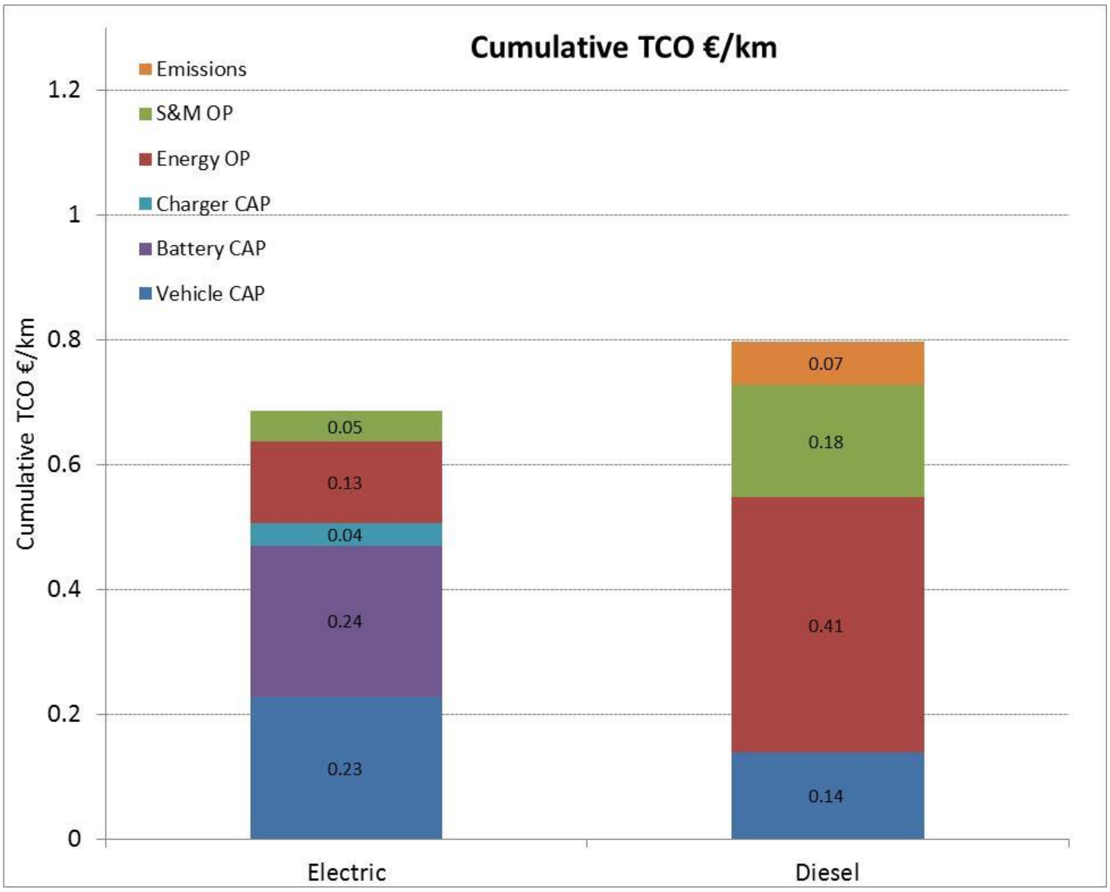


Figure 32. TCO of an average bus in group 32-33-34, opportunity charged electric bus.

The total costs of the sub fleets were also calculated over the 14 year hold period and the assumptions given above. These data are summarised for the opportunity charged case in Table 8. The total costs include the vehicles, batteries, chargers; with and without operational costs are given separately, all sums in €.

Table 8. Total costs of the bus sub fleets on lines 26-37-40 and 32-33-34 during 14 years hold time and per year.

	Opportunity 26-37-40	Diesel 26-37-40	Opportunity 32-33-34	Diesel 32-33-34
Size of bus sub fleet	12	12	14	14
Total cost w/o operational costs	7 224 000 €	9 696 000 €	8 328 000 €	11 939 200 €
Total cost	10 214 400 €	12 871 200 €	12 289 160 €	15 925 840 €
Yearly cost	729 600.00 €	919 371 €	877 797 €	1 137 560 €
Cost per bus per year	60 800 €	76 614 €	62 700 €	81 254 €

3.4 Emissions impact of electric bus operation

In the following, we will estimate the savings in the emission of greenhouse gases and of local pollutants like nitrogen oxides (NOx) and particulate matter (PM) from the exhaust of city buses, if they are exchanged against electrical buses.

In this estimation, we consider 40 conventional city buses with Euro VI diesel engines and a length of 12 m to be replaced by 40 electric city buses with a length of 12 m. The estimation includes only emissions connected to the production, transportation and combustion of the diesel fuel. In particular, emissions from wear and tear of tires and brakes are not included in this estimation. These can be considered to be in the same order of magnitude when switching from the conventional to the battery electric buses. For the combustion of diesel fuel, we calculate with 2.67 $kgCO_{eqv.}$/L fuel. Production and transportation increases the emissions by a factor of 1.1. In Norway, conventional diesel is mixed with a small share of renewable diesel (FAME), this accounts for a reduction in climate gas emission by a factor of 0.97. Regarding the local emission factors, we calculate with emission factors resulting from representative laboratory investigations [5]. For city buses with Euro VI engines, the emission factor for PM accounts for 0.01 g/km, whereas it accounts for 0.21 g/km for NO_x.

Regarding the climate impact of the generation of electric power in Tromsø, we consider the electricity to be originating to 100 % from renewable water power. This constrained, however, requires that the electricity is bought together with the respective emission trading certificate. The direct greenhouse gas emission of the electric bus then equals to zero.

Utterly important, however complex to estimate, is the environmental contribution of the production of the buses and batteries. This requires a detailed analysis of all production steps that can vary considerably between manufacturers. In this early stage of the project, however, this analysis is beyond the scope of this estimation. Therefore, we focus on the change in emissions when switching the energy carrier in the bus.

Based on data for a period of 2 years from 2014 to 2016, a fleet of 40 diesel-buses in Tromsø generated a greenhouse gas emission of 3330 ton CO2eqv per year. Considering local pollutants, emission from the exhaust of the buses sums up to 605 kg NOx and 29 kg PM.

In a 10-year perspective, the change to a battery-electric system can save 33295 ton CO2eqv, 6 ton NO_x and 0.3 ton PM in comparison to a fleet of Euro VI-diesel buses.

In addition to the savings in local- and global emissions, electric buses will reduce the noise levels, both for the passengers and drivers in the bus and the citizens experiencing the noise levels on the streets. In periods of low speed the motor noise of an electric bus will be lower than the noise from a diesel engine. At higher speeds above about 30 km/h, the noise generated by the rolling resistance will outperform the engine/motor noise. Therefore, people outside the bus will not experience lower noise levels at high speeds. For the passengers and drivers, however, a lower total noise level can be expected, even at higher speeds.

3.5 Other results

Further results in terms of PowerPoint presentations in the August workshop and in the final project seminar on the 7th of October have been handed to the Client.

4. Discussion and recommendation for next steps

4.1 General

The simulations and analysis carried out give a good picture of the type of electric buses and operation regarding these northern latitudes. The bus routes and duty cycles are more demanding than in most other cases we have analysed. The relatively long lines and steep and high hills give extra boundaries that need to be considered. Cycle and line simulations with different loads and with or without snow chains gave a good picture of the energy consumption of the electric buses. A full implementation of the auxiliary electricity consumption as a function of temperature has not been implemented in the simulation. However, the data give sufficient frame for the analysis and many of the electrical buses also have an additional gasoline heater for the coldest winter days.

Generally, for dimensioning the charging and energy management, worst case consumption and boundaries have to be considered. The aim has to be that the system runs even on the cold winter days. The operational margins depend on the charger power, battery capacity and especially charging time available in the bus timetables. Additionally, real traffic with delays and deviations is always a non-standard process. We have to the best tried to estimate from the available data the charging times that can be used for charging the buses.

The first choice is between a depot charged bus and an opportunity charged bus concept. We have in previous analyses arrived at a conclusion that the opportunity charged bus is the only electric bus concept which can compete with the conventional buses in term of the TCO. The same holds for this analysis. In both sub fleets, the opportunity charged bus is competitive in comparison with the Euro VI diesel, whereas the depot charged bus is not. The energy in the depot charged bus is not sufficient to operate over the entire days without intermediate charging at the depot. This removes the operational flexibility from the system and in the worst case forces to add vehicles in the fleet. The first conclusion is that we recommend the opportunity charged electric bus concept. Further discussion goes around the opportunity charged bus.

First, an opportunity charging power of 300 kW was used in the simulation. As can be observed from the figures in section 3.2, only line 37 can with certainty be operated continuously with a good margin. Line 26 is next, but due to the length of the line not more than 1 – 2 cycles extra can be operated without charging, in case the bus is delayed and the next departure is forced by clock. A second simulation was carried out using 400 kW as charging power. This is still acceptable for an LTO battery of 80 kWh. The situation improves and leads to the second conclusion that the charging power should be at least 400 kW, perhaps even higher.

A second topic of discussion is around the optimal battery capacity for the opportunity charged bus. Typical batteries for this type of buses are somewhere 50 – 70 kWh. In other words, we have already increased the capacity in this analysis due to the demanding cycles and terrain. All lines except the short line 37 take about 25 – 40% of the battery capacity on a single round trip when just one charger is used. While 25% is still acceptable (it means that maximum 4 four round trips could be made to completely empty the battery), 40% delta state of charge (SoC) is large. If the charger works flawlessly and there are limited delays in the traffic, the system still runs but the buffer margins are used up. Only one extra roundtrip can be made until a full charge is absolutely necessary. Line 40 is the most demanding in this respect, in a case where only one charger would be placed at Fr. Langes gate.

How to increase the operational margin? There are four options. First one: increase charging power additionally. Second one: to increase battery capacity. Third one: to increase the number of charging points. Fourth one: design a flexible vehicle rotation which can compensate for problems in charging management. The first one was already concluded; how high the charging power can be depends in the end on the battery parameters. Out of the other options, we would tend to suggest the fourth option, but the feasibility of it needs closer discussion with the bus operator. In practical terms this could mean, for example, to combine operations between lines 37 and 40 in a way that after each roundtrip at line 40 the bus continues 2-3 loops on line 37 to surely fill the battery, especially on cold and demanding days. This concept may have some but not full potential for the whole fleet. Figure 28 shows a short period with this type of operation concept on lines 37 – 40.

The third option is to add a second charger to the system for both sub fleets. The second charger for each is actually also necessary when moving from a 2-bus pilot to roll-out. For sub fleet 26-37-40, the second charger could be in Giæverbukta (of in Fr. Langes Gate, if the first one was at Giæverbukta). For the sub fleet 32-33-34 both charger 1 and 2 would be located close to the university / hospital. Then, how to utilise the two chargers may require added minutes to the timetable or moving minutes from one place to another. Again, how feasible this is requires discussion with and between the Fylkeskommune and the bus operator.

The option of increasing the battery capacity is also there. Bringing in more LTO batteries increases the weight and price, and takes up passenger space and in a way fades away the basic concept of the opportunity charged bus with rapid charging. The larger the fleet, the extra cost from even larger batteries multiplies. Whether or not the capacity increase is necessary depends first and foremost on the decision of public transport authority and operators on whether extra minutes of charging are acceptable if needed. We suggest that practical experiences from a pilot including the real operational margins give the right basis for deciding on this.

4.2 Troms fylke electric bus pilot

We suggest the following basic concept for an electric bus pilot consisting of two opportunity charged fully electric buses for Troms Fylkeskommune:

- Choose either one of the two sub fleets for the pilot. Our first suggestion is sub fleet 26-37-40. The choice of this may also depend on possible interest of the University to invest in chargers, which would speak for the sub fleet 32-33-34. (In case of going for the latter, do note that the operation in the sub fleet 32-33-34 is more demanding with smaller margin. There is more need to adjust the timetables to ensure sufficient margins.)

- Place at least one, but preferably two fast chargers of 400 – 500 kW power. In sub fleet 26-37-40 these could be Fr. Langes gate and Giæverbukta. In sub fleet 32-33-34 one charger is probably enough for the pilot and should be place at the hospital or at the university.
- Design a vehicle rotation where high utilisation and operational margins are secured, but at the same time we get proper experience with the demanding lines. A combination of lines 26, 37 and 40 in the first sub fleet would serve this well.

5. Conclusions and summary

A general comment on the feasibility of electric buses in the north of Europe is that, in the authors' opinion, it is definitely feasible. No show-stoppers that would make Tromsø different from the majority of other European cities were identified. Simulations and analysis on six of the city bus lines was carried out using GIS and vehicle data, timetables and vehicle rotation as well as techno-economic approach. The emissions impact was analysed as well.

Based on the analysis we conclude that the opportunity charged electric bus concept appears as the preferred choice. Vehicle and system design have to be adjusted to the specific requirements in Tromsø. A battery capacity of at least 70 – 80 kWh is recommended; it can also be slightly less if the operational rotation makes it possible to ensure the operational margins. The opportunity charging power should be as high as tolerated by the battery system, at least in the range of 400 kW and possibly even more. The number of the charging nodes necessary scales up with the number of buses. The pilot of 2 – 3 buses should preferably already have 2 chargers. We have recommended a choice between two sub fleets consisting of three city lines for the pilot.

The techno-economic analysis suggests that the opportunity charging fleet can be economically competitive against diesel buses. We emphasise that the conclusions is valid under assumption that no extra buses are required in operation. Whether it is realistic to implement a system with opportunity charged buses and operate it reliably and cost-efficiently is a subject of a field pilot where the technologies, operation, service and maintenance can be tried and tested in real conditions. This will also build up the necessary competence and experience among the key players to define the further steps.

Appendices / References

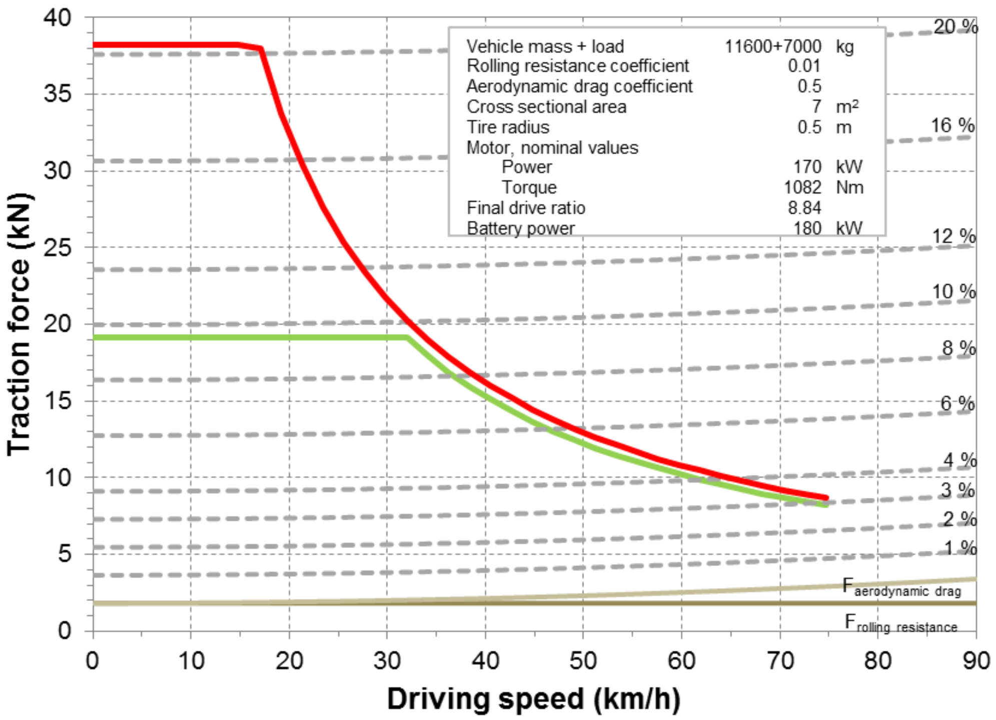
1. N.-O. Nylund, K. Belloni (Eds.), "Smart sustainable mobility - A user-friendly transport system is a combination of intelligence, low carbon energy and adaptable services", VTT Visions 5, ISBN 978-951-38-8274-7, http://issuu.com/vttfinland/docs/v5
2. ZeEUS: a flagship FP7 electromobility project coordinated by UITP. Project website http://zeeus.eu/
3. J. Laurikko, M. Pihlatie, N-O. Nylund, T. Halmeaho, S. Kukkonen, A. Lehtinen, V. Karvonen, R. Mäkinen, S. Ahtiainen, Electric city bus and infrastructure demonstration environment in Espoo, Finland, EVS28 International Electric Vehicle Symposium, Kintex, Korea, May 3-6, 2015.
4. M. Pihlatie, S. Kukkonen, T. Halmeaho, V. Karvonen, N.-O. Nylund, Fully Electric City Buses – The Viable Option, Electric Vehicle Conference (IEVC), 2014 IEEE International, DOI: 10.1109/IEVC.2014.7056145

5. Hagman, Rolf, Christian Weber, and Astrid H. Amundsen. 2015b. Utslipp Fra Nye Kjøretøy – Holder de Hva de Lover? TØI rapport 1407/2015, Oslo: Transportøkonomisk institutt.

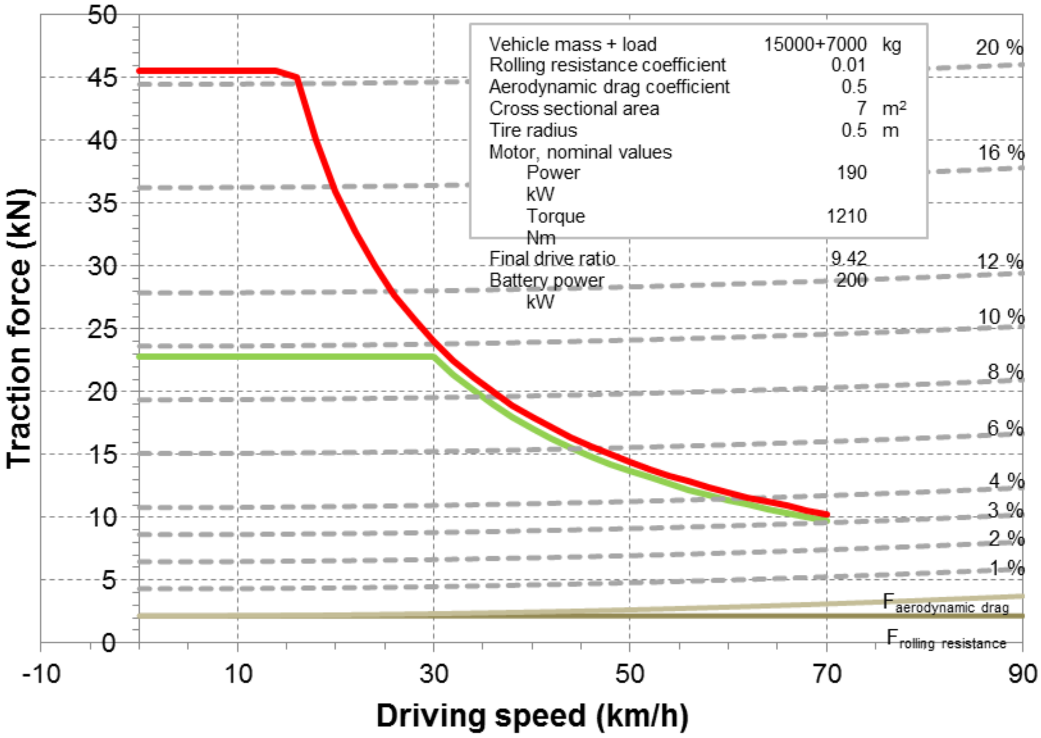
APP. A Parameters for the bus powertrain and driveline

The bus performance can be presented using tractive force and speed diagrams shown separately for the opportunity charged bus and the depot charged bus. The tractive force limit that corresponds to the rated power of the traction motor is shown with the green line. The tractive force limit that comes from battery charge and discharge power limits is shown with the red line. The slope of the road is shown by grey dashed lines. The motor can for short periods of time produce a torque that corresponds to a traction force between the red and green lines, and it can continuously produce a torque that gives a traction force below the green line. In other words, the bus can climb hills with a 20% slope for a short time, and it can continuously climb hills with a slope slightly less than 10%.

The effect of different final drive ratio between the opportunity charged bus and the depot charged bus can be seen in these diagrams as different vehicle speed that is achieved with the traction motor nominal speed. The vehicle speed at traction motor nominal speed is found in the elbow of the green line, which is $32\ km/h$ for the opportunity charged bus and $30\ km/h$ for the depot charged bus. Another effect is the maximum speed of the vehicle, which is over $75\ km/h$ for the opportunity charged bus and $70\ km/h$ for the depot charged bus.



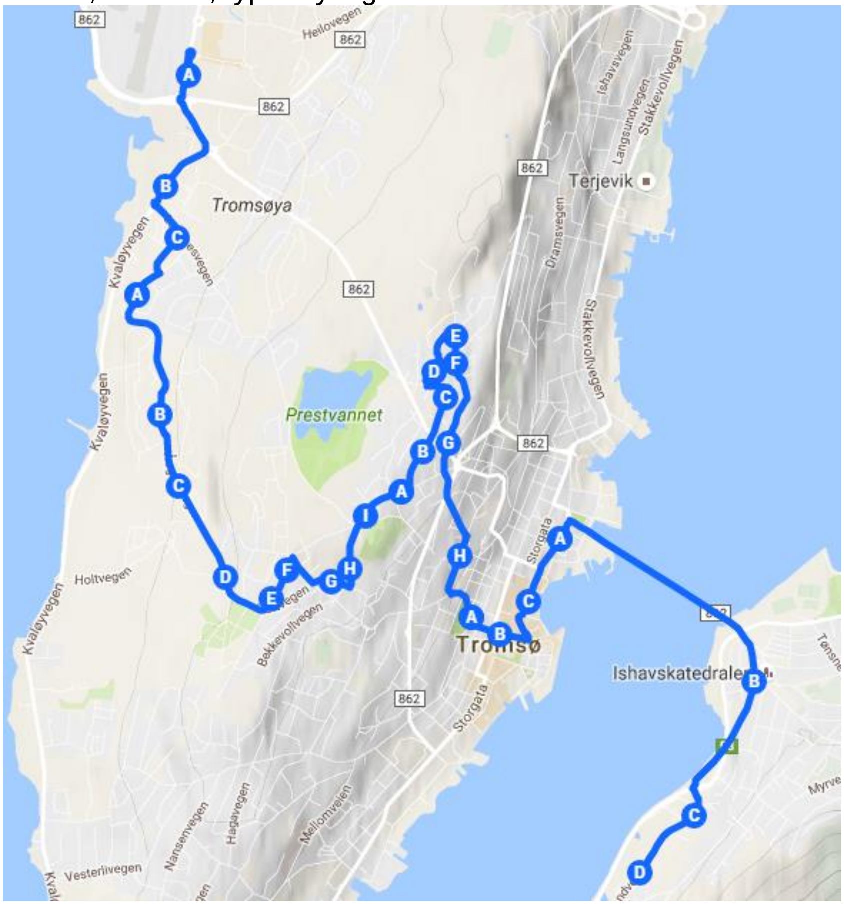
Tractive force and speed diagram for the opportunity charged bus. The bus is able to climb 20 % slope with 7000 kg load (6000 kg of passengers and 1000 kg of ice).

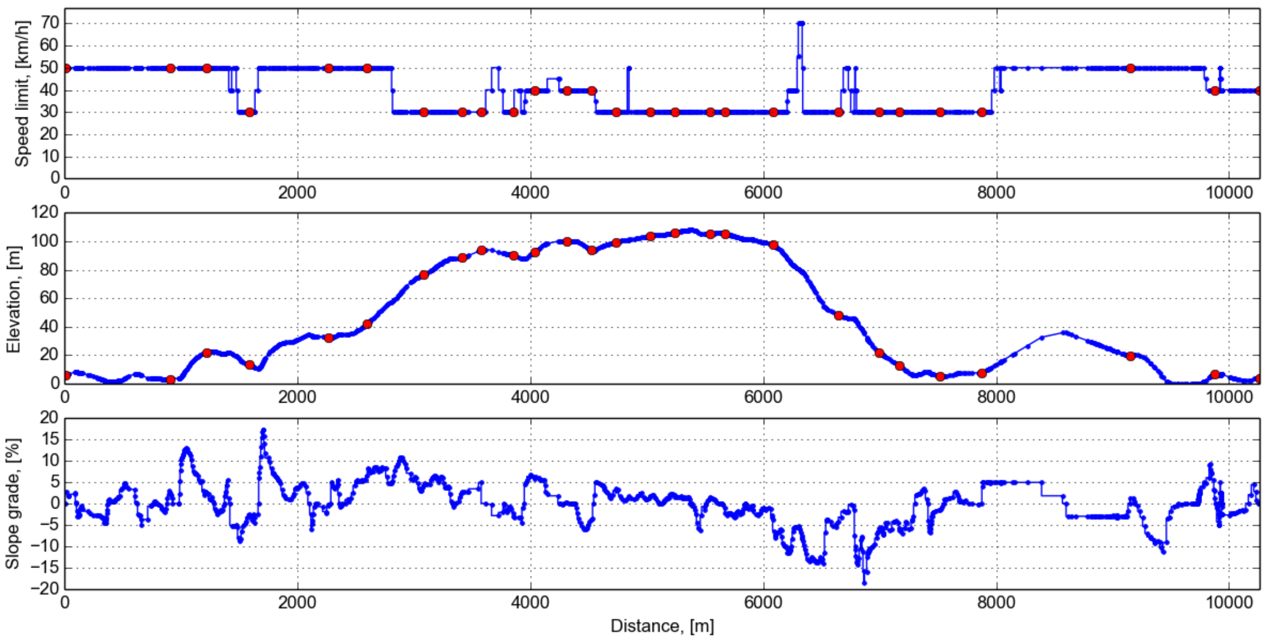


Tractive force and speed diagram for the depot charged bus. The bus is able to climb 20 % slope with 7000 kg load (6000 kg of passengers and 1000 kg of ice).

APP. B GIS Data: Line 26_1 Giæverbukta – Pyramiden

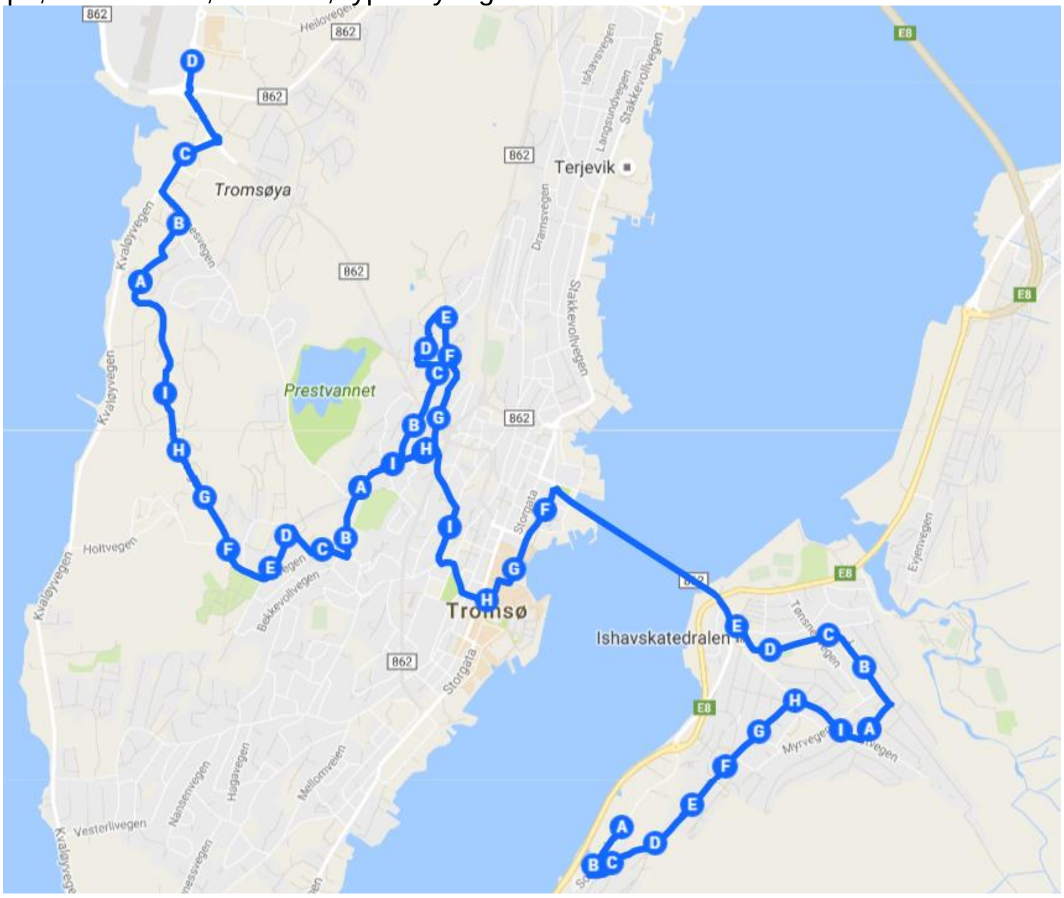
27 stops, 28 minutes, 10.3 km, typically highest use of chains

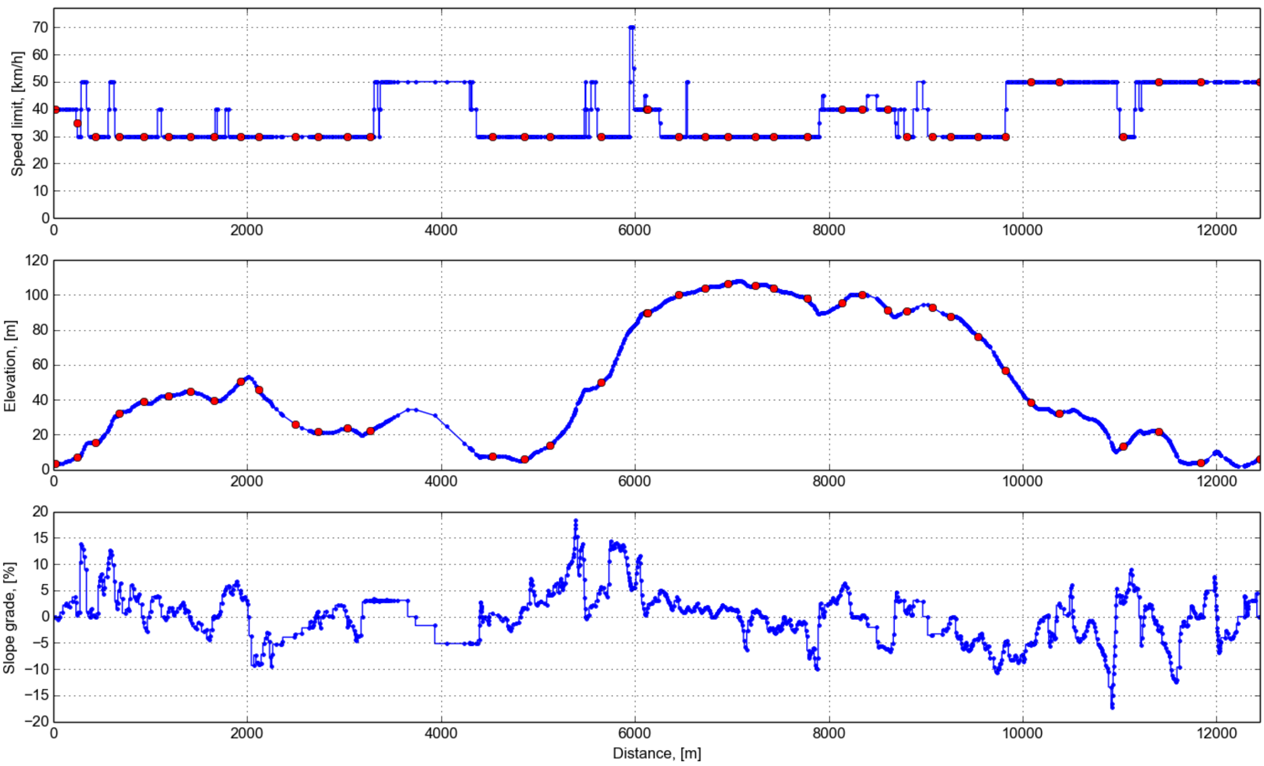




APP. C GIS Data: Line 26_2 Pyramiden – Giæverbukta

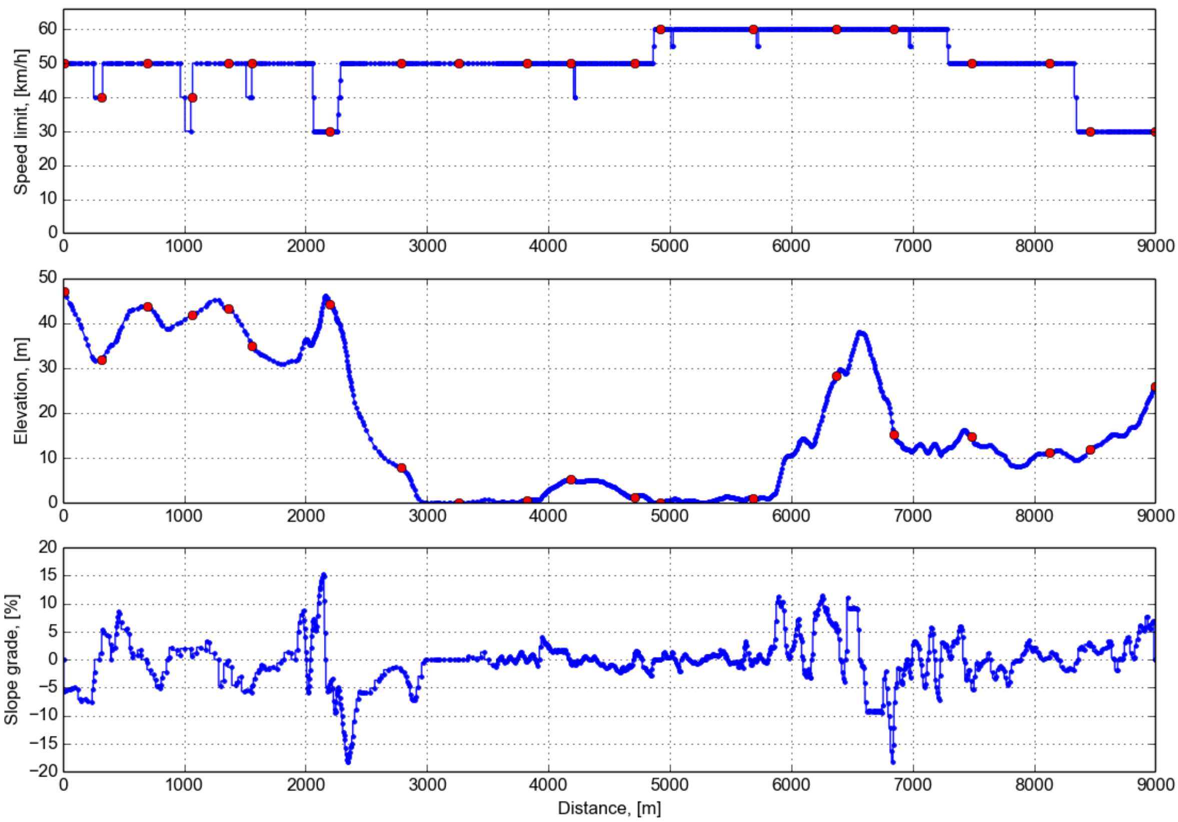
40 stops, 42 minutes, 12.4 km, typically highest use of chains





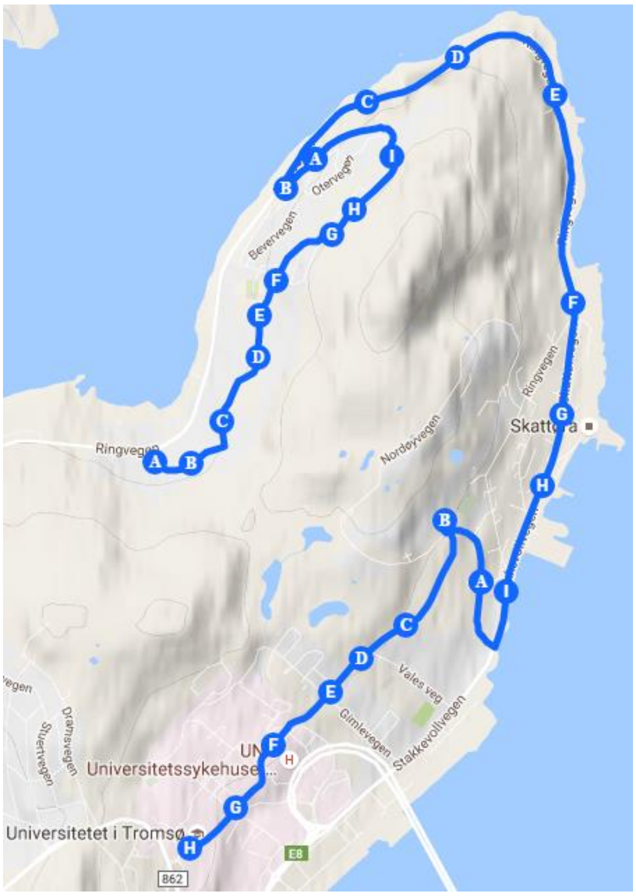
APP. D GIS Data: Line 32_1 Universitetet – Hamna sør

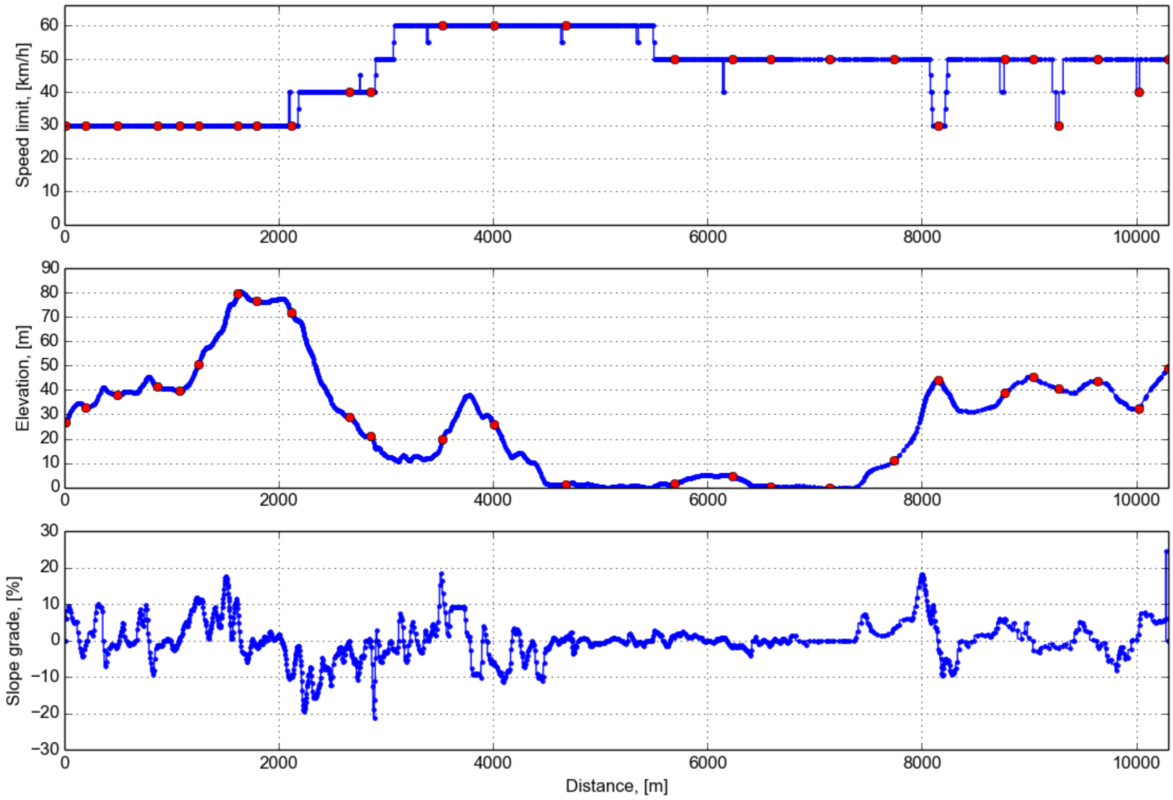
20 stops, 19 minutes, 9 km



APP. E GIS Data: Line 32_2 Hamna sør – Universitetet

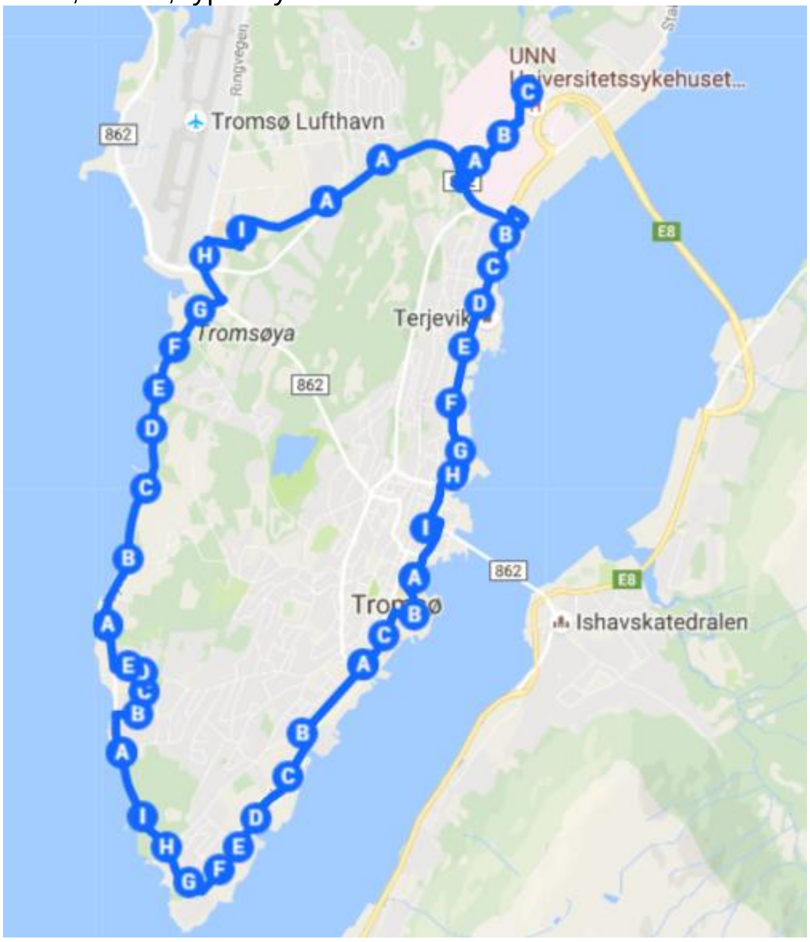
26 stops, 20 min, 10.3 km

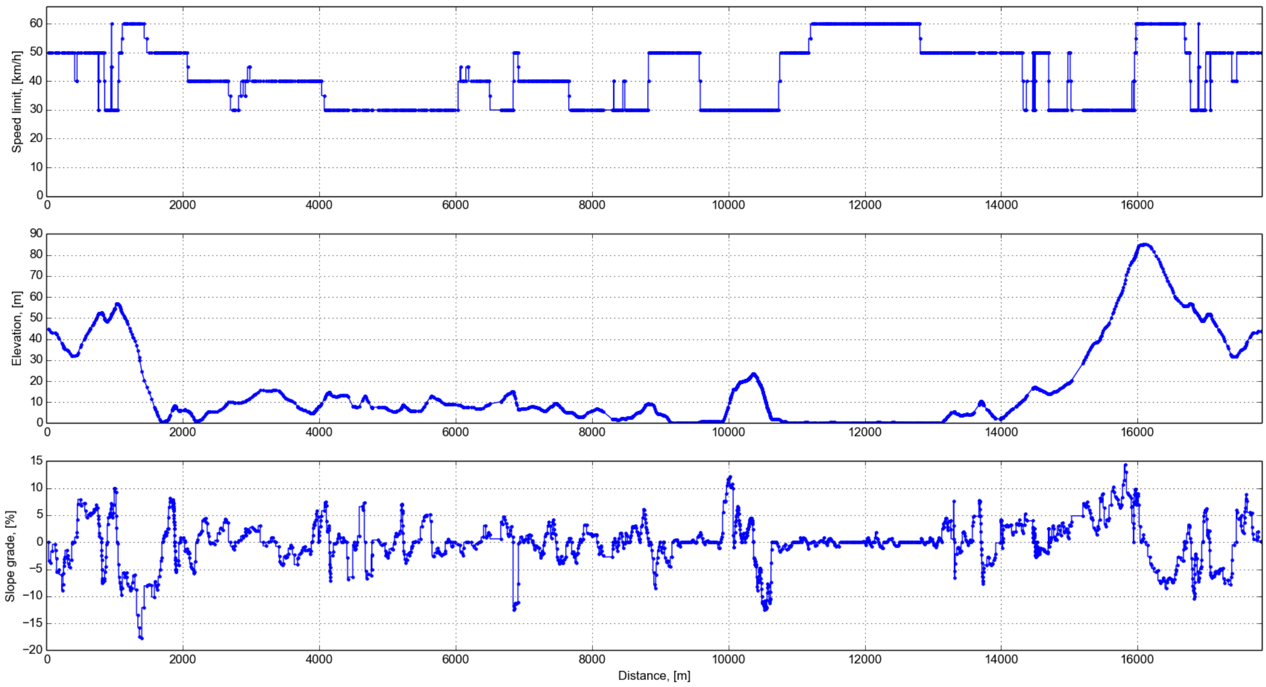




APP. F GIS Data: Line 33–34 Universitetssykehuset

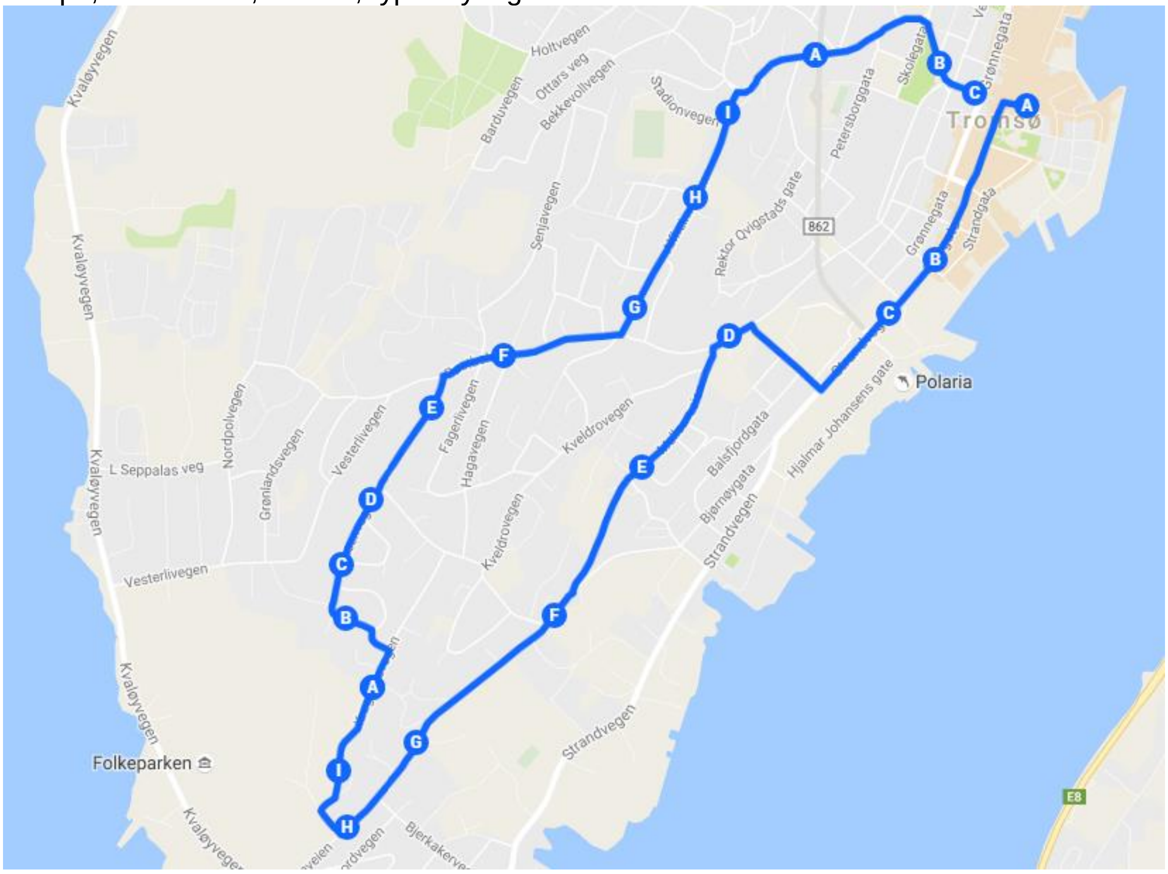
42 stops, 48 minutes, 18 km, typically low use of chains

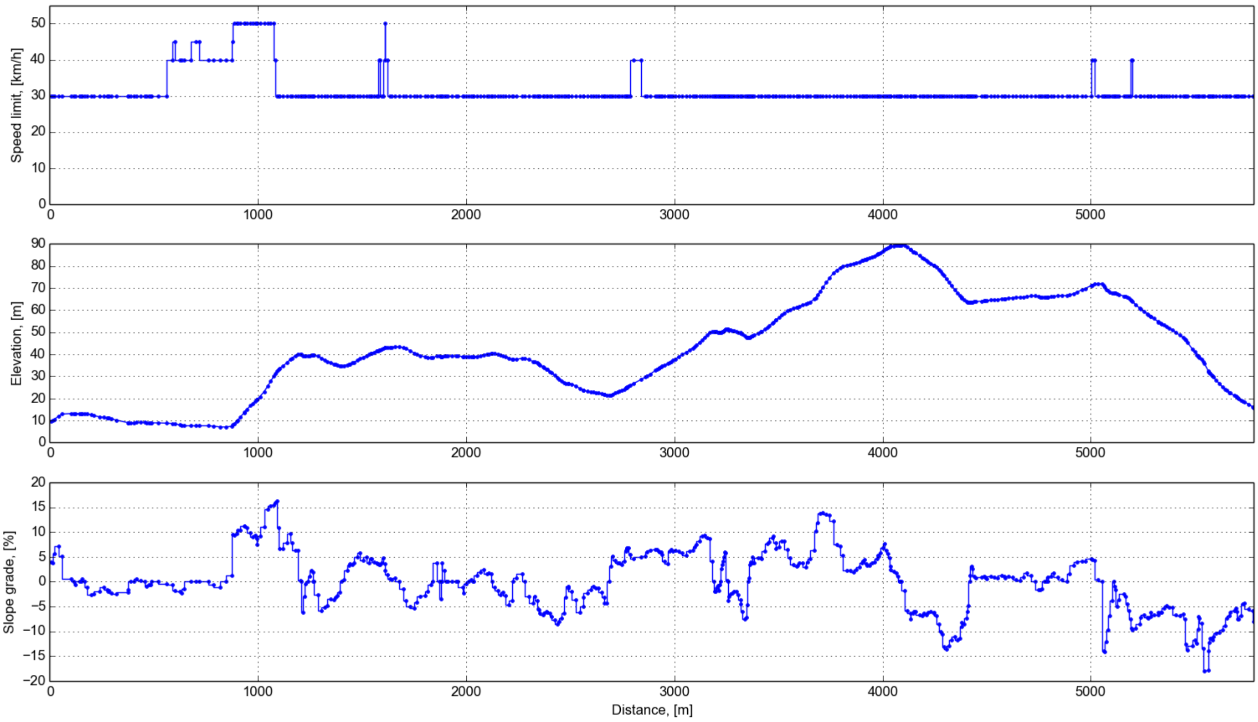




APP. G GIS Data: Line 37 Sentrum – Tromsø museum

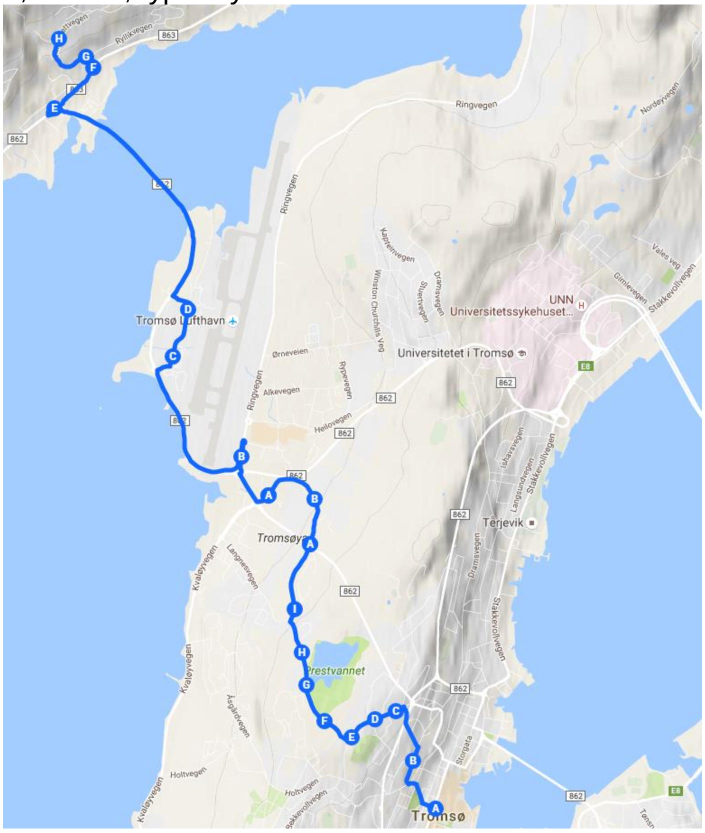
21 stops, 22 minutes, 5.8 km, typically highest use of chains

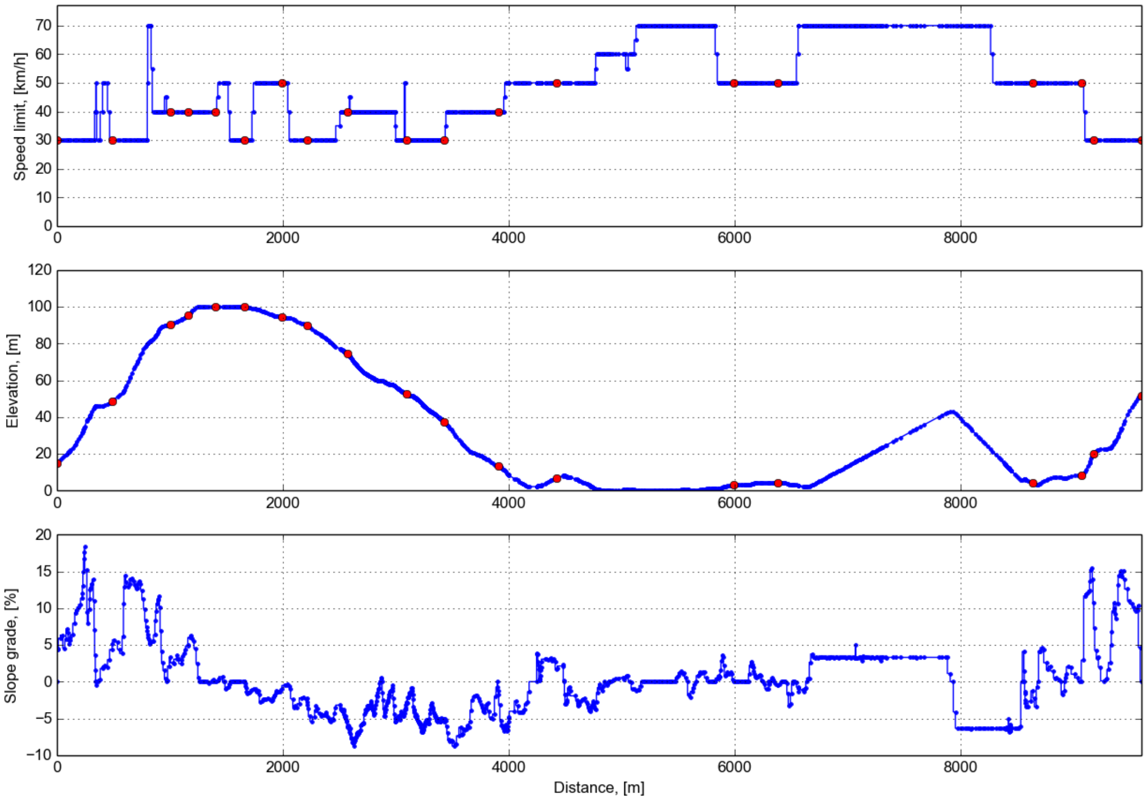




APP. H GIS Data: Line 40_1 Sentrum – Slettaelva

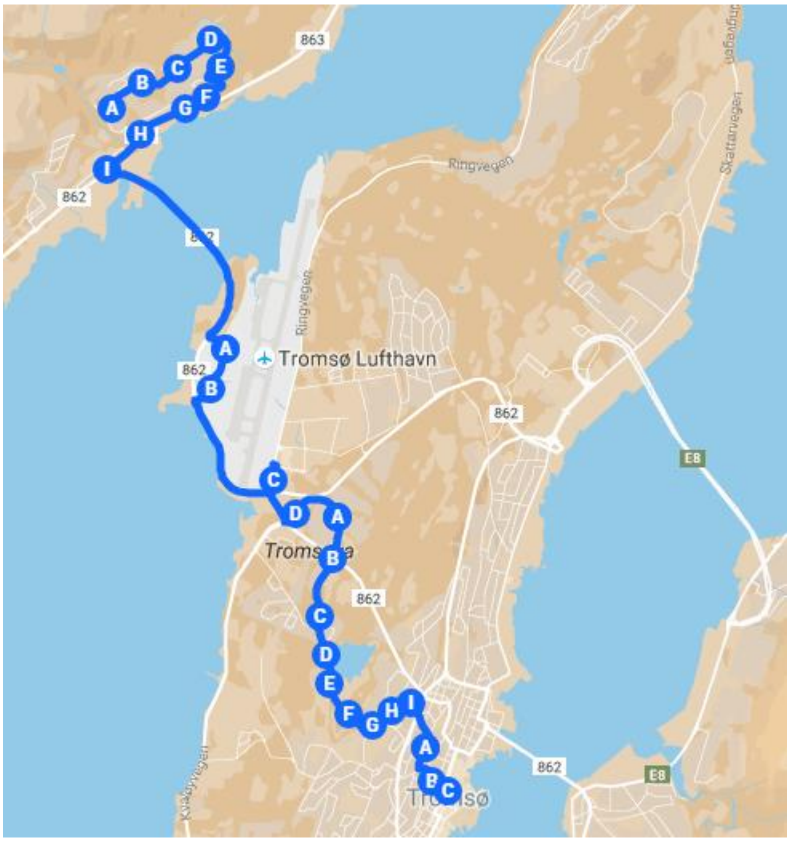
19 stops, 22 minutes, 9.6 km, typically moderate use of chains

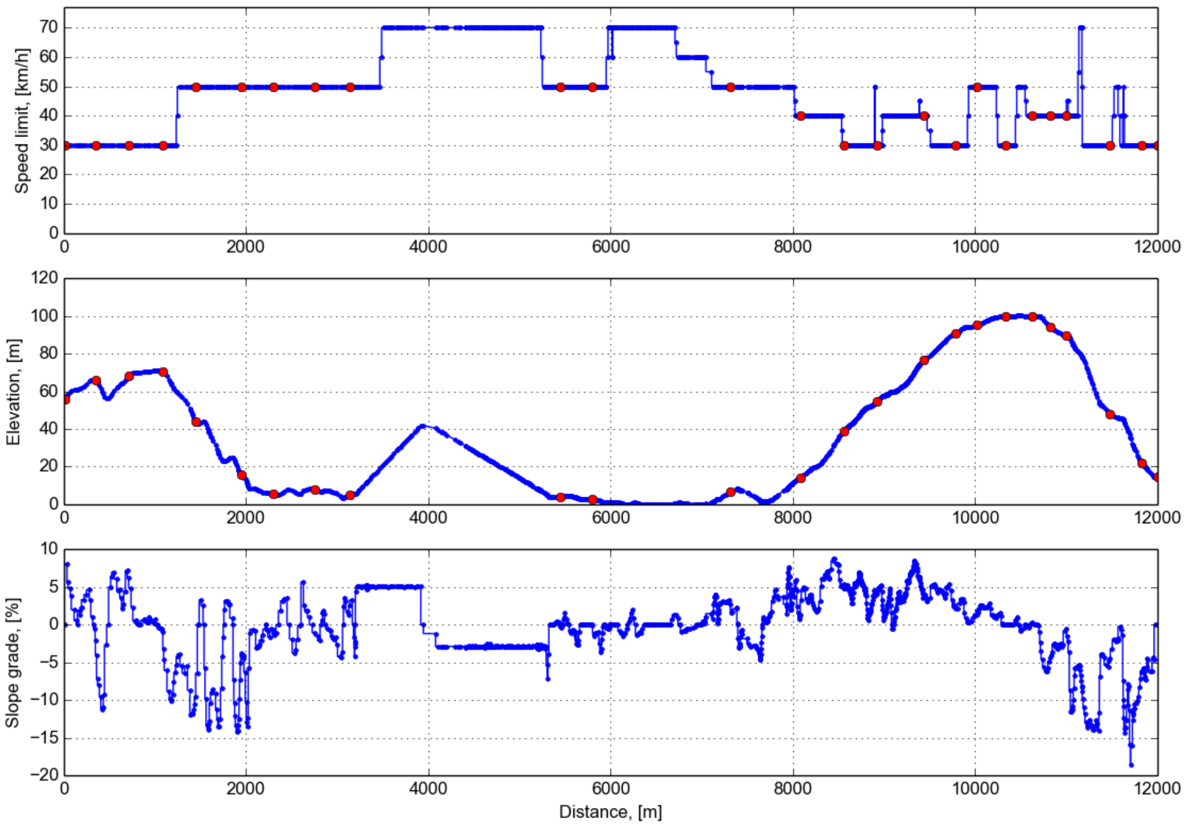




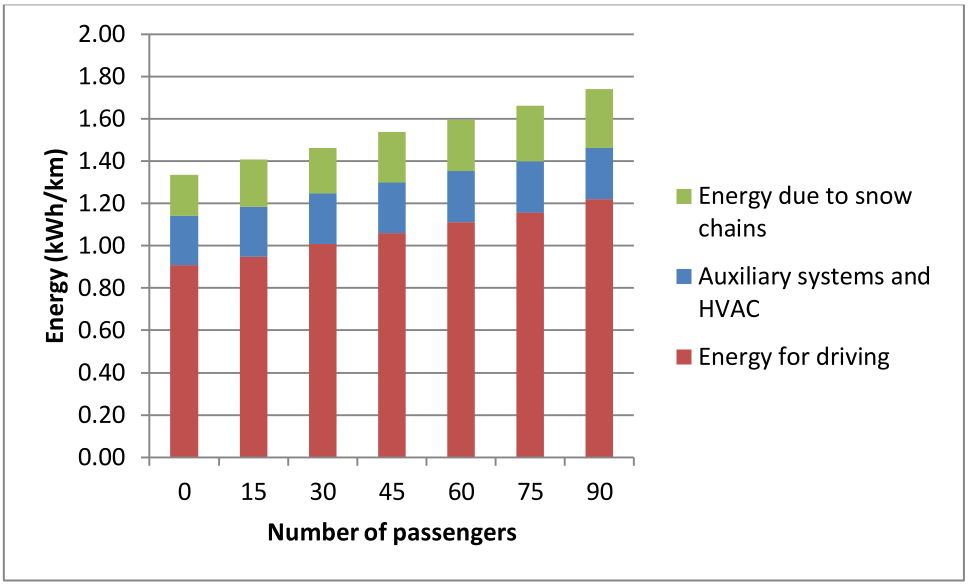
APP. I GIS Data: Line 40_2 Slettaelva – Sentrum

25 stops, 30 minutes, 12 km, typically moderate use of chains

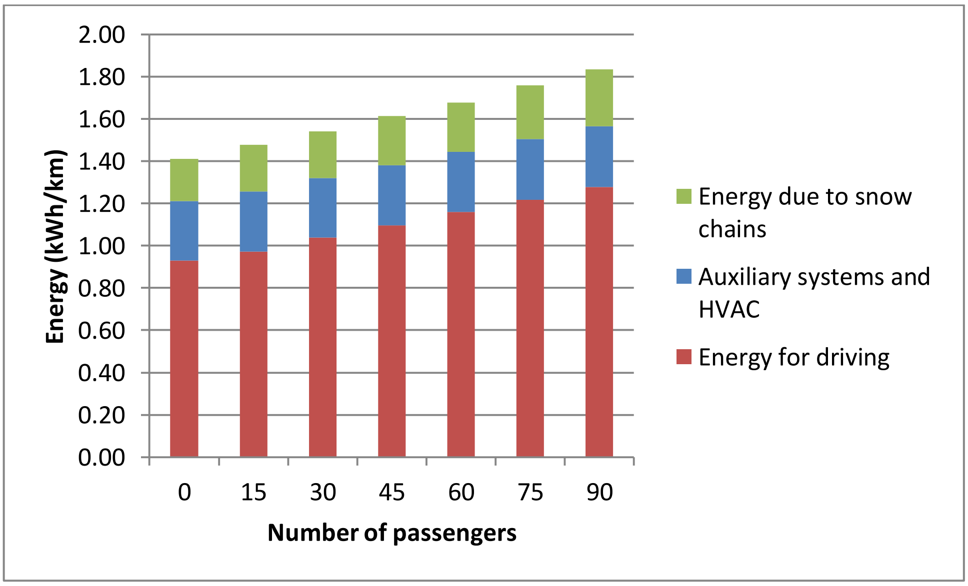




APP. J Energy consumption of depot charged bus on line 26

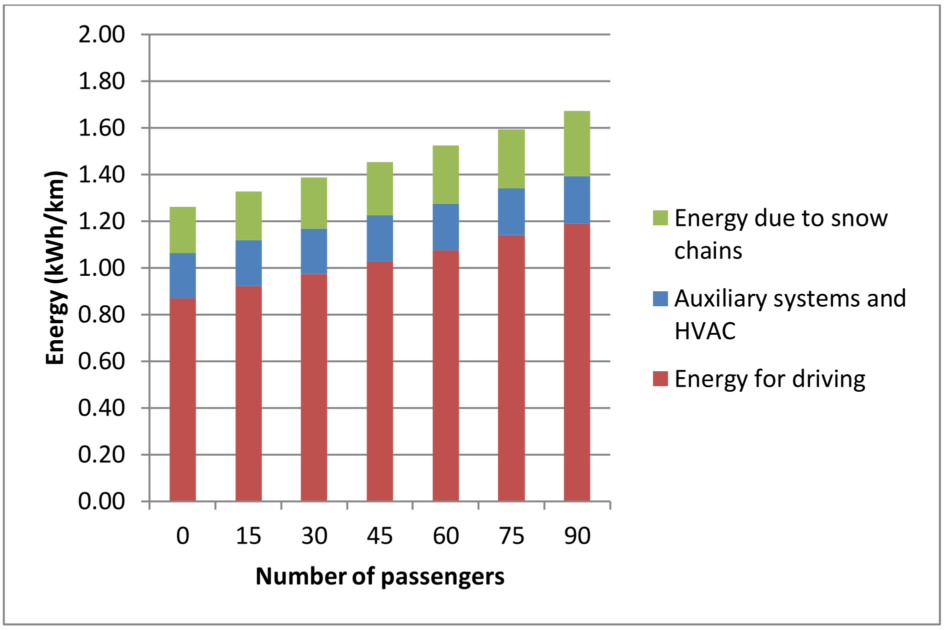


Energy use as depot charged bus stops on half of bus stops on line 26.

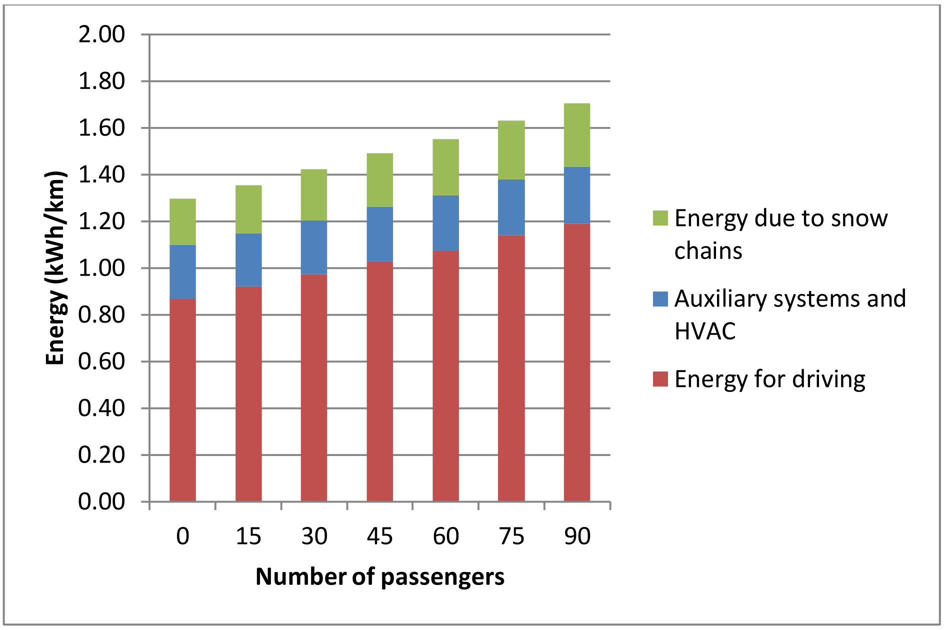


Energy use as depot charged bus stops on all bus stops on line 26.

APP. K Energy consumption of depot charged bus on line 32

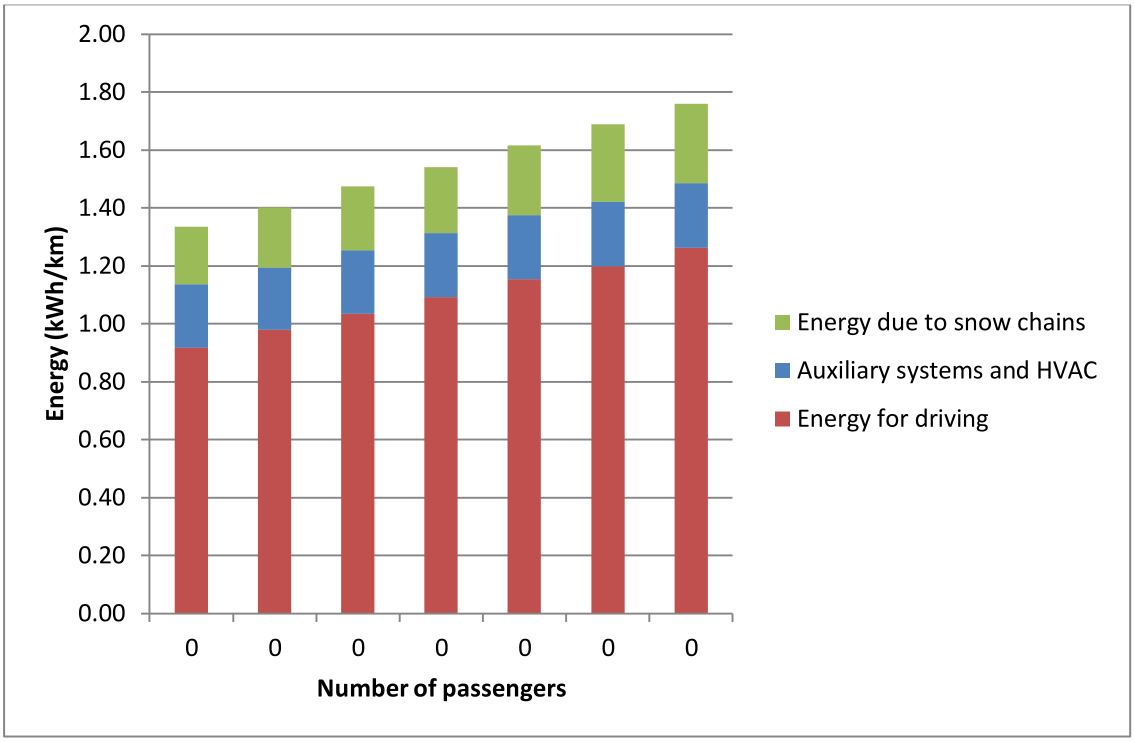


Energy used as depot charged bus stops on half of bus stops on line 32.

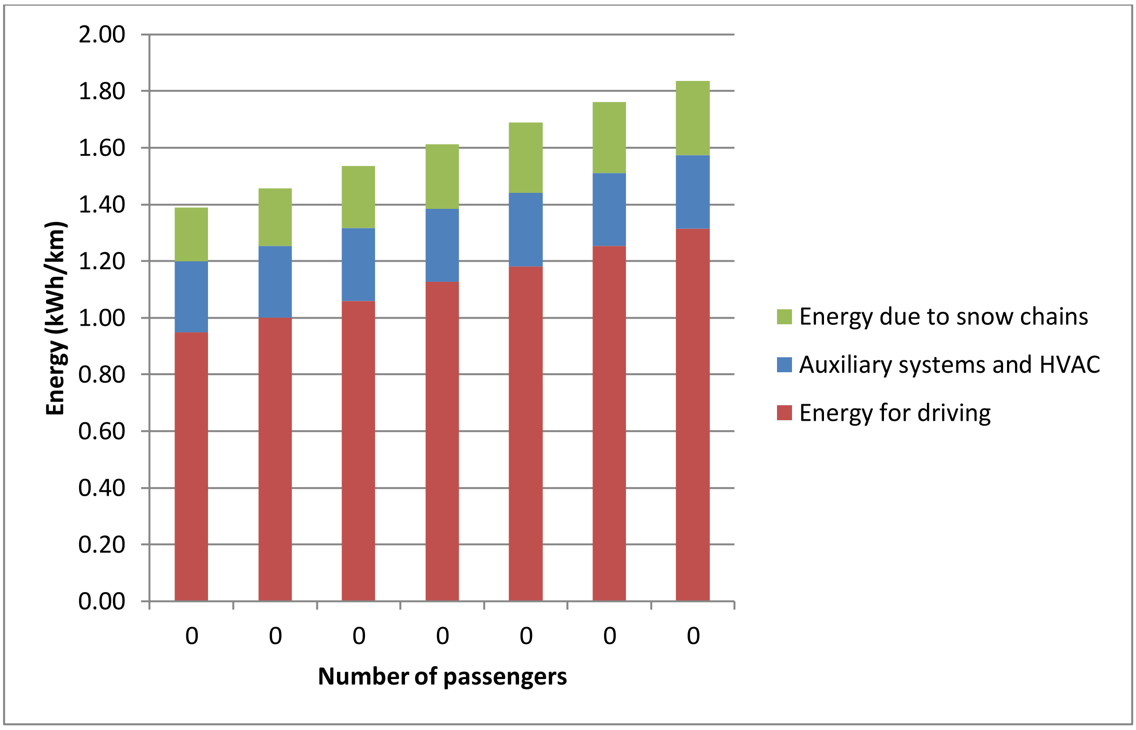


Energy use as depot charged bus stops on all bus stops on line 32.

APP. L Energy consumption for depot charged bus on line 33

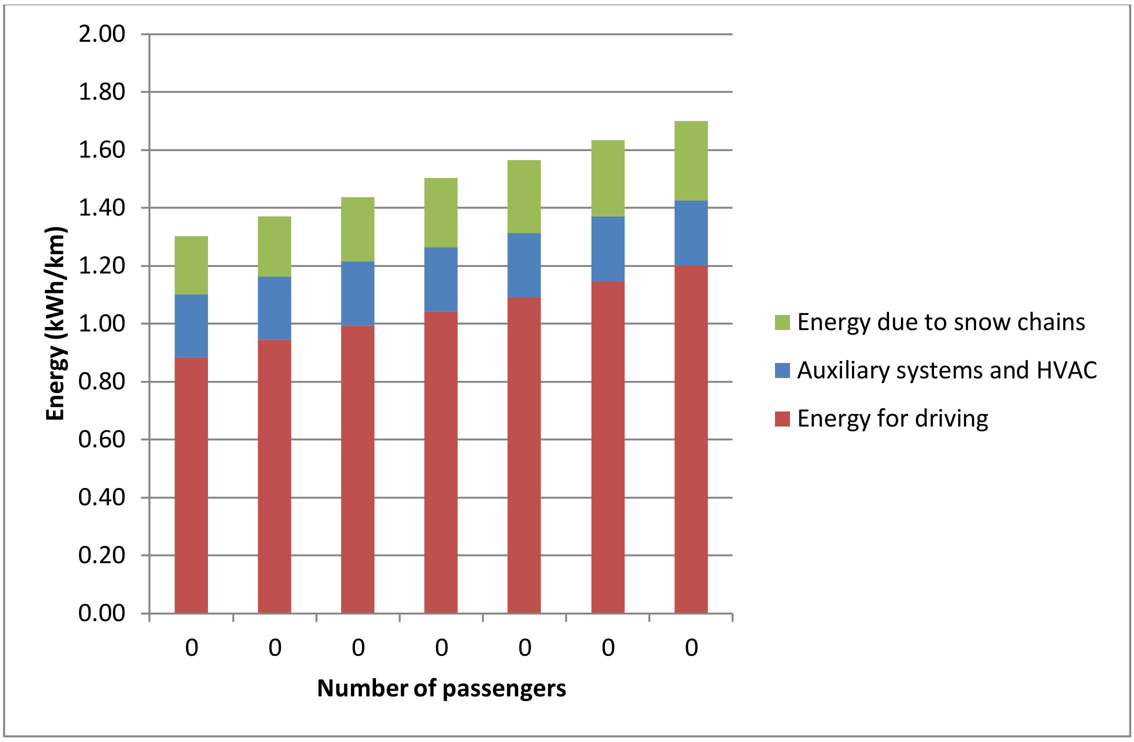


Energy used as depot charged bus stops on half of bus stops on line 33.

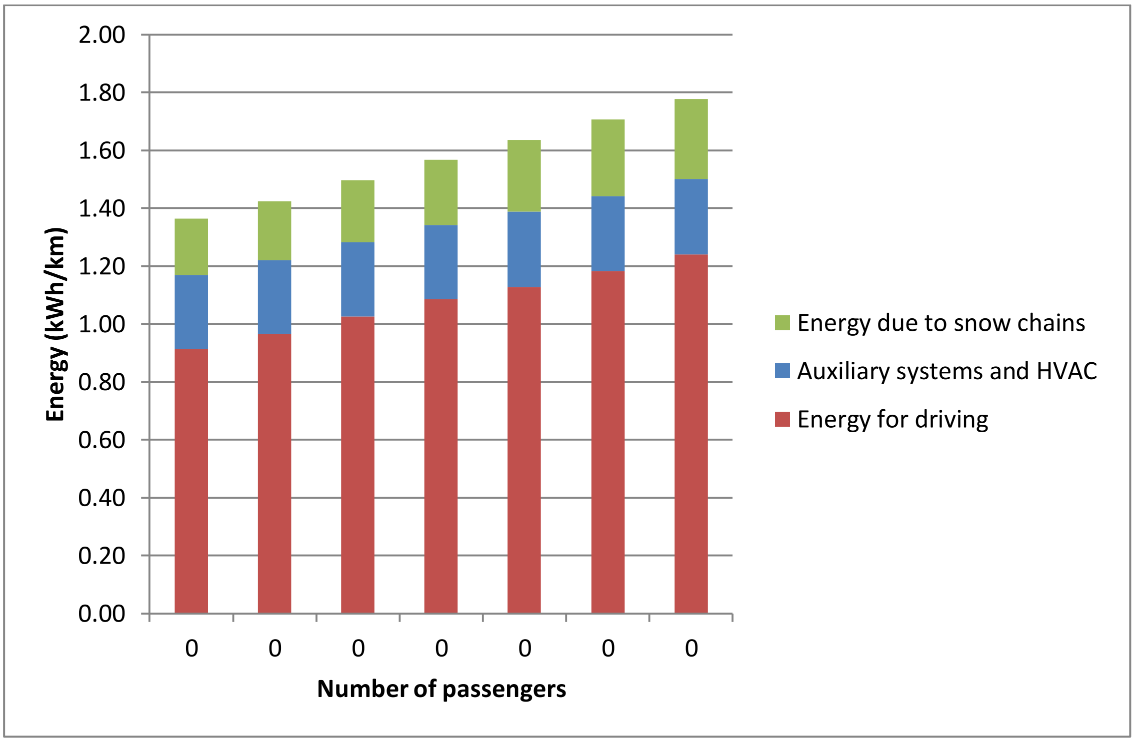


Energy use as depot charged bus stops on all bus stops on line 33

APP. M Energy consumption for depot charged bus on line 34

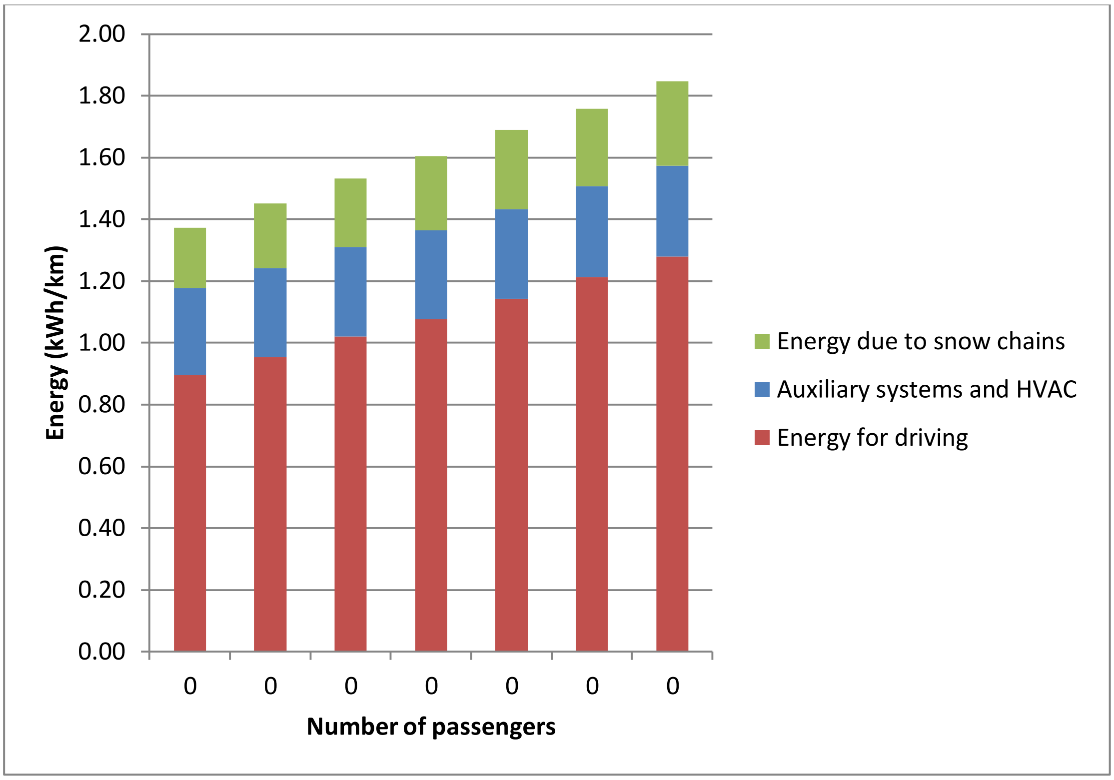


Energy used as depot charged bus stops on half of bus stops on line 34.

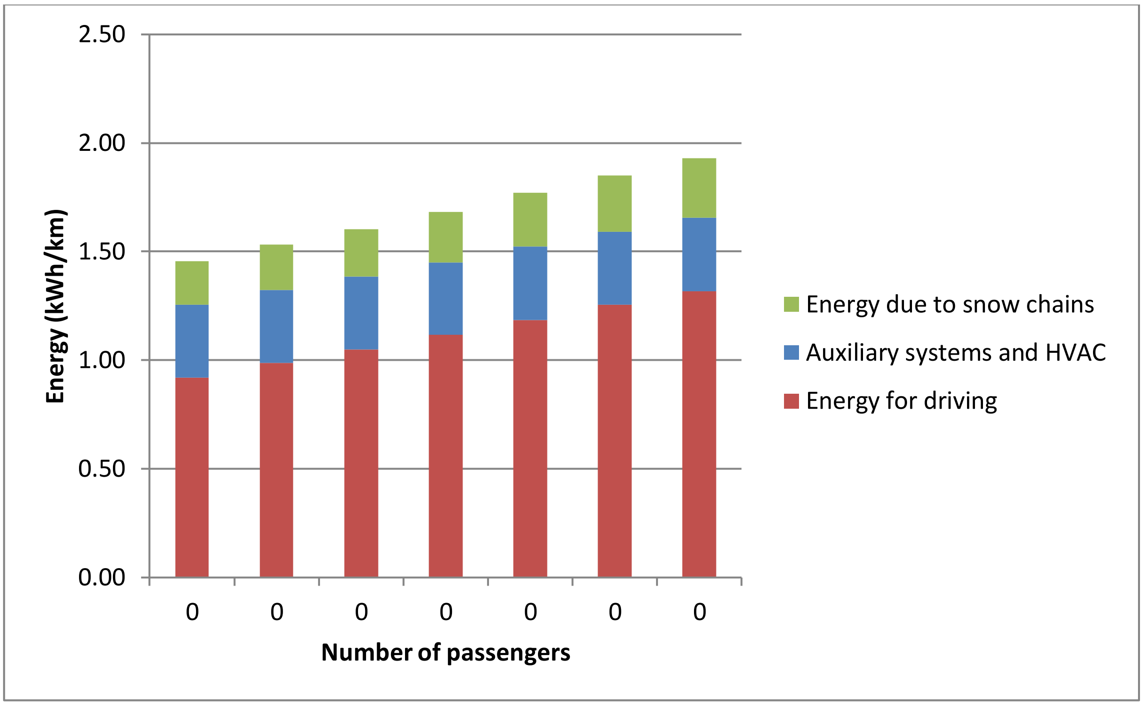


Energy use as depot charged bus stops on all bus stops on line 34

APP. N Energy consumption for depot charged bus on line 37

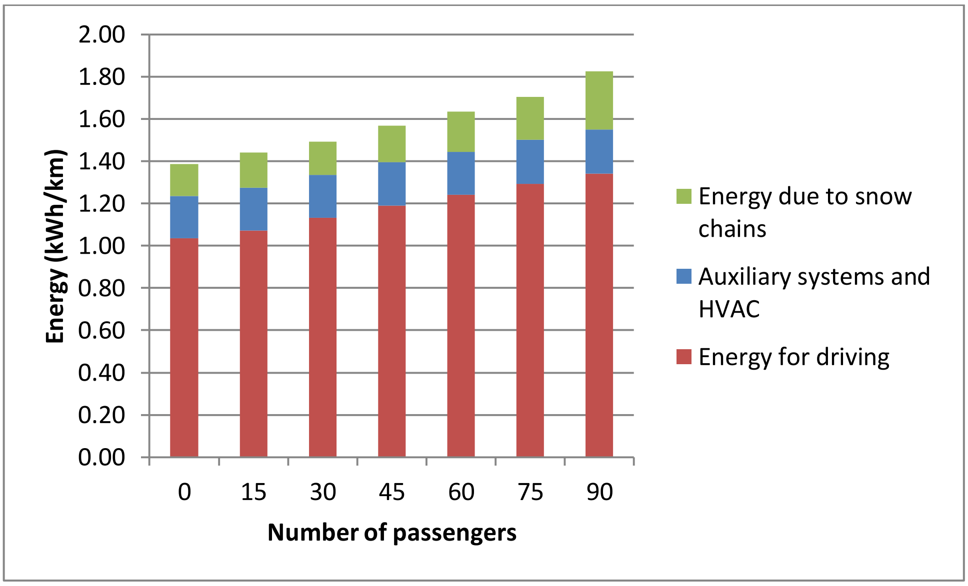


Energy used as depot charged bus stops on half of bus stops on line 37

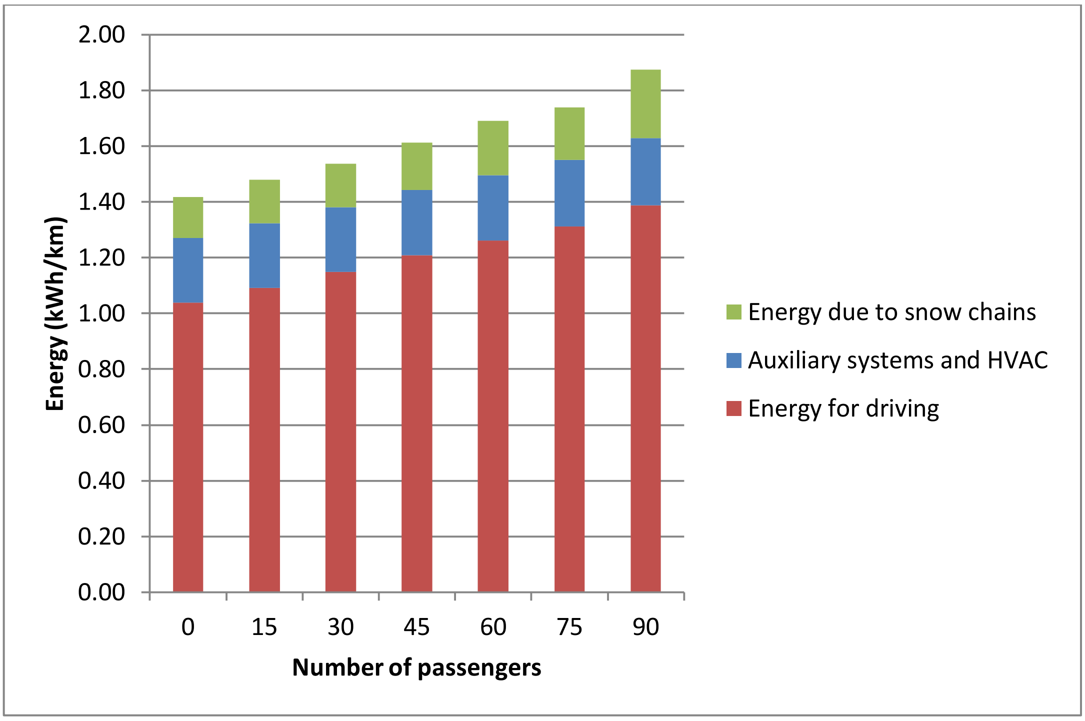


Energy use as depot charged bus stops on all bus stops on line 37

APP. O Energy consumption of depot charged bus on line 40

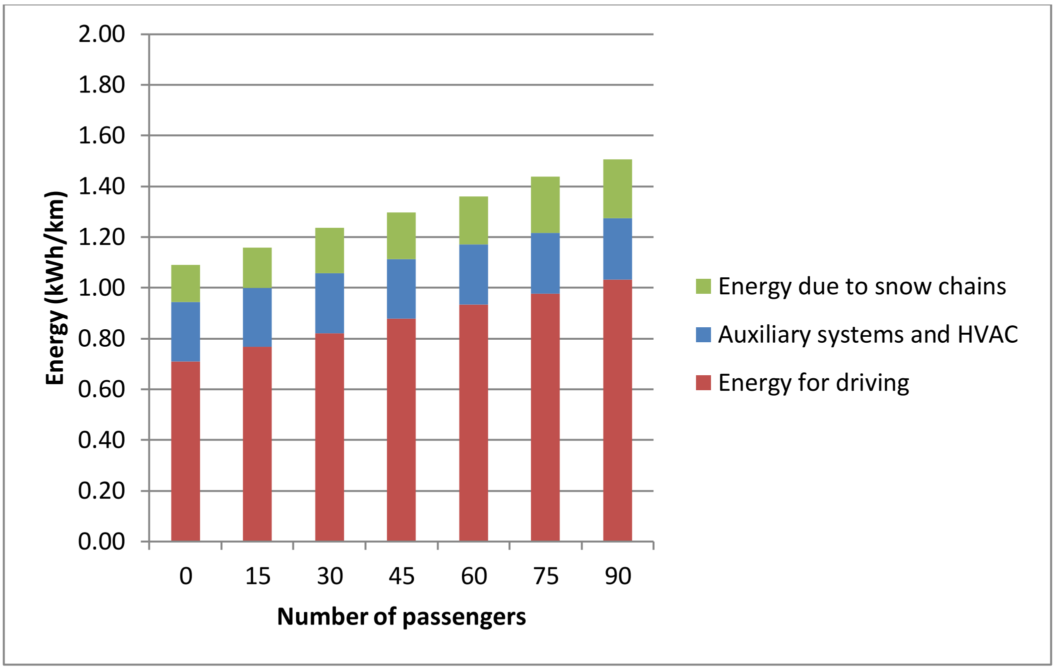


Energy use as depot charged bus stops on half of bus stops on line 40.

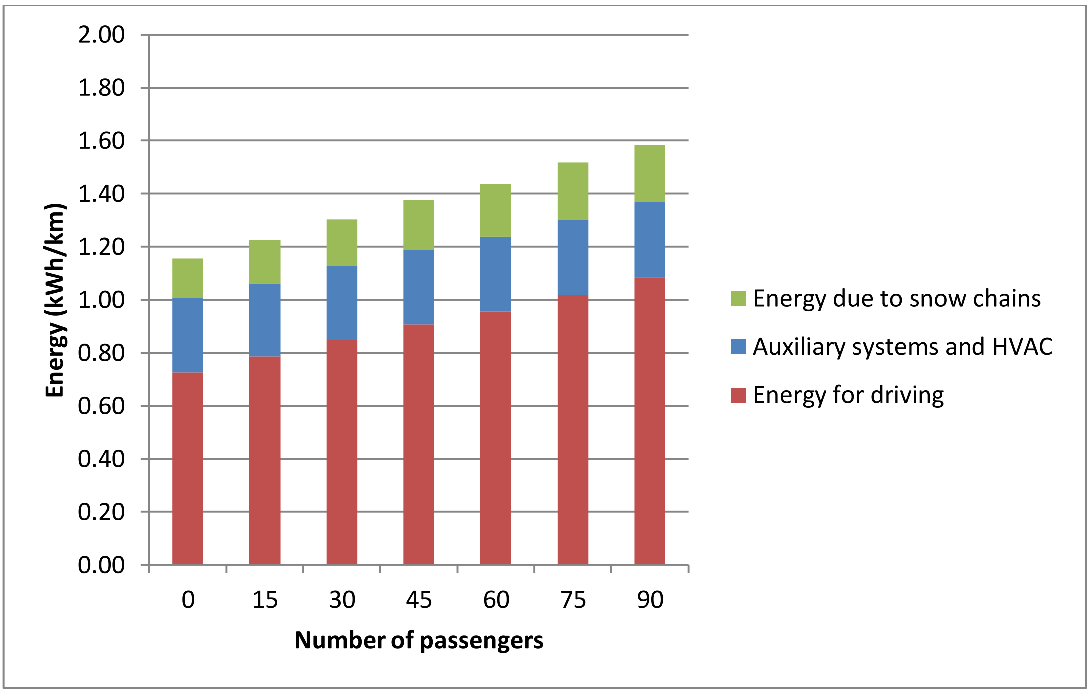


Energy use as depot charged bus stops on all bus stops on line 40.

APP. P Energy consumption of opportunity charged bus on line 26

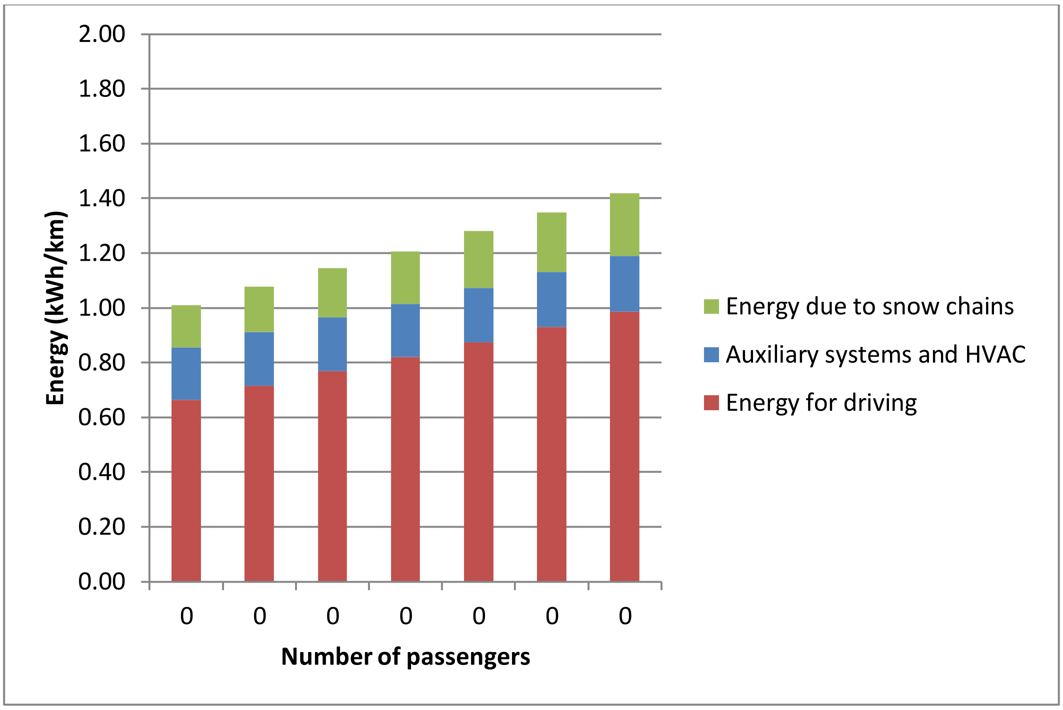


Energy use as opportunity charged bus stops on half of bus stops on line 26.

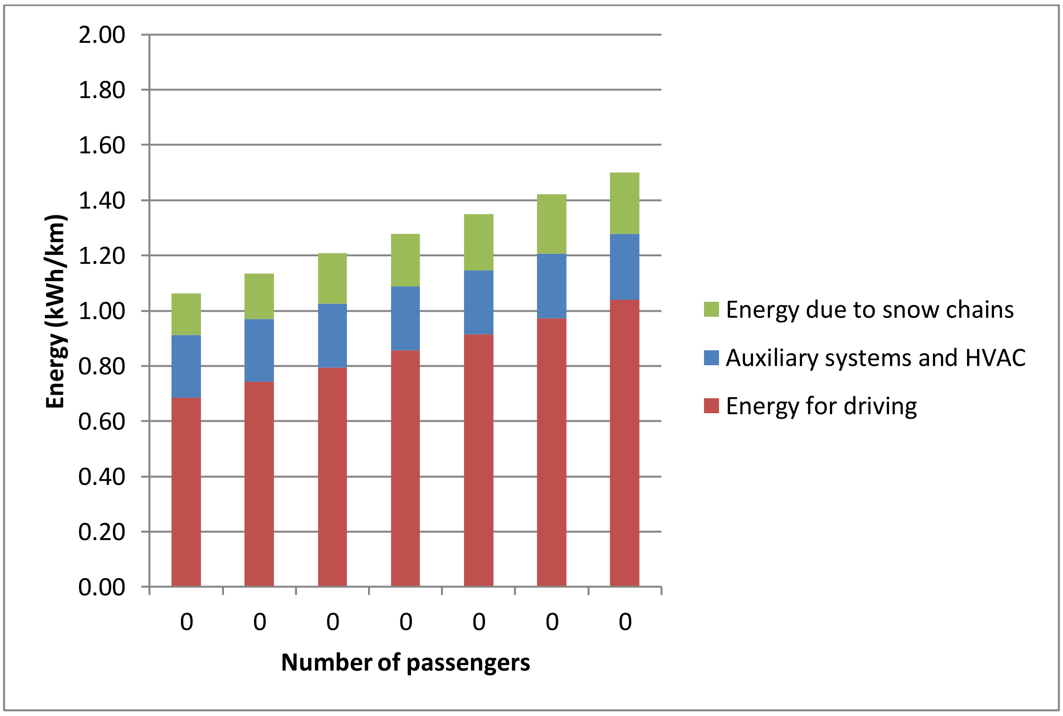


Energy use as opportunity charged bus stops on all bus stops on line 26.

APP. Q Energy consumption of opportunity charged bus on line 32

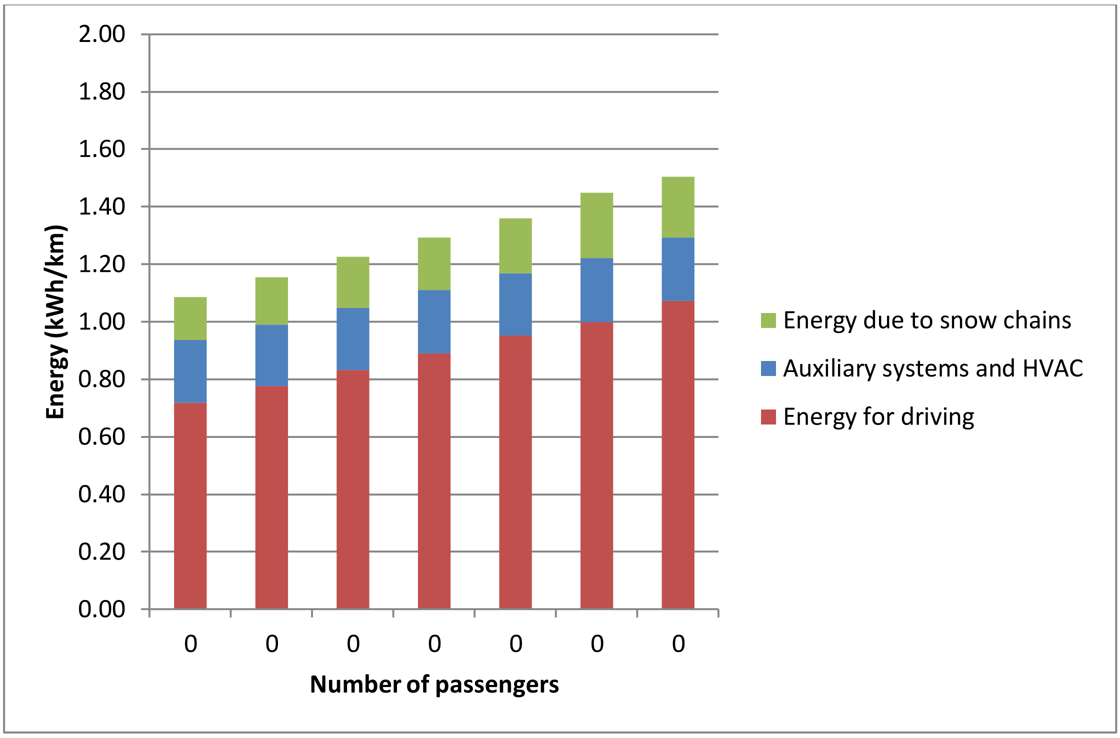


Energy use as opportunity charged bus stops on half of bus stops on line 32

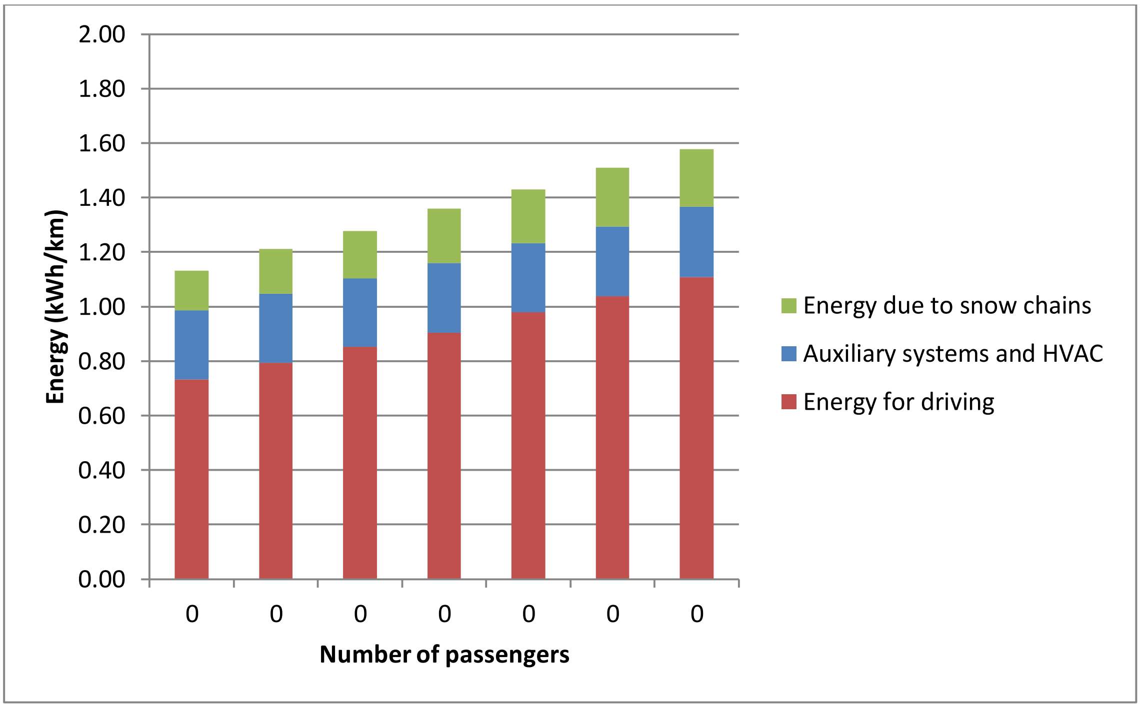


Energy use as opportunity charged bus stops on all bus stops on line 32.

APP. R Energy consumption of opportunity charged bus on line 33

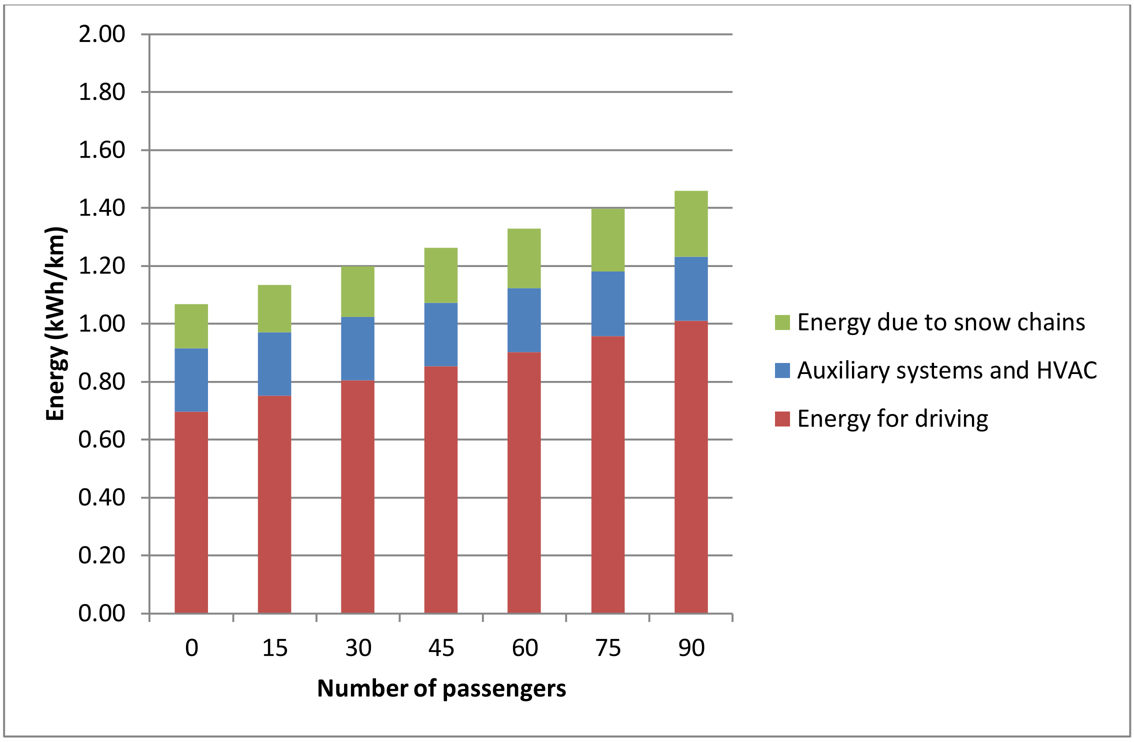


Energy use as opportunity charged bus stops on half of bus stops on line 33

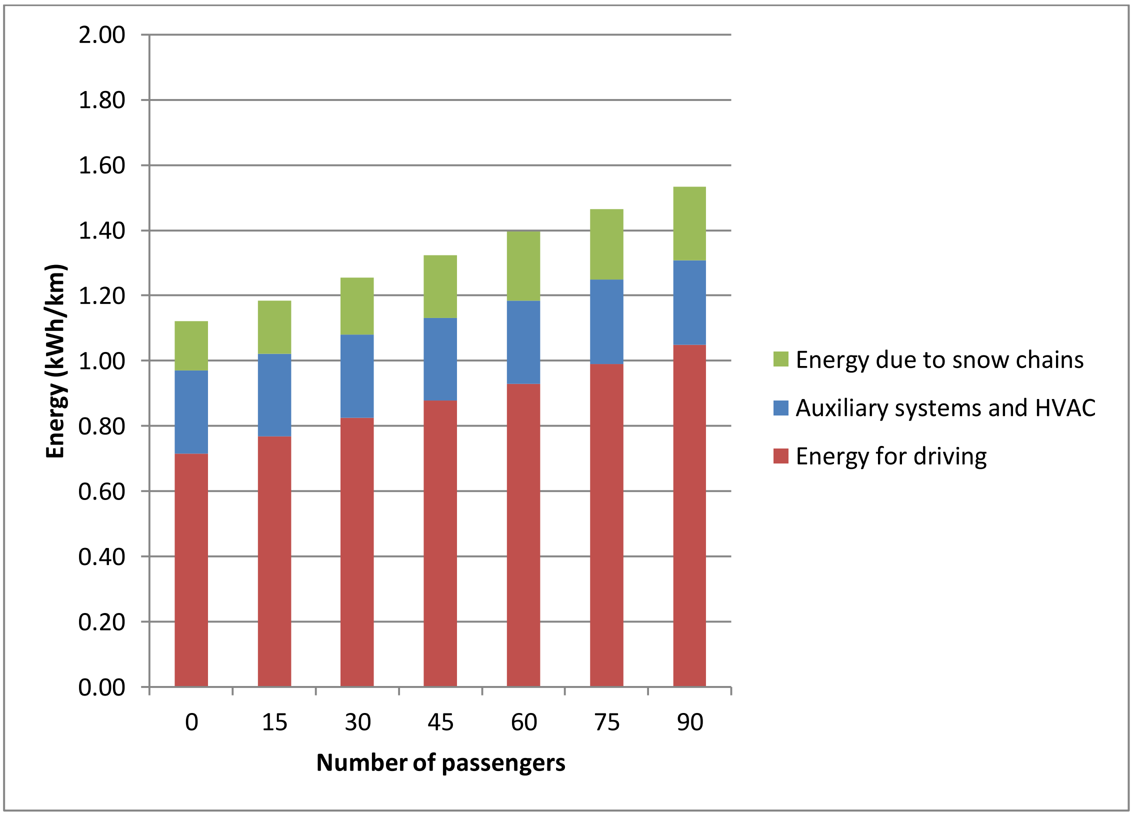


Energy use as opportunity charged bus stops on all bus stops on line 33.

APP. S Energy consumption of opportunity charged bus on line 34

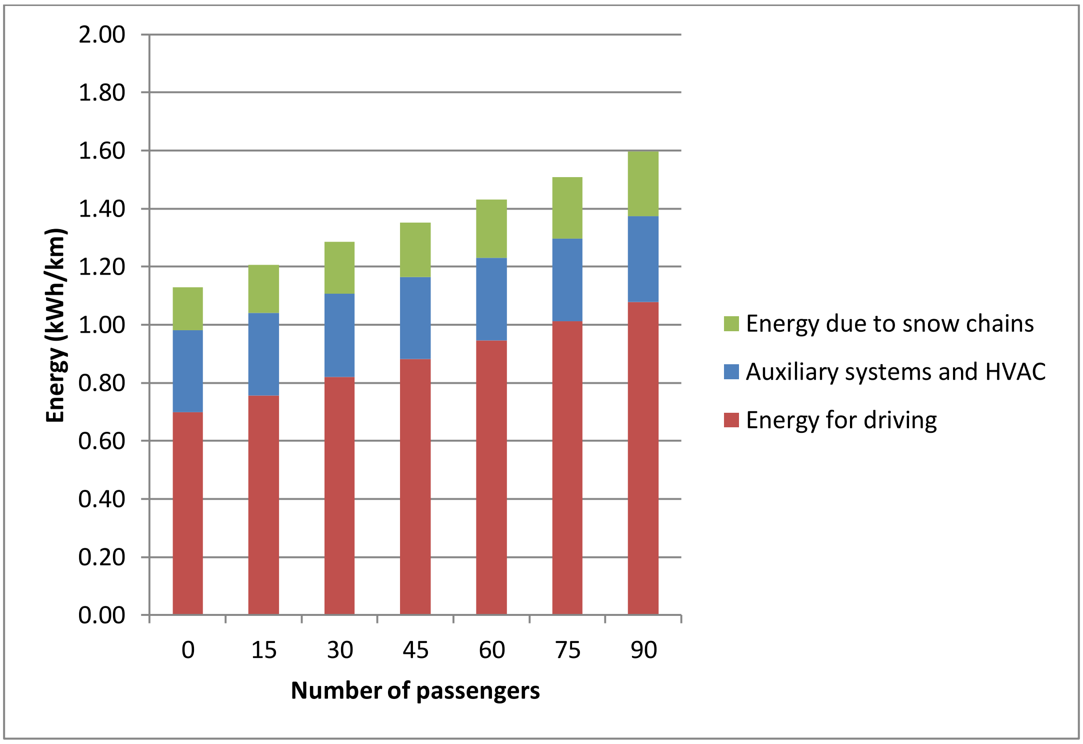


Energy use as opportunity charged bus stops on half of bus stops on line 34.

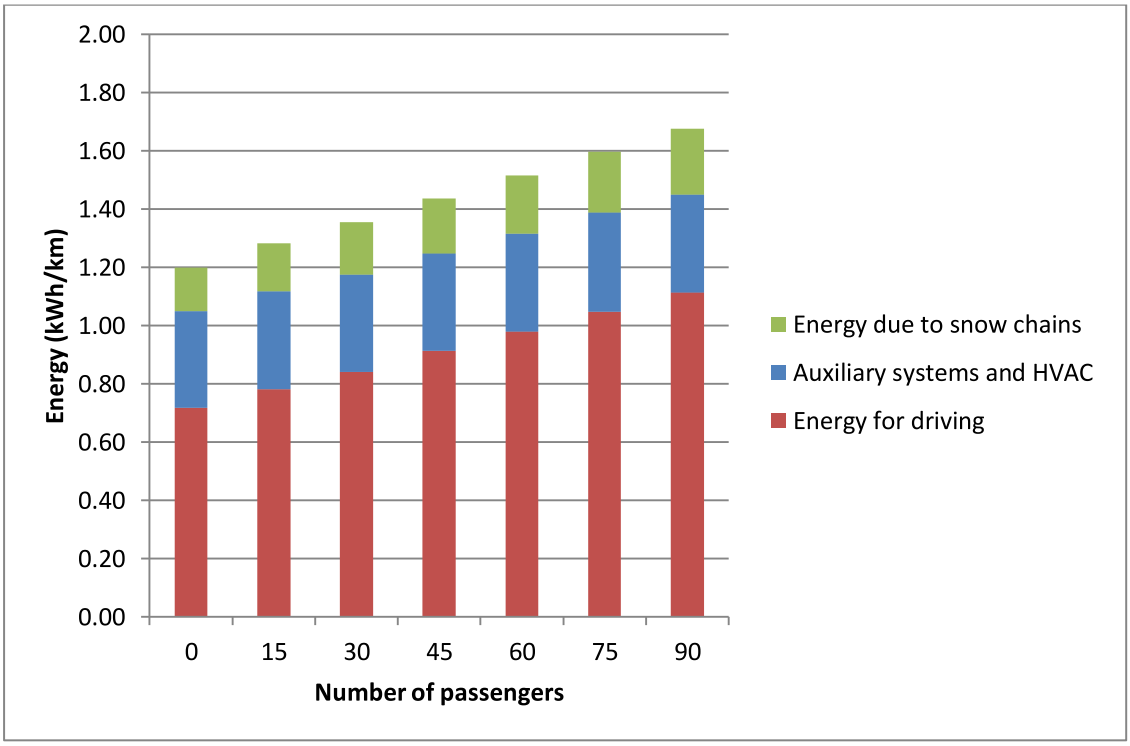


Energy use as opportunity charged bus stops on all bus stops on line 34.

APP. T Energy consumption of opportunity charged bus on line 37

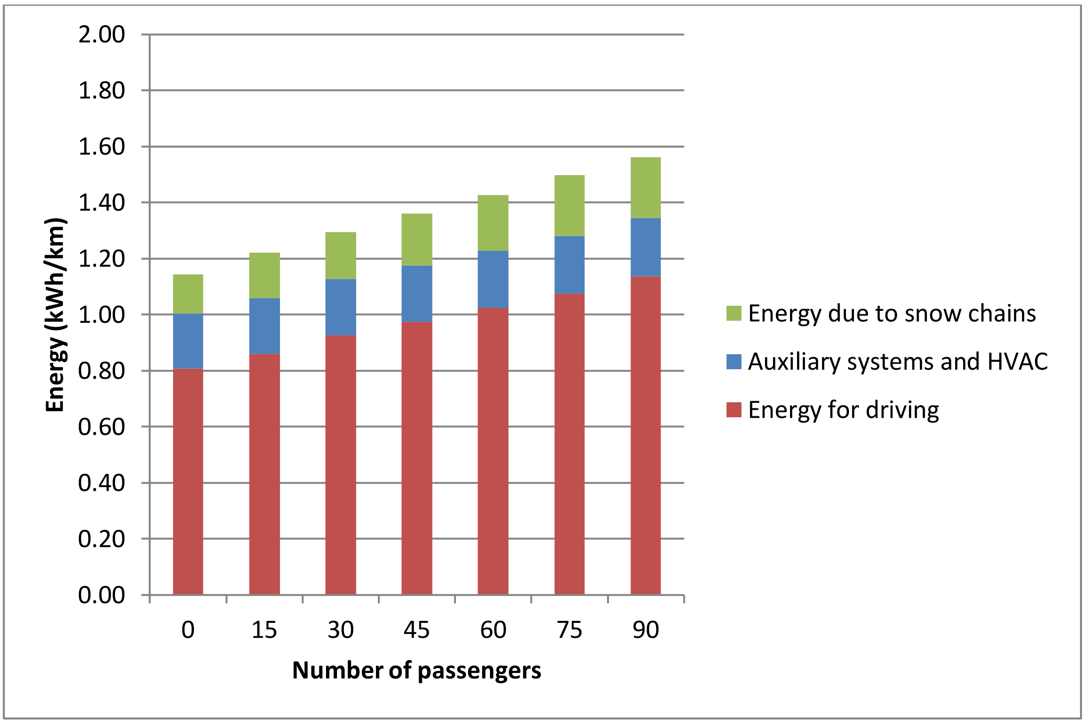


Energy use as opportunity charged bus stops on half of bus stops on line 37.

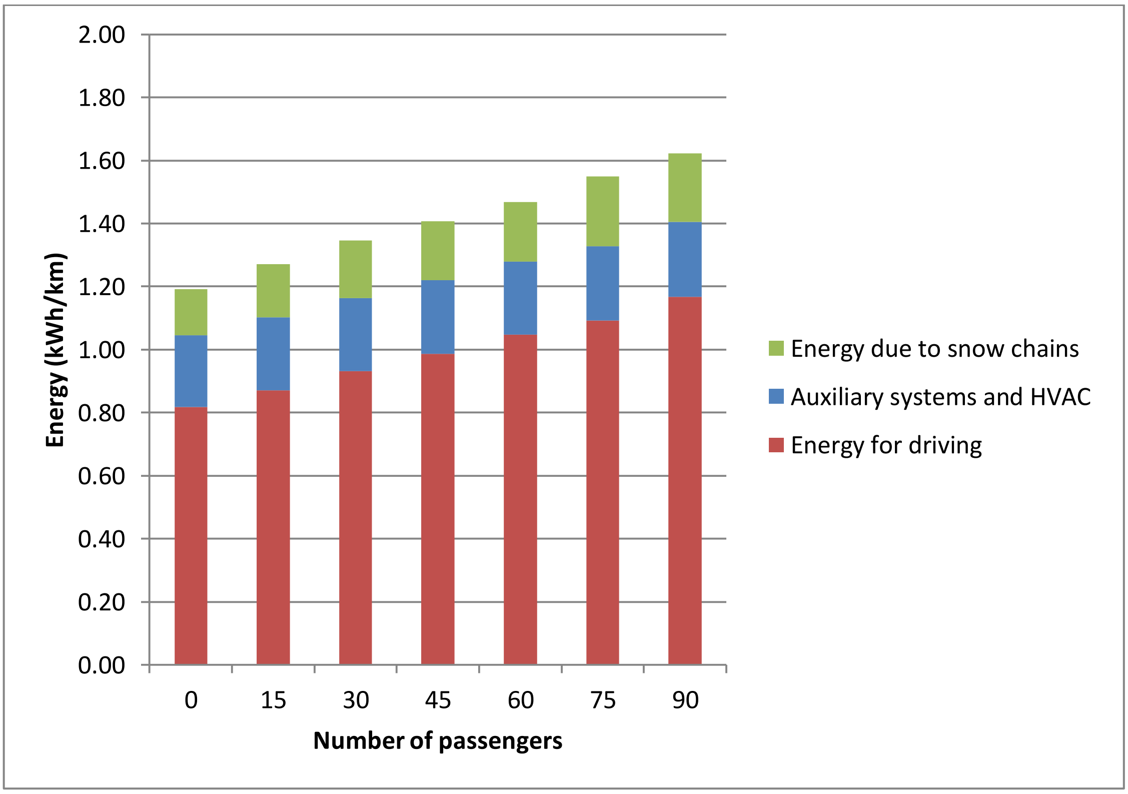


Energy use as opportunity charged bus stops on all bus stops on line 37.

APP. U Energy consumption of opportunity charged bus on line 40



Energy use as opportunity charged bus stops on half of bus stops on line 40.



Energy use as opportunity charged bus stops on all bus stops on line 40.

APP. V Norsk sammendrag

Elbusser i Tromsø

Sammendrag

For testing av elektriske busser i Tromsø, anbefales det å satse på busser som vedlikehold-lades ved ladestasjoner på linjen. Kostnadsmessig er denne løsningen konkurransedyktig med Euro VI dieselbusser. Ladekapasiteten bør være på 400-500 kW. Bussene anbefales testet ut på enten rute 26-37-40 eller rute 32-33-34.

Bakgrunn

Troms fylkeskommune vurderer å erstatte hele eller deler av bussflåten i sentrumsområdet av Tromsø med elektriske busser i forbindelse med neste anbudsrunde for bussdriften i fylket. Før en eventuell fullskalaimplementering, ønsker Troms fylkeskommune å utrede i hvilken grad elbusser er egnet for bruk i et område med Tromsøs klima og topografi. Er elbuss- og batteriteknologien moden og robust nok til å kunne innføres i Tromsø, uten for store drift- og vedlikeholdskostnader?

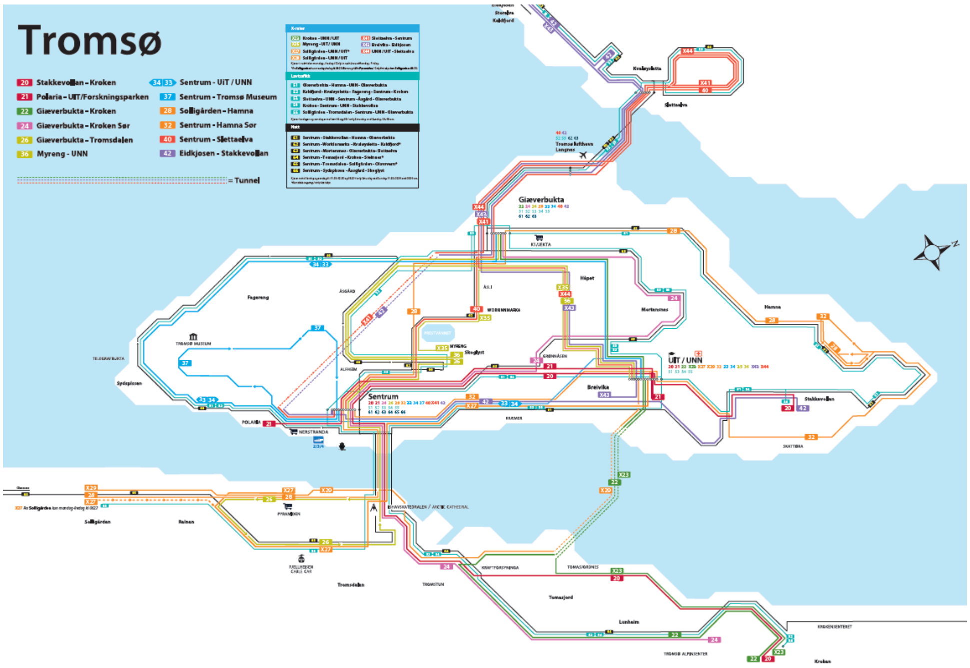
For å unngå eventuelle feilkjøp ønsker fylkeskommunen først å ha en testperiode av et begrenset antall elbusser. Analysene i denne rapporten er utført av det finske forskningsinstituttet, VTT, i samarbeid med TØI. Oppdraget har vært å vurdere grunnlaget for å igangsette en testperiode med elbusser, samt å komme med forslag til egnede bussruter for uttestingen.

Tromsø har et arktisk klima, men med forholdsvis milde vintre. Temperaturer rundt frysepunktet er vanlig, noe som medfører lange perioder med vanskelige kjøreforhold. Forholdsvis varme dager og kalde netter medfører mye is på veiene, og vann som fryser til is på kjøretøyene. Salting av veiene kan medføre rusting. I tillegg er det mange bratte bakker i byen, noe som medfører at enkelte av bussrutene har flere bratte stigninger. Dette kan være en utfordring særlig for vinterdriften av elbussene.

Simuleringer av aktuelle bussruter i Tromsø by

Sammen med fylkeskommunen ble bussrutene 26, 32, 33, 34, 37 og 40 ansett som mest aktuelle for å teste ut elbussene og ladeløsninger for batteriene. De aktuelle bussrutene ble valgt fordi de er ruter som i dag har mye trafikk, og gjenspeiler de utfordringer som vil være aktuelle for elbussene. De ligger også i forbindelse med aktuelle alternative plasseringer av ladestasjoner.

26: Giæverbukta - Tromsdalen
32: Sentrum – Hamna sør
33/34: Sentrum – UiT/ UNN
37: Sentrum – Tromsø museum
40: Sentrum - Sletteelva



Figur S.1: Rutekart for Tromsø

Med utgangspunkt i de 6 valgte bussrutene er det utført simuleringer med to forskjellige ladeløsninger. Rutenes lengde, stigningsgrad, antall stopp (stopper på alle eller halvparten av holdeplassene), passasjertall (full eller halvfull) og gjennomsnittshastigheter er brukt i simuleringene.
Følgende to løsninger er testet ut for hver rute:

- Batteriene vedlikehold-lades underveis på linjen (opportunity charging)
- Lading av batterier over natten (depot charging)

Hensikten med simuleringene er å finne ut hvilke ladeløsninger som egner seg best i Tromsø, og i hvilken grad de 6 valgte rutene er egnet for å teste ut Elbusser i virkelig trafikk.

Tabell S.1: Valgte data for elbussene ved de to ladeløsningene som er brukt i simuleringene.

Karakteristikk	Vedlikeholds-lading	Nattlading
Batterikapasitet (kWt)	80	250
Vekt av batterier (kg)	1 600	5 000
Ladekapasitet (kW)	300	300
Kjøretøyets vekt (kg)	11 600	15 000
Vekt av passasjerer (kg)	0 – 6 120	0 – 6 120
Motorstyrke (kW)	170	190
Batteri - energieffektivitet	0,97	0,97

Energibruk

Om vi for elbussene i Tromsø velger en *batteriløsning der batteriene i sin helhet lades over natten*, viser simuleringene en total kjørelengde som vist i Tabell S.2. Rute 37 (tur-retur) kan i fint vær kjøres 31 ganger mellom hver lading, men ved ekstremt dårlige føreforhold kan dette reduseres til 22 rundturer. For rute 26, 32, 33, 34 og 40, vil det være mulig å kjøre 8-10 rundturer ved normale sommerforhold, i ekstreme forhold der bussene også er avhengig av kjetting vil bussene bare kunne kjøre 6-7 rundturer. Rute 34 er ikke vist i Tabell S.2, men er tilnærmet lik som for rute 33 I de ulike simuleringene har energibruken ligget på i størrelsesordenen 20-42 kWt per rundtur for rute 26, 32, 32, 34 og 40, og på 7-11 kWt per rundtur for rute 37.

Tabell S.2: Potensiell total kjørelengde (km) for busser med «over-natten» lading, samt totalt antall rundturer mulig pr lading (i parentes).

Rute (tur-retur)	Fint vær, km	Med kjetting, km	Ekstreme forhold, km
Rute 26 (ca 23 km)	192 (8)	162 (7)	136 (6)
Rute 32 (ca 21 km)	172 (8)	-	142 (7)
Rute 33 (ca 19 km)	190 (10)	-	135 (7)
Rute 37 (ca 6 km)	183 (31)	155 (26)	129 (22)
Rute 40 (ca 22 km)	179 (8)	154 (7)	136 (6)

Om vi velger en løsning der batteriene i bussene *lades underveis* (noe som i praksis vi si at bussene lades ved start-/endeholdeplassen) vil dette gi et energibruk som vist i tabell S.3. Som i tabell 2 er simuleringene utført for forholdene: full/halvfull buss, stopper på alle/halvparten av holdeplassene, fint sommervær/vintervær med behov for kjetting. Om bussene har batterier på 80 kW, betyr dette at bussene ikke er nødt til å lades etter hver rundtur.

Tabell S.3: Energibruk (kWt) per rundtur (tur og retur) for busser med lading underveis

Rute (tur-retur)	Fint vær (kWt)	Med kjetting (kWt)
Rute 26 (ca 23 km)	22-31	25-36
Rute 32 (ca 21)	17-25	20-29
Rute 33/34)	17-24	19-28
Rute 37 (ca 6 km)	6-8	7-10
Rute 40 (ca 22 km)	22-30	25-35

Tabell S.4 gir et anslag på tiden det vil ta å lade en buss med lading ved endeholdeplassen. Ladekapasiteten er i beregningene satt til 300 kW. Det er benyttet dagens rute- og avgangstider for de aktuelle rutene, samt at det er antatt at samme buss benyttes til samme rute hele dagen. Laderen er i simuleringene plassert på endeholdeplassene for de ulike rutene.
Gitt at bussene på rute 26 bruker 25 kWt på sin tur- og returreise (se Tabell S.3), vil dette kreve en *ladetid på rundt 5 minutter* på endeholdeplassene for å ha nok batterikapasitet for en runde. For rute 40, der det er forholdsvis kort tid mellom slutt på en rundtur og starten på en ny, kan det oppstå forsinkelser, særlig på vinterstid da ruten kanskje blir noe forsinket på grunn av føreforholdene. Dette er gitt at samme buss brukes til å kjøre påfølgende rundtur.

Tabell S.4: Anslag på tidsbruk på lading, for underveis lading på endeholdeplassen.

Rute (tur-retur)	Ladetid	Betraktninger
Rute 26	Ca 5 min.	I morgenrushet er tiden mellom avslutning og start på en ny runde kortere enn 5 minutter. Dette kan kompensere for senere på dagen, da det er lengre tid mellom avgangene. Men gitt dårlig vær, og at bussen forsinkes med mer enn 3 min pga føreforholdene kan det bli noen forsinkelser.
Rute 32	Ca 4 min.	Tilgjengelig tid for lading varierer over dagen, gitt dagens rutetabeller (og bruk av samme buss) vil det kunne oppstå forsinkelser på denne ruten
Rute 33/34	Ca 4 min.	I følge rutetabellen vil man ikke ha tid til å lade mellom hver rute, dette kan forårsake forsinkelser når føreforholdene er dårlige vinterstid. Om man i stedet hadde en lader på 400 kW, ville ladetiden reduseres til ca 3 min.
Rute 37	Ca 1 min 20 sek	Siden det ikke vil være nødvendig å lade mellom hver runde bør dette fint la seg gjøre selv om enkelte avganger i rushet har kortere stopptid og en tar hensyn til dårlig vær.
Rute 40	Ca 5 min. Ca 6-7 min. i kulde	I følge dagens rutetabeller (med forholdsvis kort tid mellom slutt og start på en runde hele dagen) kan nødvendig lading (underveis-lading) bli vanskelig på denne ruten uten forsinkelser. Dette gjelder selv om en har ladere på 400 kW.

Potensielt reduserte avgassutslipp og redusert klimapåvirkning – El vs diesel

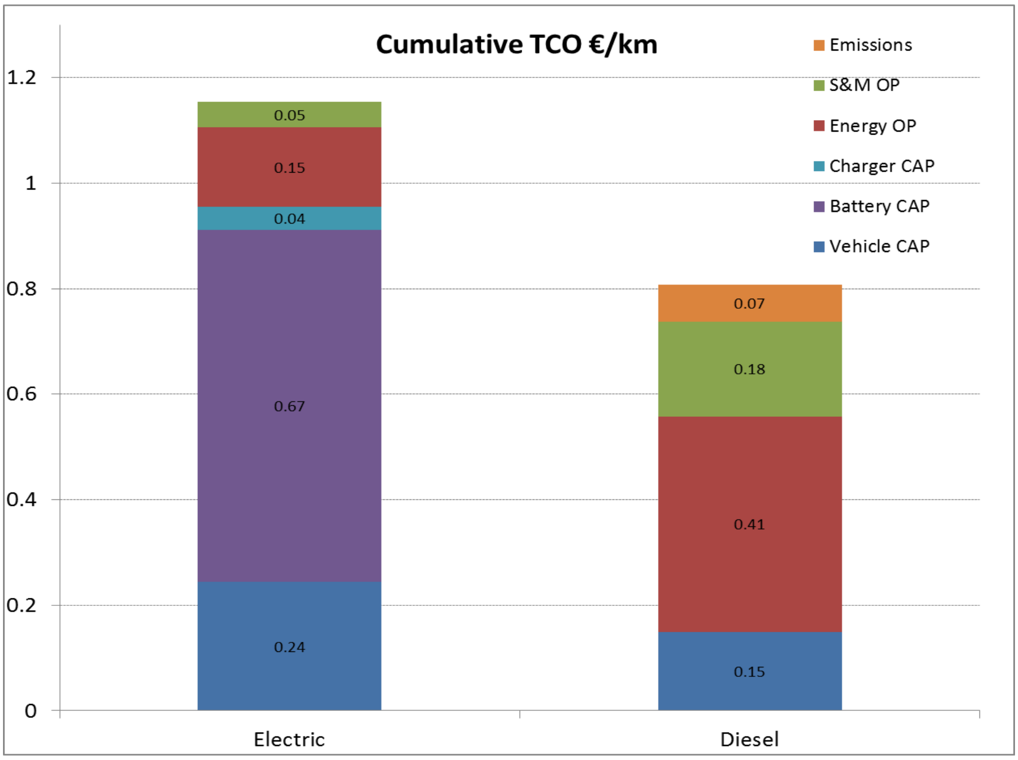
Potensialet for redusert utslipp ved overgang til elbusser er beregnet. Det er beregnet:

- Klimapåvirkning (CO_2-ekvivalenter, CO_{2ekv})
- Lokal forurensende avgasser (nitrogenoksider, NO_x og avgasspartikler, PM)

For å estimere klimapåvirkningen, tar vi hensyn til hele livsløpsutslippet av drivstoffet, inkludert produksjon, distribusjon og forbrenning. Elektrisiteten til elbussene i Tromsø antas å være strøm fra norsk vannkraft med null klimapåvirkning.
Dersom Tromsø erstatter 40 dieselbusser med Euro VI-motorer med elbusser, kan dette i løpet av en 10-års periode føre til en *reduksjon på 33 295 tonn CO_{2ekv}*. Når det gjelder lokalt forurensende stoffer, er det potensial for å *redusere utslippet med 6 tonn NO_x og 0,3 tonn PM* i løpet av en 10-års periode.

Økonomiske vurderinger

Figurene S.2 og S.3 viser de totale kostnadene ved å eie- og drifte (TCO – Total Cost of Ownership) elektriske busser med henholdsvis lading-over-natten eller lading-underveis for bussrutene 26, 37 og 40. Kostnadene (TCO) for elektriske busser med de to typene av lading sammenlignes med de tilsvarende kostnadene for dieselbusser. De elektriske bussene med vedlikeholdslading kommer klart best ut. TCO for elbusser med vedlikeholdslading er til og med beregnet å bli lavere enn for konvensjonelle dieselbusser.

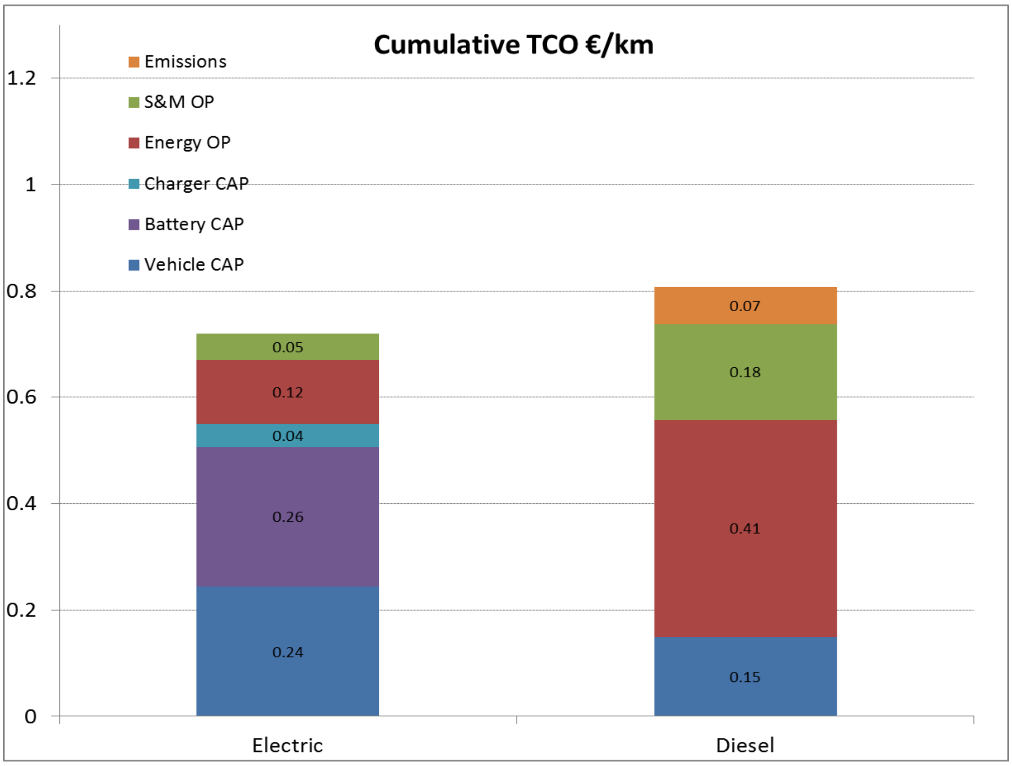


Figur S.2: Driftskostnadene (Euro/km) for en gjennomsnittlig Euro VI dieselbuss vs en elektrisk buss med over-natten-lading, snitt for bussrutene 26, 37 og 40.

Forslag til test-ruter og batteriløsninger

Dagens bussruter i Tromsø har en lengde og topografi som kan være utfordrende, samt at føreforholdene vinterstid ofte krever bruk av kjetting. Dette kan være krevende for alle busstyper, også de elektriske.

For Tromsø anbefaler vi å teste ut elektriske busser, og det *anbefales å satse på busser basert på vedlikeholdslading* (opportunity charging) fremfor busser der batteriet skal lades over natten (depot charging). Dette skyldes at disse er mer konkurransedyktige med dieselbussen med hensyn til de totale kostnadene (se Figur S.3).



Figur S.3: Driftskostnadene (Euro/km) for en gjennomsnittlig Euro VI dieselbuss vs en elektrisk buss med vedlikeholdslading, snitt for bussrutene 26, 37 og 40.

I følge simuleringene skal elbusser med vedlikeholdslading kunne klare å betjene rute 37 uten problemer. Ladingen er da plassert i Fr. Langes gate (sentrum).
Det er tre måter å forsikre seg om høyere grad av sikker drift for de foreslåtte bussene med hensyn på elektrisk kapasitet og lading i forhold til:

- øke bussenes batterikapasitet
- øke antallet ladepunkter
- etablere en fleksibel rotasjon av bussene.

Vi anbefaler å først forsøke en fleksibel rotasjon av kjøretøyene, men dette må avklares i tett kontakt med bussoperatørene.
Våre forslag for uttesting:

- Utfør testingen på enten rute 26-37 og 40, eller på rute 32-33-34. Rutene 32-33-34 er mer krevende, og vil sannsynligvis i større grad kreve justeringer av dagens rutetabell.
- Ha en eller helst to ladere med 400-500 kW. For rute 26-37-40 bør denne plasseres i Fr. Langesgate og eventuelt også i Giæverbukta, mens for rutene 32-33-34 bør den plasseres ved sykehuset eller Universitetet.
- Utvikle en rotasjon (mellom rutene) som gir bedre marginer for lading, men som samtidig gir utfordringer nok for å teste bussene i utfordrende situasjoner.