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School of Energy & Power Engineering
Направление подготовки – Электроэнергетика / Direction – Electric Power and electrotechnics
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Студент / Student

Группа /Group (Class)	ФИО / Surname Name	Подпись / Signature	Дата / Date
5АМ7Ч	Андрлэ Карэл / Andrle Karel		

Руководитель / Supervisor

Должность / Position	ФИО / Surname Name	Ученая степень, звание / Degree, title	Подпись / Signature	Дата / Date
Доцент	Плотников Игорь Александрович / Plotnikov Igor	к.т.н. /Ph.D.		

КОНСУЛЬТАНТЫ / CONSULTANTS:

По разделу «Финансовый менеджмент, ресурсоэффективность и ресурсосбережение» / Chapter «Financial management, resource efficiency and resource saving»

Должность / Position	ФИО / Surname Name	Ученая степень, звание / Degree, title	Подпись / Signature	Дата / Date
Доцент	Плотников Игорь Александрович / Plotnikov Igor	к.т.н./ /Ph.D		

По разделу «Социальная ответственность» / Chapter « Social Responsibility »

Должность / Position	ФИО / Surname Name	Ученая степень, звание / Degree, title	Подпись / Signature	Дата / Date
Доцент	Плотников Игорь Александрович / Plotnikov Igor	к.т.н./ /Ph.D		

ДОПУСТИТЬ К ЗАЩИТЕ / ADMIT FOR THE DEFENSE:

Зав. кафедрой / Head of the Department	ФИО / Surname Name	Ученая степень, звание / Degree, title	Подпись / Signature	Дата / Date
Доцент	Рахматуллин Ильяс Аминович	к.т.н./ /Ph.D		

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Группа / Group (Class)	**ФИО. / Surname Name**
5АМ7Ч	Андрлэ Карэл / Andrle Karel

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Срок сдачи студентом выполненной работы / Deadline student work done:	31.07.2019

ТЕХНИЧЕСКОЕ ЗАДАНИЕ / PRELIMINARY SPECIFICATIONS:

Исходные данные к работе / Initial data	Introduce current state of the tram industry with focus on types of propulsion. Demonstrate it on the leading market manufacturers. Investigate energy storage technologies. Choose two tram tracks (one in Prague, second in Tomsk) according to their altitude profiles. Use a physical model to describe tram ride on chosen tracks. Calculate energy consumption data of a riding tram. Use this data to design technically corresponding energy storage system, which would enable catenary-free operation. Calculate costs of the projects. Make an analysis based on economic indicators. Present and discuss sensitivity analysis. Compare both projects. Decide, whether the projects are economically viable and under which conditions.
Перечень подлежащих исследованию, проектированию и разработке вопросов / List to be investigated, design and development issues	– Currently used tram propulsions – Energy storage technologies – Suitable tram tracks for further investigation – Model describing tram ride – Energy demands of a tram – Costs of presented projects – Sensitivity analysis of the main parameters – Recycling procedures of batteries

Код	Результат обучения*	Требования ФГОС ВО, СУОС, критериев АИОР, и/или заинтересованных сторон
Общие по направлению подготовки		
Р1	*Совершенствовать* и развивать свой *интеллектуальный* и *общекультурный уровень*, добиваться *нравственного и физического совершенствования* своей личности, обучению новым методам исследования, к изменению научного и научно-производственного профиля своей профессиональной деятельности.	Требования ФГОС ВО, СУОС ТПУ (УК-1,6; ОПК-1, 2), Критерий 5 АИОР (п. 2.1, 2.5), согласованный с требованиями международных стандартов *EUR-ACE* и *FEANI,* требование профессионального стандарта 01.004 «Педагог профессионального обучения, профессионального образования и дополнительного профессионального образования».
Р2	*Свободно пользоваться русским и иностранным языками* как средством делового общения, способностью к активной социальной мобильности.	Требования ФГОС ВО, СУОС ТПУ (УК-4,5; ОПК-3), Критерий 5 АИОР (п. 2.2), согласованный с требованиями международных стандартов *EUR-ACE* и *FEANI.*
Р3	*Использовать* на практике *навыки и умения* в *организации* научно-исследовательских и производственных работ, в *управлении* коллективом, использовать знания правовых и этических норм при оценке последствий своей профессиональной деятельности.	Требования ФГОС ВО, СУОС ТПУ (УК-2,3; ОПК-1; ПК-1, 2, 3), Критерий 5 АИОР (п. 2.6), согласованный с требованиями международных стандартов *EUR-ACE* и *FEANI,* требование профессионального стандарта 20.012 (B/01.6-B/06.6, Выполнение работ всех видов сложности по организационному и техническому обеспечению полного цикла или отдельных стадий эксплуатации электротехнического оборудования ТЭС).
Р4	*Иметь* представление о методологических основах *научного познания и творчества*, роли научной информации в развитии отрасли, навыки проведения работ с привлечением *современных информационных технологий*, синтезировать и критически резюмировать информацию.	Требования ФГОС ВО, СУОС ТПУ (УК-1,6; ОПК-1, 4), Критерий 5 АИОР (п. 1.6, 2.3), согласованный с требованиями международных стандартов *EUR-ACE* и *FEANI,* требование профессионального стандарта 40.011 (A/01.5-A/03.5, Проведение научно-исследовательских и опытно-конструкторских разработок по отдельным разделам темы)
Р5	*Применять углубленные естественнонаучные, математические, социально-экономические и профессиональные знания* в междисциплинарном контексте в инновационной инженерной деятельности в области электроэнергетики и электротехники.	Требования ФГОС ВО (УК-5, ОПК-4; ПК- 4-6), Критерий 5 АИОР (п.1.1), согласованный с требованиями международных стандартов *EUR-ACE* и *FEANI,*

По профилям подготовки		
Р6	Ставить и *решать инновационные задачи* инженерного анализа в области электроэнергетики и электротехники с использованием глубоких фундаментальных и специальных знаний, аналитических методов и сложных моделей в условиях неопределенности.	Требования ФГОС ВО (ПК-1, 7,8), Критерий 5 АИОР, согласованный с требованиями международных стандартов *EUR-ACE* и *FEANI,* требование профессионального стандарта 40.011 (D/01.7,Формирование новых направлений научных исследований и опытно-конструкторских разработок)
Р7	Выполнять *инженерные проекты* с применением оригинальных методов проектирования для достижения новых результатов, обеспечивающих конкурентные преимущества электроэнергетического и электротехнического производства в условиях жестких экономических и экологических ограничений.	Требования ФГОС ВО (ПК-2, 9, 10, 11), Критерий 5 АИОР, согласованный с требованиями международных стандартов *EUR-ACE* и *FEANI,*
Р8	Проводить инновационные *инженерные исследования* в области электроэнергетики и электротехники, включая критический анализ данных из мировых информационных ресурсов.	Требования ФГОС (ПК-3, 13, 14, 15, 24-26), Критерий 5 АИОР, согласованный с требованиями международных стандартов *EUR-ACE* и *FEANI,* требование профессионального стандарта 40.011 (В/01.6, В/02.6, Проведение научно-исследовательских и опытно-конструкторских разработок при исследовании самостоятельных тем)
Р9	Проводить *технико-экономическое обоснование* проектных решений; выполнять организационно-плановые расчеты по созданию или реорганизации производственных участков, планировать работу персонала и фондов оплаты труда; определять и обеспечивать эффективные режимы технологического процесса.	Требования ФГОС (ПК-11, 12, 13, 16-21, 24, 26), Критерий 5 АИОР (п. 1.5, 2.1), согласованный с требованиями международных стандартов *EUR-ACE* и *FEANI*
Р10	Проводить *монтажные, регулировочные, испытательные*, наладочные работы электроэнергетического и электротехнического оборудования.	Требования ФГОС (ПК-22, 23, 25, 26), Критерий 5 АИОР (п. 1.5), согласованный с требованиями международных стандартов *EUR-ACE* и *FEANI.*

Р11	*Осваивать новое* электроэнергетическое и электротехническое *оборудование;* проверять техническое состояние и остаточный ресурс оборудования и организовывать профилактический осмотр и текущий ремонт.	Требования ФГОС (ПК-27, 28), Критерий 5 АИОР (п. 1.4), согласованный с требованиями международных стандартов *EUR-ACE* и *FEANI,* требование профессионального стандарта 20.016 «Работник по эксплуатации электротехнического оборудования тепловой электростанции (С/01.5, выполнение работ всех видов сложности по эксплуатации электротехнического оборудования ТЭС)
Р12	Разрабатывать рабочую проектную и научно-техническую документацию в соответствии со стандартами, техническими условиями и другими нормативными документами; организовывать метрологическое обеспечение электроэнергетического и электротехнического оборудования; составлять оперативную документацию, предусмотренную правилами технической эксплуатации оборудования и организации работы.	Требования ФГОС (ПК-29, 30), Критерий 5 АИОР (п. 1.3, 2.1), согласованный с требованиями международных стандартов *EUR-ACE* и *FEANI*

DECLARATION

I hereby declare that the presented thesis is my own work and that I have cited all sources of information in accordance with the Guideline for adhering to ethical principles when elaborating an academic final thesis. I acknowledge that my thesis is subject to the rights and obligations stipulated by the Act No. 121/2000 Coll., the Copyright Act, as amended. In accordance with Article 46(6) of the Act, I hereby grant a nonexclusive authorization (license) to utilize this thesis, including any and all computer programs incorporated therein or attached thereto and all corresponding documentation (hereinafter collectively referred to as the "Work"), to any and all persons that wish to utilize the Work. Such persons are entitled to use the Work for non-profit purposes only, in any way that does not detract from its value. This authorization is not limited in terms of time, location and quantity.

In Mnichovice, 11th July 2019 ……………………….

Bc. et. Bc. Karel Andrle

Tomsk Polytechnic University

Institute of Power Engineering

Czech Technical University in Prague

Faculty of Electrical Engineering

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LIST OF ABBREVIATIONS

LRV	Light Rail Vehicle
IGBT	Insulated Gate Bipolar Transistor
HES	Hybrid Energy Storage
MES	Mobile Energy Storage
DLC	Double-Layer Capacitor
AM	Asynchronous Motor
TCMS	Train Control and Monitoring System
FES	Flywheel Energy Storage
RPM	Rotation Per Minute
LSD	Low Self-Discharge
Li-NCA	Lithium-Nickel Cobalt Aluminium
Li-NMC	Lithium-Nickel Manganese Cobalt
EV	Electric Vehicle
HEV	Hybrid Electric Vehicle
DOD	Depth Of Discharge
GPS	Global Positioning System
NPV	Net Present Value
IRR	Internal Rate of Return
DCF	Discounted Cash Flow

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1 INTRODUCTION

Nowadays, city transport is experiencing its renaissance. In the time of rapid technological evolution, huge global climate change and the longest global economic growth in the history, bigger and bigger attention is attracted by improvement of natural environment, which affects every day's life of millions of people. These efforts are visible in real life as, for example, restrictions on entry for cars to the city centres of many capitals and other huge cities and support for city transport instead. This can be a subway, overhead railway, common train or suburban train, car sharing, but also trams, to which connection "renaissance" fits the best.

Nevertheless, all of these have the same denominator – zero or low production of greenhouse gases and generally environmental friendliness. This is closely connected to the mean of propulsion. Combustion engines are slowly but constantly becoming a subject of history and they are being replaced by electric engines, which can provide several important advantages like lower carbon trace, lower energy consumption or lower acoustic smog.

This progress is happening right now, but it is slow and requires vast, complicated and time-demanding planning, because it is very closely connected with urban, architecture and construction concept of the whole city, which is very difficult to change. Talking about trams, natural evolution leads towards catenary-free operation, but still using electrical engines, and this is the keystone of this work.

The idea is to, at first, present historical and contemporary situation in the tram and city transport industry and to track indicators of its future development. Next, two tram tracks (one in Prague, the other one in Tomsk) will be chosen as a laboratory example. Further a simulation of a ride of a tram on these tracks will be a subject of physical model (script) in MATLAB programme. From this, values of energy necessary for tram ride should be obtained. Further, investment and economic calculations considering building catenary-free track will be presented together with several possibilities of energy storage for energy saved from braking during ride on these chosen tracks. In the end, based on cost analysis and related indexes as NPV and IRR, a decision of economical profitability will be given. Also, a sensitivity analysis focusing on the most important input parameters will be presented. This should help to understand and identify the most (economically and technically) significant indexes and determine, which should be investigated very carefully while deciding about realisation of the project.

In the end of the work, in Social Responsibility part, a look on connected environmental and ecological site of such a project will be taken. This means, that a brief description of this problematic will be given, because since projects like this aim mainly at ecological situation improvement, a recycling procedure of device's components should not be neglected.

THEORETICAL PART

2 HISTORICAL BACKGROUND

History of tramcars can be traced up to the very beginning of 19th century, into the times of the first industrial revolution. Evolution of tramcars could be logically divided by used motive power.

Naturally, the very first tramcars were drawn by horses and this mean of motive power was used until thirties of the 20th century. Nevertheless, with technological progress, supported by the industrial revolution, a significant evolution has started.

First big step was made by switching from live horse power to the mechanical one – steam power. This happened in 1883 in Munich, Germany. But steam power was very limited by the size of the engine, therefore such tramcars were usually underpowered. Steam tramcars lasted until the turn of the century, when they were replaced by electric trams.

In the meantime, there were some attempts to find another motive power, but they were predetermined to remain in the minority. From those, gas or cable-hauled can be named. Gas tramcars operated mainly in the late 19th and early 20th century for example in Melbourne, Australia, Berlin and Dresden, Germany, in the UK, Estonia or Poland. Cable-hauled trams recorded a slightly bigger success, as some of them are operating until nowadays – for example in San Francisco, USA or in North Wales, UK.

The biggest expansion of tramcars as a mean of urban transport started in Lichterfelde, near Berlin, Germany, in 1881, when Werner von Siemens presented the world’s first electric tram line. This was first commercially successful electric tram. Those trams originally drew current from the rails. Overhead line was installed two years later. Then, in 1887, Siemens designed an improved version of overhead line – so called “bow collector”. It was in operation in Thorold, Ontario and was considered quite successful at the time. It operated until 1950s. Nevertheless, worldwide success of electric trams would not be possible without a contribution of Frank J. Sprague, who built a tram railway in Richmond, Virginia, USA, in 1888 and significantly improved the technology of collecting electricity from overhead lines.

Tracing the technological evolution of tramcar’s electric energy supply since the very beginning of the tramcar history, we can name three ways how it was done. First, it was a system which draws current from the rails, but it suffered from many disadvantages, mainly safety ones. Second, an overhead current collection appeared. As we can see in many cities nowadays, this became the most successful solution. Third, and the most important for this work, is catenary-free current collection. In 2000, two world leading companies in tramcar manufacturing industry introduced their catenary-free designs – it was Canadian Bombardier and French Alstom. Technologies based on this idea are expected to make a small revolution in tramcar industry. That is why we will focus on them in this work further.

3 CURRENT TRAMCARS

To describe and understand current situation in a tramcar market, technology and its trends, leader companies in the industry will be presented in the following part of the work, with a brief list and comparison of their most successful tramcar models and technological solution of its propulsion.

3.1 BOMBARDIER

3.1.1 Vehicles [1]

Bombardier is a Canadian company, which has two divisions – aerospace and transportation. The transportation division, which manufactures tramcars, is based in Berlin, Germany and as a market leader registers the highest number of firm orders – 962 as at February 2017. Bombardier offers several types of tramcars from its *FLEXITY* family.

FLEXITY product line consists of four main vehicle types: *FLEXITY Trams, FLEXITY 2 Trams, FLEXITY Freedom* and *FLEXITY Light Rail Vehicles (LRV).* As the company states itself, this product line is a benchmark in the industry – as of 2015, more than 3500 *Flexity* vehicles were in operation around the globe.

Bombardier's production is based on adaptable modular platforms, which provides wide opportunities to customize the product for specific demands of every city. This approach also enhances innovation and connectivity within the city and contributes to lowering lifecycle costs. Moreover, in those tramcars so called Obstacle Detection Assistance System is installed, for which Bombardier was awarded as Innovation Leader in Rail Transport. Within this product family, the company offers 100% low-floor trams, 70% low-floor trams and LRVs, all of them both in bi- and uni-directional systems.

In the *FLEXITY* family, there are six standard models – *FLEXITY 2, Classic, Outlook, Swift, Link* and *Freedom*. *Classic* and *Outlook* models are considered as classical tramcars and *Swift* and *Link* represent the LRV part of the *FLEXITY* family. Thanks to their modular design, they are customizable in many areas, including a variety of track gauges (usually 1000 or 1435mm), voltages (usually 600 or 750V DC overhead lines), low-floor construction (from 50% to 100%), maximum power (usually 4 x 120kW – 160 hp), and of course dimensions.

Propulsion [2]

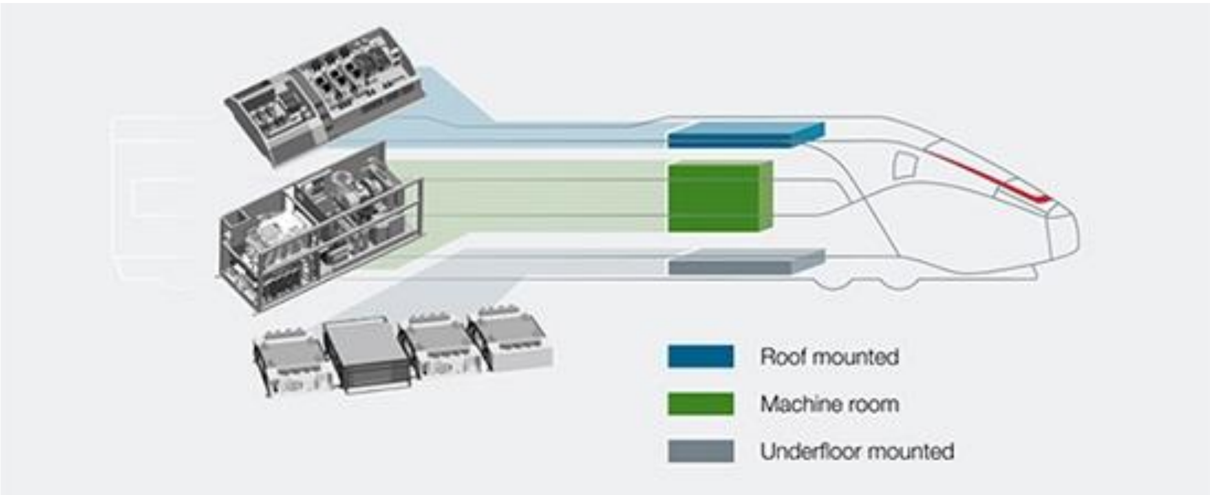
Bombardier's core propulsion product is called *MITRAC* (Modular Integrated TRACtion system). It consists of three major systems:

- Propulsion Converters – convert power from an energy source or engine
- Traction Drives – enable traction effort to the wheel (motors and gears)
- Electronics – provides communication, controls the propulsion etc.

3.1.2 Propulsion

Propulsion Converters are to the train what the heart is to the body. This device connects the energy source with train's drive and control system and converts the energy into the form that is used to move the train. European *MITRAC* version fulfils several functions, including power conversion on AC as well as DC supplies with full recuperation during braking. This system provides very efficient and stable performance even in locations with different power systems. There is also a dual power system *MITRAC* Hybrid converter, which can provide traction power from both catenary-free and diesel engines (usually locomotives). Converters can be mounted in three ways – underframe (metros, commuter, regional and intercity trains, high-floor trams), roof (low-floor vehicles) and machine room (when necessary to incorporate the converter inside the car body – double-deck trains, locomotives). *MITRAC* converters are available in three versions according to their power range – low power (*MITRAC 500*), medium power (*MITRAC 1000*) and high power (*MITRAC 3000*). For the tramcar purposes, low power version is used. In the Picture 1, types of mounting solution of MITRAC converters are presented.

Picture 1: Mounting of MITRAC Converters. (Source: bombardier.com)



In *MITRAC* technology, one of the most advanced innovation is *MITRAC* Energy Saver. It uses double-layer ultra-capacitors together with a set of intelligent technologies. While braking, the energy is stored in the system and then, it is used for acceleration or operation. Energy savings are about 30%, with future company's goal to reach 35%. This contributes to significant reduction of both costs and emissions. In the Picture 2, detail of inside of MITRAC energy saver is shown.

Picture 2: MITRAC Energy Saver. (Source: bombardier.com)

As this work deals with tramcars, a closer look to the corresponding version of *MITRAC* 500 Propulsion System will be taken on the following lines.[3]

Propulsion converter *MITRAC* 500 is based on industry standard IGBT (Insulated Gate Bipolar Transistor) modules. In the market, it has the best power-to-weight ratio with environment friendly cooling system. More than 4200 units are operating in the world to date.

Bombardier keeps the same construction idea as at car bodies. Propulsion converters are based on a unique concept that enables extensive standardization. It consists of one modular and scalable core design that can be adapted to a wide variety of applications and power ranges. The converters are based on the *MITRAC* CM-S converter module, which is forced air-cooled and contains up to 12 IGBTs and provides outputs for two to four AC motors, two brake resistors and the energy storage system.

Parameters are 2 x 360 kW for one motor each or 720 kW for two motors in parallel, in combination with the basic rheostatic brake and the *MITRAC* Energy Saver system. It supports the 600 / 750 V DC standard supply systems and is also available with a second system for vehicles that run under mainline systems (15 kV AC 16 2/3 Hz).

Stand-alone auxiliary converters (*MITRAC* AU 500 family, similar shown in Picture 3) are available with output power of up to 75 kVA and up to 12 kW DC output for the 24 V DC vehicle control system as well as for the vehicle battery charging. Different power ratings allow the vehicle builder to optimize the auxiliary supply to the customers' needs. For further detailed information and source of the data see documents [2], [4], [5], [6], [7].

Picture 3: MITRAC TC 530 for underfloor mounting. (Source: bombardier.com)

3.2 SIEMENS

3.2.1 Vehicles

As mentioned in the Historical Background, it was Mr Werner von Siemens who built the first electric tram in 1881. Company is based in Berlin and Munich, Germany, and holds its position of one of the biggest players in the industry – Siemens registered 557 firm orders as at February 2017.

Siemens' tramcar flagship is called *Avenio*. Similarly, to Bombardier's *FLEXITY*, it is a 100% low-floor tram based on a modular construction. Nevertheless, there are two main construction types – single-articulated (*Avenio*) and multi-articulated (*Avenio M*). This unit is usually based on 1435mm track gauge and 750 V DC line voltage. [8]

Tram is constructed with noiseless electric brakes, it is 95% recyclable, electromagnetic radiation is minimized, and it provides 30% energy savings thanks to light construction, energy management, traction converter and optional on-board energy-storage unit. It can also operate in a catenary-free mode using modular on-board energy storage consisting of battery and ultra-caps.

To compare precise technical data, properties of four-unit Avenio for The Hague can be taken. Traction power is 6 x 120 kW, track gauge 1435mm and traction supply voltage is 600 V. [9]

3.2.2 Propulsion

Electrical heart of Siemens's tram is placed on roof of the car body. Again, similarly to Bombardier, IGBT power semiconductor technology is used as traction converter. This solution permits an enormous cost-saving potential: These flexible converters use the energy that is regenerated when braking to supply the auxiliaries. Traction system consists of three pulse inverters, six low-maintenance three-phase induction motors, and three traction control units (Sibas® 32). The vehicle control uses a bus transmission system in conjunction with a hardwired control system.[10] [11]. In the Picture 4, traction unit used on Avenio trams is visible.

Picture 4: Avenio traction unit. (Source: siemens.com)

This technology combines two devices, which store electric energy – a capacitor and a traction battery. Such batteries tolerate frequent charging and discharging as well as deep discharge, but they cannot provide big current instantly. On the other hand, capacitor provides energy instantly – for example while a tram is accelerating, and the consumption is highest. Also, charging differs a lot. Charging traction battery takes longer time, but it provides energy for significantly longer period. Charging capacitor is far faster. To charge both devices not only braking energy recuperation is used, but it can be charged also from an overhead line or from special charging stations placed at tram stops. This device is roof-mounted (which allows using it also with older tram body cars) and it is electrically connected to the feed-in point of the vehicle by means of a DC/DC-chopper. Specific technical data for Siemen's system are presented in the following Picture 5.

Picture 5: Technical data for Sitrac HES system's capacitors and batteries. (Source: siemens.com)

Technical data		
Energy storage: Double-layer capacitors		
Usable energy content	[kWh]	0.85
Maximum power	[kW]	2 x 144
Range of operating voltage	[V]	190 - 480
Cooling		forced air cooling
Dimensions (width x depth x height)	[mm³]	2,000 x 1,520 x 630
Weight	[kg]	820
Energy storage: Traction battery		
Usable energy content	[kWh]	18
Maximum power	[kW]	105
Nominal voltage	[V]	528
Cooling		water cooling
Dimensions (width x depth x height)	[mm³]	1,670 x 1,025 x 517
Weight	[kg]	826

Siemens' described system is called Sitras HES (Hybrid Energy Storage) and it consists of Sitras MES (Mobile Energy Storage), which is a double-layer capacitor (DLC) and of a nickel-metal hydride battery.

Double-layer capacitors feature a high level of efficiency, an extremely dynamic charge-transfer capacity, very high cycle strength and a long service life. They are also resistant to exhaustive discharge and maintenance-free.

The used nickel-metal hydride cells (Ni-MH) feature following benefits: constant voltage for the used operating range, high power availability for a short-time, high energy content availability, using the high energy content for operation without overhead contact line, simple integration into rail vehicles (electrical and mechanical). Look

Picture 6: Traction battery and double-layer capacitor. (Source: siemens.com)

This construction allows to combine advantages of both capacitor and batteries, which are in many ways completely opposite. Thanks to recuperated energy saved in the system during braking, tram can operate on up to 2500m long parts of the track, where there is no overhead line. It can be useful notably in historical city centres, where overhead line could disturb historical character of the place, or under bridges, in tunnels or on big crossroads, and they are especially environment-friendly and save energy. Vehicles equipped with energy storage systems consume up to 30 percent less energy per year and produce up to 80 metric tons less CO2 emission than vehicles without energy storage systems.[12][13]

3.3 ŠKODA TRANSPORTATION

3.3.1 Vehicles [14]

Škoda is based in Plzeň, Czech Republic. In 1922 it started manufacturing tram components for other producers. Production of whole tramcars started in 1990s, when a daughter company Škoda Transportation was founded.

Currently, Škoda's flagship model line is called *ForCity* and in this family, there are 4 tramcars – Classic, Smart, Plus and Alfa. Besides, there is an older model called *Elektra*.

ForCity models are all 100% low-floor. They combine pivoting and non-pivoting bogies, when Classic is built just on non-pivoting, Smart on pivoting, Plus on both and Alfa on pivoting ones. As in 2016, there were 389 tramcars from *ForCity* family operating in Czech Republic, Slovakia, Hungary, Latvia, Finland and Turkey

All the *ForCity* family tramcars are manufactured both in uni- and bi-directional construction with track gauge 950 – 1524 mm and trolley voltage 600 - 750 V DC. Maximum output power depends on a model: Classic 480 – 1200 kW, Smart 240 – 1200 kW, Plus 480 – 1200 kW and Alfa 184 kW multiplied by number of driven bogies (368 – 920 kW).

Tramcar *Elektra* is 50% low-floor model with a non-rotatable chassis. As for the model operated in Prague, track gauge is 1435 mm, trolley voltage 600 V DC, output power 540 kW. Currently, this tramcar model is operated not only in the Czech Republic, but also in Wroclaw, Poland; Cagliari, Italy and Portland and Tacoma, USA. Altogether, there were manufactured 221 *Elektra* tramcars (2016). In the Picture 7, there is brand new tram from Skoda, model 15T, on the track in Prague.

Picture 7: ForCity Alfa Prague, model 15T. (Source: skoda.cz)

3.3.2 Propulsion

As in competition, Škoda is using IGBT technology for its VVVF (Variable Voltage Variable Frequency) traction inverters with wide power output range for providing high dynamic performance of the trams. These units can be mounted both on the roof and in the chassis. They are mostly forced air cooled, but liquid cooling is also available alternatively.

Both squirrel cage Asynchronous Motors (AM) and Permanent Magnet Synchronous Motors (PMSM) have been applied in the different types of trams. The AMs are mostly self-ventilated but forced air or liquid cooling is also available depending on the bogie construction. The direct axle drives with PMSM are cooled by liquid.

Škoda also supports catenary-free operation of trams, using onboard traction batteries. Its size is customizable, according to the length of the section without catenary and the frequency of the operation from the battery. This system consists of Traction Motor with Gearbox, Traction Unit, Static Converter, Battery Unit and Train Control and Monitoring System (TCMS).

Traction Motors with Gearbox are a readymade solution adapted for the actual bogie. Traction Unit works on IGBT technology and is of a modular construction. Usually each bogie has its own container with a converter, but also more converters can be installed in one container – depending on the motor type. Static Converters are also based on IGBT technology with high switching frequency. They contain 3 phase converters for the tram devices which consume AC and a charger of the auxiliary battery. Battery Unit has its own independent charger operated from the overhead line. TCMS is a microprocessor-based system, which controls algorithms on vehicle level as well as monitors other subsystems. [15]

Picture 8: Škoda traction equipment. (Source: skoda.cz)

4 ENERGY STORAGE TECHNOLOGIES

There are many electric energy storage technologies, but they vary a lot in many aspects. For use in trams, the most important demands are capacity, availability of the output power and dimensions. In the following part of the work the most convenient and mostly used technologies will be described and compared.

Energy can be stored in various forms – mechanical, electrical, electromagnetic, electrochemical, thermal or chemical. Nevertheless, for use in trams, only some of them can be useful, notably mechanical, electrical, electromagnetic or electrochemical.

4.1 FLYWHEEL [16]

Flywheel energy storage (FES) is a mechanical way to store energy. It consists of a wheel rotating with a very high speed, so the energy is stored in a form of rotational energy. When energy is being stored, the speed of wheel is increasing, when the energy is being extracted, it is slowing down. Rotating wheel is usually placed in a vacuum enclosure to lower friction and reduce energy loss. Bearings of the wheel can be mechanical or magnetic, when second solution also contributes to lowering friction. Its rotation usually varies from 20000rpm to 50000rpm.

FES are best used for high power, low energy applications that require many cycles. One of the advantages of such a system is speed, in terms of reaching the maximum capacity more quickly than other technologies – it can be charged very fast, within seconds. Next advantages are its long lifetime with almost no need of maintenance and no memory effect, high number of charging cycles, specific energy (100-130 $\frac{W \cdot h}{kg}$) and a large maximum output power. It also works with a very high energy efficiency up to 90%. Its typical capacity ranges from 3 kWh to 133 kWh.

On the other hand, from disadvantages a danger of explosion can be named. The biggest construction problem is a binding of the rotor. When maximal tensile strength is exceeded, the binging can crack, which leads to releasing all the energy at once – this is called ‘explosion’. In such a case, fragments of the rotating device can be as fast as a bullet.

For purposes of this work is important, that this technology has been used in transport industry. In 1950s, there were flywheel-powered buses (so called “gyrobuses”), in Switzerland and Belgium. Over battery power systems, there are big advantages as a higher capacity, shorter charge times, lower weight, and longer lifetimes. Flywheel can also store energy through regenerative braking. Next, in 2013 Volvo presented a car, with a flywheel fitted to the rear axle. Braking spins the flywheel to 60000rpm, which results in 25% reduction in fuel consumption and allows the car to reach 100 km/h in 5,5s.

To compare flywheel to a classical electric battery as one of the most commonly used way of storing energy, following information can be obtained. Flywheels can work in wider temperature scale, they do not suffer from various failures as chemical batteries, they are more ecological since they do not contain any chemicals and their remaining capacity can be counted easily. Despite all those pros, the biggest disadvantage are dimensions. Flywheel technology is not that customizable in terms of size as a battery is, which can cause problems in application in vehicles, where there is a need to mount such a device under the chassis, on the roof etc.

4.2 CAPACITORS

Capacitor is a passive electrical component which can store potential energy in an electric field between its two conductive plates. Usually a foil, thin film, sintered bead of metal or electrolyte is used as a conductor. Electrical conductors are separated by a dielectric medium, which increases capacitor’s charge capacity. Usually air, vacuum, glass, ceramic, plastic film, paper or oxide layers are used as a dielectric medium.

4.3 SUPERCAPACITORS

Supercapacitors (or EDLC - Electric Double-Layer Capacitor) are based on an electric double layer and they do not contain any insulating material – electrodes are separated from electrolyte only by electrochemical potential. Because of this, they are designed just for small voltages (compared to other capacitors), usually 2-3 V. The main advantage is very big capacity, which is caused by very thin insulating layer and by porous electrodes with great area. They store 10 to 100 times more energy per unit volume than electrolytic capacitors, they charge, and discharge significantly faster than batteries and they tolerate significantly more charging cycles than rechargeable batteries. [17]

The most challenging operating conditions for storage devices on board of traction vehicles are high number of load cycles during the vehicle lifetime, relatively short charge and discharge times as well as high charge and discharge power values. According to the features mentioned above, supercapacitors are used in applications, where there is a need to provide energy instantly rather than in a longer period – for regenerative braking, short-term energy storage etc. Because of that, they are used in cars, buses, trains, cranes and trams.

Using supercapacitors in trams is a technology, which all the major manufacturers are following in last 15 years. It contributes not only to ecological trends, such as lowering carbon trace and reducing pollution made by public transport in the cities, but also provides economical advantage in terms of sparing energy or allows to build catenary-free tram tracks and improve look of streets.

As described in previous chapter, all the major manufacturers have their technology based on energy recuperation.

Bombardier has its *MITRAC* energy saving system, which stores braking energy in a double-layer supercapacitor, which is made of 192 capacitors with 2700 F / 2.7 V interconnected in three parallel lines. In contrast to high-maintenance, flywheel-based mechanical energy storage systems, the *MITRAC* Energy Saver operates on a purely electrical basis. Parameters of the whole system are 518 V and 1.5 kWh. A vehicle uses this for acceleration, when it provides 600 kW, which is enough to power the tram for up to 1 km, where there is then no need of overhead line. As mentioned above, this system saves up to 30% of energy and during acceleration up to 50 km/h the peak power demand is reduced by up to 50%. [18]

Siemens developed its system *SITRAS HES* (Hybrid Energy Storage). It also stores braking energy which is then used for propulsion and therefore enables catenary-free operation as well. This system combines advantages of supercapacitors and traction batteries - double-layer capacitors for high power requirements (traction) and traction battery for low power requirements (e. g. auxiliaries). In the numbers: it saves up to 30% of supplied energy, produces 80 t less CO_2 emissions per year and tram, it stabilizes the line voltage. Concerning capacitors usable energy content 4.3 kWh, maximum power 860 kW, operating voltage from 190 to 720 V, forced air/water cooling. Concerning traction batteries usable energy content 45 kWh, maximum power 300 kW, water cooling.

Data mentioned above are general numbers, those values differ from one project to another. [19]

4.4 BATTERIES

Batteries are an electrochemical method of storing energy, currently it is the most common way, how to store electrical energy. Hereafter the most used technologies according to potential use in tramcars will be presented.

4.4.1 LEAD-ACID BATTERY

This battery type was invented in 1859, it was the first rechargeable battery and it is widely used until now.

Contemporary lead-acid batteries are made with a lead grid lattice, but lead is used in a form of an alloy, because lead itself is not stable enough and alloy also improves electrical features. Usually antimony, calcium, tin or selenium are used as a dash. Some of them improve characteristics of deeply discharged batteries, some of them lower self-discharge, but it also has a negative effect – for example higher water consumption or oxidation of lead grid during overcharging. [20]

Generally, lead-based systems are quite heavy, and their lifespan is lower compared to the systems using lithium or nickel, mainly if it is often overcharged or deeply discharged. On the other hand, they are quite reliable and cheap, and they can also work in a bigger temperature range.

Lead-acid batteries are divided into two groups – starting batteries and traction batteries (also deep-cycle batteries). Starting batteries are designed to provide large current instantly and in a very short period, usually one second, to just to start the engine. Straight from this basic feature of starting batteries, it is clear, that it is not possible to use them as they are as a propulsion in trams. However, second type – traction batteries – have more interesting characteristics. They are designed for maximum capacity and reasonable number of charging cycles. The biggest construction difference between these two types is width of electrodes – traction batteries are made with bigger electrodes, which suit better to periodical charging and discharging cycles. Nevertheless, a combination of starting and traction batteries exists, and it is used as a source of energy for bigger vehicles – cars, buses etc. – but still, power-to-weight ratio is poorer than other batteries. [20] [21]

4.4.2 LITHIUM BATTERIES [22] [23]

Recently, in almost all the areas, lithium batteries are taking a leading role. Its parameters are significantly better compared to nickel or lead batteries, which are Li-Ion batterie's predecessors. Basic advantage is smaller weight, higher energetical density and possibility to manufacture such a battery in any shape. Next, its self-discharging effect is lower (up to 5%), there is no charging memory effect and they are available in large scale of different types. Lithium batteries are manufactured with wide range of capacity from mAh to hundreds of Ahs. Its charging process is very similar to the one of lead batteries, but different from nickel ones. It is done with Constant Current – Constant Voltage (CC-CV) method.

Lithium batteries can, according to their type, contain liquid or solid electrolyte. Positive electrode (cathode) is made of solid lithium-based materials, negative one (anode) of carbon material and $LiPF_6$ serves as an electrolyte. They work with higher rated voltage (up to 3.7 V), which is also the reason of its higher energetical density. Nevertheless, their disadvantage is, that lithium is quite reactive element and it degrades fast while in contact with air, or that they are losing capacity even when they are not being used (and this effect arises with higher temperature). Also, lithium batteries are losing its performance with lowering temperature and a deep discharge can damage the battery.

Mostly used lithium batteries in transport industry are lithium-ion battery cells (Li-Ion) in “18650” design. This number refers to its dimensions – 18 mm wide and 65 mm long. It is used not only in notebook batteries, but also in electrical car industry. For example – Tesla company uses them in their cars, when several thousands of 18650 battery cells form the Tesla Model S battery (see Picture 9).

Picture 9: 18650 Li-Ion battery cells used in Tesla Model S. (Source: Wikipedia.com)

4.4.3 NICKEL-BASED BATTERIES

<u>NiCd</u>

This type of battery offers several advantages over its predecessor – lead-acid batteries. They are one of the most robust batteries, that can survive harsh conditions with proper maintenance.

Cathode is made of NiO(OH), anode of cadmium and electrolyte is potassium hydroxide. Rated voltage of one battery cell is 1.2 V. [24]

Advantages are its ruggedness, good load performance, long life shelf life with possibility of storing in a discharge state and good low-temperature performance. Also, it is a battery that can be ultra-fast charged with little stress. On the other hand, unfortunately, these batteries suffer from memory effect, which means that periodical charging to not full level causes loss of capacity. Next disadvantage is presence of toxic cadmium, high self-discharge and low cell voltage only 1.2 V. [25]

NiMH

Nickel-metal-hydride batteries were developed after NiCd types and they provide 40% higher specific energy, which can approach that of a Li-Ion battery. Currently it is one of the most used battery types, which is mainly thanks to its big capacity, ability to supply quite high current and acceptable price. [26]

Construction consists of the same cathode as at NiCd version – nickel oxide hydroxide NiO(OH) – then of anode made of special metal alloy (nickel, cobalt, mangan and some rare metals) and of electrolyte, which is aqueous potassium hydroxide. [27]

Advantages of NiMH batteries are higher capacity, absence of memory effect and lower toxicity (to NiCd), compared to Li-Ion it is mainly lower internal resistance. Disadvantages are lower resistance to harsh conditions (low temperature, mechanical stress) and higher self-discharge [28]. Nevertheless, there are also so-called NiMH LSD (Low Self-Discharge) batteries, which have somewhat lower capacity (20-30%), but they can store 70% of its capacity after 3-year storage (compared to classical ones, which loose whole capacity in several months). [26]

4.4.4 COMPARISON [29]

As it was described in previous articles, there are really many types of rechargeable battery cells on a market which differ a lot from each other. Usually the most important features are nominal voltage, energy density, specific power, cost, discharge efficiency, self-discharge rate and number of charging cycles. But there are many more, which are important according to its application – it can be weight, dimensions, used materials, charging speed, working temperature, etc. Basic properties of investigated batteries and double-layer capacitor are shown in the table 1 hereafter.

Table 1: Characteristics of chosen types of battery cells and double-layer capacitor. (Source: batteryuniversity.com) [29]

Storage type		Lead-acid	Li-Ion	NiCd	NiMH	NiMH LSD	EDL Capacitor
Nominal voltage [V]		1.75	3.6	1.2	1.2	1.2	2.3-2.75
Energy density	by mass [Wh/kg]	25-50	100-250	45-80	60-120	95	5
	by volume [Wh/L]	60-110	250-693	50-150	140-300	353	10-30
Specific power [W/kg]		180	250-340	150-200	250-1000	250-1000	2k-10k
Cost [$/kWh]		57-148	250-1000	-	303	-	10000
Discharge efficiency [%]		50-92	80-90	70-90	66-92	-	95
Self-discharge rate [%/month]		5	<5	20	30	0.42	54
Cycle durability		<300	500-2000	1000	300-500	500-1500	100k-1000k
Charge time		8-16 h	1-4 h	1-2 h	2-4 h	2-4 h	1-10 s
Charge temperature [°C]		-20 to 50	0 to 45	0 to 45	0 to 45	0 to 45	-40 to 65
Discharge temperature [°C]		-20 to 50	-20 to 60	-20 to 65	-20 to 65	-20 to 65	-40 to 65

Lead-acid batteries, according to their biggest advantages – low price, ruggedness – and despite their biggest disadvantages – low specific energy, long charging time – are still commonly used in small vehicles like scooters, wheelchairs, golf cars or forklifts. On the other hand, Li-Ion batteries can also happen to be cheaper. This can be thanks to their longevity, which is far higher than lead batterie's, and therefore cycle costs can be lowered significantly.

One of big advantages of Li-Ion cells is high cycle count and low maintenance. They can be stored in any level of discharge for a long time without adverse side effects. On the other hand, the price is higher, mainly because it needs a protection circuit due to safety issues. But as described higher, high cycle count can overweight this disadvantage.

NiCd has high discharge current, it is rugged and enduring. Only this type of chemical battery allows ultra-fast charging with low stress. Thanks to its good safety record it is used in aircrafts, then in medical devices or power tools.

NiMH has replaced NiCd in some applications, mainly because it provides higher specific energy and it does not contain toxic cadmium. It is used in medical instruments, hybrid cars and in industrial application.

The most important difference between batteries and capacitor is clearly visible – capacitor stores times less energy, but its specific power, charge time and mainly number of charging cycles is immense compared to any type of chemical-based batteries. Currently the most used batteries are Li-Ion and NiMH LSD, which is supported by the data in the table as it has the best properties among batteries. [30]

In electrical vehicles, Li-Ion is the leading battery type. They are used in many modifications, for example Li-manganese, Li-NCA (Nickel, Cobalt, Aluminium), NMC (Nickel, Manganese, Cobalt) and others. Usually 16-30 kWh batteries are used, but for example Tesla S has huge 90 kWh battery pack. Li-Ion batteries are mostly used in 18650 forms, when Tesla S battery is composed from 7616 battery cells with average weight around 200kg, Tesla S 540kg. With this power source, driving range is usually around 130km, but for Tesla S it is 424km. [31]

PRACTICAL PART

5 ENERGY STORAGE DEVICES AND PROPULSION

As the energy demand calculations were done in the previous part of the work, following text will focus on choosing suitable propulsion system. For this purpose, a scheme of combining Li-Ion batteries and ultracapacitors is considered. Nowadays, this is combination is the most used one in tram's propulsion.

Energy storage devices for rail vehicles, such as trams, require specific demands from the rest of the market. They must be robust and reliable, with low maintenance requirements and long lifespan. Next, smooth working in peak currents, high duty cycles and fast rate discharge/charge cycles.

5.1 Li-Ion BATTERIES

Nowadays, the fastest evolving branch using electrical batteries is probably electric car industry. That is why, when searching for a battery for a tramcar application, it is convenient to first check battery types used in electro vehicles (EV) and hybrid electro vehicles (HEV). Mostly, in such an application LiFePO4 batteries in "18650" design are used, but not only in this shape. Hereafter are briefly presented chosen types of such batteries and in the end of this part in the table 3, there is a technical data comparison.

5.1.1 LiFePO4 Battery pack 3.2V, 60Ah

This battery is manufactured by AA Portable Power Corp, California, USA. It is already said in the description that intended application is EV, HEV. This pack is made of 4 identical LiFePO4 rechargeable cells, 18650 type, 3.2V, 15Ah (1 cell).

5.1.2 LiFeMnPo4 Prismatic Module 3.2V, 400Ah

Another interesting option could be Prismatic Module manufactured also by AA Portable Power Corp, California, USA. Its recommended use is also for EVs and HEVs. There are also available similar modules with capacity 40, 60, 100, 200 and 300Ah, but here the biggest possible was chosen. Technical data of this module are in the table 4.

5.1.3 LiFePO4 Liotech battery LT-LYP380

This battery is manufactured by Liotech company, Novosibirsk, Russian Federation. It is available in capacities 200, 240, 300, 380, 700 and 770Ah. Here 380Ah variant was chosen, because it is comparable to previous variant.

Table 2: Technical data comparison of chosen batteries. (Source: http://www.batteryspace.com; http://www.b-eco.ru)

-	*LiFePO4 Battery pack 3.2V, 60Ah (see [1])* [32]	*LiFeMnPo4 Prismatic Module 3.2V, 400Ah (see [2])* [33]	*LiFePO4 Liotech battery LT-LYP380 (see [3])* [34]
Voltage [V]	3.20 (working)	3.20 (nominal)	3.20 (nominal)
	3.65 (peak)	3.80 (cell charge)	3.90 (max charge)
		2.50 (cell discharge)	2.50 (min battery voltage)
	2.50 (cut-off)	3.55/cell (batt. pack charge)	
		2.80/cell (batt. pack discharge)	
Capacity	60Ah (192Wh)	400Ah	380Ah
Terminals	Screw terminal 6 mm	Screw terminal	
Cycle life	> 1000 cycles (80 % DOD at 0.2 C rate, IEC Standard)	1500 times (80 % DOD)	3000 times (80 % DOD)
Energy Density	91.42 Wh/kg		105 Wh/kg
Charging rate	30 A (0.5 C rate)	Stand. Charge Current: 0.3 C (120 A) to 1.0 C (400 A)	0.5 C (recommended)
		Best Charge Current: 0.5C (200A)	3 C (limit)
		Max Charge Current: ≤2 C (800A)	
Max. Discharge Rate	60 A (Continuous discharge)	Max Constant Current: ≤2 C (800 A)	0.5 C (recommended)
	600 A (<30 sec Max Surge Rate)	Impulse Current: ≤ 10 C (4000 A)	3 C (limit)
		Self-discharging <3 % monthly	Self-discharging <3% monthly
Dimensions (LxWxH)	88x88x189mm	365x73x312mm	167x163x337mm
Weight	2.1Kg (4.0 lbs 9.9 Oz)	13.2Kg (29.1LB)	14.8Kg
Price[4]	195 USD	624 USD	363 USD

[1] http://www.batteryspace.com/lifepo4-40152s-battery-3-2v-60ah-192wh-150a-rate-18-0.aspx
[2] http://www.batteryspace.com/lifemnpo4-prismatic-module-3-2v-400ah-1280wh-2c-rate---un38-3-passed.aspx
[3] http://b-eco.ru/battery_cable/liotech/LT%E2%80%93LYP380/
[4] Dollar Exchange rate on 29.5.2018

5.2 ULTRACAPACITORS

Maxwell Technologies' ultracapacitor systems and modules are fulfilling required demands mentioned in the beginning very well. Maxwell is the leading company in the industry and manufactures wide range of energy storage parts for propulsion solutions (battery and ultracapacitor combinations). This system allows to use smaller batteries, enlarges battery's lifespan and thanks to ultracapacitors it provides engine and assisted starting. [35]

Generally, ultracapacitors complement a classical primary energy source. Due to its specific features, together with classical energy sources it creates very effective scheme of propulsion. In contrast to, for example batteries or combustion engines, ultracapacitors can repeatedly provide quick bursts of power (used for example for acceleration), which is harvested from regenerative braking system. [36]

Ultracapacitors fulfil three main objectives in the transport industry – voltage stabilisation, propulsion and locomotive engine starting. For the purposes of this work, propulsion usage is crucial. Therefore, hereafter related Maxwell products will be presented with its technical data, they will be compared and discussed which would suit the most to the given simulation.

5.2.1 K2 3.0V/3000F Cell

The newest and most advanced Maxwell ultracapacitor is the 3-volt, 3000-farad cell. Maxwell's first 3-volt cell meets the same typical life performance criteria as the 2.7-volt cell, with the added benefit of increased power capability – a 31% increase over the 2.7-volt cell and a 15% increase over the 2.85-volt cell. K2 3-volt cell has industry-standard cylindrical design with 60 mm diameter and an electrostatic storage capability that can cycle a million charges and discharges without performance degradation. The cell is available in quick- and easy-to-implement threaded terminals. It provides overall higher energy density for all transportation applications including hybrid/plug-in hybrid bus and wayside or onboard rail. [37]

This cell is designed to work together with batteries for applications where there is a need of not only constant power supply, but also of pulse power for peak loads. Working in this scheme, ultracapacitor relieve batteries while working in peak power and thanks to it extends its life, reduces size and cost and contributes to better overall efficiency of the propulsion. [37]

Technical data concerning K2 3-volt cell are shown in the following table 2.

Table 3: Data sheet of Maxwell's K2 3.0 V ultracapacitor. (Source: http://www.maxwell.com/images/documents/K2_3V_DS_3001423_EN_1.pdf)

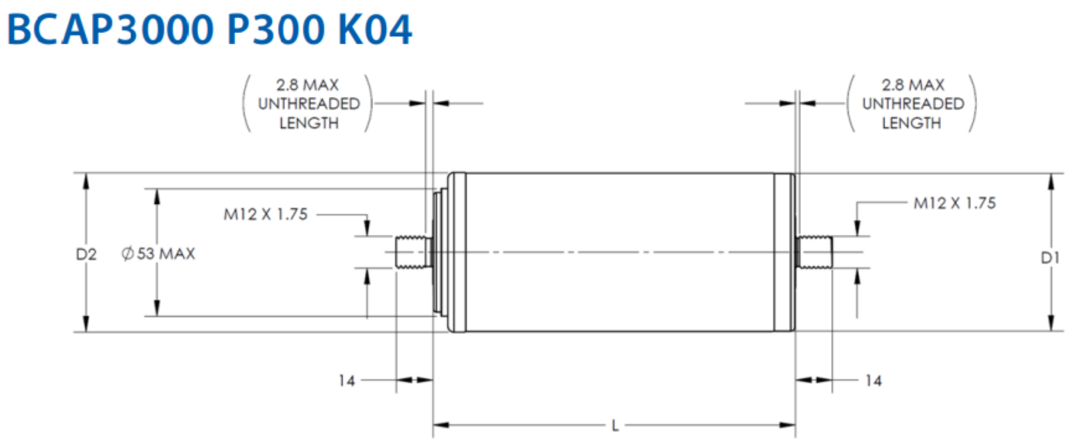
PRODUCT SPECIFICATIONS

ELECTRICAL	BCAP3000
Rated Voltage	3.00 V
Minimum Capacitance[1], initial, rated value	3,000 F
Maximum ESR_{DC}[1], initial, rated value	0.27 mΩ
POWER & ENERGY	
Usable Specific Power, P_d[2]	7.7 kW/kg
Impedance Match Specific Power, P_{max}[3]	16 kW/kg
Specific Energy, E_{max}[4]	7.2 Wh/kg
Stored Energy, E_{stored}[5]	3.75 Wh
SHOCK & VIBRATION	
Vibration Specification	ISO 16750-3, Tables 12 & 14
Shock Specification	SAE J2464, IEC 60068-2-27, -29
SAFETY	
Short Circuit Current, typical (Current possible with short circuit from rated voltage. Do not use as an operating current.)	11,000 A
Certifications	RoHS, REACH
THERMAL	
Thermal Resistance (R_{ca}, Case to Ambient), typical	3.2°C/W
Thermal Capacitance (C_{th}), typical	600 J/°C
Maximum Continuous Current (ΔT = 15°C)[6]	130 A_{RMS}
Maximum Continuous Current (ΔT = 40°C)[6]	210 A_{RMS}

TYPICAL CHARACTERISTICS

TEMPERATURE	BCAP3000
Operating temperature range (Cell case temperature)	
Minimum	-40°C
Maximum	65°C
ELECTRICAL	
Leakage Current at 25°C, maximum[7]	12 mA
Absolute Maximum Voltage[8]	3.25 V
Absolute Maximum Current	2,200 A
LIFE	
DC Life at High Temperature[1] (held continuously at Rated Voltage & Maximum Operating Temperature)	1,500 hours
Capacitance Change (% decrease from rated value)	20%
ESR Change (% increase from rated value)	100%
Projected DC Life at 25°C[1] (held continuously at Rated Voltage)	10 years
Capacitance Change (% decrease from rated value)	20%
ESR Change (% increase from rated value)	100%
Projected Cycle Life at 25°C[1, 9, 10]	1,000,000 cycles
Capacitance Change (% decrease from rated value)	20%
ESR Change (% increase from rated value)	100%
Shelf Life (Stored uncharged at 25±10°C)	4 years
PHYSICAL	
Mass, typical	520 g
Threads	M12 X 1.75[11]

Picture 10: Dimension data of Maxwell's K2 3.0 V ultracapacitor. (Source: maxwell.com)



Part Description	Dimensions (mm) L (±0.3mm)	D1 (±0.2mm)	D2 (±0.7mm)	Package Quantity
BCAP3000 P300 K04	138	60.4	60.7	15

Maxwell ultracapacitors are already in use in Light Rail Systems, for example (as Maxwell describes in their feed) in Southeastern Pennsylvania Transportation Authority. In this system ultracapacitors are wayside-located. It recovers braking energy, which is happening several thousand times a day and lasts up to 15 or 20 seconds. Energy harvested in such a way allows to reduce grid-supplied electrical energy by 10-20%. [38]

6 SIMULATION OF TRAMWAY’S ENERGY CONSUMPTION

After doing a research on tramcars and its propulsion and energy storage devices, it is finally possible to proceed to an energy consumption simulation itself.

In this chapter is described choice of real tram lines to be simulated, physical background of the model and simulation, creating a simulation script itself in MATLAB software and finally interpretation of obtained data and graphs and choice of propulsion and energy storage system based on obtained values.

6.1 PHYSICAL BACKGROUND OF THE SIMULATION

To approach the simulation in a most real way possible, it is needed to consider all the physical forces acting on a move of a tramcar. For these purposes, three stages of moving of a tramcar are considered as follows.

6.1.1 RIDING MODES OF A TRAMCAR

- **Acceleration mode**

  Acceleration mode acts after every stop to gain desired constant speed. Driving force is greater than all resistive forces acting against the move of a vehicle. When desired constant (operating) speed is reached, a tramcar enters next mode – constant speed mode. Therefore, driving force needed for acceleration must be equal to the sum of acceleration force, resistance forces acting against the movement of a tramcar and projected gravitational force:

$$F_{drive} = F_{inertial} + F_R \pm F_g \cdot sin\alpha \ \ , where$$

$F_R - total\ resistance\ force$
$F_g - gravitational\ force$
$\alpha - ascent/descent\ angle$

- **Constant speed mode**

While in the constant speed mode, a tramcar is moving forward with a constant speed, which was reached at the previous stage. There is no acceleration or deceleration. To maintain tramcar's constant speed, it is just necessary to overcome the resistive forces:

$$F_{drive} = F_R \pm F_g \cdot sin\alpha \ \ , where$$

$F_R - total\ resistance\ force$
$F_g - gravitational\ force$
$\alpha - ascent/descent\ angle$

- **Braking mode**

When approaching a tram stop in constant speed mode, tramcar starts to brake with a constant negative acceleration. Therefore, this mode is the same as the acceleration mode with only one, but important, difference – acceleration has an opposite sign. During this mode, for the purposes of this work, reasonable 30% of used braking energy is expected to be saved and stored in an energy storage system and used later for acceleration.

6.1.2 LIST OF ACTING FORCES

Hereafter is a list of all acting forces on any tramcar during its ride between any two stops:

- $F_{inertial} = m \cdot a$, $where$

  $m - effective\ mass\ of\ a\ tramcar$
  $a - tramcar\ acceleration$

  Inertial force represents forces acting during acceleration ($+a$) and deceleration ($-a$). During ride with constant, not changing speed, acceleration $a = 0$, and that is why in this ride mode $F_{inertial} = 0$. This is a result of 1st Newton's law and basically it represents 2nd Newton's law. (Picture 11)

Picture 11: Description of inertial force values together with speed and acceleration.

- $F_{RR} = F_r \cdot sgn(v)$, $where$

$$F_r = \omega_0 \cdot mg = (a + b \cdot v + c \cdot v^2) \cdot mg = (5 + 0.0031 \cdot v^2) \cdot mg$$
$\omega_0 - friction\ coefficient$
$v - vehicle\ speed$
$m - effective\ mass\ of\ a\ tramcar$
$g - gravitational\ acceleration$

Rolling resistance force represents friction coming from a contact of a vehicle with rails (or generally ground). For its implementation to the calculations, it is necessary to use coefficient ω_0, which was taken from the source in Appendix 1. The formula then contains gravitational force, but not projected into direction of ride as in previous case. The last particle $sgn(v)$ reflects whether a tramcar is braking or accelerating and that is how it is described if this force acts against or towards direction of movement.

- $F_{drag} = \mu \cdot |v| \cdot v$, $where$

$$\mu = \frac{1}{2} \cdot \rho_{air} \cdot C_d \cdot A_f - aerodynamic\ drag\ coefficient \ , \qquad where$$
$\rho_{air} - air\ density$
$C_d - aerodynamic\ drag\ coefficient$
$A_f - projected\ frontal\ area\ of\ a\ vehicle$
$m - effective\ mass\ of\ a\ tramcar$
$g - gravitational\ acceleration$
$v - vehicle\ speed$

Aerodynamic drag force represents the resistance of air acting on the frontal area of a vehicle and therefore against the direction of movement. As well as at rolling resistance force, the sign of this force in calculations depends on the fact, if a vehicle is braking or accelerating, which is implemented by putting velocity v into absolute value.

- $F_{grad} = F_g \cdot \sin(\alpha) = mg \cdot \sin(\alpha)$, $where$

  $m - effective\ mass\ of\ a\ tramcar$
  $g - gravitational\ acceleration$
  $\alpha - ascent/descent\ angle$

  Gradient (or gravitational) force depends on a gradient of the track. In calculations it physically represents whether a vehicle is moving downhill or uphill with an angle of inclination α. By this formula, calculations reflect the tram line's altitude profile and that is how F_{grad} changes its sign – it is positive when moving uphill and negative when moving downhill.

6.1.3 INCLINATION ANGLE α

To include altitude profile into calculations through described force F_{grad}, it is needed to determine inclination angle α on every part of the track, thus between every two stops. From altitude profile, values for altitude and distance are available. Using goniometric function $arctg$, angle α can be easily calculated as follows:

$$\alpha = arctg\frac{\Delta z}{\Delta x} \cdot \frac{180}{\pi} \ , \qquad where$$

$\Delta z - altitude\ difference\ between\ two\ stops$

$\Delta x - distance\ between\ two\ stops$

According to this calculation, positive or negative angle values in $radians$ are obtained and that is how the difference from flat surface is determined. These values can be approximated using a fitting polynomial function, which is how altitude profile is projected to necessary calculations.

6.2 TRAM LINE ALTITUDE PROFILE

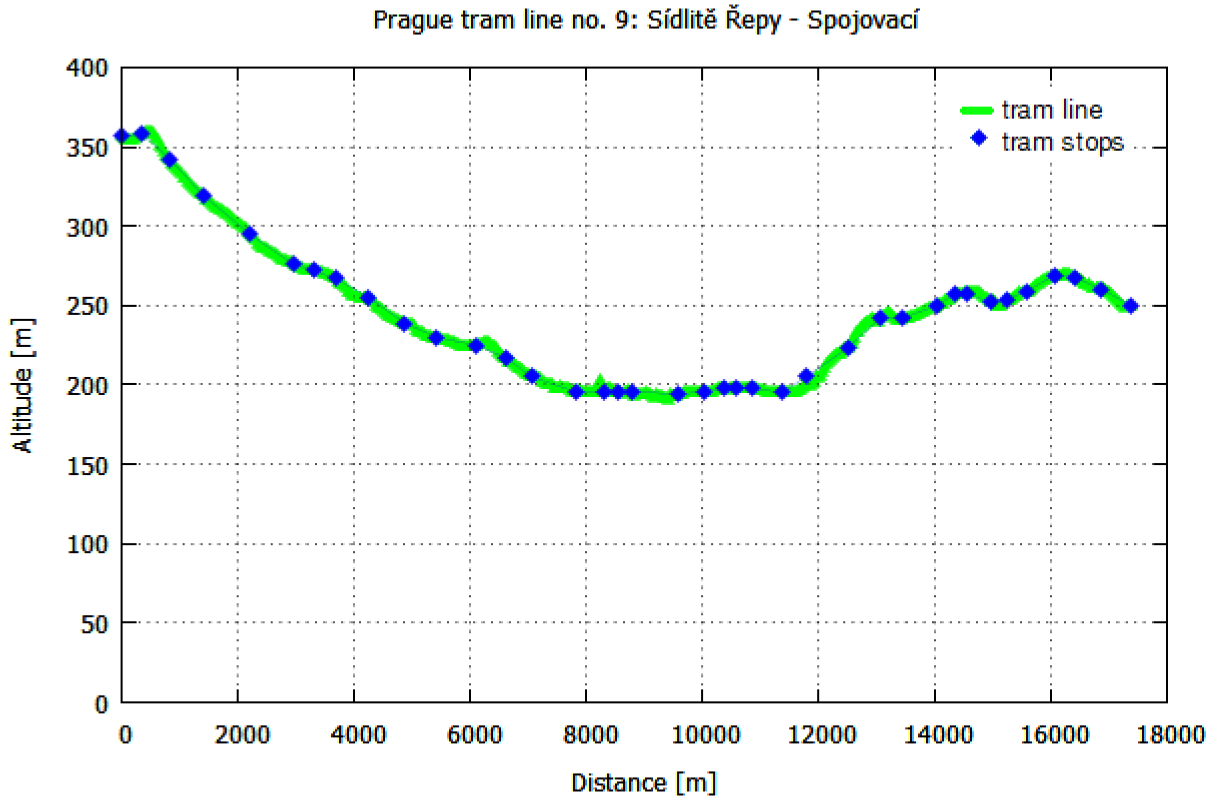
To make calculations of a power demand for specific tramcar lines using tramcars with braking energy storage, an altitude profile is needed. Altitude data in the following graphs was obtained from GPS data from mapy.cz online application.

Since this work is written as a double degree diploma thesis between Prague and Tomsk university, tram lines in these cities are chosen to be simulated.

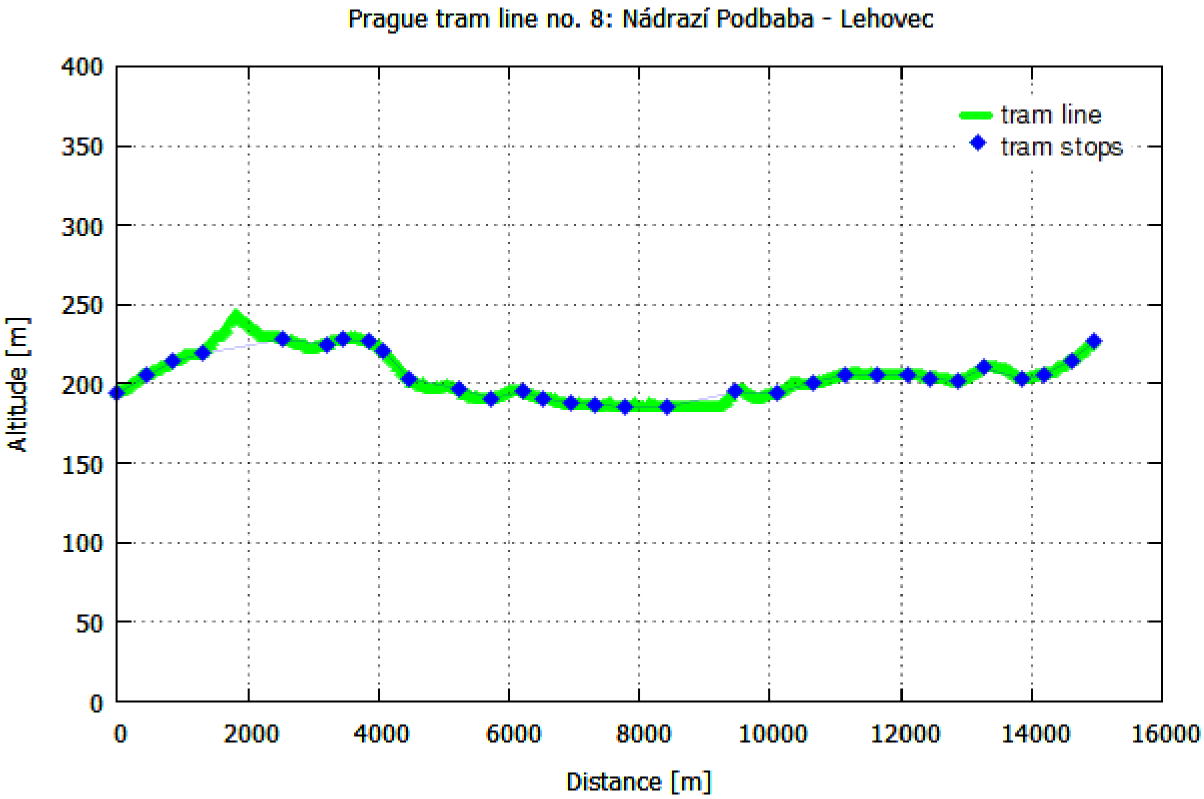
6.2.1 TRAM LINES IN PRAGUE

In Prague, many tram lines copy riverside of river Vltava, therefore their altitude profile is quite flat and not interesting to make braking energy storage simulations. According to this fact, tram lines 9, 8, 22 and 24 were chosen because of their interesting altitude profiles, where there are both high ascents and descents. Altitude profiles are shown on graphs 1, 2, 3 and 4.

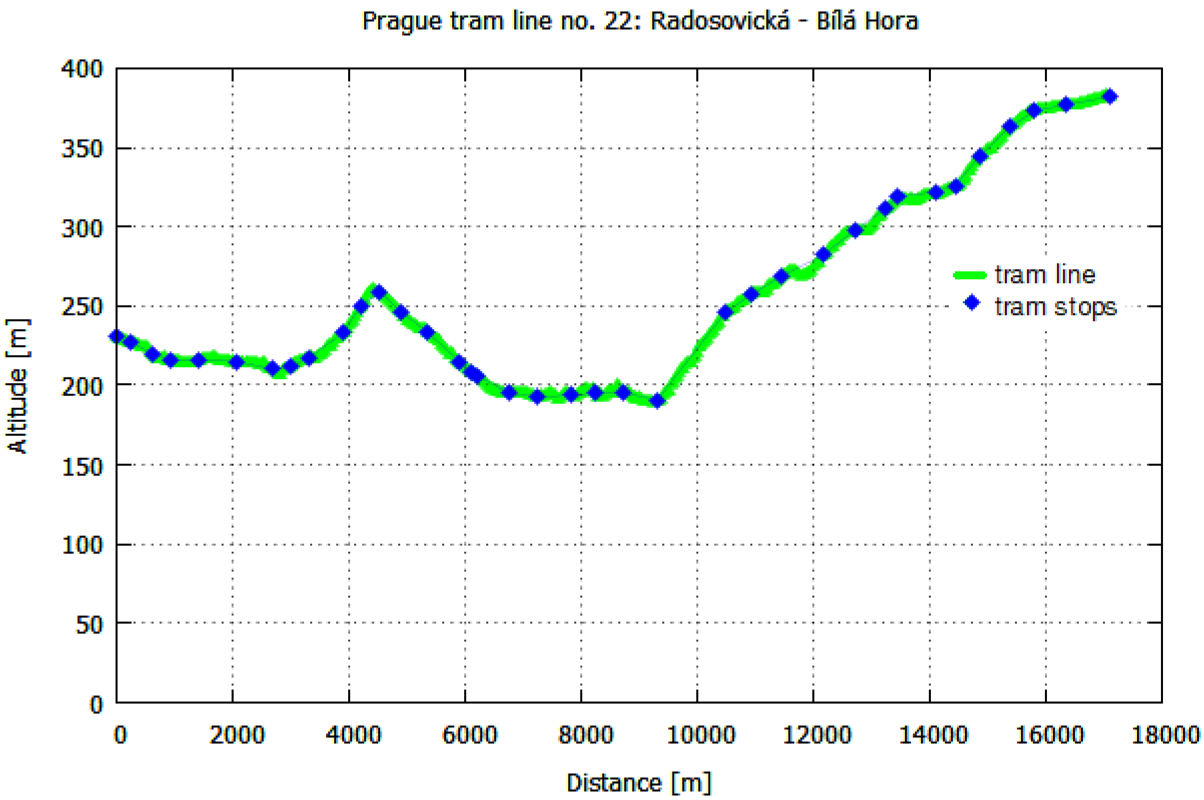
Graph 1: Graph of altitude of tram line number 9 in Prague.



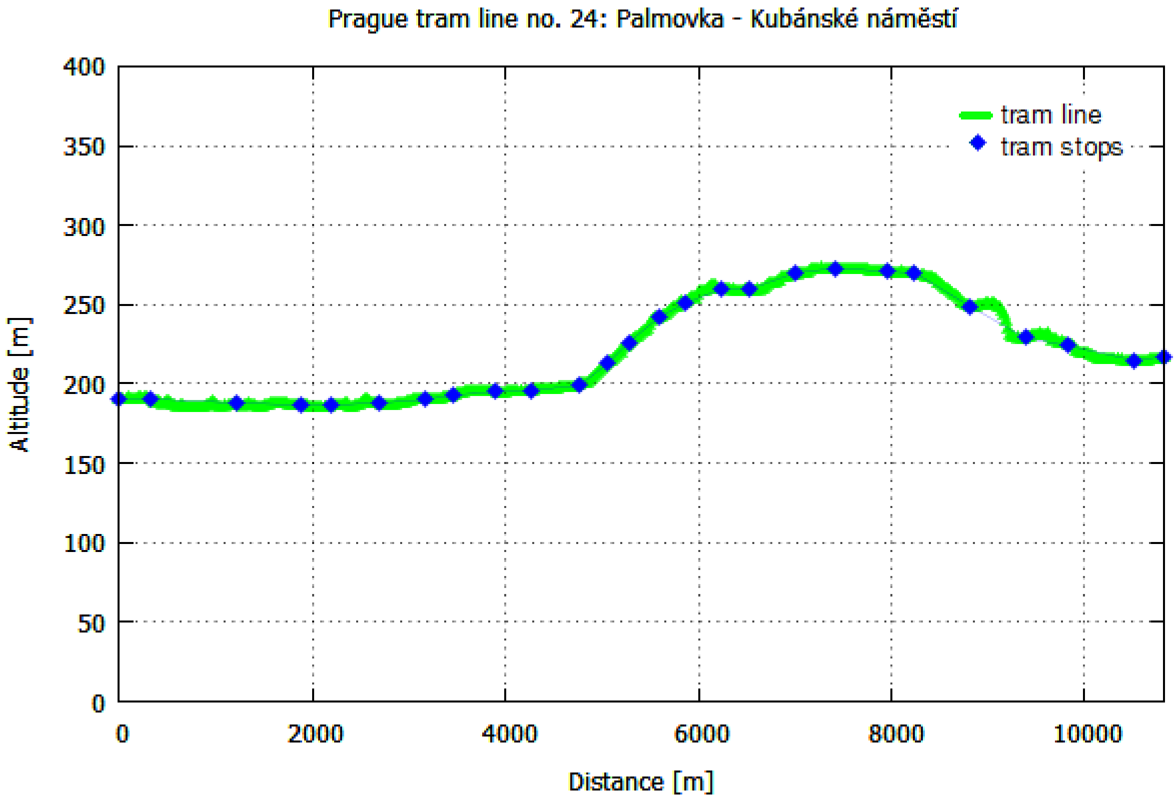
Graph 2: Graph of altitude of tram line number 8 in Prague.



Graph 3: Graph of altitude of tram line number 22 in Prague.



Graph 4: Graph of altitude of tram line number 24 in Prague.



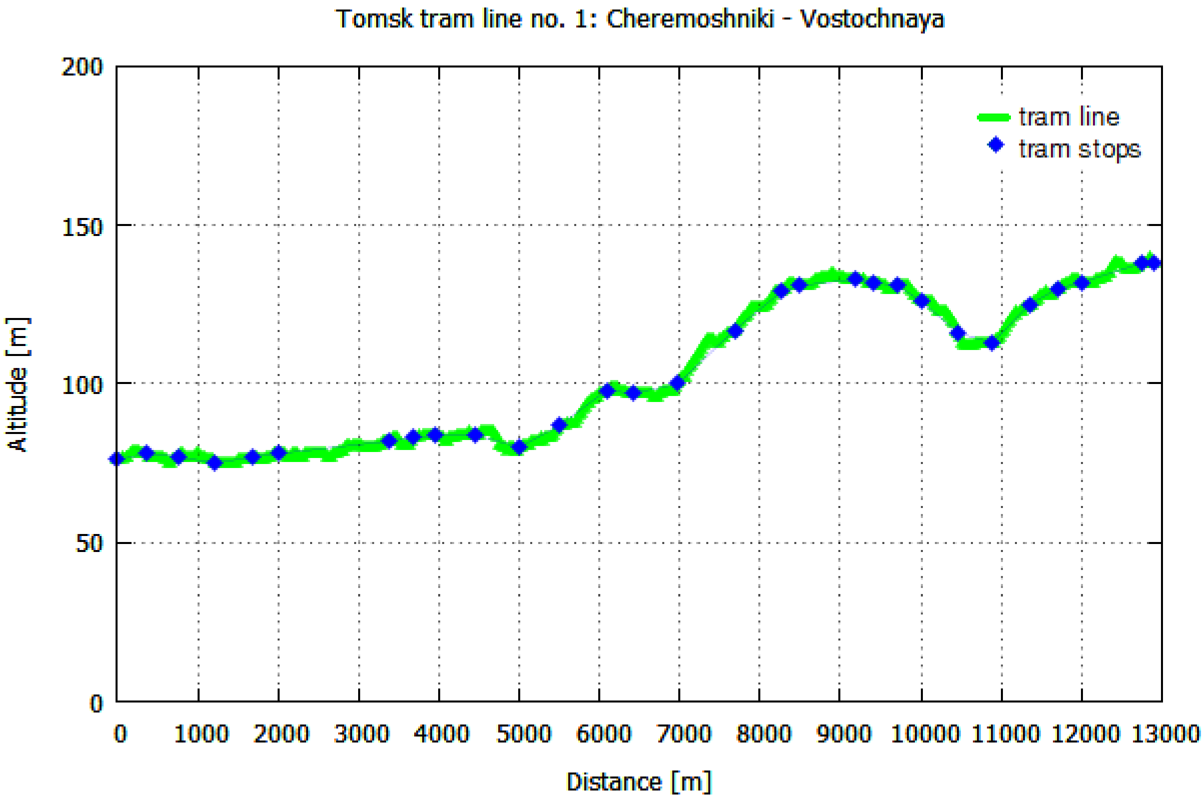
For this work the higher altitude difference and the steeper ascents and descents the better for the braking energy storage simulation, because on such lines it is possible to store more energy than on the flat ones and therefore all the input and output data will be more synoptical.

From this reason tram line number 22 from Radošovická stop to Bílá hora stop is chosen for further simulations.

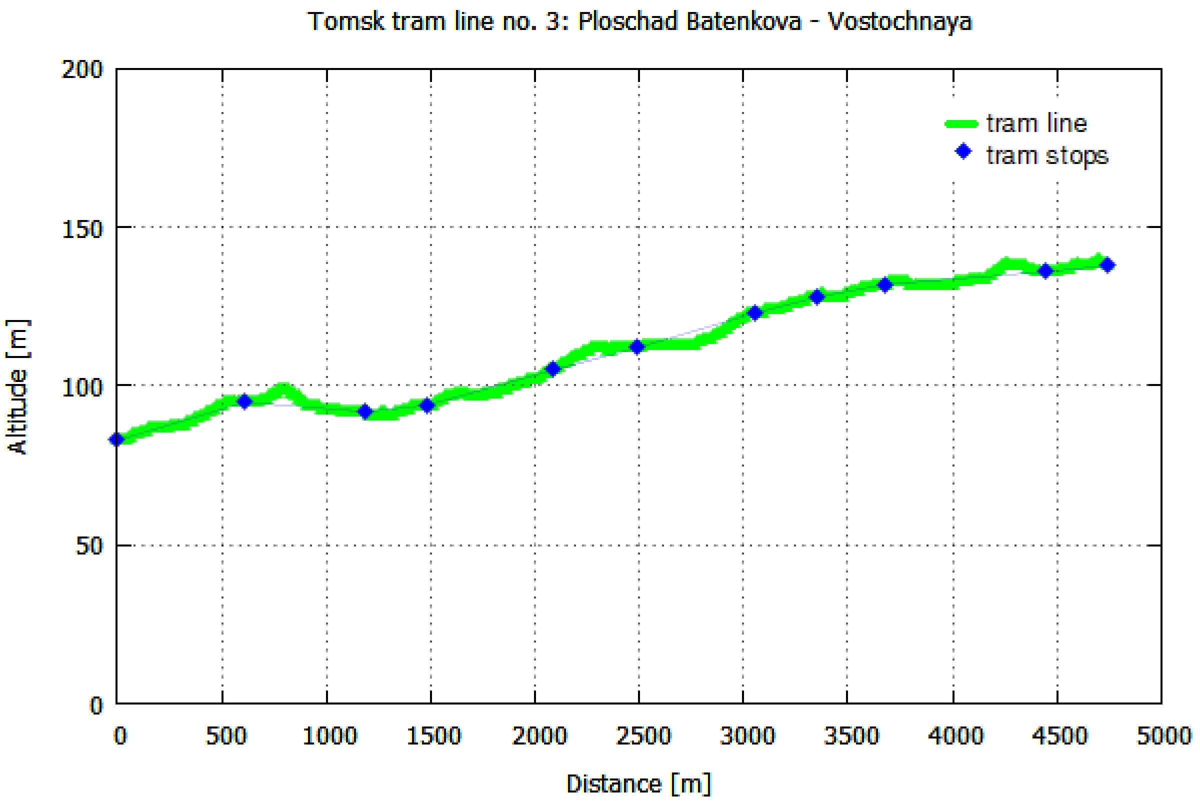
6.2.2 TRAM LINES IN TOMSK

In Tomsk, there are only 4 tram lines at all and compared to Prague, city's altitude profile is quite flat. Therefore, there were not so many options to choose. Altitude profiles of tram line number 1 and 3 are shown on graphs 5 and 6, respectively.

Graph 5: Graph of altitude of tram line number 1 in Tomsk.



Graph 6: Graph of altitude of tram line number 3 in Tomsk.



Finally, tram line number 1 from Cheremoshniki stop to Vostochnaya stop is chosen. Its altitude profile is continuously slightly ascending with an about 25 altitude meters drop before its final station. Tram line number 3 is shorter and has even milder profile, therefore is not that interesting for intended simulations.

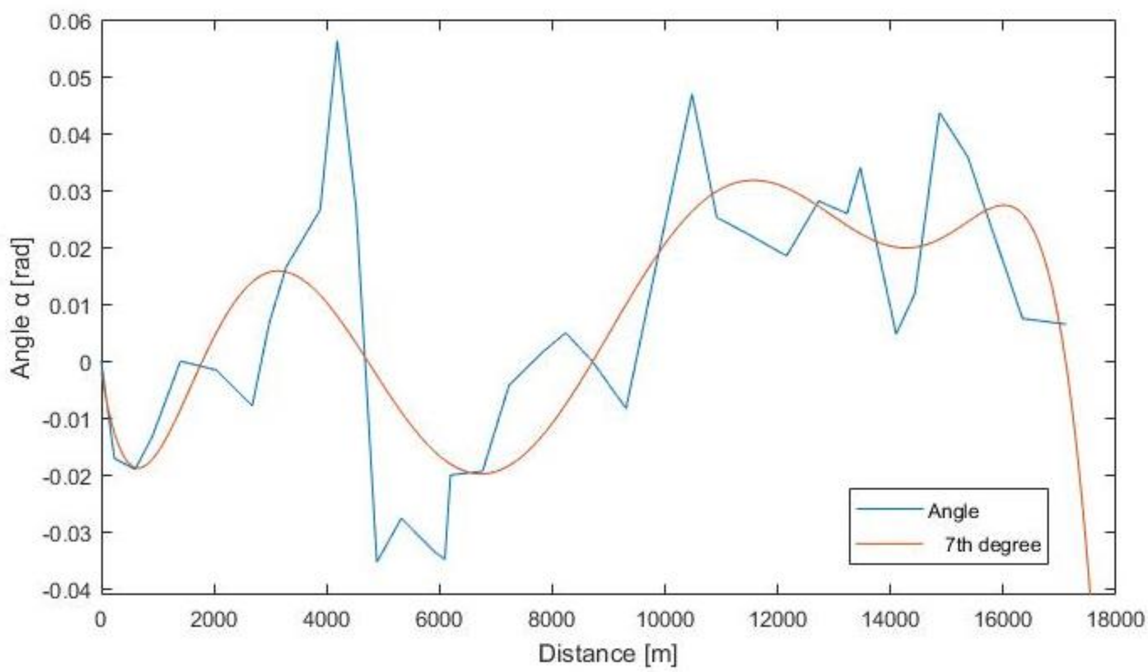
6.3 SIMULATION FOR PRAGUE TRAM LINE no. 22

Hereafter follows presentation of simulation calculation for energy consumption for a tram on the track number 22 in Prague.

6.3.1 CALCULATIONS AND DATA

As mentioned above, for Prague tram simulation tram line number 22 was chosen for further calculations. Its altitude profile is shown above in graph 3. Distance and altitude data were used to calculate inclination angle α as described in the chapter 5.1.3 and changing of this angle depending on the distance together with its fit function is shown in graph 7.

Graph 7: P22 – Inclination angle α describing altitude profile of the track and fit function y(x).



Obtained angle values were fitted with a 7th degree polynomial function:

$$y\,(x) = -2.3086 \cdot 10^{-28} \cdot x^7 + 1.411 \cdot 10^{-23} \cdot x^6 - 3.3852 \cdot 10^{-19} \cdot x^5 + \\ + 4.0045 \cdot 10^{-15} \cdot x^4 - 2.3933 \cdot 10^{-11} \cdot x^3 + 6.5537 \cdot 10^{-8} \cdot x^2 - \\ - 5.9278 \cdot 10^{-5} \cdot x - 0.0020389$$

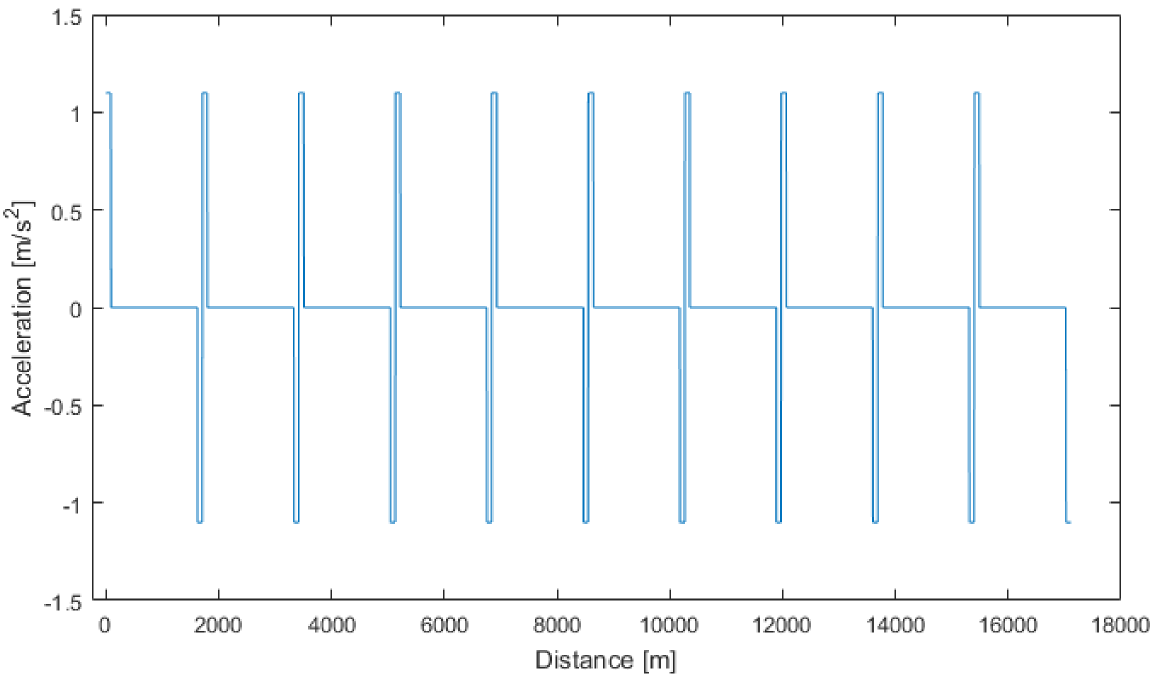
This function was fitted for the whole distance with maximum number of stops available to reach the highest accuracy possible.

At this point, all the data was collected for a successful simulation. Finally, it was done only for 10 fictional stops, because for the whole pack of 36 stops calculated energy demand values were too low to be further processed.

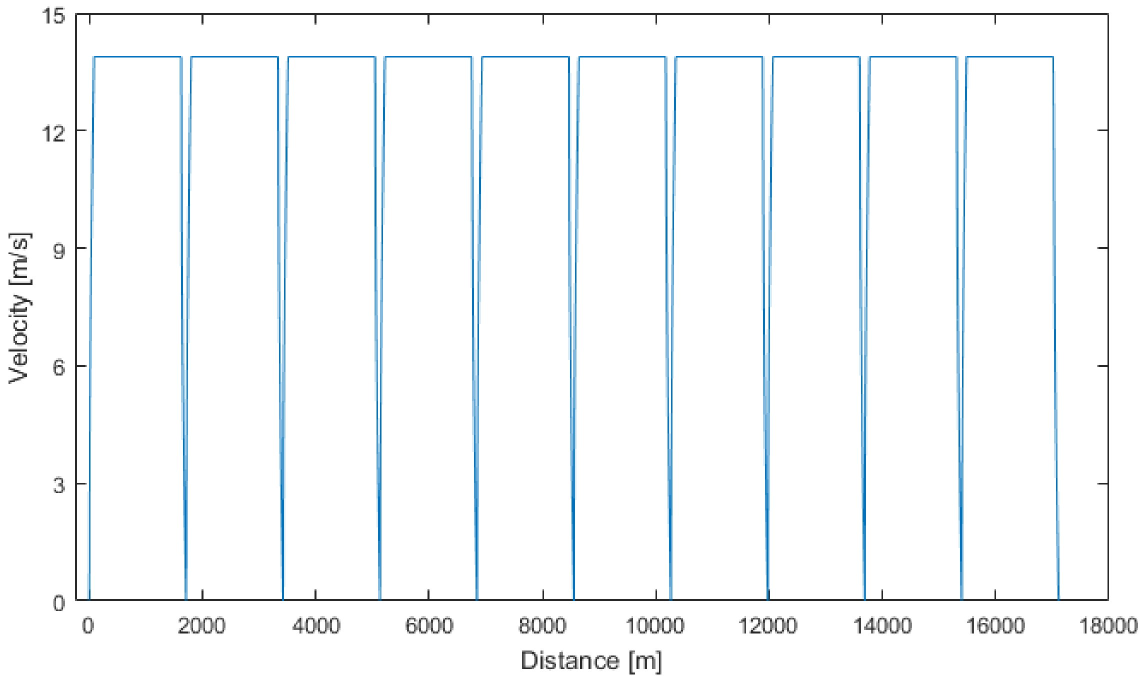
Hereafter follow several graphs obtained from the calculation and describing movement of the tram on the track.

Acceleration and velocity of the tram is shown on the graph 8 and 9, respectively, and it corresponds to predicted reality – three main modes of movement are clearly visible between any two stations– acceleration, constant speed and braking mode. Tram's acceleration and deceleration are both initial set values $a = \pm 1.1\, m/s^2$ and the tram is reaching desired maximum speed between stops $v = 14\, m/s$.

Graph 8: P22 – Acceleration and deceleration depending on distance.

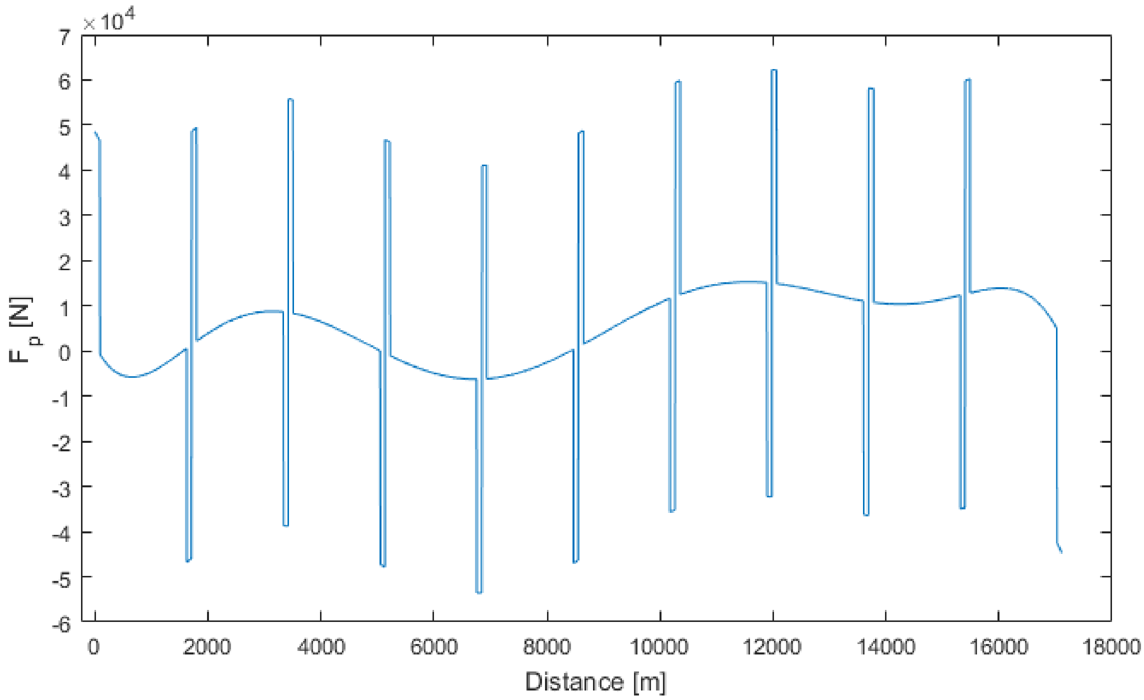


Graph 9: P22 – Velocity depending on distance.



Based on forces acting on the tramcar, which are described in the chapter 4.1.2, force needed to accelerate the tramcar and force to be possibly stored while braking is shown in the graph 10. As described earlier, calculations are interconnected with the altitude profile using fit function $y(x)$. In graph 10, force above this curve represents force which is needed for acceleration, whilst force under the curve is force “wasted” for braking if there is no storage or recuperation system.

Graph 10: P22 – Force needed to be supplied or and to be possibly stored.

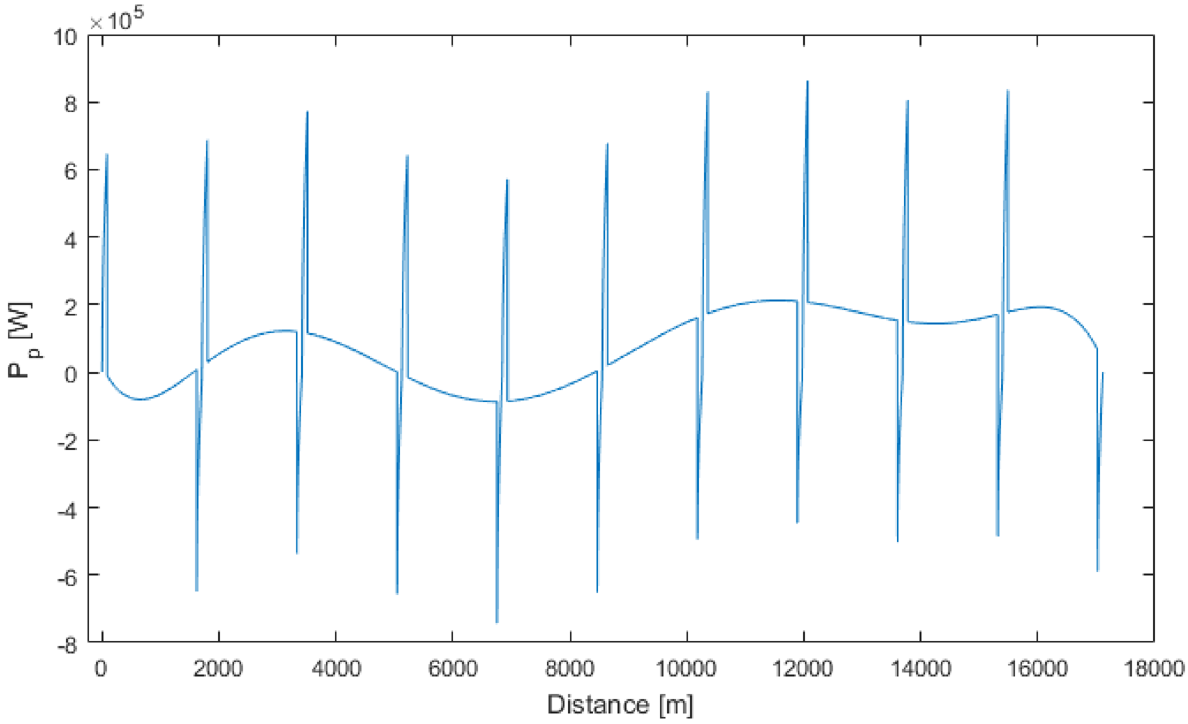


For calculating and choosing suitable energy storage system, it is necessary to calculate power. This can be easily done by multiplying force by the velocity.

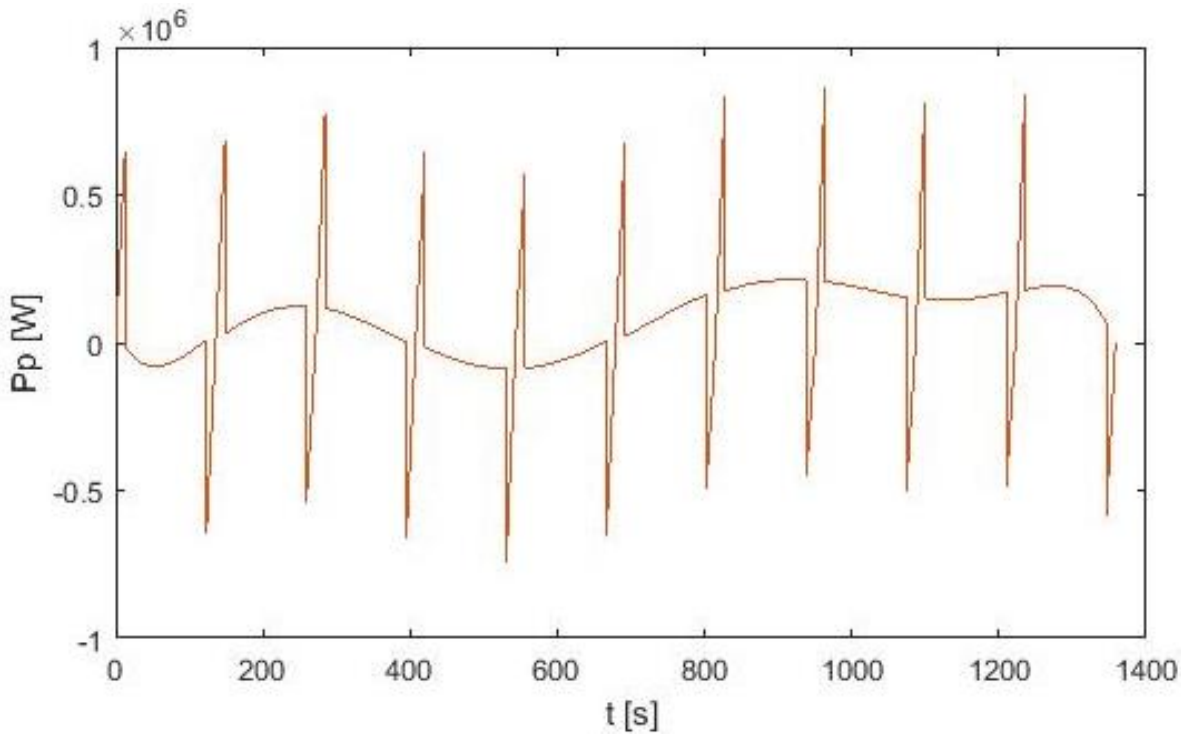
$$P_p = F_p \cdot v \ \ [W]$$

In the graph 11, there is shown power P_p depending on distance. Again, as expected, it copies fit function which represents altitude profile.

Graph 11: P22 – Power needed to be supplied and to be possibly stored.



Graph 12: P22 – Power evolution in time.



Next step is to calculate how much power is consumed and how much can be possibly stored. This is done by using integral functions to calculate area under the graph, which mathematically represents the power. Power from acceleration and constant speed mode (in the graph represented by the areas bordered by the curve above the leading fit function and areas under the fit function, but only in the parts, where there is only fit function itself without negative peaks) is the power which is needed to be supplied in 100% of its amount. On the other hand, power from braking mode (in the graph represented as areas below the main fit function bordered by the negative peaks of the curve) can be saved, stored and used for propulsion when needed. However, due to losses during saving, storing and again using this energy, it is not possible to use its 100% amount. That is why for the purposes of this simulation it will be calculated, that reasonable 80% [39] of this whole braking energy is possible to save, store and "reuse".

Nevertheless, by integration, power is calculated in $Joules$, but for further calculations concerning energy storage, $Watthours$ are required. Since $\frac{J}{s} = W$, it is just needed to divide $Joules$ by $3600s$ to obtain *Watthours*

Values and numbers describing this calculating scheme are shown in the table 2.

Table 4: P22 – Energy used for acceleration, ride and braking for tram line no. 22 in Prague; 10 stops model.

# stop	**Action**	**E [J]**	**E [kWh]**	**0.8*E [kWh]**	**E [kWh]**	**E [kWh]**	**E [kWh]**
		used/saved energy	*used/saved energy*	*cumulative value of saved energy with 80% re-use*	*energy consumed from grid*	*time evolution of battery charge*	*consumed energy without recuperation*
1	acceleration	4 168 300	1.16	0.00	1.16	30.84	1.16
	ride	-5 574 800	-1.55	-1.24	0.00	32.08	0.00
	braking	-4 083 000	-1.13	-2.15	0.00	**32.99**	0.00
2	acceleration	4 302 900	1.20	-0.95	0.00	31.79	1.20
	ride	10 496 000	2.92	0.00	1.96	28.88	2.92
	braking	-3 386 700	-0.94	-0.75	0.00	29.63	0.00
3	acceleration	4 886 200	1.36	0.00	0.60	28.27	1.36
	ride	7 218 100	2.01	0.00	2.01	26.27	2.01
	braking	-4 149 400	-1.15	-0.92	0.00	27.19	0.00
4	acceleration	4 078 400	1.13	0.00	0.21	26.06	1.13
	ride	-6 819 700	-1.89	-1.52	0.00	27.57	0.00
	braking	-4 693 000	-1.30	-2.56	0.00	28.62	0.00
5	acceleration	3 603 700	1.00	-1.56	0.00	27.61	1.00
	ride	-5 583 300	-1.55	-2.80	0.00	28.86	0.00
	braking	-4 108 100	-1.14	-3.71	0.00	29.77	0.00
6	acceleration	4 253 100	1.18	-2.53	0.00	28.59	1.18
	ride	10 489 000	2.91	0.00	0.38	25.67	2.91
	braking	-3 116 500	-0.87	-0.69	0.00	26.37	0.00
7	acceleration	5 226 100	1.45	0.00	0.76	24.91	1.45
	ride	22 411 000	6.23	0.00	6.23	18.69	6.23
	braking	-2 819 300	-0.78	-0.63	0.00	19.32	0.00
8	acceleration	5 459 000	1.52	0.00	0.89	17.80	1.52
	ride	20 070 000	5.58	0.00	5.58	12.22	5.58
	braking	-3 175 400	-0.88	-0.71	0.00	12.93	0.00
9	acceleration	5 097 700	1.42	0.00	0.71	11.51	1.42
	ride	16 770 000	4.66	0.00	4.66	6.85	4.66
	braking	-3 060 700	-0.85	-0.68	0.00	7.54	0.00
10	acceleration	5 262 300	1.46	0.00	0.78	6.07	1.46
	ride	18 577 000	5.16	0.00	5.16	0.91	5.16
	braking	-3 752 100	-1.04	-0.83	0.00	1.75	0.00
					31.09	**32.00**	**42.32**

In the table 2, there can be seen energy values on each part of the track in Joules and in the 4^{th} column this value is recalculated to Watthours. In the next column, cumulative value of saved energy is shown. In these values 80% energy recovery is expected (as mentioned above). This means, that maximal energy that would be stored in a battery system on this track would be 3.71 kWh. This would be a useful number for calculations considering using catenary system with braking energy recuperation. Here it is shown only for the purpose of further calculations. 6^{th} column shows values of energy, which would be consumed from the grid in such case. What is really important here is 7^{th} column showing the time evolution of battery (dis)charge. Based on this data can be determined necessary volume of the battery. To maintain enough energy in the battery during the whole track, at least 32 kWh capacity battery is needed in the vehicle. Nevertheless, the highest volume of stored energy would be 32.99 kWh. This is the value which must be considered while designing proper energy storage. Finally, in the last column is shown energy which would be necessary to be supplied to the vehicle without re-using braking energy recovery and with catenary system. Generally, it can be expected that using recuperation of braking energy and energy storage allows to spare around 9 kWh on every ride on the examined track. Now it is too early to decide whether it is a lot or not, but one must keep in mind, that resources are not spared only in this energy, but also in not-building of catenary system.

6.3.2 DESIGNING ENERGY STORAGE SYSTEM USING BATTERIES

According to calculated values of energy and according to the fact that this is simulation for catenary-free operation it is clear, that maximum is $E_{max} = 32.99\ kWh \cong 33\ kWh$. To keep some reserve, 40 kWh will be used for further calculations. Now it is necessary to design a battery system which would take this volume.

For this application, after a brief prospecting, LiFePO4 battery, type LT-LYP380, from Russian manufacturer Liotech (Novosibirsk) was chosen. It is described in detail in the table 5. Its parameters are rated voltage 3.2 V, max continuous current 0.5 C (190 V) and capacity 380 Ah.

Minimum number of batteries needed to store $40\ kWh$ is calculated according to the following formula, where $DOD = 0.8$ refers to battery's Depth Of Discharge. This constant takes into account, that the battery cannot be discharged whole to zero, but only to 20% of its capacity.

$$n_{batteries} = \frac{E_{max}}{C_{battery}[Ah] \cdot DOD \cdot U_{rated}} = \frac{40\ 000}{380 \cdot 0.8 \cdot 3.2} = 41.12 \approx 42$$

Table 5: P22 – Battery storage details, first draft.

BATTERIES						
consequential	parallel	total	voltage [V]	current [A]	P [kW]	E [kWh]
			rated voltage 3.2 V	max continuous current 0.5C = 190A		
			=#conseq.*3.2V	=#parallel.*190A		
20	1	20	64	190	12	24
35	1	35	112	190	21	43
50	1	50	160	190	30	61

Now, it is necessary to check voltage and current of such a system and decide whether to connect batteries in parallel, consequently or in a combination of these. It is advisable to maintain voltage around $300 - 600\,V$, because with lower voltage, there would be higher current and therefore higher losses. On the other hand, with higher voltage we would need to use an inverter with power transistors, which are expensive, so this scheme would make the system uneconomical.

Using only consequential interconnection would provide too high voltage and too low capacity, so it is necessary to find a suitable combination of consequential and parallel interconnection.

Because of that, it is necessary to add more parallel branches and by that also increase current. This will lead to increasing not only power, but also energy. Next, total voltage for for example 94 consequently connected batteries is 301 V, which is a minimum desired value. Therefore, increasing power and energy should be done by increasing number of parallel branches, which will increase only current and not voltage.

From the table 5 above it is clear, that using only consequential connection is not advisable, because we reach too low both voltage level and power. As described above, an optimal combination of consequential and parallel connections must be chosen. This is shown in the following table 6.

Also, maximum power must be checked. This is done by checking maximum power value in kW in graph 11. The peak value occurs between 11 000 and 12 000 meters of the track and it reaches approximately 900 kW. This peak value represents necessary power, which is needed to be supplied during acceleration on this part of the track. If it was lower, the tram would not be able to accelerate on the set constant speed. Unfortunately, this fact makes number of batteries skyrocket to crazy numbers. Nevertheless, calculations will be finished with this number to show that the solution of propulsion with batteries only is not the most ideal one.

Table 6: P22 – Final design of the (only) battery storage.

BATTERIES						
consequential	parallel	total	voltage [V] rated voltage 3.2 V =#conseq.*3.2V	current [A] max continuous current 0.5C = 190A =#parallel.*190A	P [kW]	E [kWh]
94	16	1 504	301	3 040	914	1 829
135	11	1 485	432	2 090	903	1 806
165	**9**	**1 485**	**528**	**1 710**	**903**	**1 806**
185	8	1 480	592	1 520	900	1 800

In the table 6 above, there is marked combination of 165 consequently connected batteries in 9 parallel branches. In this scheme desired voltage 528 V is reached together with significantly higher power. Therefore, from adjusted calculation data the best option is to use 9 parallel branches with total number 1485 batteries with 528 V and 1 710 A.

Price of one LiFePO4 battery, type LT-LYP380, from Russian manufacturer Liotech (Novosibirsk) is approximately $ 363 (22 800 rubles, 8 115 CZK) (see the comparison in the table above in chapter 4.1). 1485 batteries are needed, which gives total price 12 050 775 CZK for such a storage system design. The price is quite high, but according to the minimum necessary power there is no other way. It could be possible to lower the expenses by using cheaper batteries with lower capacity, but calculations were done, and the price varies just slightly. Also, calculation was done using retail battery prices, so it can be assumed, that for a serial factory production, it should be possible to negotiate a lower price. For example, while purchasing supercapacitors, price varies according to number of ordered units. Thousand and half per one vehicle is a large amount, so quite high savings could be expected. If it was 30 % of the retail price (considering also tax-free purchase etc.), total price is around 8 500 000 CZK, which seems to be more realistic. Next, since this work assumes catenary-free operation, higher expenses on propulsion and connected devices are justifiable by the fact, that a transport company would spare a fortune on not building this whole catenary background. All these investments can be transferred into battery and propulsion purchase. Considering all above-mentioned facts, designed variant can be considered as optimal and final for the battery storage type.

6.3.3 DESIGNING ENERGY STORAGE SYSTEM USING SUPERCAPACITORS

For storage system based only on supercapacitors a Maxwell BCAP3000 P300 K04 ultracapacitor 3.0 V, 3000F was chosen.

Just as in the previous case, number of such capacitors is calculated by dividing maximum stored energy with capacity of one cell:

$$n_{capacitors} = \frac{E_{max}}{\frac{1}{2 \cdot 3600} C_{cap.}[F] \cdot (0.8 \cdot U_{rated})^2} = \frac{34\,000}{\frac{1}{2 \cdot 3600} \cdot 3000 \cdot (0.8 \cdot 3)^2} = 14\,167$$

Now it is necessary to check some combinations of consequential and parallel interconnections, so that this system has desired values of energy and power, which depends on the voltage and current. Voltage should again fit within an interval $300 - 600\,V$. Knowing rated voltage of one supercapacitor, which is $3.0\,V$, minimum and maximum number of consequently-interconnected supercapacitors can be easily determined – from 100 to 200.

Energy of the designed supercapacitor storage system is calculated as follows.

$$E_S = E_{max} - E_{min} = \frac{1}{2} C V_{max}^2 - \frac{1}{2} C V_{min}^2$$

So, for example for the first setup with 100 serial and 16 parallel interconnections:

$$E_S = \frac{1}{2} \cdot \left[\left(\frac{100}{3000} \right)^{-1} \cdot 16 \right] \cdot (300^2 - (0.2 \cdot 300)^2) \cdot \frac{1}{3600} \cdot \frac{1}{1000} = 5{,}76\ kWh$$

In the table 7, there are shown values for different serial/parallel combinations.

Table 7: P22 – Supercapacitor storage details, first draft.

SUPERCAPACITORS							
serial	parallel	total	voltage [V]	current [A]	P [kW]	C [F]	E [kWh]
			rated voltage 3.0 V	max continuous current 130 A			
			=#conseq.*3 V	=#parallel.*130 A			
100	16	1600	300	2080	624	480	5.76
120	14	1680	360	1820	655	350	6.05
140	12	1680	420	1560	655	257	6.05
160	10	1600	480	1300	624	188	5.76
180	8	1440	540	1040	562	133	5.18
200	6	1200	600	780	468	90	4.32

As it is clearly visible, both power and mainly energy values are extremely low. Low energy values are implied from the physical properties of a capacitor and therefore number of capacitors must be significantly raised. To keep voltage in defined boundaries, the only possibility is to add parallel branches (but this will make current rise also significantly). To reach energy value around desired 34 kWh the options are as follows in the table 8.

Also, minimum power value must be checked. According to the graph 11, maximum peak power reaches values around 900 kW. Naturally, by reaching desired energy volumes sufficient power value is obtained in nearly all presented variants.

Table 8: P22 – Final design of the (only) supercapacitor storage.

SUPERCAPACITORS							
serial	parallel	total	voltage [V]	current [A]	P [kW]	C [F]	E [kWh]
			rated voltage 3.0 V	max continuous current 130 A			
			=#conseq.*3 V	=#parallel.*130 A			
100	95	9500	300	12350	3705	2850	34.20
120	79	9480	360	10270	3697	1975	34.13
140	68	9520	420	8840	3713	1457	34.27
160	59	9440	480	7670	3682	1106	33.98
180	53	9540	540	6890	3721	883	34.34
200	48	9600	600	6240	3744	720	34.56

Knowing that from physical point of view this solution is not a proper one, if a setup should be chosen, a compromise consisting of 160 serial connections in 59 parallel branches (total 9440 BCAP300 units) providing power 3 682 kW (where there is requested limit minimum 900 kW) and energy nearly 34 kWh could be picked.

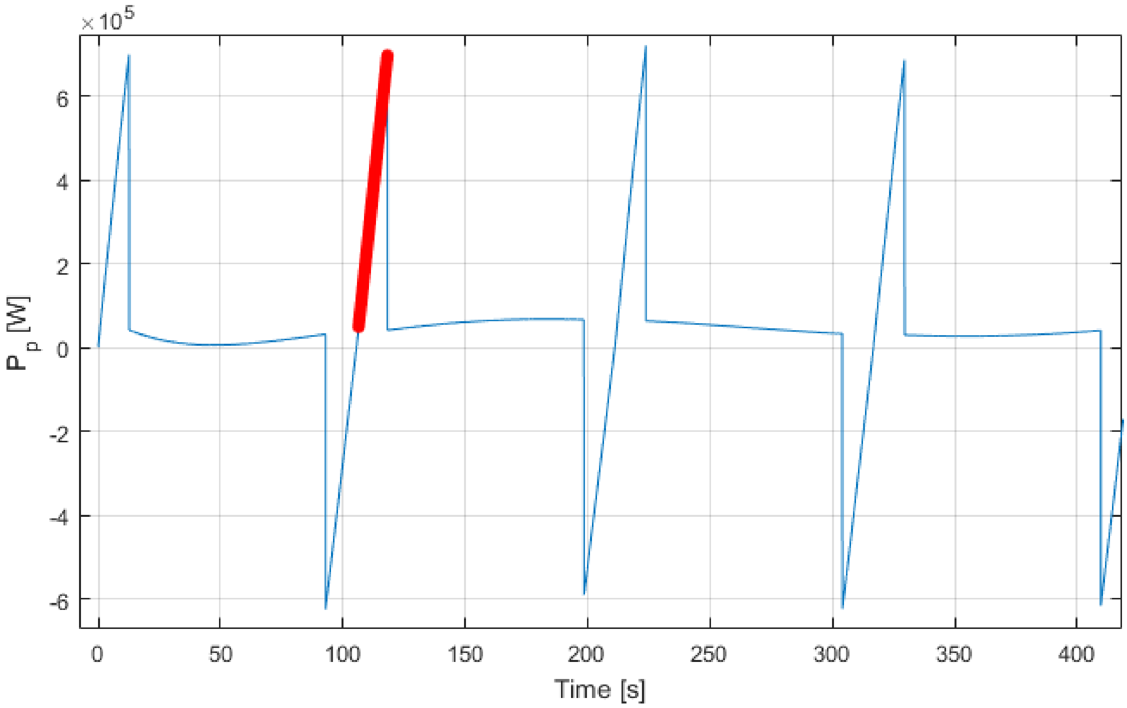
Price of such a storage would be quite high – one supercapacitor costs around 3300 rubles (1170 CZK) [40] in retail prices per unit while purchasing 50 units. Just as before with batteries, it can be assumed, that a lower price could possibly be negotiated while purchasing nearly 10 thousand units. Further argument for lower price is, that the price would be tax-free. From these reasons price around 2300 rubles (800 CZK) could be considered. Using 9440 BCAP3000 supercapacitors gives price of the whole energy storage 7 552 000 CZK.

6.3.4 DESIGNING ENERGY STORAGE SYSTEM USING SUPERCAPACITORS AND BATTERIES

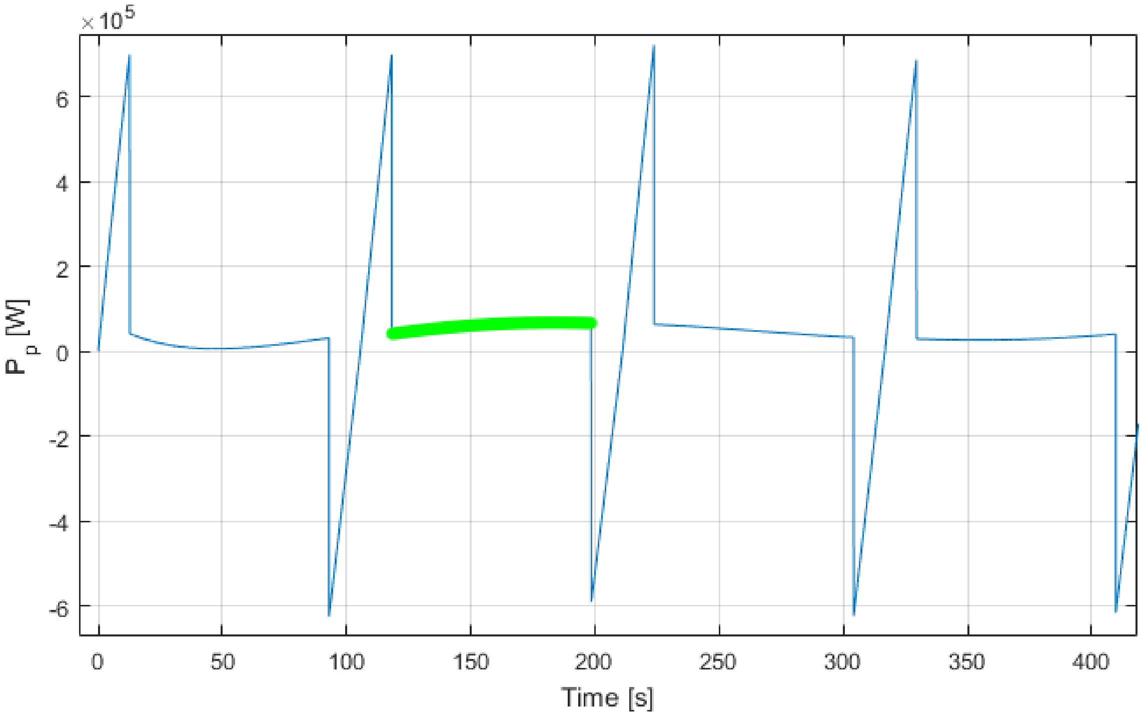
As it is visible from calculations made in previous two subchapters, systems based only on batteries or only on supercapacitors are not an ideal solution. Both have very good advantages, but also disadvantages. This is mainly ratio power/energy, when batteries have good values of energy density, but poor power values, and on the other hand supercapacitors are convenient because of their power density values, but certainly not for stored energy volumes and their price.

Therefore, the best option would be to combine them and create a hybrid system based both on batteries and supercapacitors. Then, supercapacitors could supply engines with power in the peak power demand – mainly for acceleration (see graph 13 – supercapacitors would supply energy represented by the area under the red highlighted curve, which describes accelerating mode). On the other hand, batteries would be used when power demand is more stable and continuous – in the constant speed mode (represented by the green curve in the graph 14).

Graph 13: P22 – Highlighted power for acceleration part of the track.



Graph 14: P22 – Highlighted power for constant speed mode part of the track.



In the following table 9, there are values of energy used separately for acceleration, constant speed mode and saved energy between each two stops with last column presenting data for 80 % of braking energy which could be stored and re-used. Based on the storage volume of supercapacitors and batteries, the highest value is picked, just as described in the previous article.

Table 9: P22 – Values of energy used separately for each part of the ride.

# stop	**acceleration**	**ride**	**saved**	
	E [kWh]	E [kWh]	E [kWh]	80 % E [kWh]
1	1.16	-1.55	-2.68	-2.15
2	1.20	2.92	-0.94	-0.75
3	1.36	2.01	-1.15	-0.92
4	1.13	-1.89	-3.20	-2.56
5	1.00	-1.55	-2.69	-2.15
6	1.18	2.91	-0.87	-0.69
7	1.45	6.23	-0.78	-0.63
8	1.52	5.58	-0.88	-0.71
9	1.42	4.66	-0.85	-0.68
10	1.46	5.16	-1.04	-0.83

SUPERCAPACITOR STORAGE

Supercapacitor storage will supply energy in peak power demands, which is acceleration and reaching desired constant speed after every stop. Designing this will be done just as in the previous chapters.

For this work it is considered, that energy saved from braking is used for supercapacitor charging only, because its faster than charging batteries thus more efficient. Battery pack would be fully charged before tram starts its ride and its capacity would be derived from the data in the table above.

In the following table 10 minimal necessary capacity of supercapacitor storage is calculated easily. From this data comes a value of 4.0 kWh, which is calculated in such a way, that 80 % of stored energy from the last column of the previous table 9 is added to the actual capacity of supercapacitor and value of energy necessary for acceleration is subtracted from this value. By keeping the value positive during all ride, minimal capacity value is set. To maintain at least 2.37 kWh of the supercapacitor system charged (which is enough to accelerate on any part of the track), value 4.0 kWh was reached.

Table 10: P22 – Calculation of minimal necessary supercapacitor storage capacity.

# stop	**acceleration**	**80 % of braking energy**	**energy in supercapacitors**
	E [kWh]	E [kWh]	E [kWh]
1	1.16	-2.15	-2.84
2	1.20	-0.75	-3.79
3	1.36	-0.92	-3.19
4	1.13	-2.56	-2.98
5	1.00	-2.15	-4.53
6	1.18	-0.69	-5.51
7	1.45	-0.63	-4.75
8	1.52	-0.71	-3.86
9	1.42	-0.68	-3.15
10	1.46	-0.83	-2.37
minimum total			-4.00

The design of supercapacitor storage will be made in the same way as in the previous subchapter. Also, completely the same supercapacitors Maxwell BCAP3000 P300 K04 ultracapacitor 3.0 V, 3000F are used for construction of this storage to reach better and more relevant comparison results through all examined variants. With respecting voltage limits, possible options are in the following table 11.

Table 11: P22 – Design of the supercapacitor part of the hybrid energy storage system.

SUPERCAPACITORS							
serial	parallel	total	voltage [V]	current [A]	P [kW]	C [F]	E [kWh]
			rated voltage 3.0 V	max continuous current 130 A			
			=#conseq.*3 V	=#parallel.*130 A			
111	10	1110	333	1300	433	270	4.00
159	**7**	**1113**	**477**	**910**	**434**	**132**	**4.01**
185	6	1110	555	780	433	97	4.00

The middle option using 1113 supercapacitor units in 159 serial and 7 parallel connections seems to be the most convenient one. Voltage 477 V is completely enough as well as capacity 4.01 kWh and power 434 kW.

Considering the same price 800 CZK per one supercapacitor unit as described in the previous subchapter 5.3.3, total price of this storage consisting of 1113 BCAP3000 supercapacitors is 890 400 CZK. This is significantly more acceptable number than 7.5 million CZK for a storage made only of supercapacitors.

BATTERY STORAGE

This “hybrid” case will be calculated considering using the same battery type LiFePO4 battery, type LT-LYP380, rated voltage 3.2 V, max continuous current 0.5 C (190 V) and capacity 380 Ah, by Liotech, Novosibirsk, just as in the previous subchapter. Again, this will help to compare all storage types which were investigated in a more illustrative way.

To design a battery storage type, sum of all consumed energy on every constant speed mode part of the track is made. The values are shown in the table 12 below.

Table 12: P22 – Total consumed energy on every part of the track.

# stop	**ride**
	E [kWh]
1	0.00
2	2.92
3	2.01
4	0.00
5	0.00
6	2.91
7	6.23
8	5.58
9	4.66
10	5.16
total	29.45

This gives total minimum necessary energy stored in battery storage 29.45 kWh. To keep some reserve, value 35 kWh will be used for further calculations. Now it is possible to proceed to battery system calculations.

Minimum number of batteries to store 65 kWh is again calculated according to the following formula:

$$n_{batteries} = \frac{E_{max}}{C_{battery}[Ah] \cdot DOD \cdot U_{rated}} = \frac{35\ 000}{380 \cdot 0.8 \cdot 3.2} = 35.98 \approx 36$$

Nevertheless, this number can change according to the construction type of the battery pack – combination of serial and parallel connections – and, also, according to required limits for voltage and current.

Next, voltage and current check must be made to keep both values in desirable limits. By doing this, it can be decided of how many parallel and serial branches system must consist. Voltage limit is again between $300 - 600\ V$.

Calculated combinations showing each design's parameters – voltage, current, power and energy – are shown in the table 13. Recalculations as in the previous cases are not shown anymore, because the steps and logical construction of the design is still the same.

Table 13: P22 – Design of the battery part of the hybrid energy storage system.

BATTERIES						
consequential	parallel	total	voltage [V]	current [A]	P [kW]	E [kWh]
			rated voltage 3.2 V	max continuous current 0.5C = 190A		
			=#conseq.*3.2V	=#parallel.*190A		
100	3	300	320	570	182	365
130	2	260	416	380	158	316
160	**2**	**320**	**512**	**380**	**195**	**389**
180	2	360	576	380	219	438

In this "hybrid" design, power for acceleration is performed by supercapacitors. On this part of the ride the highest power is needed thus there are significantly lower demands on battery storage power values than while using battery storage only (because in this case it provides propulsion only on constant speed mode of the track). Thanks to this fact it is possible to lower the amount of used batteries. Choosing middle variant provides enough power as well as energy.

Just as in the previous case, where only battery or supercapacitor storage was considered, maximum energy value must be checked – to do so, see graph 11. Peak value reached by green colour highlighted fit function (without its positive and negative peaks, because batteries are expected to cover power demand from constant speed mode only) must be chosen. This is somewhere between distance 11 000 and 12 000 m in the graph and the value is around $200\,kW$, which corresponds to power values shown in graph 11 above.

From the table 13 the variant with 160 batteries connected in series in 2 parallel branches is the optimal one. Total number of battery cells in such a construction is 320. It provides voltage and current in desired boundaries as well as required power and energy values together with minimized number of batteries.

Full price per unit of LiFePO4 battery, type LT-LYP380 is again \$ 363. Using 320 units in presented design gives total price \$ 116 160, which is approximately 2 600 000 CZK. Following the same assumption as before, with expected 30 % savings, the value lowers to 1 820 000 CZK.

HYBRID SOLUTION SUMMARY

To sum this solution up, hybrid variant of the propulsion looks like follows in the table 14. It is compiled of 320 batteries and 1113 supercapacitors.

Table 14: P22 – Summary of designs of supercapacitor and battery energy storage.

SUPERCAPACITORS							
serial	*parallel*	*total*	*voltage [V]*	*current [A]*	*P [kW]*	*C [F]*	*E [kWh]*
159	7	1113	477	910	434	132	4.01
BATTERIES							
160	2	320	512	380	194.56	n/a	389.12

6.3.5 COST ANALYSIS

In the previous chapters, three different types of energy storage and propulsion were presented and calculated. The summary presenting costs of each variant is shown in the table 15 below. As expected, the best variant is not only technically and physically, but also economically the hybrid one.

Table 15: P22 – Costs of investigated variants.

	quantity		**price [CZK]**	
			per unit	total
battery	1 485		5 681	8 435 543
supercap	9 440		800	7 552 000
	battery	*supercap*		
hybrid	320		5 681	2 708 160
		1113	800	

To decide, whether the hybrid variant is economically effective or not, several steps must be made. First, it is necessary to add all the other features for this system. This system needs a converter which could be used both with supercapacitor and battery system with appropriate power. It is quite difficult to set a price of this item, but according to other works and internet search, for this work, the cost of converter is estimated on 500 000 CZK. Concerning human labour, costs are neglected, because it is assumed, that a brand-new tram is purchased. That is why just costs for this exact type of energy storage are considered. This makes final costs for such a design 3 208 160 CZK.

From this value, savings made by not-building catenary system should be subtracted. This is probably the most difficult approximation, because it is quite complicated to find relevant data how much does 1 km of catenary system cost. It will be assumed, that (also according to [41]) the costs are 1000 CZK per 1 meter of the catenary system in urban area, which gives 1 000 000 CZK per kilometre. The length of the track of the tram no. 22 is approximately 21 kilometres, which means, that costs to build power supply line would be 21 000 000 CZK. It is necessary to mention, that this is just a gross estimation. Because of this, it could be advised to stay conservative and therefore this estimation will be raised by a coefficient 1,5. Also, nowadays it is a rule that infrastructure constructions rarely reach the pre-estimated costs. This gives total 31 500 000 CZK.

These costs for building completely new catenary system will be now divided between all the tram vehicles, which would serve this track. Since a ride in one direction from the beginning to the final stop takes 63 minutes and, in the morning, where there is a peak transport time, there are 6-8 trams in one hour, this gives approximately 15-17 trams on the track at one moment (maximum). [42]. To make the estimation conservative, 20 trams will be considered as necessary to serve this track (including reserves, necessary repairs etc.). If the cost of a catenary system is divided between all 20 trams, it gives savings 1 575 000 CZK per one vehicle. This value will be subtracted from the purchase price of the energy storage system.

Next savings are on electricity. From the table 4 it is visible, that energy demands of a tram on this track are 42 kWh. In the same table, there is marked consumption 31.09 kWh. This is a consumption, which would be taken from the outer grid (catenary system) in case of re-using energy from braking, but without using energy storage system for the whole track. This shows, that 10.91 kWh is spared on every ride from the beginning to the final stop on this track. To asses this savings in money, data for price per kWh consumed by tram in Prague is necessary. This is quite difficult to find, because it is not an information which would be easily accessible for public. Nevertheless, according to press release [43] from 2012 and according to a document which was released due to law about publicly accessible information, it can be found, that the total consumption of Dopravní podnik hlavního města Prahy (Transport company of the capital Prague) in 2012 was 370 GWh with cost 996 646 000 CZK. This gives price 2.69 CZK/kWh. According to the trend of electricity price [44] since 2012, it can be assumed, that in 2019 the price is the same. The calculation of saving is done as follows:

$$savings\ per\ tram\ per\ year = \frac{190 \times 10.91 \times 2.69}{20} \cdot 365 = 101\ 764\ CZK,$$

where 190 stands for the number of all rides made on the track during one ordinary day in both directions, 10.91 is saved energy in kWh (calculating this number is described above), 2.69 is the price in CZK per kWh, division by 20 represents 20 trams operating on this track and multiplication by 365 recalculates this to annual values.

Given reasoning leads to annual savings on electricity costs per one tram 101 764 CZK.

Now it is possible to investigate cash flows during whole lifetime of this investment and based on this decide, whether this project is economically viable. Net present value (NPV) will be the main criterion for making the decision. Next, value of internal rate of return (IRR) will be calculated and sensitivity analysis will be presented in the end.

Key element of following calculations is lifetime of the investment. Due to type of the project, lifetime will be set to 15 years. It may be quite a conservative estimation, but regarding fact, that the core of the project is a battery storage, which has limited number of recharging cycles, it does not have to be necessarily out of scope. Other features of the designed system may serve without large (re)investments significantly longer – probably up to 30 years. Service and repair costs can be neglected, because compared to the value of the initial investments they are marginal (supposing no big crash happens).

Next thing to define before calculations, is a discount rate. It is difficult to set a constant value, and that is why this will be done by sensitivity analysis for the interval between 2-10 % and results will be interpreted. These values are also consistent with discount rate presented in [45].

Results for the variant with lifetime 15 years and discount rates 2.5, 5.0, 7.5 and 10.0 % are presented in the table 16 below. The project with these parameters could not be recommended for realisation in any of its variant, because NPV values are negative in all cases. Concerning IRR, it is not possible to calculate it, because its value shall be negative as well, but we cannot reach negative discount rate. Considering nature of the project, it could possibly happen, that there would be some subsidy (European Union, government, etc.). This could turn the numbers into black, because NPV for quite realistic discount rate 5 % is -576 886 CZK and with investment partly financed (lower tens percentages) by subsidy, this could improve significantly. But this is just a consideration, since it is not the aim of this work.

Table 16: P22 – Cost analysis calculations for lifetime 15 years and different discount rate values.

year		0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
investment		-1 633 160															
CF			101 764	101 764	101 764	101 764	101 764	101 764	101 764	101 764	101 764	101 764	101 764	101 764	101 764	101 764	101 764
	discount rate																
DCF	*2.50 %*	-1 633 160	99 282	96 860	94 498	92 193	89 944	87 751	85 610	83 522	81 485	79 498	77 559	75 667	73 822	72 021	70 264
cumulative		-1 633 160	-1 533 878	-1 437 018	-1 342 520	-1 250 327	-1 160 383	-1 072 632	-987 022	-903 499	-822 014	-742 516	-664 958	-589 290	-515 469	-443 448	-373 183
NPV		**-373 183**															
DCF	*5.00 %*	-1 633 160	96 918	92 303	87 907	83 721	79 735	75 938	72 322	68 878	65 598	62 474	59 499	56 666	53 968	51 398	48 950
cumulative		-1 633 160	-1 536 242	-1 443 939	-1 356 032	-1 272 310	-1 192 576	-1 116 638	-1 044 316	-975 439	-909 841	-847 367	-787 867	-731 201	-677 234	-625 836	-576 886
NPV		**-576 886**															
DCF	*7.50 %*	-1 633 160	94 664	88 060	81 916	76 201	70 884	65 939	61 339	57 059	53 078	49 375	45 930	42 726	39 745	36 972	34 393
cumulative		-1 633 160	-1 538 496	-1 450 436	-1 368 521	-1 292 320	-1 221 435	-1 155 496	-1 094 157	-1 037 098	-984 020	-934 645	-888 714	-845 988	-806 243	-769 271	-734 878
NPV		**-734 878**															
DCF	*10.00 %*	-1 633 160	92 513	84 102	76 457	69 506	63 187	57 443	52 221	47 474	43 158	39 234	35 668	32 425	29 477	26 798	24 361
cumulative		-1 633 160	-1 540 647	-1 456 545	-1 380 088	-1 310 582	-1 247 395	-1 189 952	-1 137 731	-1 090 257	-1 047 100	-1 007 865	-972 198	-939 773	-910 295	-883 498	-859 136
NPV		**-859 136**															
DCF [IRR %]	*0.00 %*	-1 633 160	101 764	101 764	101 764	101 764	101 764	101 764	101 764	101 764	101 764	101 764	101 764	101 764	101 764	101 764	101 764
cumulative		-1 633 160	-1 531 396	-1 429 632	-1 327 868	-1 226 105	-1 124 341	-1 022 577	-920 813	-819 049	-717 285	-615 522	-513 758	-411 994	-310 230	-208 466	-106 702
NPV		**-106 702**															

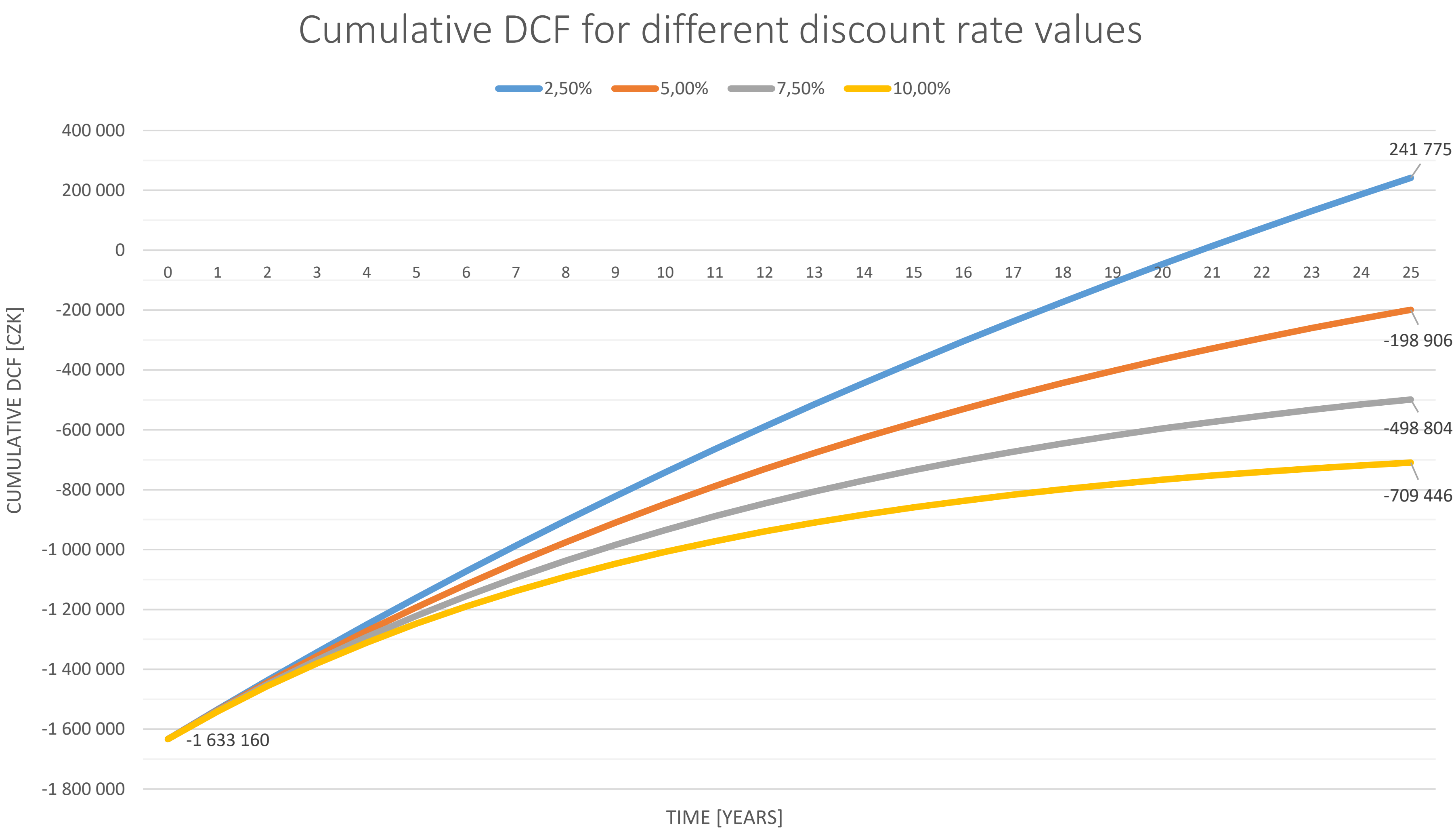
To find conditions, under which this project would turn viable, lifetime will be prolonged to 25 years. These calculations are shown in the table 17 below. As described two and three pages above, this estimation is not an unrealistic one, the only question is how much capacity will lose battery storage after this period. It must be admitted, that it could be quite a relevant number, but some reserve was added during design calculations and this reasoning is mainly to show how costs of this investments differs under changing conditions.

After condition's adjustment, the results have changed to some extent. Positive NPV value was obtained only for discount rate 2.5 %, for 5.0, 7.5 and 10.0 % it remains negative. The turning point of discount rate is 3.75 % (which is IRR), where NPV value equals zero. Therefore, if an investor would be able to reach discount rate 3.75 % or lower, the investment to catenary-free operating trams with its own hybrid (battery and supercapacitor) energy storage would be profitable. This is shown in the graph 15 below. Unfortunately, such a low discount rate is rather unreal to reach in this business field – values around 5-7 % could be a realistic estimation. Thus, this investment is (under presented conditions and with given reasoning) not profitable now. On the other hand, if some features would change a little bit, it is advised to re-check results and make a new decision, because a field of energy storage is a subject to vast innovations and rapid changes.

Table 17: P22 – Cost analysis calculations for lifetime 25 years and different discount rate values.

year		0	1	2	3	4	5	....	18	19	20	21	22	23	24	25
investment		-1 633 160														
CF			101 764	101 764	101 764	101 764	101 764	....	101 764	101 764	101 764	101 764	101 764	101 764	101 764	101 764
	discount rate															
DCF	*2.50 %*	-1 633 160	99 282	96 860	94 498	92 193	89 944	....	65 248	63 656	62 104	60 589	59 111	57 669	56 263	54 890
cumulative		-1 633 160	-1 533 878	-1 437 018	-1 342 520	-1 250 327	-1 160 383	....	-172 507	-108 850	-46 747	13 842	72 953	130 622	186 885	241 775
NPV		**+241 775**														
DCF	*5.00 %*	-1 633 160	96 918	92 303	87 907	83 721	79 735	....	42 285	40 271	38 354	36 527	34 788	33 131	31 554	30 051
cumulative		-1 633 160	-1 536 242	-1 443 939	-1 356 032	-1 272 310	-1 192 576	....	-443 583	-403 311	-364 958	-328 430	-293 642	-260 511	-228 957	-198 906
NPV		**-198 906**														
DCF	*7.50 %*	-1 633 160	94 664	88 060	81 916	76 201	70 884	....	27 685	25 753	23 957	22 285	20 730	19 284	17 939	16 687
cumulative		-1 633 160	-1 538 496	-1 450 436	-1 368 521	-1 292 320	-1 221 435	....	-645 439	-619 686	-595 729	-573 444	-552 714	-533 430	-515 491	-498 804
NPV		**-498 804**														
DCF	*10.00 %*	-1 633 160	92 513	84 102	76 457	69 506	63 187	....	18 303	16 639	15 127	13 751	12 501	11 365	10 332	9 392
cumulative		-1 633 160	-1 540 647	-1 456 545	-1 380 088	-1 310 582	-1 247 395	....	-798 553	-781 914	-766 787	-753 036	-740 534	-729 170	-718 838	-709 446
NPV		**-709 446**														
DCF [IRR %]	*3.75 %*	-1 633 160	98 089	94 546	91 131	87 840	84 668	....	52 486	50 590	48 763	47 002	45 304	43 668	42 091	40 571
cumulative		-1 633 160	-1 535 071	-1 440 525	-1 349 394	-1 261 554	-1 176 886	....	-317 990	-267 400	-218 637	-171 635	-126 330	-82 662	-40 571	0
NPV		**0**														

Graph 15: P22 – Cumulative discounted cash flow values for different discount rate values.



6.4 SIMULATION FOR TOMSK TRAM LINE no. 1

As mentioned in the beginning of the work, simulations are done for two tram lines in different cities. This subchapter contains similar calculations to these, which were done in case of Prague’s tram line. Basic scheme of calculation and calculation steps are the same as before, so the description is not that exhausting as in previous example. Therefore, in case of a problem with interpreting the data, previous chapter provides deeper analysis.

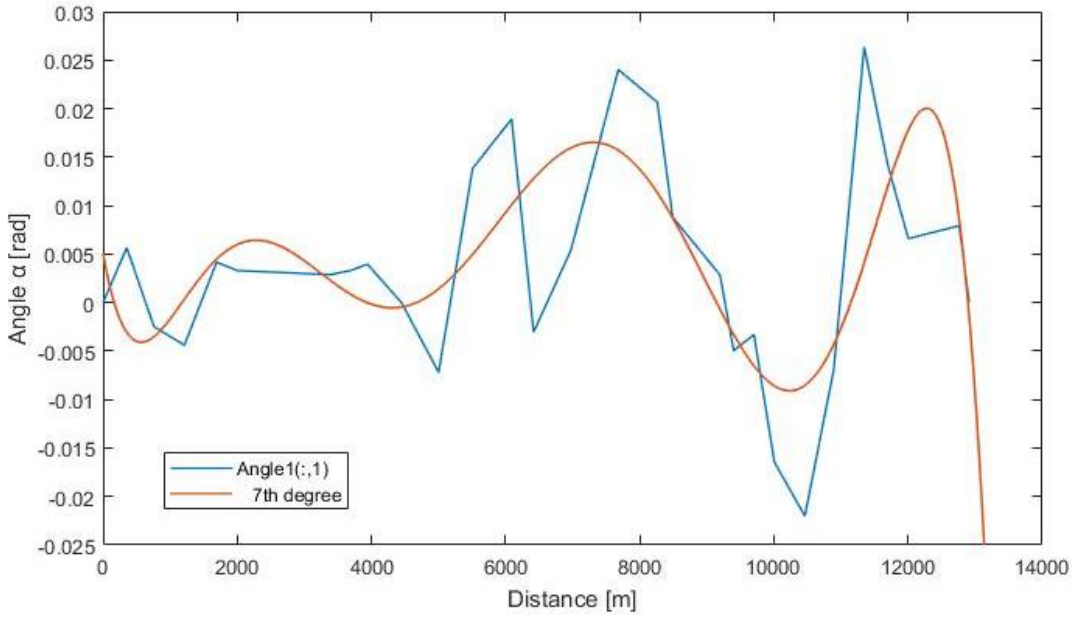
6.4.1 CALCULATIONS AND DATA

Since the step sequence is basically the same as for previous calculations, it will be kept in the same order.

First, altitude profile of investigated tram line is needed to start the calculations. Again, distance and altitude data were used to calculate inclination angle α, just as described in the chapter 5.1.3.

Deviation of this angle from flat line $\alpha = 0\, rad$ is shown in the following graph 12.

Graph 16: T1 – Inclination angle α describing altitude profile of the track and fit function g(x).



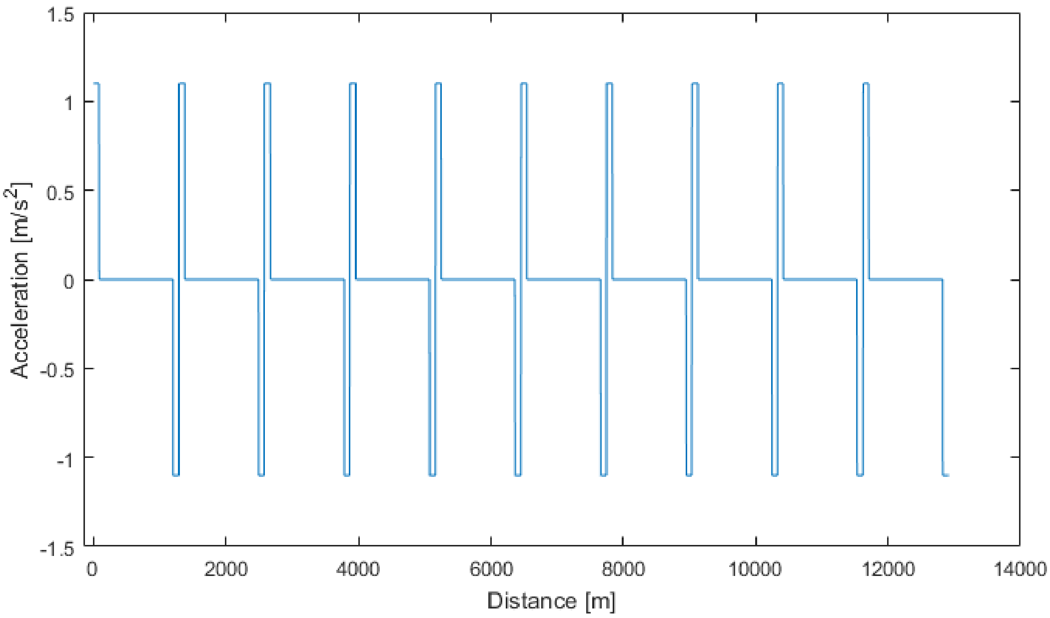
Obtained angle values were fitted with a 7th degree polynomial function:

$$g\ (x) = -1.0777 \cdot 10^{-27} \cdot x^7 + 4.6487 \cdot 10^{-23} \cdot x^6 - 7.8014 \cdot 10^{-19} \cdot x^5 + $$
$$+ 6.4212 \cdot 10^{-15} \cdot x^4 - 2.6848 \cdot 10^{-11} \cdot x^3 + 5.314 \cdot 10^{-8} \cdot x^2 - $$
$$- 3.8727 \cdot 10^{-5} \cdot x + 0.0050538$$

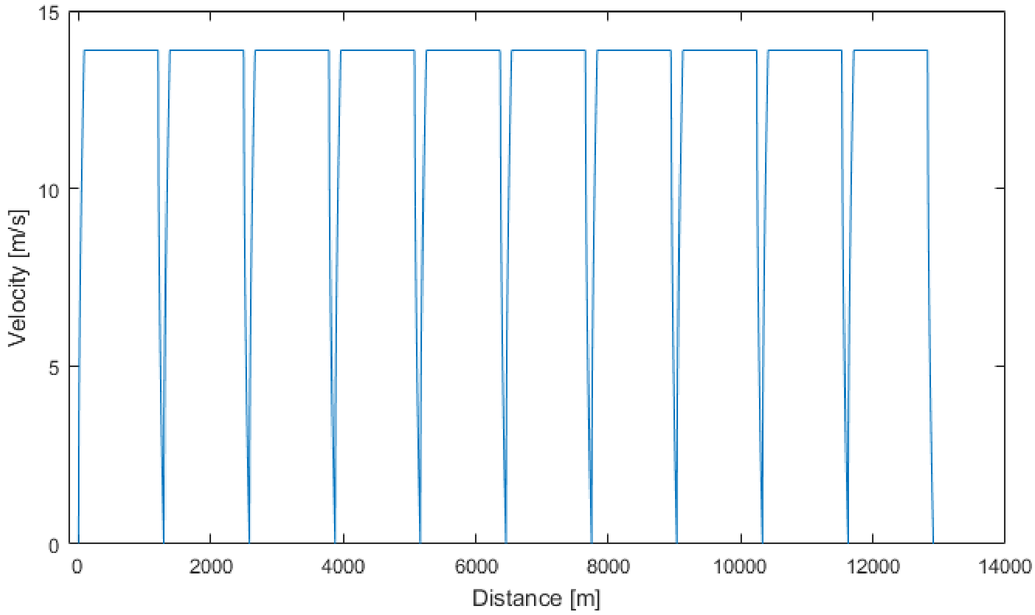
This fit function $g\ (x)$ was again obtained using all the available data, to reach high accuracy. But further calculations are again based on 10 fictional stops, just as in the previous case.

Acceleration on the track looks basically the same as before, just with other distance, and it is shown on the graph 13. The same values for acceleration and deceleration $a = \pm 1.1\, m/s^2$ are used, as well as maximum velocity $v = 14\, m/s$. Velocity is shown in the graph 14.

Graph 17: T1 – Acceleration and deceleration depending on distance.

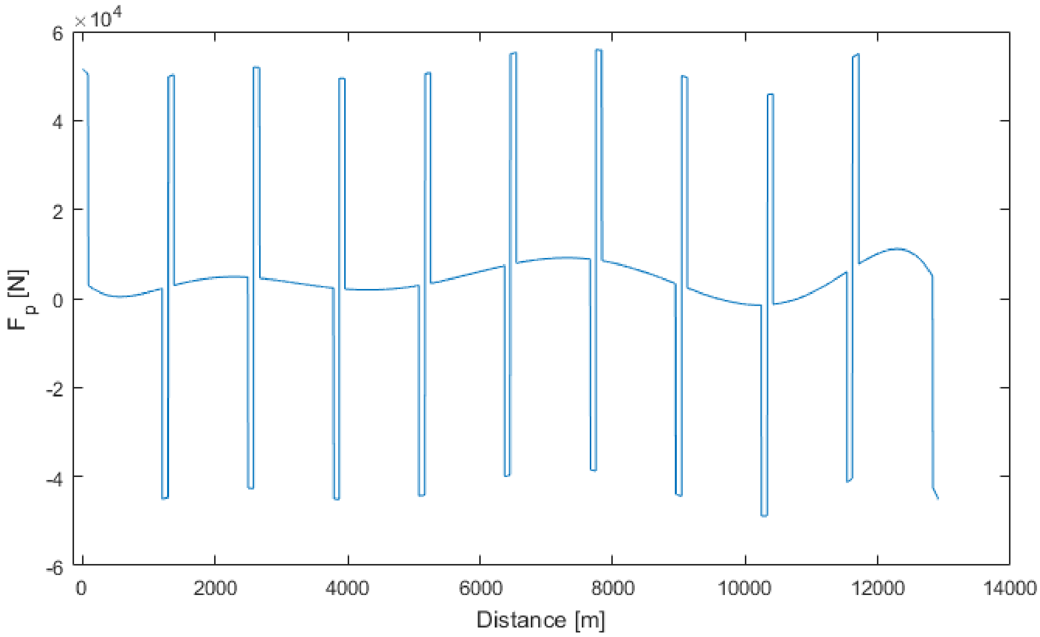


Graph 18: T1 – Velocity depending on distance.



With given data and knowing theoretical physical background, forces necessary to accelerate or brake the tram while approaching the tram stop are calculated. This force is shown in the graph 15

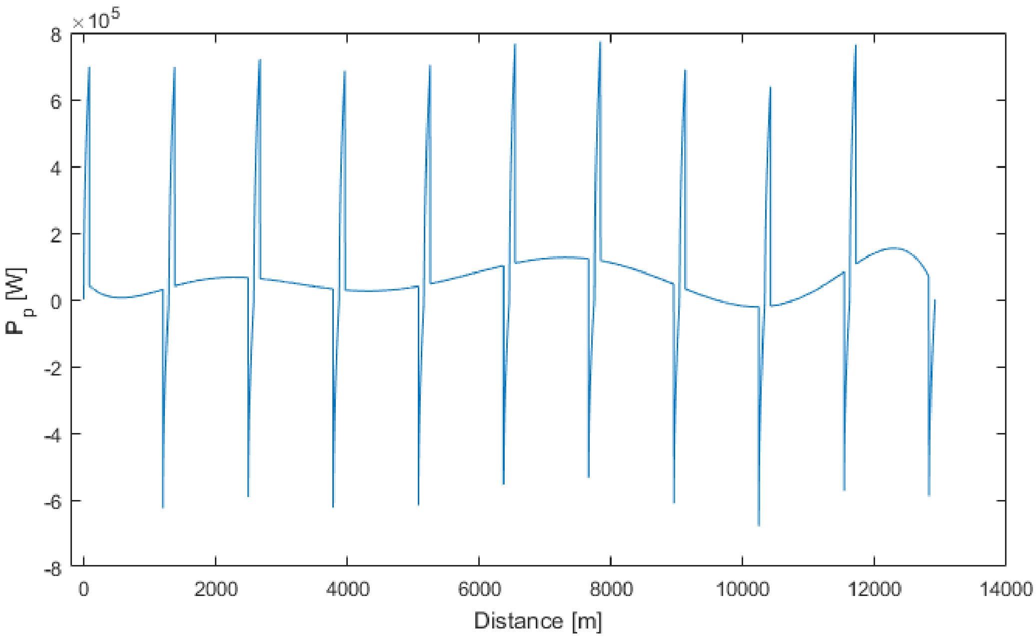
Graph 19: T1 – Force needed to be supplied or and to be possibly stored.



Now it is possible to proceed to calculation of power. Again, power is calculated by multiplying force and velocity.

In the graph 16, there is shown power P_p depending on distance.

Graph 20: T1 – Power needed to be supplied and to be possibly stored.



Now it is possible to calculate consumed power and power which could be stored. It is done just as before – using integral function, which calculates the area below the graph, which represents the power. Again, 80% of braking energy is spared and reused. Values are shown in the following table 18.

Table 18: T1 – Energy used for acceleration, ride and braking for tram line no. 1 in Tomsk; 10 stops model.

# stop	Action	E [J]	E [kWh]	0.8*E [kWh]	E [kWh]	E [kWh]	E [kWh]
		used/saved energy	*used/saved energy*	*cumulative value of saved energy with 80% re-use*	*energy consumed from grid*	*time evolution of battery charge*	*consumed energy without recuperation*
1	acceleration	4 462 500	1.24	0.00	1.24	18.76	1.24
	ride	1 302 300	0.36	0.00	0.36	18.40	0.36
	braking	-3 943 600	-1.10	-0.88	0.00	19.28	0.00
2	acceleration	4 390 000	1.22	0.00	0.34	18.06	1.22
	ride	4 836 700	1.34	0.00	1.34	16.71	1.34
	braking	-3 730 100	-1.04	-0.83	0.00	17.54	0.00
3	acceleration	4 550 400	1.26	0.00	0.44	16.28	1.26
	ride	3 867 700	1.07	0.00	1.07	15.20	1.07
	braking	-3 942 400	-1.10	-0.88	0.00	16.08	0.00
4	acceleration	4 335 500	1.20	0.00	0.33	14.87	1.20
	ride	2 426 500	0.67	0.00	0.67	14.20	0.67
	braking	-3 887 000	-1.08	-0.86	0.00	15.06	0.00
5	acceleration	4 433 000	1.23	0.00	0.37	13.83	1.23
	ride	5 983 900	1.66	0.00	1.66	12.17	1.66
	braking	-3 495 500	-0.97	-0.78	0.00	12.95	0.00
6	acceleration	4 828 700	1.34	0.00	0.56	11.61	1.34
	ride	9 834 300	2.73	0.00	2.73	8.87	2.73
	braking	-3 374 900	-0.94	-0.75	0.00	9.62	0.00
7	acceleration	4 895 900	1.36	0.00	0.61	8.26	1.36
	ride	6 925 900	1.92	0.00	1.92	6.34	1.92
	braking	-3 861 100	-1.07	-0.86	0.00	7.20	0.00
8	acceleration	4 372 200	1.21	0.00	0.36	5.98	1.21
	ride	-148 380	-0.04	-0.03	0.00	6.02	0.00
	braking	-4 278 800	-1.19	-0.98	0.00	6.97	0.00
9	acceleration	4 022 000	1.12	0.00	0.13	5.85	1.12
	ride	1 725 800	0.48	0.00	0.48	5.37	0.48
	braking	-3 607 100	-1.00	-0.80	0.00	6.17	0.00
10	acceleration	4 784 000	1.33	0.00	0.53	4.84	1.33
	ride	10 659 000	2.96	0.00	2.96	1.88	2.96
	braking	-3 752 600	-1.04	-0.83	0.00	2.72	0.00
					18.12	**20.00**	**25.73**

Just as in the previous case in Prague, from the physical model from written script in MATLAB (see Appendix 2), various energy values were obtained.

Again, the most important is 7^{th} column of the table 18, which shows time evolution of storage's (dis)charge. To maintain enough energy for propulsion in the storage, minimal necessary volume of this storage must be at least 20 kWh. With this value, a tram can pass through whole track with keeping at least 1.88 kWh of energy still stored.

In the last column energy taken from the grid in case of no recuperation is showed. This means that in average a tram riding through this "laboratory" track could spare around 7 kWh on one ride in one direction.

6.4.2 DESIGNING ENERGY STORAGE SYSTEM USING SUPERCAPACITORS AND BATTERIES

Calculations for energy storage device for this example will be done just for "hybrid" storage consisting of battery and supercapacitor storage, because in previous chapters, for Prague tram case, results were clear, since they showed, that any other energy storage type is uneconomical.

In the table 19, values of energy for different types of ride are shown together with 80 % of braking recuperated energy.

Table 19: T1 – Values of energy used separately for each part of the ride.

# stop	**acceleration**	**ride**	**saved**	
	E [kWh]	E [kWh]	E [kWh]	80%
1	1.24	0.36	-1.10	-0.88
2	1.22	1.34	-1.04	-0.83
3	1.26	1.07	-1.10	-0.88
4	1.20	0.67	-1.08	-0.86
5	1.23	1.66	-0.97	-0.78
6	1.34	2.73	-0.94	-0.75
7	1.36	1.92	-1.07	-0.86
8	1.21	-0.04	-1.23	-0.98
9	1.12	0.48	-1.00	-0.80
10	1.33	2.96	-1.04	-0.83

SUPERCAPACITOR STORAGE

It is again assumed, that this storage will supply power only in acceleration mode. Reasons are described in the article 6.3.4.

In the table 20, minimal necessary capacity of supercapacitor storage is calculated. The value is slightly higher than it was in Prague, 6.5 kWh.

Table 20: T1 – Calculation of minimal necessary supercapacitor storage capacity.

# stop	**acceleration**	**80 % of braking energy**	**energy in supercapacitors**
	E [kWh]	E [kWh]	E [kWh]
1	1.24	-0.88	-5.26
2	1.22	-0.83	-4.92
3	1.26	-0.88	-4.48
4	1.20	-0.86	-4.15
5	1.23	-0.78	-3.79
6	1.34	-0.75	-3.22
7	1.36	-0.86	-2.61
8	1.21	-0.98	-2.26
9	1.12	-0.80	-2.12
10	1.33	-0.83	-1.59
minimum total			-6.50

Still the same supercapacitors BCAP3000 from Maxwell are intended for use. Chosen combination is shown in the table 21. The middle option is chosen as the most suitable one regarding voltage, power and energy values.

Table 21: T1 – Design of the supercapacitor part of the hybrid energy storage system.

SUPERCAPACITORS							
serial	parallel	total	voltage [V]	current [A]	P [kW]	C [F]	E [kWh]
			rated voltage 3.0 V	max continuous current 130 A			
			=#conseq.*3 V	=#parallel.*130 A			
103	20	2060	309	2600	803	583	7.42
158	**13**	**2054**	**474**	**1690**	**801**	**247**	**7.39**
187	11	2057	561	1430	802	176	7.41

With the price of one supercapacitor 800 CZK (see subchapter 5.3.3), costs on designed storage are 1 643 200 CZK.

BATTERY STORAGE

Assumptions for battery storage are still the same, while LiFePO4 battery, type LT-LYP380 are used again.

Sum of total used energy on each ride part of the track is presented in the table 22. According to this, at least 13.21 kWh capacity of the battery energy storage is needed. Minimum will be raised to at least 20 kWh to keep some reserve, but due to power demands on the storage, final value will be much higher.

Table 22: T1 – Total consumed energy on every part of the track.

# stop	**ride**
	E [kWh]
1	0.36
2	1.34
3	1.07
4	0.67
5	1.66
6	2.73
7	1.92
8	0.00
9	0.48
10	2.96
total	13.21

Setup of the battery storage for this case is chosen from the table 23 below. 3rd variant is taken as the most optimal one, where all the conditions are fulfilled.

Table 23: T1 – Design of the battery part of the hybrid energy storage system.

BATTERIES						
consequential	parallel	total	voltage [V]	current [A]	P [kW]	E [kWh]
			rated voltage 3.2 V	max continuous current 0.5C = 190A		
			=#conseq.*3.2V	=#parallel.*190A		
100	3	300	320	570	182	365
120	2	240	384	380	146	292
145	2	290	464	380	176	353
180	2	360	576	380	219	438

Total number of batteries is 290, which, at assumed lowered price 5 681 CZK per piece, gives 1 647 490 CZK.

HYBRID SOLUTION SUMMARY

Merging two types of storages together gives final variant as follows in the table 24.

SUPERCAPACITORS							
serial	*parallel*	*total*	*voltage [V]*	*current [A]*	*P [kW]*	*C [F]*	*E [kWh]*
158	13	2054	474	1690	801	247	7.39
BATTERIES							
145	2	290	464	380	176	n/a	353

6.4.3 COST ANALYSIS

Costs of this hybrid storage are presented together by supercapacitor storage cost 1 643 200 CZK and by battery storage cost 1 647 490 CZK. This gives 3 290 690 CZK. Estimating purchase of supplementary features at cost 500 000 CZK, value 3 790 690 CZK is reached.

Assessing costs on (not) building catenary system at this case is even more difficult than in Prague. In Russian Federation, costs should be lower with high probability. But to guess how much a very difficult question is. Generally, compared to the Czech Republic, it can be assumed, that prices are approximately 15-20 % lower. This leads to very general approximation of costs 800 000 CZK per 1 kilometre of the catenary system. Since the length of the track number 1 in Tomsk is almost 13 kilometres, total costs will be estimated (also considering 1,5 raising coefficient) and rounded at 15 000 000 CZK.

One ride in one direction takes approximately 60 minutes, while maximum number of trams on the track at one moment will be assumed 15. This is slightly less than in Prague, because Tomsk tram network is not the primary city transport mean. By dividing savings from not-building catenary system between all trams, 1 000 000 CZK is obtained.

Second savings are electricity costs. Total energy demand on this track is 25.73 kWh, which is shown in the table 18. In the same table, in the 6th column, there is marked consumption 18.12 kWh. This is a consumption, which would be taken from the outer grid (catenary system) in case of re-using energy from braking, but without using energy storage system for the whole track. This shows, that 7.61 kWh is spared on every ride from the beginning to the final stop on this track. To find price per 1 kWh in Tomsk a brief search was done, and it could be possibly estimated around 3 roubles (approximately 1 CZK) per kWh [46] [47], which is the lower value from the interval given in the source.

Costs saved on electricity are low – 27 777 CZK per year per tram. This is caused by flat profile of Tomsk city, therefore there is not possible to re-use as much braking energy as in Prague. Second reason is, that electricity price in Russian Federation is significantly lower than in the Czech Republic. And the third reason could be lower costs on building infrastructure projects such as catenary system. These three major facts contribute to the low savings the most. This, with very high probability, will lead to the result, which will not pay back the investment in a reasonable time horizon.

Reasoning of the investment calculation and used indicators are exactly the same as in previous case. Various calculations were done and none of them led to economical result. Therefore, only the variant for lifetime 25 years is shown below, because it is the most optimistic one, however also not economical.

From the calculations presented in the table 24, there is no doubt, that this project is not suitable for realisation in Tomsk. As described above, together electricity price, flat city profile and infrastructure construction costs are the reason. Combining these three factors together gives totally uneconomical results. Cost savings do not even approach the value of the initial investment.

And this pays for all variants – all combinations of assumed discount rate and lifetimes. It is not even possible to calculate IRR, because it would have to be negative. Therefore, in the last rows, only variant for zero discount rate is shown and it is completely uneconomical as well. Consequently, such a project cannot be recommended for realisation at all and at any circumstances.

Table 24: T1 – Cost analysis calculations for lifetime 25 years and different discount rate values.

year		0	1	2	3	4	5	....	18	19	20	21	22	23	24	25
investment		-2 790 690														
CF			27 777	27 777	27 777	27 777	27 777	....	27 777	27 777	27 777	27 777	27 777	27 777	27 777	27 777
	discount rate															
DCF	*2.50 %*	-2 790 690	27 099	26 438	25 793	25 164	24 550	....	17 809	17 375	16 951	16 538	16 134	15 741	15 357	14 982
cumulative		-2 790 690	-2 763 591	-2 737 153	-2 711 360	-2 686 196	-2 661 645	....	-2 392 004	-2 374 629	-2 357 678	-2 341 140	-2 325 005	-2 309 265	-2 293 908	-2 278 925
NPV		**-2 278 925**														
DCF	*5.00 %*	-2 790 690	26 454	25 194	23 994	22 852	21 764	....	11 542	10 992	10 469	9 970	9 495	9 043	8 613	8 202
cumulative		-2 790 690	-2 764 236	-2 739 042	-2 715 048	-2 692 196	-2 670 432	....	-2 465 994	-2 455 002	-2 444 533	-2 434 563	-2 425 068	-2 416 025	-2 407 412	-2 399 210
NPV		**-2 399 210**														
DCF	*7.50 %*	-2 790 690	25 839	24 036	22 359	20 799	19 348	....	7 557	7 029	6 539	6 083	5 658	5 264	4 896	4 555
cumulative		-2 790 690	-2 764 851	-2 740 815	-2 718 456	-2 697 657	-2 678 309	....	-2 521 091	-2 514 062	-2 507 523	-2 501 440	-2 495 782	-2 490 518	-2 485 622	-2 481 067
NPV		**-2 481 067**														
DCF	*10.00 %*	-2 790 690	25 251	22 956	20 869	18 972	17 247	....	4 996	4 542	4 129	3 753	3 412	3 102	2 820	2 564
cumulative		-2 790 690	-2 765 439	-2 742 483	-2 721 614	-2 702 642	-2 685 395	....	-2 562 883	-2 558 342	-2 554 213	-2 550 460	-2 547 047	-2 543 945	-2 541 125	-2 538 562
NPV		**-2 538 562**														
DCF [IRR %]	*0.00 %*	-2 790 690	27 777	27 777	27 777	27 777	27 777	....	27 777	27 777	27 777	27 777	27 777	27 777	27 777	27 777
cumulative		-2 790 690	-2 762 914	-2 735 137	-2 707 361	-2 679 584	-2 651 808	....	-2 290 713	-2 262 937	-2 235 160	-2 207 384	-2 179 607	-2 151 831	-2 124 054	-2 096 278
NPV		**-2 096 278**														

7 SOCIAL RESPONSIBILITY

A topic, which is closely related to any project using batteries, is its recycling. Recently, it is even gaining in importance – together with a bigger emphasis, which is being put on the ecological site of any project – not only buyers but also governments through law conditions are supporting the importance of sustainable economy. Also, with a rise of electric vehicles, not only trams, but mainly cars, if this evolution will continue in its emerging trend, in several years there will be tons of used batteries. To to get an idea of the situation, quantity of batteries coming to Europe is following: 800 000 tons in automotive industry, 190 000 tons in the industry and 160 000 tons in consumer market. [48] These numbers offer several challenges, but not only in its "negative" fact – to find out how to recycle it in a physical point of view, but also a challenge offering vast investment and economic opportunities. Hereafter, briefly, a look on this issue will be presented.

The main elements, which are, from the economical point of view, the most important while recycling li-ion batteries, are cobalt, lithium and nickel. Lithium is a part of its electrolyte and cobalt is what electrodes are made of. It is important to keep in mind, that not every battery type is suitable for recycling. For example, Lithium Iron Phosphate battery does not contain any economically valuable element, so the reasons for recycling are very low. This is the case of this work, where those batteries were chosen for battery storage. Next, this battery contains aluminium, where there are high CO2 emissions during production.

Generally, battery recycling industry is still developing, together with progress of electric vehicles. These batteries are somewhat different from the classic ones, which are nowadays present on the consumer market. Mainly, its about their size, weight and capacity. These measures demand special recycling techniques.

This is supported by legislation. In the European Union, there are several directives, which describe basic demands on a recycling process. It is about Directive of the European Parliament and Council 2006/66/ES on batteries and accumulators and waste batteries and accumulators [49], Commission Regulation EU 493/2012 [50] and further several connected commission decisions (2008/763/EC, 2009/851/EC) and regulations (1103/2010, 493/2012). They define some general numbers like that at least 95 % batteries, which are supplied to the market, must be collected back or that 50 % of weight of these collected batteries must be recycled. That li-ion battery recycling is becoming more and more important issue is visible also in the USA. Ministry of Energetics has announced Lithium-Ion Battery Recycling Prize 5.5 million dollars, which should enhance further development of recycling technologies and lower dependence on supply of strategical minerals. [51]

It is not all about recycling forced by law, but also economical and sustainable reasons of the battery production chain itself. It is for example limited amount of some elements, such as lithium. Only responsible recycling can offer sustainable and long-term using of this technology. Main benefits are sparing construction materials, which contributes to a stable price of these components, then it is, of course, lowering CO2 emissions and reducing the amount of hazardous substances which could possibly get into the environment. Next benefit is also a lower dependence on countries with big lithium reserves. Next, it is said, that contemporary recycling methods for li-ion batteries are five times more expensive than original mining. On the other hand, there is completely different situation with classic lead-acid batteries, where in developed countries 99 % are recycled.

It is important to point out, that contemporary battery recycling situation is still evolving. Extensive manufacturing of electric vehicles has started just several years ago, therefore most of the batteries did not reach the end of their lifespan.

This will happen when the first generation of mass-produced electric vehicles will come to an end of their lifetime, and this will trigger off higher (economical) interest in this field. Nevertheless, first, these batteries are ideal to be re-used in their “second life” – usually, for example, in houses to store the electric energy from photovoltaic systems. This would significantly contribute to better stabilization of energetic grids.

When another use is not possible anymore, recycling itself becomes the only solution. Nowadays there is only one commercially used method for li-ion battery recycling – pyrometallurgical method. This method consists of thermal and electrical processes and allows to gain cobalt, zinc and copper. The other present elements, such as iron, aluminium and lithium are not fully exploited yet. There is also a hydrometallurgical process, which processes the materials at low temperature. Nevertheless now, it is only prototypical in the USA, and it allows to extract also aluminium and a chemical compound of lithium. Also, there are methods which can regain 90 % of cobalt, which is present in batteries. It is said, that, at first, it is logical to focus on cobalt recycling. It is a strategical element just as lithium is, but moreover, cobalt is poisonous and even worse available. Now, approximately half of the world cobalt production goes to battery industry. Determining fact is the quality of these extracted products, which is the most important in further manufactory. The problem is that the quality is usually not high enough to use these elements in battery manufacturing again. A main motivation to improve this process should be the fact, that using recycled cathodes reduces the impact on the environment by 70 %. [52] [51]

There are some promises to the future, when, for example, in San Diego’s university, California, USA, scientists have significantly improved recycling process of batteries using NMC technology (mostly used in electric vehicles). Now it works at a pressure of 1 atmosphere, but temperature demands still stand high – 850 °C at the most demanding part of the process. Nevertheless, the results were practically ideal, while regenerated cathodes had the same capacity and power as the original ones. This could possibly extend batteries' lifetime significantly. [53] Next option is to invent completely new battery type, which would be independent from difficult mining processes of these elements. There are some promises to the future, but a path to industrial usage will still be very long. For example, Tesla Motors are investigating a new accumulator type, which would be cobalt-free. It is anticipated, that, slowly but surely, contemporary batteries will be replaced by special ultracapacitors working on a physical principle using graphene and nanotechnologies. Since carbon is easily accessible in a large measure, this would solve many problems including those concerning ecology. [51]

8 CONCLUSION

In the first part, the work has investigated a situation in the tram industry and transportation from the historical roots and its very beginnings through contemporary situation in the field to possible evolution trends. This was done with an accent put on propulsion and energy saving devices contemporary used in trams.

In the practical part, first, a summary of tram tracks in two investigated cities – Prague and Tomsk – was done. From obtained data, such as altitude profiles of several tracks in both cities, a decision, which track to choose as the most suitable one for further calculations in each city, was done. In Prague, it was tram line number 22 from Radošovická station to Bílá Hora station and in Tomsk it was line number 1 from Cheremoshniki to Vostochnaya. It was a positive fact, that the altitude profiles of mentioned cities differ a lot, which, in the end, contributed to very effective comparison of profitability of these variants. Second, programme MATLAB was used to calculate energy consumption along chosen tracks, together with energy savings from braking. To do this, a script including all important physical forces acting on a riding tram was used. The output was a complete energy consumption data describing the ride, which was the core of the work. Based on this, design of the energy storage system was done. From this came out, that a hybrid storage combining batteries and supercapacitors is the most suitable one both from economical and technical point of view. Thus, following detailed cost analysis focused only on this type of solution. It is important to point out, that a catenary-free option with re-using braking energy was investigated. Nevertheless, the result was negative. Under such conditions (technical solution, accessible technologies, up-to-date prices and economic indicators) it is not profitable to realise this project neither in Prague, neither in Tomsk.

While in Tomsk a return on investment was totally unreachable under any circumstances (mainly due to external causes such as low electricity price, extremely flat altitude profile of the city and partly also low costs on construction of infrastructure projects like catenary supply system), in Prague the situation is not that extreme. Here, under certain conditions, the project and the investment could turn profitable. It is mainly because of quite hilly city profile, which allows to gain more energy from braking, but also because of higher electricity price. Nevertheless, other conditions would have to get behind certain boundaries. This is mainly lifetime of the project. If it could reach at least 20 years in operation with a quite low discount rate around 2-3 %, then the investment could be recommended for realisation.

It is also necessary to keep in mind, that an infrastructure project like this, probably, would be partly financed from subsidies (EU, government etc.), so it would not be a private business investment. This could support realisation of the project even with slightly (or more) negative NPV or other economic indicators, but this would rather be a policy question. Anyway, low discount rate or reasonably negative NPV does not have to necessarily devaluate the whole project. Also, a situation in the field can change rapidly. If electricity price would rise significantly in any of investigated examples, the project could turn profitable easily. The same is the situation in battery industry – if prices fall rapidly (or if it would be possible to find cheaper alternative), costs on the project would fall as well, which could make the whole investment economically profitable.

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10 APPENDIX

Appendix 1: Resistance coefficient ω_0 values. (Source: ОСНОВЫ ЭЛЕКТРИЧЕСКОГО ТРАНСПОРТА, КРАСНОЯРСК 2008)

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Таблица 2.1

Эмпирические формулы удельного основного сопротивления движению для различных типов ЭПС

№ п/п	Тип подвижного состава	Движение под током, Н/кН	Движение без тока, Н/кН
1	Электровозы	$\omega_0 = 1.9 + 0.01V + 0.0003V^2$	$\omega_0' = 2.4 + 0.011V + 0.00035V^2$
2	Электропоезда	$\omega_0 = 1.1 + 0.012V + 0.000267V^2$	$\omega_0' = 1.24 + 0.02V + 0.000267V^2$
3	Вагоны метрополитена	$\omega_0 = 1.1 + (0.09 + 0.022n)\dfrac{V^2}{mg}$	$\omega_0' = 1.0 + \dfrac{52}{mg/n} + 0.025V + (0.09 + 0.022n)\dfrac{V^2}{mg}$
4	Трамвайные вагоны серии КТМ	$\omega_0 = 5.0 + 0.005V^2$	$\omega_0 = 9.0 + 0.005V^2$
5	Трамвайные вагоны серии ЛМ	$\omega_0 = 4.5 + 0.0028V^2$	$\omega_0 = 5.0 + 0.0031V^2$
6	Троллейбусы	$\omega_0 = 12 + 0.004V^2$	$\omega_0 = 16 + 0.004V^2$

Примечание: n – число вагонов в подвижном составе;
V – скорость поезда, км / ч.;
m – масса электроподвижного состава, т.
Остальные величины в принятых размерностях.

```
% ОПИСАНИЕ НАЧАЛЬНЫХ ДАННЫХ
a0 = 1.1;                          % постоянное ускорение на интервалах разгона
                                   % и торможения [m/s^2]
V0 = 13.89;                        % постоянная скорость на маршевом участке
[m/s]                              % V0=50 km/h
Nst = 11;                          % количество дистанций
Ssum = 12912;                              % полная дистанция
Mt = 38000;                        % масса трамвая [kg]
Mp = 5000;                         % масса пассажиров [kg]
g = 9.8;                           % ускорение свободного падения
% Вычисление основных параметров
S0 = Ssum/(Nst-1);                 % дистанция между остановками
Trs = V0/a0;                       % время разгона (торможения)
Srs = 0.5*V0*Trs;                  % дистанция разгона (торможения)
Sm = S0-2*Srs;                             % длина маршевого участка
Tm = Sm/V0;                        % время маршевого участка
dTrs = Trs/1000;                   % шаг по времени на участке р/о
dTm = Tm/1000;                             % шаг по времени на маршевом участке
Td = 2*Trs+Tm;                             % время прохождения одной дистанции
% Fk = 5.0*0.001*(Mt+Mp)*g;                % сила сухого трения
mu2 = 0.0031*0.001*(Mt+Mp)*g/(3.6^2);  % коэффициент сил вязкого трения
% Fin = (Mt+Mp)*a0;                        % сила инерции при разгоне
Rmod = 0;                          % режим движения: 0 - разгон; 1 - марш;
                                   % 2 - торможение
n = 1;                             % начало отсчета
Ns = 27000;                        % конец отсчета
Ni = 1;                            % номер интервала

% ОПИСАНИЕ ПЕРЕМЕННЫХ
t = zeros(1,27000);                % время
S = zeros(1,27000);                % путь
V = zeros(1,27000);                % скорость
A = zeros(1,27000);                % ускорение
Alpha = zeros(1,27000);            % угол наклона
Gx = zeros(1,27000);               % проекция силы тяжести
Fin = zeros(1,27000);                      % сила инерции
Fk = zeros(1,27000);               % сила сухого трения
Fa = zeros(1,27000);               % аэродинамическая сила
Fp = zeros(1,27000);               % сила привода
Pp = zeros(1,27000);               % мощность привода
DE = zeros(1,27000);               % прирощение энергии

while n<Ns                         % ОСНОВНОЙ РАСЧЕТ
 if Rmod == 0                      % РАЗГОН
 for n=n:(n+1000)
 t(n) = (n-3000*(Ni-1))*dTrs+(Ni-1)*Td;
 S(n) = (Ni-1)*S0+V0/(2*Trs)*(t(n)-(Ni-1)*Td)^2;
 V(n) = (V0/Trs)*(t(n)-(Ni-1)*Td);
 A(n) = a0;
```

```
Alpha(n)=-1.160034e-20*S(n)^5+3.73245e-16*S(n)^4-4.4492e12*S(n)^3+...
2.47758e-8*S(n)^2-0.5986e-4*S(n)+0.1593e-1;
Gx(n) = (Mt+Mp)*g*sin(Alpha(n));
Fin(n) = (Mt+Mp)*a0;
Fk(n) = 5.0*0.001*(Mt+Mp)*g;
Fa(n) = mu2*abs(V(n))*V(n);
Fp(n) = Fin(n)+Gx(n)+Fk(n)+Fa(n);
Pp(n) = Fp(n)*V(n);
DE(n) = Pp(n)*dTrs;
end

Rmod = 1;
elseif Rmod == 1                    % МАРШ
for n=n:(n+1000)
t(n) = Trs+(n-1000-3000*(Ni-1))*dTm+(Ni-1)*Td;
S(n) = (Ni-1)*S0+Srs+V0*(t(n)-Trs-(Ni-1)*Td);
V(n) = V0;
A(n) = 0;
Alpha(n)=-1.16034e-20*S(n)^5+3.73245e-16*S(n)^4-4.4492e12*S(n)^3+...
2.47758e-8*S(n)^2-0.5986e-4*S(n)+0.1593e-1;
Gx(n) = (Mt+Mp)*g*sin(Alpha(n));
Fk(n) = 5.0*0.001*(Mt+Mp)*g;
Fa(n) = mu2*abs(V(n))*V(n);
Fp(n) = Gx(n)+Fk(n)+Fa(n);
Pp(n) = Fp(n)*V(n);
DE(n) = Pp(n)*dTm;

end
Rmod = 2;
elseif Rmod == 2                    % ТОРМОЖЕНИЕ
for n=n:(n+1000)
t(n) = Trs+Tm+(n-2000-3000*(Ni-1))*dTrs+(Ni-1)*Td;
S(n) = (Ni-1)*S0+Srs+Sm+V0/(2*Trs)*(t(n)-Tm-Trs-(Ni-1)*Td)^2;
V(n) = V0-(V0/Trs)*(t(n)-Tm-Trs-(Ni-1)*Td);
A(n) = -a0;
Alpha(n)=-1.16034e-20*S(n)^5+3.73245e-16*S(n)^4-4.4492e12*S(n)^3+...
2.47758e-8*S(n)^2-0.5986e-4*S(n)+0.1593e-1;
Gx(n) = (Mt+Mp)*g*sin(Alpha(n));
Fk(n) = 5.0*0.001*(Mt+Mp)*g;
Fa(n) = mu2*abs(V(n))*V(n);
Fin(n) = -(Mt+Mp)*a0;
Fp(n) = Fin(n)+Gx(n)+Fk(n)+Fa(n);
Pp(n) = Fp(n)*V(n);
DE(n) = Pp(n)*dTrs;
end
Rmod = 0;
Ni = Ni+1;
end
```