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FACULTY OF MECHANICAL ENGINEERING
DEPARTMENT OF AUTOMOTIVE, COMBUSTION ENGINE
AND RAILWAY ENGINEERING

DETERMINING THE ENERGY PERFORMANCE OF CITY BUS ROUTE

BACHELOR THESIS

2015 LUKÁŠ KENDÍK

Declaration of Authorship

I do solemnly declare that I have written following bachelor thesis by myself without undue help from a second person and without using such tools other than specified.

Where I have used thoughts from external sources, directly or indirectly, published or unpublished, this is always clearly attributed. In the selection and evaluation of research materials, I have received support from my supervisor. The presented intellectual work of this bachelor thesis is my own.

Throughout the research, I have been supervised by Ing. Josef Morkus, CSc..

Prague, 10th May 2015

Signature

Dedication

I dedicate this thesis to all commuters in the world, who use buses to get to work or school.

Appreciation

I would kindly like to thank to my supervisor, Ing. Josef Morkus, CSc., for his patience and his helpful consultations whenever needed. Honest thanks also belongs to my parents and grandparents, who have always provided me with everything I needed, and positive emotions on top of that.

I wouldn´t have been able to finish this work were it not for my friends, students and acquaintances, who have supported me in the most difficult times.

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Abstract in English

The main task of this thesis is to practice ways of measuring and determining the energy needs of an urban bus. Firstly, there is short study of an environmental impact of buses on the environment. Explanation of the data acquisition and conditions during measuring follows, along with mathematical theory behind the calculations of drive resistances. Their exact values are then determined and they serve as a basis for energy balance calculations. Behind conclusion are attached diagrams showing determined values.

Abstract in Czech

Hlavním cílem této práce je seznámení s měřením a určováním energetické náročnosti městského autobusu. Nejprve je vedena krátká studie dopadu provozu autobusů na životní prostředí. Následuje vysvětlení získávání dat a podmínky během získávání dat, dále je uvedený teoretický podklad pro určení jízdních odporů. V dalších kapitolách jsou vypočítány jejich přesné hodnoty, které slouží jako základ pro výpočet energetické náročnosti autobusu. V závěru práce jsou přiloženy grafy zobrazující vypočítané skutečnosti.

Key words

Urban air pollution, emissions, public transport, hybrid buses, hybrid driveline, SOR NB 12 City, route height profile, route speed profile, drive

resistances, rolling resistance, gradient resistance, aerodynamic drag, inertia resistance, energy balance, energy consumption

Use: Base for further research, information material

Table of contents

Values Overview

G .... vehicle gravity [N]
α .... angle of the incline [°]
R_{rl} .... rolling resistance [N]
R_g .... gradient resistance [N]
R_i .... inertia resistance [N]
R_a .... aerodynamic resistance [N]
f .... rolling resistance coefficient (here f = 0,013)
m .... mass of the vehicle including passengers [kg]
g .... gravity acceleration [m/s^2] (here $g = 9,81\ m.s^{-2}$)
R_{it} .... momentum of body
R_{ir} .... rotational inertia
I_e .... moment of inertia of engine rotating masses [kg.m^{-2}]
i_f .... final gear from engine to wheels [-] (here $i_f = 1,429$)
I_g .... moment of inertia of drivetrain rotating masses [kg.m^{-2}]
i_d .... differential gear [-]
η .... mechanical efficiency [-]
I_{wi} .... moment of inertia of all wheels [kg.m^2]
ϑ .... coefficient of rotating masses [-]
ρ .... air density [kg.m^{-3}] (here $\rho = 1,25\ kg.m^{-3}$)
A_f .... vehicle frontal area [m^2] (here $A_f = 6,25\ m^2$)
c_x .... coefficient of aerodynamics resistance [-] (here $c_x = 0,49$)
v_f .... vehicle velocity [m.s^{-1}]
W .... work [J]
E .... energy [J]
F .... applied force [N]
s .... distance [m]
a .... vehicle acceleration [m.s^{-2}]
v_1 .... vehicle starting velocity [m.s^{-1}]
v_2 .... vehicle end velocity [m.s^{-1}]
M_r .... inertia of rotational parts
r_d .... tire radius [m]
M_{re} .... torque needed to set the engine into motion [N.m]
M_{rg} .... torque needed to rotate the gearbox shafts [N.m]
M_{rW} .... torque needed to rotate the wheels [N.m]
I_{WF} .... moment of inertia of front wheels [kg.m^2]
I_{WR} .... moment of inertia of rear wheels [kg.m^2]
E_{rl} .... energy to overcome rolling resistance[J]
E_a .... energy to overcome aerodynamic drag [J]
E_i .... energy to overcome inertia resistance [J]
E_g .... energy to overcome gradient resistance [J]
E_{au} .... energy consumed by auxiliary compnents [J]

E_u.. ultimate consumed energy [J]
t... time [s]
P.. power [W]

1 Introduction

Although not stated in the name, the reason for this research is to create a template and proposal for urban hybrid bus powertrain in the future. This research is only a piece of possibly deeper research. Since this technology is still quite rare on our roads in the Czech Republic, in the first two chapters, I would like to outline the basic principles of a hybrid bus. Because this technology is often doubted for its overall benefits, I also attach brief overview of today´s environmental situation.

Exhaust gases have recently climbed to the top of many municipal government's agenda. It is no wonder, because the number of megacities and cities around the globe is rapidly rising and so is the necessity to transport all its inhabitants.

At the same time, statistics clearly show the influence of exhaust gases on our health. In the 2013, 53 000 people in the world died as a result of air pollution from combustion engines. Research carried out in California claims that vehicle emissions in cities are responsible for 5 to 15 % higher probability of children suffering from cancer. However, there are indirect effects of air pollution on people´s lives. [1]

The most worrying and discussed part of gases created by internal combustion engines is the CO_2, carbon dioxide in other words. Although not toxic and thus harmless to living creatures, it is the cause of greenhouse effect and increase of holes in ozone layer. The latter is dangerous for its negative effect on our skin, increasing the number of skin cancer treated people. [2]

Global warming is well known phenomenon of today. It seems as overpublicized issue recently, but it should not be underestimated. Not only does it affect our health, but world economy, biological diversity and geography of the Earth as well. The most alarming predictions of scientists point at 4 degrees higher average temperatures on the surface of the planet at the end of 21st century. That could have terminal effects on humankind. [3]

Although there are various and more important causes for exhaust gases emissions, they often aren´t immediate and direct threat for our health, because they´re not in the proximity of people. Even though it´s necessary to solve that problem as well, we have to focus firstly on the most dangerous parts of air pollution.

Scientific predictions based on today´s trends show that by the year 2045, there will be 9 billion inhabitants on our planet. [4] More worryingly, three quarters of them are predicted to live in megacities. That in effect means that we soon need to find ways how to move all the people around.

1.1 Greenhouse effect [5]

It is known that in the last three or two more million years, the climate of our planet has changed few times. The cause for these changes isn´t human intervention and we can´t avoid them. There are, however, many areas in which we can significantly change the chemical composition of the Earth´s atmosphere.

Especially here come into question the gases created during burning fossil fuels. They strongly contribute to the greenhouse effect, which causes the global warming. Many people argue that the greenhouse gases would be in the atmosphere regardless of our actions. That is correct, but they would be in much lower levels.

Greenhouse effect happens as the solar radiation falls to the atmosphere. The shortwaves are then reflected from the Earth´s surface as light energy and long waves are reflected as heat energy. The issue is absorption of these long waves by certain substances in the air. The major of them are water vapor and mentioned carbon dioxide, with other trace gases contributing to the pollution in smaller measure. And as their amounts in the air rise, so does the ability to absorb the heat radiated by the Sun and that leads to the warming of the Earth´s atmosphere.

The levels of the CO_2 in the atmosphere before the industrial revolution is estimated to be as low as 260 parts per million volume. In 2012, it was 396 ppmv. Computer calculated models based on today´s trend show, that by the end of the century, it will be 500 ppmv. Causes for the increase part of the CO_2 in the air are mostly the burning of fossil fuels and the change in land use. For this work, only the first process is to be concerned.

There are other gases though, that are dangerous for the atmosphere. Their effect might be minor, but when they´re observed as a group, they are bigger threat than carbon dioxide. They are, to name few, methane (CH_4), nitrous oxide (N_2O) and carbon tetrafluoride. It is thought that if the present trends continue, the combined effects of all the greenhouse gases will be similar to the doubling of the CO_2 levels by 2030 when compared to pre-industrial situation.

Another concern remains the residence time of greenhouse gases in the atmosphere. For example, even if we halt the production of CO_2 immediately, it would remain in the air for another 100 years. And it does take even longer for N_2O to disappear, up to 200 years. [5]

1.2 Urban air pollution [5]

As I have stated earlier, human beings these days strongly contribute by their behavior to climate changes. This is most evident is large urban areas, where are situated many power stations, cars, and factories.

It is as well necessary to note that climate changes in densely inhabited areas happen as a result of more issues. Those, such as high buildings and vast concrete areas, aren´t subject of this research and are therefore not going to be mentioned.

The urban air pollution has been present since the times of industrial revolution, but the nature of it has changed. At the beginning of the nineteenth century, for example, the major pollutant were emissions from the burning of the coal. These days, major pollutants come from vehicles. But situation and background for research is made difficult by the fact that each city has its own unique situation. In the city of Prague, for example, the road traffic contributes to the NO_x emissions by 68 %. When looking at the PM10 dust particles, road transport in Prague is responsible for 95% of those.

Positive trend can be seen in the developed cities, where has the amount of pollutants in the air been reduced in the recent years. In the less developed countries, though, the air quality keeps worsening. This has been especially dramatic in China, where the levels of N_2O are the highest in the world. Heavy reliance on coal or even on wood for heating and cooking and most importantly old motor vehicles are issues in these areas.

As a leader in respect of lowering vehicular emissions could be taken Los Angeles in California. The levels of ozone have been decreasing since the 1970s, despite growth in population. It is due to the fact, that local government has been offering benefits to the drivers of environmentally friendly cars and supporting clean products.

According to the United Nations, half of the world´s population lived in the cities at the end of the year 2008. The same organization predicts that by 2050, this percentage will rise to 66%. It would be naïve to think that with such growth in population wouldn´t come need for transport and higher air pollution. [6]

1.3 Low emissons zone

One way for reducing exhaust gases presence in the city centers is to create so called “Low emission zones”. This is area of the city, which can only be entered with a vehicle with certain ecological credentials. The first city in Europe to launch such idea was London. Since the 17th February 2003, whoever wants to drive their car to the area of “Greater London” has to pay charge per day, according to the ecological level of their vehicle.

Another system is employed in Germany, where “Umweltzone” exists in 50 towns all over the country. It doesn´t charge drivers for driving through the area. Each car has to have special sticker stuck on its windscreen, having different color according to the EURO emissions standard level. It´s then up to the municipal authorities to decide, how clean cars can enter they´re city. However, all but two cities now only allow entrance to vehicles with green sticker. That is awarded to all petrol-powered cars with catalytic converters.

There are other solutions in cites to encourage drivers to behave more ecologically around the world. In Los Angeles, California, low emission vehicles are allowed to use special lanes on highways. In Oslo, Norway, owners of plug-in hybrids don't have to pay fees for parking and other motoring services.

The city of Prague is preparing establishing low-emission zone from 1st January 2016. Only vehicles manufactured after 2001 (complying with the EURO III) will be allowed to enter the area. [7]

1.4 Public transport

The obvious help in reducing air pollution in cities and easing the jammed roads is higher use of the public transport. The best option would be to employ only electric driven vehicles, such as trams, trolleybuses or subway. That way, we could cut local exhaust gases in city centers altogether. But it is often not possible or it would be too expensive to build subway or to lay down railways in every city in the world. Even stretching electric lines above every street to provide power for trolleybuses would be expensive. And besides, all named vehicles don't offer such flexibility in their routes as conventional buses.

These use mostly big capacity diesel engines that emit exhaust gases. What's more, diesel engines produce the toxic NO_x, dangerous to humans. Even though most modern buses employ modern measures to cut emissions, such as particle filters, SCR or AdBlue, they produce considerably more local emissions than above-mentioned electrical means of transport.

What's more, when compared to tram, conventional bus makes considerably more noise than tram. So does it produce more vibrations and is therefore less comfortable for passengers.

Diesel engines are typically well known for their low fuel consumption. That may be the truth when speaking about long journey services, where the engines keep running at constant, low revs. In urban areas though, buses have to come to a full stop and then accelerate in short distances. This creates the most pollutants and repeated stops mean that all the gathered momentum is wasted and dissipated as heat through braking.

2. Hybrid buses

2.1 History of the hybrid bus

Hybrid bus as we know it today has begun its development in the 1980's. The technology of hybrid drivetrain, though, is as old as the motorized vehicle itself.

The world's first hybrid vehicle is widely known to be the "Sempre Vivus" developed by Ferdinand Porsche in 1899. It was serial hybrid, with two small gasoline engines charging batteries, which in turn provided power for two hub-mounted electric machines. The range of the carriage was 200 km and top speed was respectable 35 km/h. [8]

At the first NY automobile show in 1900, majority of questioned visitors said they preferred electric vehicle to petrol powered one for its silence and comfort. Until 1920's, there were more than 100 manufacturer of electric or hybrid cars in the world. The advancements in internal combustion engines, inexpensive petroleum fuels and lower prices thank to advancements in mass manufacturing meant that interest in hybrid and electric vehicles declined rapidly. [9]

It is thought that the first ever hybrid bus was produced in between 1979 and 1981 by the Mercedes-Benz. There were 20 examples of type 0 305 converted into dual powered vehicles. Their main sources of energy were batteries, which were charged from the mains or by the diesel engine working as range-extender. After the testing period, though, their development was halted. [10]

It wasn't until mid 1980's that the development of hybrid propulsion systems started to take off again. Governments around the world put cleaner transport to the top of their agendas and rising petrol prices also meant that drivers started asking more efficient drivetrains. Especially North American and Japanese manufacturers began developing the hybrid drive systems for mass production. At the same time, the development of such technology for buses began. [11]

The first trials of hybrid bus technology began in 1980's in England in the city of Exeter. The government has realized the need to replace the ageing double decker buses and so the minibuses equipped with electric motors as well as with conventional engines began transporting passengers.[12]

In the 1998, the first hybrid bus entered regular service in the New York City. It was Daimler Orion city bus using propulsion system called HybriDrive, developed by the BAE systems. It is series type drivetrain using smaller capacity diesel engine connected to the generator, which stores energy in batteries. The first examples relied on nickel-metal hydride technology. Just a year later, in 1999, the company Allison presented their vision of hybrid powertrain for the city bus.[13]

Despite regular service and development, it was at around the year 2005 when combined power of internal combustion engine and electric motor gained necessary support from manufacturers around the world. The first company in Europe to present hybrid bus was the Wrightbus company of Ireland, that has delivered six research buses to London in 2006.

Other renowned European manufacturers followed shortly after. In 2007, polish manufactured delivered first hybrid versions of their Urbino 18 to Switzerland. Both Swedish Volvo and German MAN offer hybrid propulsion systems for their urban model lines in 2010. Volvo chose lithium-ion batteries to store the energy, whereas MAN decided for super capacitors.

Another milestone among hybrid buses is the project called "New Bus For London". This was designed specifically for the British capital to replace the old diesel Routemaster buses. Being in regular service since 2011, the powertrain comprises of Siemens electromotor and 4,5 l Cummins engine working as range extender.

Belgian Van Hool offers dual engine solution for their vehicles since 2013, Swedish Scania produces diesel-electric model since 2014 and it's worth noting that even Czech SOR has a hybrid technology in its portfolio. Volvo has presented second generation of their solution, now being able to charge itself at the stops via roof-mounted pantograph.

Few manufactures (Mercedes-Benz, MAN, Van Hool…) have been researching using fuel cells instead of diesel engine in their vehicles since as early as 2004. Some of them are in service (Mercedes-Benz buses are used in Hamburg), but they're still in development. It is generally thought of hydrogen-powered buses as of future technology. They still have to overcome difficulties though, the major of them being sourcing of the hydrogen.[10]

2.2 Hybrid drive system [14], [15]

Firstly, it has to be noted that the term "hybrid" can describe myriad of powertrain configurations. The definition of the word means that the vehicle utilizes two sources of energy for its propulsion. Thus, even a bus powered by engine capable of running on either E85 or petrol is, in fact, a hybrid. Future fuel cell buses, currently in development, are hybrids as well.

This thesis, though, only covers and researches diesel-electric buses. This conception has become widely popular and can be realized in two different ways, due to be described:

Table 2.1 Hybrid drive components

Electric drive motor – converts electricity into mechanical energy and powers the vehicle
Controller and Inverter – regulates the amount of energy flowing to/from energy storage device
Energy storage device – collects and releases the electric energy and balances the average power requirement of the vehicle
Auxiliary power unit (APU) – converts fuel into electrical energy. Usually an engine/generator, could be fuel cell
Auxiliary systems – various components that drain power out of the power sources, such as ventilation system or power steering.

2.2.1 Parallel hybrid concept

Here, both power sources are directly mechanically connected to the driven wheels. In between, they´re independently connected. The electric motor draws energy from the storage device when supporting the ICE during heavy acceleration or in small speeds, when the bus is only powered by electricity. E-machine is then used to return energy to the storage device under regenerative braking.

The advantages of this system are its lower weight due to the smaller storage device and lower complexity. The conventional engine can power the vehicle during constant higher speeds, with electric assistance during acceleration. The EM also works as a generator during braking to recover energy and can work as a starter.

The greatest advantages of such system are efficiency and low weight. Since in the serial hybrid, energy generated by the ICE has to be cycled through the batteries and up to 35% of it could be lost. Another pro of parallel solution is a smaller storage device and smaller ICE resulting in lower weight while maintaining desired performance. The best use of them is on lines where the bus partly rides at constant speed.

2.2.2 Series hybrid concept

In this combination of drivetrains, the wheels are driven exclusively by the electric motor(s). The APU only powers the generator which supplies storage device with electric energy. From there, e-motors draw energy. Since the APU can be managed independently from the vehicle, it can theoretically run at optimal revs all the time. This could increase the efficiency of a diesel engine from 30% up to 40%.

There are, however, dents in such powertrains. Firstly, not all the generated energy is effectively used, since storage devices are less than 90% efficient. Further energy losses are then created when powering the e-machines.

On the other hand, these drivetrains strongly benefit from energy regeneration under braking and the ICE is more often turned off. It can also be of smaller displacement and thus benefit from lower weight. This solution also offers huge packaging benefits. The small combustion unit with generator can be placed in the back of the vehicle, occupying less space than conventional unit with gearbox. The storage devices can be placed at different places in the chassis, helping ideal weight distribution. For forward motion, there could be used wheel hub E-motors or smaller in-built machines. This would make the bus 100% low floor and easily accessible throughout.

This concept of drivetrain for bus is very beneficial on inner-city lines, where the vehicle drives in stop-and-go traffic most of the time. Since the engine only runs in the optimal revs and forward motion is gained only through the e-motors, these buses have lesser NVH levels.

2.3 Benefits of hybrid bus in practice [16]

The main driver behind the massive development of hybrid buses are, obviously, reduced emissions levels. To that, these machines benefit from lower maintenance costs and decreased fuel consumption.

In the USA, NY, where the hybrid buses have been in use the longest, the results support first theories. Particulate matter emission of a hybrid bus showed to be 90 percent lower than at conventional diesel bus. Emissions of the toxic nitrogen oxides (NO_x) were between 30 and 40 percent lower than with the diesel buses.[14]

European authorities and cites are more cautious when quoting the results of their trials. Most of German cities run hybrid buses on few of their lines and the results are encouraging. The city of Dresden quotes 25% less emissions with partly electrified buses. Hannover, where were used different bus models, quotes 30 % lower fuel consumption with new solution. Should we calculate the savings over 12 year lifecycle of urban bus, we find out that such vehicle would save 88 100 liters of diesel per such period. Other German cities claim their new hybrid buses have 10 liters per 100 km lower fuel consumption.

Andreas Dufen, of the city Duisburg school, also points out that battery equipped busses possess better acceleration and braking distances. To that, passengers rate positively low vibration levels and seamless and strong acceleration of electrically driven buses.

There are further evidence of the benefits of such vehicles. That is, however, not the main concern of this work.

3. Conditions of the research

3.1 Introduction

In order to propose a working and efficient drivetrain of a hybrid bus, it is necessary to know the energy needs of similar vehicle. Due to the character of my research, I have chosen bus line near my home and the most usual bus that operates there. It is important to note that the measurements were mostly carried out in winter, so the results will be for the worst-case scenario.

3.2 The route

When choosing the right route for such a study, I wanted to find a route that is the most comprehensive and includes inclines, declines as well as medium traffic density. The route shouldn't have been too long, to make the evaluation easier to conduct.

In the end, I chose bus line number 235. It's located in the suburbs of Prague, and it is at its peak at morning and evening rush hour. It connects residential area "Velká Ohrada" populated by 14 000 thousand inhabitants to the nearest subway station "Nové Butovice".[17]

The line is suitable for my research for many reasons. Measuring 5879 m there and back, it is relatively short. We can find long decline followed by long incline, resulting in total altitude difference of 45 m. Interesting is also a section with 70 km/h speed limit, which is energetically demanding part of route. Of a benefit to research is also fact that this route is operated by all kinds of buses, mostly by SOR NB 12.

Because the number of stops is different on each way, I have decided to evaluate the whole loop. That totals 14 bus stops and the advantage of always having full bus on one way, and almost empty on the other for balanced measurements. Regarding traffic situation, since most of this line is driven on dual-line road, it is quite unaffected by rush hour.

In the end, I have divided the route into 24 sections. The important points are either bus stops, traffic lights or gradient change. There would of course be possible to create even more sections, but it would hugely complicate the results and wouldn't bring that more precise results.

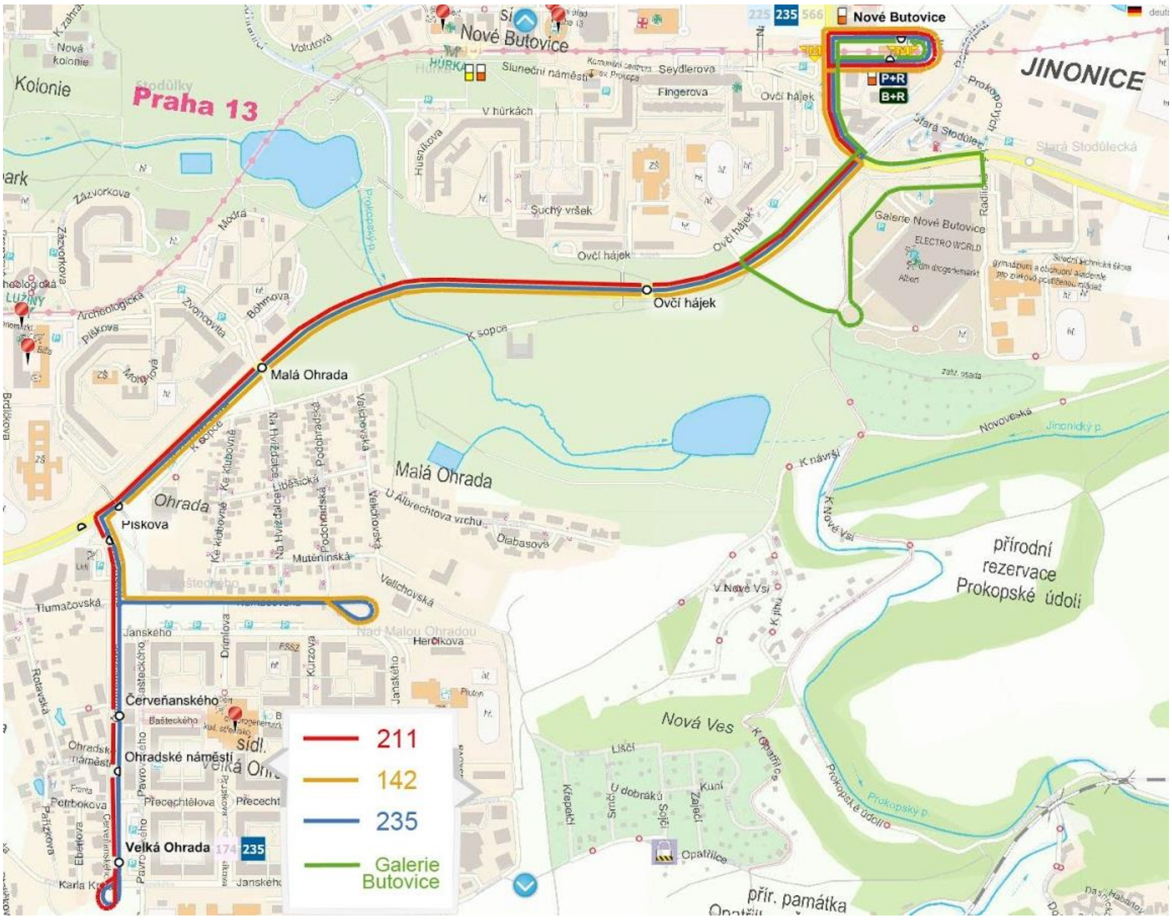
The table with section number and their limits follows below. For more details regarding the single route sections, see "Table 4.1" Map with highlights stops is to be found in the attachments.

I have decided to work with "worst case scenario", and therefore I presume the bus stops at every traffic light and at every stop. This means a lot of accelerating and braking, thus increasing the power demands on the powertrain.

Table 3.2 Sections definition

No.	Start point	End point
1	First Stop "Nové Butovice"	Traffic Lights at "Nové Butovice"
2	Traffic Lights at "Nové Butovice"	Traffic Lights at "Galerie Nové Butovice"
3	Traffic Lights at "Galerie Nové Butovice"	Traffic Lights at "Ovčí Hájek"
4	Traffic Lights at "Ovčí Hájek"	Bus Stop "Ovčí Hájek"
5	Bus Stop "Ovčí Hájek"	Gradient Change at "Vulcano"
6	Gradient Change at "Vulcano"	Traffic Lights at "Malá Ohrada"
7	Traffic Lights at "Malá Ohrada"	Bus Stop "Malá Ohrada"
8	Bus Stop "Malá Ohrada"	Traffic Lights at Lidl
9	Traffic Lights at Lidl	Bus Stop "Červeňanského"
10	Bus Stop "Červeňanského"	Bus Stop "Ohradské náměstí"
11	Bus Stop "Ohradské náměstí"	End Stop „Velká Ohrada“
12	End Stop „Velká Ohrada“	Parking Lot
13	Parking Lot	First Stop "Velká Ohrada"
14	First Stop "Velká Ohrada"	Bus Stop "Červeňanského"
15	Bus Stop "Červeňanského"	Traffic Lights at Lidl
16	Traffic Lights at Lidl	Bus Stop at "Píškova"
17	Bus Stop "Píškova"	Traffic Lights at "Malá Ohrada"
18	Traffic Lights at "Malá Ohrada"	Bus Stop "Malá Ohrada"
19	Bus Stop "Malá Ohrada"	Gradient Change at "Vulcano"
20	Gradient Change at "Vulcano"	Bus Stop "Ovčí Hájek"
21	Bus Stop "Ovčí Hájek"	Traffic Lights at "Ovčí Hájek"
22	Traffic Lights at "Ovčí Hájek"	Traffic Lights at "Galerie Nové Butovice"
23	Traffic Lights at "Galerie Nové Butovice"	Traffic Lights at "Nové Butovice"
24	Traffic Lights at "Nové Butovice"	End Stop „Nové Butovice“

Figure 3.1 Map of the route



3.3 The bus [18], [19]

Choice of the bus, whose energy needs will be subjected to the research, was restricted to the lineup of Prague Transportation Company. Due to advances in technology, it was necessary to choose the most advanced vehicle in the fleet. That has to be the SOR NB 12, of which there will be 620 examples by 2018. Therefore it's also not difficult to ride one for data collection. The advantage of this model is also its availability as a hybrid, using Allison parallel drivetrain.

The first prototype was made in 2006 and mass production followed in 2008. The design in itself is a development of version BN, which was first made in 1995. For the new city bus, however, the components were heavily reworked. The SOR NB 12 CITY is 100% low floor bus developed for urban service, designed is line with modern technologies and regulations.[20]

The chassis and frame are in-house designed, with most vital components bought from renowned manufacturer. The power comes from IVECO NEF six-cylinder diesel engine complying with EURO VI norm. It sends drive to the rear portal axle manufactured by ZF through a six-speed automatic gearbox bought from the same company. Independent heating system is bought-in from the Eberspächer. For more detail about the bus, see chart below.

Table 3.2 SOR NB 12 CITY Specification

Length	12 180 mm
Width	2 550 mm
Height	2 900 mm
Weight (service)	10 990 kg
Mass (maximum)	18 000 kg
Capacity	103
Top speed	80 km/h
Engine	FPT F4AFE612F EURO VI
Displacement	6 728 cm^3
Power	210 kW @ 2 500 rpm
Torque	1 000 Nm @ 1 250 rpm
Fuel Tank	270 l
Transmission	ZF Ecolife 6AP1200B
Front Axle	SOR NB 004
Rear Axle	ZF AV132 II
Front wheels	7.50 x 19.5 / 285/70 R 19,5
Rear wheels	8.25 x 22,5 / 275/70 R 22,5
Independent heating	Eberspächer Hydronic L-II
Batteries	Varta / 225 Ah

Figure 3.2 Bus SOR NB 12 City [18]

3.4 Prevailing conditions

The data collection was done between January and March 2015. The temperatures during the process were between 0 and 12 degrees above zero. All measurements were done during dry weather.

Data regarding the route, such as length, distances from stop to stop and altitude numbers were collected during walking along the route with GPS software (see below). Because of data evaluation, I did all the runs along the route repeatedly, as not to rely only on one data set and to minimize possible mistakes and uncertainties in the results.

3.5 Measuring equipment

To get the necessary data, I have used iPhone 6 and its in-built GPS sensor. Manufacturer promises increased precision than with conventional GPS devices due to use of cellular data antenna for additional position sensing.

To get a first idea and rough data about the route, I have used online maps (Google maps). Then, to measure the altitude and distance on the route, I used the MotionX-GPS application. This software shows all the necessary data, such as speed, altitude, distance and also offers possibility to safe a point on a map for later revision. Due to its easy controls, I used this application for the speed measurements as well.

To verify numbers gathered by described app, I used Sports Tracker application. It offers slightly confusing graphic environment, but also offers route capturing and provides all the necessary data. To obtain the times for acceleration and stops times, I relied upon pre-installed stopwatch application in the phone. As software for data evaluation and for calculating all the equations, I used Microsoft Excel 2013. All the diagrams and charts were created in this program. The whole work was then written in Microsoft Word 2013.

4. Route evaluation

4.1 Route topography [21]

One of the most important factors defining energy consumption of any vehicle, let alone heavy one such as bus, is the height profile of its route. Fuel consumption and energy demands are rising during steep or long inclines. Because the Gradient resistance is dependent on the gravity, which is itself function of a mass, we can see it affects heavy vehicles much more than light cars.

$$R_G = G. \sin \alpha$$

Seen from the energy point of view, the engine has to develop more power during ascents. That means more revs, less efficiency, more emissions and higher heat production. For the purposes of this research, uphill section are described as positive and downhill sections are described as negative in the equations.

On the other hand, when the bus drives down long or steep decline, it has to keep its speed under control and therefore brake. Be it by conventional mechanical disc brakes or exhaust retarder, considerable amount of energy is wasted, usually as heat. This is, however, very inefficient, since the momentum gathered before such section is wasted.

Hybrid drivetrains are suggested to deal with such energy efficiency and minimize the losses. They're supposed to capture kinetic energy when slowing down and release it back into the powertrain when more demanding parts of route are to be driven through.

It is therefore very important to determine route topology, if it is to be used as a basic parameter for calculating bus energy demands.

To get the most precise topography of chosen route as possible, I have walked along the route with GPS device. I set off from the first bus stop and I have written down altitude parameter at every gradient change and every important stop (bus top, traffic lights…).

In the end, I found out that the maximum height difference at the route is 45 m. For detailed data, please see the table below. There's always section number, its length and most importantly the height difference. If the section is incline, the number is positive, if there's a decline in the section, the number is negative. For the graphic presentation of route height profile, see the attachments. It is necessary to note that negative gradient (downhill sections) is mathematically expressed as negative number as well, hence "-" in front of few section height difference values. This convention further simplifies recognition of downhill sections and their effects in the research.

Table 4. 1 Section height difference

Section no.	Section length [m]	Section height difference [m]	Average section velocity [km/h]
1	100	3	14,4
2	250	- 3	16,2
3	160	- 3	13,4
4	385	- 6	47,5
5	450	- 5	47,2
6	333	9	55,7
7	90	7	17,9
8	341	14	30,8
9	264	13	22,3
10	255	2	32,0
11	220	- 4	26,0
12	73	- 5	9,1
13	87	- 1	11,1
14	348	7	22,2
15	342	- 6	24,8
16	76	- 4	18,2
17	334	-18	46,6
18	119	- 3	23,2
19	110	-13	26,6
20	581	5	59,0
21	177	5	46,5
22	316	2	37,8
23	283	12	25,0
24	121	- 3	18,3

4.2 Route speed profile [21]

Regardless of route topography, there's second profile of the measured route to determine. That is the speed profile. Any motor vehicle can be – viewed from the respect of speed – in four states.

First is the stage of acceleration. Here, the vehicle uses most of energy, since it has to reach desired speed from a standstill. Thus, there's acceleration occurring.

Second phase is the cruise. Here is no acceleration in effect and the vehicle maintains its speed. There's usually notably less energy used than in the previous phase, because there's the inertia resistance missing.

Third possible state of the vehicle is coasting. Here, the vehicle is neither accelerating nor braking. It is only driving, gearbox in neutral and it's using it momentum for movement. It is usually slowing down.

Last possible state of the vehicle is deceleration, which is the reverse of acceleration. Driver is braking and the bus isn't using any energy, it is only wasting it, in case of conventional non-hybrid vehicle.

In my calculations, I don't include the third phase – coasting. As I have observed, on such a short distances as urban bus line covers, there isn't time for coasting. And the second reason is that vehicles weighting more than 3,5 t mustn't coast by law.

There can be only one phase in a section. In my measurements, though, most of the sections include three phases. The parts of the route divided by gradient change include only two phases, cruise and either acceleration or braking.

It is also noteworthy to mention that the maximum speed in section doesn't always correspond with maximum allowed speed. As I have observed during measurements and data acquisition, the buses have rarely the opportunity to reach the speed limit. It also depends on the bus driver, since some of them drive very vigorously, whereas some are rather calm. I have therefore taken in mind average of these two extremes and I have used the real top speed that the drivers reach.

For the diagram showing route speed profile, please see the attachments.

4.3 Number of passengers

Due to the proximity of bus route no. 235 to my house, I was able to observe the loading of buses throughout the week. As I have already written, this line connects dense residential area with subway station. Therefore buses are fully loaded in the rush hours. In the morning (between 7 and 9 o'clock) the vehicles are full on the way to station "Nové Butovice". In the evening rush hour (16:30 to 19:00), buses on the other part of the route – to Velká Ohrada – are fully loaded. Needless to say, in the peak times, every second bus that drives the route is articulated SOR NB 18 CITY in order to cope with the demand.

Manufacturer quotes the maximum capacity of 93 to 103 passengers, dependent on interior configuration. These are probably optimistic numbers. When the bus was full and more commuters could hardly fit it, I have counted fewer than 80 people. In my calculations, for fully loaded bus during peak times, I use as number of passengers including driver and me as 78. When I took the bus on Sunday afternoon (approx. 15:30) there were 8 people travelling from "Nové Butovice" and 10 going back there. Therefore, for the off-peak times, I will use 10 passengers as minimal load.

Numbers of passengers of course differ stop to stop. I have observed, though, that on the way to "Velká Ohrada", there is fully loaded bus going from the first stop "Nové Butovice" all the way to the stop "Červeňanského", where few passengers get off (about 10). The same trend follows at the stop "Ohradské náměstí", and the rest of the people finally get off at the last stop.

On the journey to "Nové Butovice", the situation is vice versa. Most of the commuters (50 – 60) get on the bus on the first stop, while significant number of people gets on the bus at the second stop "Červeňanského", about 10 – 20. The intermediate stops aren't even permanent, the bus stops there only at notice of passenger. If the bus stops, then, there is an exchange of maximum 5 people.

During my calculations, I used changing number of passengers. The character of this line, though, shows that the bus is either full from the beginning to the end of the route, or empty. And no big changes in number of people happen during the drive, which is convenient for the research.

4.4 Total mass calculation

Total mass of the vehicle has important role in the determination of energy consumed. All but one resistances the bus has to overcome are dependent on its total mass.

In the following chapters, I always determine the mass as a mass of the vehicle, which is constant (10 990 kg) and I´m adding up load according to the number of passengers aboard. Various norms and regulations in Europe define the weight of a passenger between 75 and 80 kg. I think of average of these numbers and so I use 78 kg as a reference weight of a person with his belongings. Column called "Load weight" is then always calculated as a number of passengers times 78 kg.

5. Resistances

5.1 Resistances overview

Every vehicle that rides on the road has to overcome several resistances, in order to even set off from standstill. Most of these resistances are functions of a vehicle and are its characteristics. They can be slightly eliminated by the vehicle construction. These resistances are closely observed these days, since they're reduction can improve energy efficiency of a bus. There are also a number of resistances that are route dependent. These cannot be eliminated and have to be accounted by. Every resistance will be explained below. Here's the list:

1. R_{rl} - Rolling Resistance
2. R_g - Gradient Resistance
3. R_i - Inertia resistance
4. R_a - Aerodynamic Resistance

The complete results of each resistance and values that are accounted with are attached in a table A.2.

5.2 Rolling resistance [22]

Rolling resistance exists as a result of the tire rolling along the road. Tires are the only contact patches that join the vehicle and road together. Hence, these bits of rubber have to transfer many forces. The rear tires have to transfer all the tractive power on the road. The front tires are responsible for steering the vehicle. In addition, all the wheels carry huge forces when braking and cornering.

To precisely determine this drag is very difficult and complex. It is dependent on many conditions and is not often constant. First, it depends on the surface of the road. Rough asphalt or smooth concrete make a difference. Second, it relies heavily on the tires. Tire width is one of factors defining this coefficient. Thread pattern and tire compound make a difference as well. That can be seen at different fuel consumptions on winter and summer tires.

Weather conditions influence behavior of the tires as well. The colder it is, the denser the gas inside tires is and so can they be more flexible. It is as well necessary to mind the pressure in the tires. The higher it is, the stiffer the tire is and there's smaller contact area between it and the road. The tire is then also stiffer and its deformations are smaller. That is beneficial for fuel consumption, but is dangerous for the driving behavior of the bus. And the deformations themselves influence the drag of tires as well.

For the purposes of this thesis, though, I'll be counting with data obtained from the manufacturer and less complex equation:

$$R_{rl} = f.G.\cos\alpha$$

And the vehicle gravity is:

$$G = m.g$$

5.3 Gradient resistance [22]

Gradient resistance is present every time the vehicle has to drive up a hill. When driving up a steep slope, it might be the largest of all the drive resistances. However, it is not always negative. When driving downwards, this drag actually becomes beneficial and the engine can produce less power, thus consume less fuel.

It is calculated as:

$$R_g = G.\sin\alpha$$

Because this resistance is as well dependent on the vehicle's weight, it significantly affects heavy bus. It will play important role in the energy needs of a bus on the route I have chosen, due to its profile. It is in this section, as well, that it is important to know route topography.

5.4 Inertia resistance [22]

Inertia is the resistance of a vehicle (or any other physical object) to any change in motion. Therefore, it tries to prevent the bus from accelerating and when slowing down, it implies against braking. It consists of two parts:

$$R_i = R_{it} + R_{ir}$$

Momentum of body is simple to describe:

$$R_{it} = m.a$$

The inertia resistance is more difficult to tell. The basic formula is:

$$R_{ir} = \frac{M_r}{r_d}$$

And:

$$M_r = M_{re} + M_{rg} + M_{rW}$$

Thus, the used equation for determining the inertia resistance equals:

$$R_i = \left[1 + \frac{\left(I_e.i_f^2 + I_g.i_d^2\right).\eta + \sum I_{Wi}}{m.r_d^2}\right].m.a = \vartheta.m.a$$

This resistance is one the most significant when speaking of bus, since the rotating masses are significant and this resistance in fact dictates the necessary power of the drivetrain.

In order to simplify the formula and final determination of energy needed to overcome this resistance, I have used different equation. See chapter 6.3.

5.5 Aerodynamic resistance [22]

The environment around the vehicle, in this case, creates the aerodynamic drag by the air flowing around the body of a bus. It is a force pushing against the vehicle and therefore it's necessary to overcome it. This drag depends on squared value of speed, and is therefore more significant at higher speeds. It can be defined by the following equation:

$$R_a = \frac{1}{2}.\rho.A_f.c_x.v_r^2$$

One of the most defining factor of aero drag is the drag coefficient of vehicle and its frontal area. That is always going to be considerable when referring to a bus.

Drag coefficient is carefully observed number these days. Although largely defined by overall vehicle shape, little tweaks on its body can lower it. Therefore, modern vehicles employ spoilers, body overlapping wheels, aerodynamic hubcaps, clean underbody and others. Such measures aren't subject of this thesis. In our case, manufacturer provided us the drag coefficient data for SOR NB 12 CITY.

It is important to note here, though, that the aerodynamic resistance isn't such an issue in case of urban buses. As I have already stated, this resistance increases with speed and as breakeven speed, where air drag is starting to influence energy demands of a bus are above 70 km/h. Hence, it is not going to be the biggest drag force in this research.

In my calculations, I have used this formula only for calculation the drag force in the coasting sub-sections of the route. It is beneficial to use this equation as a basis for determining the resistance force being created by aerodynamic drag and then use it to determine the energy in the mentioned sub-sections.

For the rest of the route, where the bus either accelerates or decelerates, I determine the resulting necessary energy from the balance of kinetic energy in each of these sub-sections. See chapter 6.4.

5.6 Auxiliary components energy consumption

The resistances listed above might be the most significant ones, but they only consider the vehicle and its behavior. Especially during the bus service, there are many components and subsystems that drain energy off the engine. To name the most important systems necessary to drive the bus, there is power steering, brakes servo or water pump.

In addition, there are many systems enhancing the passengers comfort, such as independent heating, door opening, information system, driver ventilation or daytime running lights. These are powered by electricity and are connected to the main battery.

Energy consumption of described systems is constant throughout the ride and is not related to the speed of the vehicle or its load. They are, however, dependent on the time of the whole ride (power steering, information system …) and on the weather conditions (independent heating …). It is important to note, for the results, that at time of measurements, the heating system was fully working.

It would be difficult to measure these consumptions as part of this thesis, therefore I will rely on data quoted by the manufacturer [19]:

Electric power of the additional heating……………………….. 80 W
Electric power of water pump ………………….……………….. 110 W
Total electrical consumption……………………………………… 190 W

Sadly, manufacturer has not been able to provide me with complete overview of the total energy consumption of all auxiliary devices. Therefore, to make the results more precise, I count at least with the two obtained values. It is evident, then, that the energy needed by the auxiliary electrical components would be higher in real service. However, I didn´t manage to measure these data, since it would require close cooperation with manufacturer and transport provider.

6. Energy consumption

As the name of this thesis states, the ultimate result will be the energy balance of a bus. This energy will be equal to the energy necessary to overcome all the resistances. First, then, I need to calculate energies used to overcome single resistances. I will then add up all the values to get the total energy consumed during a loop of bus line 235.

As well as in chapter 5, all the results and values of each energy are in the table A.2 in the attachment.

6.1 Energy from rolling resistance

Because the rolling resistance in not dependent on speed or acceleration, it is quite simple to determine. Using the general equation for calculating work:

$$W = F.s$$

As is known from physics, work equals energy, so I can apply this equation on my research. I have always simply taken the value of force stemming from this resistance and multiplied it by the distance of each sub-section. It is also noteworthy that this energy need to be overcome regardless of the bus slowing down, accelerating or ascending or descending.

The constant nature of this resistance is positive for the drivetrain of a bus, since there aren't any sharp peaks in energy needs. Thus, the drivetrain components can be designed with certain number in mind and will often work with constant load. That's also beneficial for the reliability of components.

6.2 Energy from gradient resistance

Second resistance, the gradient resistance, is also not dependent on the velocity of the bus. Therefore, the amount of energy necessary to overcome it can be defined using the same formula as in chapter 6.1. Here, instead of force created by rolling resistance, I use force created by gradient resistance.

Energy levels calculated here are not constant and are very variable. Not only that, when the bus is going downhill, this resistance actually helps to power the vehicle. Even though the chosen bus line 235 doesn't include such evident altitude differences, even here can be seen that energy needed or created here puts high demands on the whole powertrain of a vehicle. Powerful components needed to power full bus uphill are made redundant when going downhill. Not only that, their heavy weight puts further demand on the braking system of the vehicle.

It's easy to see the potential of utilization of brake recuperation though. On a route with more varied altitude profile, captured energy during downhill drives could be used for supporting the engine when ascending.

6.3 Energy from inertia resistance

Since the amount of energy needed to overcome inertia resistance depends on speed, it is necessary to approach it differently, because of the phases of acceleration and deceleration.

I have decided to determine energy necessary to overcome this resistance as the difference of kinetic energy values. Mathematically expressed as:

$$E_i = \frac{1}{2}\vartheta.m.(v_2^2 - v_1^2)$$

Although simple equation, it is often difficult to exactly determine the coefficient ϑ. I decided to define it using equation for energy balance. It goes as following:

$$\frac{1}{2}\vartheta.m.v^2 = \frac{1}{2}.m.v^2 + \frac{1}{2}.I_e.\omega_e^2 + \frac{1}{2}I_g.\omega_g^2 + \sum \frac{1}{2}I_W.\omega_W^2$$

$$\frac{1}{2}\vartheta.m.v^2 = \frac{1}{2}.m.v^2 + \frac{1}{2}.I_e.\left(\frac{v.i_f}{r_d}\right)^2 + \frac{1}{2}I_g.\left(\frac{v.i_d}{r_d}\right)^2 + \sum \frac{1}{2}I_W.\left(\frac{v}{r_d}\right)^2..$$

$$\vartheta.m = m + I_e.\left(\frac{i_f}{r_d}\right)^2 + I_g.\left(\frac{i_d}{r_d}\right)^2 + \sum I_W.\left(\frac{1}{r_d}\right)^2$$

$$\vartheta = 1 + \frac{I_e.i_f^2 + I_g.i_d^2 + \sum I_W}{m.r_d^2}$$

However due to a lack of measuring equipment, which is necessary to measure all the ratios and moments of inertia, I have simplified the determination of ϑ as following:

$$\vartheta = 1 + \frac{I_e.i_f^2 + \sum I_W}{m.r_d^2}$$

The reasons are further though. Sadly, manufacturer didn´t provide me with moment of inertia of rotating masses in drivetrain, neither with the efficiency of the whole powertrain. The fact is as well that these number would be minor and so would change the results only slightly.

The data I have used in the end were sent me by the SOR Company. For the moment of inertia of wheels, the bus has got two front wheels and rears consisting of four bigger rims. Since it was impossible to determine the gear changes and their timing with my equipment, I have chosen one fix engine-to-wheels ratio. Since most of the time, the bus was in third gear, I have chosen this value. The gearing data were provided by manufacturer. The numbers from manufacturer are following:

Moment of inertia of front wheels	$I_{WF} = 7{,}8\ kg.m^2$
Moment of inertia of rear wheels	$I_{WR} = 9{,}7\ kg.m^2$
Moment of inertia of the engine	$I_e = 1{,}5\ kg.m^2$
Engine-to-wheel ratio	$i_e = 1{,}429$

Dynamic wheel radius $r_d = 0{,}465\ m$
Average calculated ϑ $\vartheta \cong 1{,}02$

Overview of the values is to be found in the attachment. The value of coefficient ϑ is calculated for each section, since it is dependent on a mass of a vehicle, which is not constant throughout the route.

6.4 Energy from aerodynamic resistance

As I have stated in paragraph 5.5, the equation for determining the energy necessary to overcome aerodynamic drag is different to the equation of aerodynamic drag. Mathematically expressed, it is:

$$E_a = \frac{1}{2}.\rho.A_f.c_x.\frac{1}{a}.\left(\frac{v_2^4}{4} - \frac{v_1^4}{4}\right)$$

Since each route section consists of 3 sub-sections (some only of 2) I have to determine the final energy used in each section as a result of these three values. I have used this equation always in the first and last sub-section of each section, where the bus changes it´s velocity. This resistance always prevents the bus from accelerating and thus the engine has to compensate for it.

In the sections, where the bus reaches higher speed, this resistance becomes more important. However, due to the speed profile of chosen route with lower velocities, the resistance is mostly marginal. For exact results, please see attachment.

6.5 Energy consumed by auxiliary electrical components

The ultimate energy balance will be influenced by the energy consumption of auxiliary components, which obtain energy from the electrical circuit in the vehicle. The amount of energy needed to power them only depends on their power and duration for which they work. Since in this category belongs heating, door opening systems, power steering etc., the energy consumed depends very much on the time of the year, actual weather and driving conditions.

Because SOR couldn´t provide me with complete overview of these consumptions nor with a complete number, to estimate the energy necessary and to at least present a way how to continue the research in the future, I utilized two consumptions I was given. The mathematical formula is then following:

$$E_{au} = t.\sum P$$

Of the two power demands I received from the manufacturer, I calculated, that during one 18 minutes long ride of the bus on this loop, they consume:

$$E_{au} = 1080\ [s].190\ [W] = 205\ 200\ J$$

6.6 Ultimate energy balance [23], [25]

It is the task of this research to determine the amount of energy used throughout one loop of bus line 235. Of higher importance for further research is a graph showing in which sections is the most energy needed/generated and how fast is it needed. See attachments.

Determining the ultimate energy balance meant calculating the energy need in each of the sub-section. There are different resistances in effect when accelerating, when coasting, either going uphill or downhill. Therefore, I had to create a system how to add the energies up. To display it, I devised a table below. Please note that positive value means, that the bus is consuming energy and negative value means the vehicle has more energy than necessary. This is usually dissipated as a heat during braking.

Table 6.1 Deciding negative/positive resistance during bus ride

	Acceleration	Coasting	Braking
Rolling resistance	+	+	+
Aerodynamic drag	+	+	+
Gradient resistance	+/-	+/-	+/-
Inertia resistance	+	0	-

(Note: gradient resistance values: "uphill"/"downhill")

Mathematically expressed:

$$E_u = E_{rl} + E_a \pm E_i \pm E_g + E_{au}$$

I have applied this value convention to sub-sections. On these results I have created the resulting graph. See attachments. The results are showing increased energy needs during uphill sections with a full load and during acceleration. During few braking phases, the balance is negative. That means the bus doesn´t need more energy to maintain its movement.

In the end, the total energy consumption of a SOR NB 12 CITY on a bus line 235 during its one loop (calculated with average load, during moderately cold spring, with auxiliary devices of heating and water pump) is:

$$E_u = 11{,}21\ MJ$$

7. Conclusion

Energy balance of any vehicle is a crucial basis for developing new alternative powertrain, or even optimizing conventional powertrains with respect to reliability. I have conducted this research in the busy sub-urban area, where should be many peaks in the energy demands.

Even the data acquisition showed me that for precise results, expensive measuring equipment would be necessary and so would many repeated runs. I was able to measure the speeds, distances and time. But I wasn´t able to exactly measure the energy consumption of auxiliary devices on board. I also had to take into account average driving style, since each driver drives in a different manner. These uncertainties could be measured by advanced diagnostic device that can capture the positions of pedals at given time and also measure accelerative forces in the vehicle.

Despite mentioned imprecision, the results of the research are beneficial and can be used in many ways. Not only do we see the total energy needed to power the bus along the route, which can be used as a reference value for dimensioning the capacity of energy storage facilities. It´s interesting to note that the energy that a bus needs on measured route is only slightly higher than maximum allowed electric capacity per lap (8 MJ) for racing cars at the famous Le Mans race.

The results can also give an idea, where is the energy most used, and thus which resistance is necessary to optimize. Form the calculated energy amounts, it is the rolling resistance that consumes most energy. This could be reduced by the use of low rolling resistance tires. However, even road surface is the cause here.

As I have stated in the chapter 5.5, because of low speeds reached by the bus on chosen route, the aerodynamic drag is low compared to other resistances. This fact can be seen when we compare drag resistance in the section with 15 km/h speed limit (R_a = 32 N) and in the fastest section (v = 70 km/h, R_a = 695 N). When speaking of urban bus then, it is not of the major concern.

Inertia and gradient resistances are more difficult to optimize. Inertia resistance is significant during acceleration and braking phases, when the bus consumes most or second-most energy to overcome it. It could be decreased by lighter components of engine or lighter wheels. It is also necessary to note that I have taken the average engine-to-wheel ratio, therefore I have eliminated the effect of changing gears. The value of gradient resistance depends on the route height profile, so it is impossible to compensate for it.

The resulting energy balance graph shows the energy flow during the bus service on given route. There are three significant peaks where the vehicle needs most energy (sub-sections 5.2, 6.2 and 20.2). These parts of the line are long and all have the highest speed limit. Therefore, here are most significant rolling resistance and aerodynamic drag. It is not of a surprise, that the rough profiles of a route height profile and speed profile are similar.

On the other hand, in few sub-sections (most in 16.3) the bus has actually more energy than it needs. Therefore, in these phases the driver has to brake and waste the energy. And when designing a bus nowadays, these areas of service should be watched closely.

The resulting graph represents total energy balance, with two auxiliary components consumptions added. Even though there´s a pressure on manufacturers to lower these consumptions, as we can see here on an example of a bus, they are only marginal. Furthermore, in warm periods of the year, it will be even lower, since heater will not be functional.

The results could be made more precise with accounting for a factor of traffic lights. Should the bus only ride and not stop often on a crossroads, the energy consumption caused by the inertia resistance would be lower. I can imagine finding out in my next research.

Despite few generalizations, I think this research could be used as a basis for developing hybrid drivetrain for urban buses. I can imagine that as a next stage of my research, possibly in the next thesis, that I would use this energy balance for dimensioning the drivetrain components. I know how much energy do I need to store, what are the energy currents and from where they stem, so I could choose the correct energy storage.

Another possible extension of this work could be designing the kinetic energy recovery facility. As can often be seen in the braking sections of the route, the bus actually has more energy than necessary. It could be captured by the drivetrain and power, for example, the auxiliary components.

In the era of hybrid and alternative powered vehicles, I think this research is a relevant for their settings. Using today´s engineering capabilities, it could contribute to a design of sustainable transport of the future.

8. List of Figures

9. List of Tables

10. Used Sources

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11. Attachments

Figure 11.1 Route Height Profile Diagram

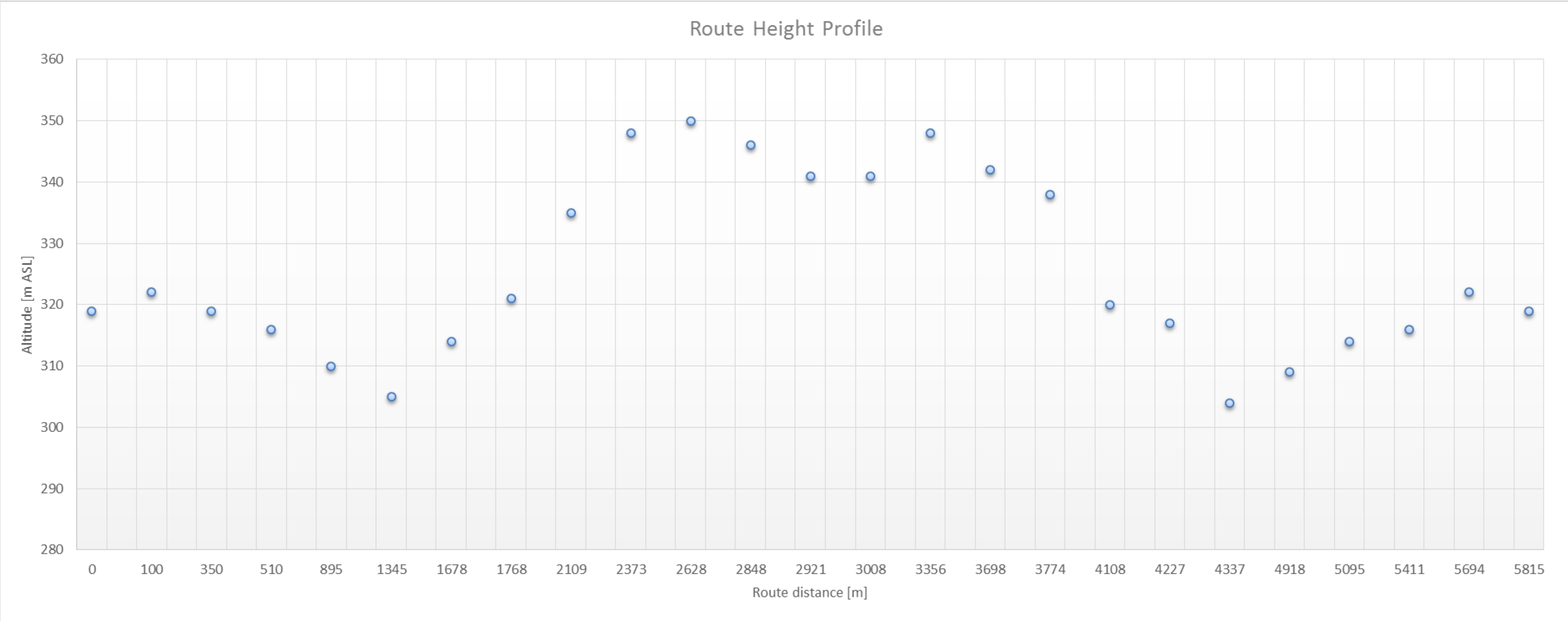

Figure 11.2 Route Speed Profile Diagram

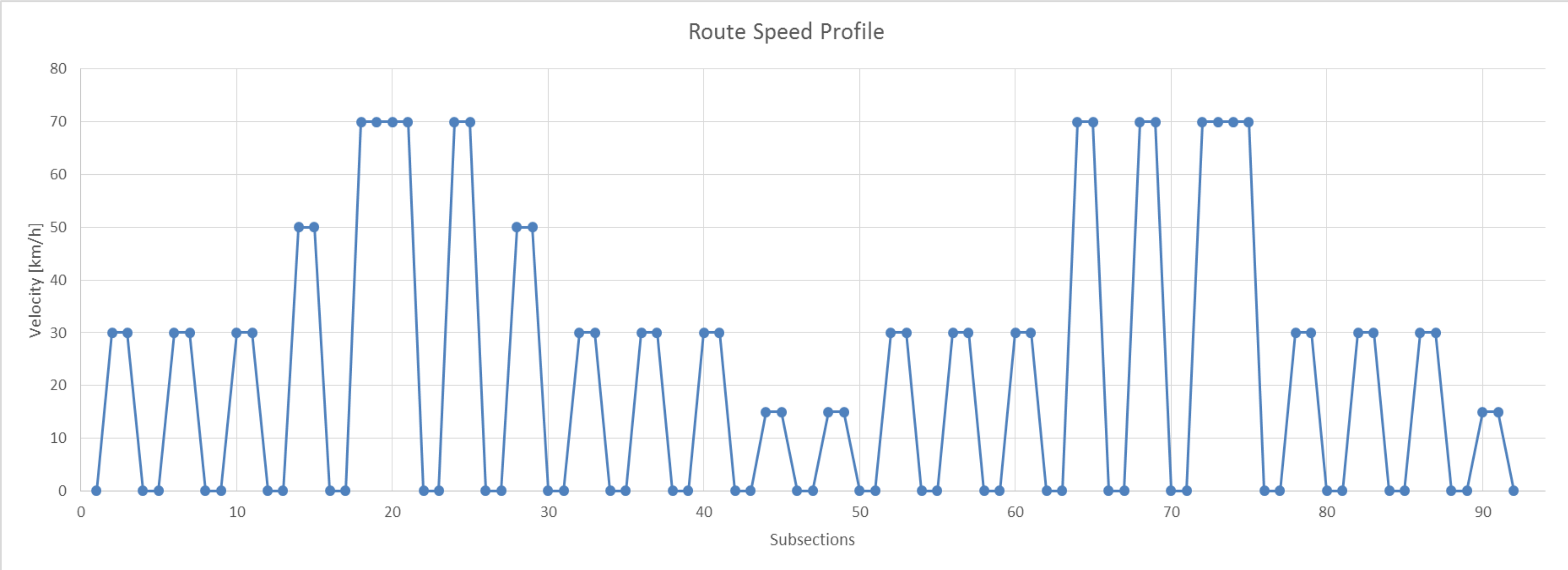

Figure 11.3 Energy Balance of SOR NB 12 CITY on the route 235