MASTER THESIS

Thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Engineering at the University of Applied Sciences Technikum Wien - Degree Program Intelligent Transport Systems

Transport safety assessment of road adaptive lighting implementation

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- Evaluation of situation with standart lighting
- Evaluation of situation with adaptive lighting
- Mutual comparison, conclusions

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Bibliography:
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Directive 2008/96/EC of the European Parliament and of the Council of 19 November 2008 on road infrastructure safety management and successive documents

Rune Evlik, The handbook of road safety measures

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Prague .... May 4, 2014

Declaration

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Abstract [EN]

This master thesis is concerned with road traffic safety assessment in Angyalföldstraße in Vienna. This street was recently equipped with new adaptive LED road lighting system, which decreases lighting intensity in night hours from 11pm to 5am, in order to decrease energy consumption. The goal of this thesis is to assess possible changes in road safety, caused by the decreased lighting intensity. The safety assessment itself is based on comparison of safety influencing factors – mean speed and speed variance. This data was obtained during a period with the classical road lighting (July 2014) and also during a period with the new adaptive LED lighting (September 2014). Means of the assessed variables from July and September were compared using statistical hypothesis testing. Because of dependency between the two datasets, two sample paired t-test was chosen as the most appropriate test statistic. We found out, that the calculated differences in the safety influencing factors are considered to be insignificant by the means of statistic testing and therefore we rejected the null hypothesis, which stated that road traffic safety will get worse after adaptive LED lighting implementation.

Abstrakt [CZ]

Tato diplomová práce se zabývá vyhodnocením dopravní bezpečnosti ve vídeňské ulici Angyalföldstraße. V této ulici byl nedávno nainstalován nový adaptivní LED systém silničního osvětlení, který snižuje intenzitu osvětlení v nočních hodinách od 23 do 5 hodin za účelem snížení spotřeby elektrické energie. Úkolem této práce je posoudit možné změny v dopravní bezpečnosti, které by mohly být zapříčiněny sníženou intenzitou osvětlení. Dopravně bezpečnostní posouzení je založeno na srovnání faktorů ovlivňujících bezpečnost – průměrné rychlosti a rozptylu rychlosti. Tato data byla získána jak z období s klasickým osvětlením (červenec 2014) tak i z období s adaptivním LED osvětlení (září 2014). Červencové a zářiové průměrné hodnoty posuzovaných parametrů, byly následně porovnány za pomoci statistického testování hypotéz. Vzhledem k tomu, že jsou oba soubory dat na sobě závislé, byl jako nejvhodnější testovací statistika vybrán párový t-test. Zjistili jsme, že vypočítané rozdíly mezi faktory ovlivňujícími bezpečnost z obou období jsou podle vybrané testovací statistiky nevýznamné, a proto byla zamítnuta nulová hypotéza, která říkala, že dopravní bezpečnost se zhorší po instalaci adaptivního LED systému silničního osvětlení.

Klíčová slova: Silniční osvětlení, dopravně bezpečnostní posouzení, adaptivní osvětlení, testování hypotéz

Abstrakt [DE]

Diese Diplomarbeit beschäftigt sich mit der Auswertung der Verkehrssicherheit in der Wiener Angyalföldstraße. In dieser Straße wurde vor kurzem ein neues adaptives LED-System der Straßenbeleuchtung installiert, das die Beleuchtungsintensität in den Nachtstunden von 23 bis 5 Uhr zum Zweck der Verringerung des Verbrauchs von elektrischer Energie verringert. Zweck dieser Arbeit ist es, mögliche Veränderungen in der Verkehrssicherheit zu bewerten, die durch die verringerte Beleuchtungsintensität verursacht werden könnten. Die verkehrssicherheitstechnische Bewertung ist auf dem Vergleich von Faktoren begründet, welche die Sicherheit beeinflussen - die durchschnittliche Geschwindigkeit und die Streuung der Geschwindigkeit. Diese Daten wurden sowohl im Zeitraum mit einer klassischen Beleuchtung (Juli 2014) als auch im Zeitraum mit einer adaptiven LED-Beleuchtung (September 2014) erhoben. Die durchschnittlichen Werte der begutachteten Parameter im Juli und September wurden nachfolgend mittels eines statistischen Tests von Hypothesen verglichen. Hinsichtlich dessen, dass beide Datenkomplexe voneinander abhängig sind, wurde als geeignetste Teststatistik der abhängige t-Test ausgewählt. Wir haben festgestellt, dass die berechneten Differenzen zwischen den Faktoren, welche die Sicherheit von beiden Zeiträumen beeinflussen, nach der ausgewählten Teststatistik unbedeutend sind, und deshalb wurde die Nullhypothese abgelehnt, die besagt, dass die Verkehrssicherheit sich nach der Installation des adaptiven LED-Systems der Straßenbeleuchtung verschlechtert.

Acknowledgments

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1 Introduction

Main subject of this master thesis is an assessment of implementation of a new road lighting system developed together by Swarco and Philips. The most significant difference in comparison with current road lighting is the usage of LED and the possibility to control the level of resulting luminance. LED technology was chosen mostly because it can offer lower energy consumption in comparison with classical high pressure sodium lamps, which are used most commonly these days. Furthermore it also provides the possibility to smoothly change the luminance output of lighting faster when compared to current lighting system. This feature enables the system to change the luminance level according to the actual traffic flow. The main idea is to dim the lighting when the traffic flow during night is low or when no vehicle is present, and on the other hand, when the traffic flow increases, the luminous intensity will also increase accordingly, possibly up to 100% of luminance output performance. This adaptive lighting system is currently (March 2014) being implemented in Angyalföldstraße in Vienna as a pilot project of this system. The aim is to assess it from two main points of view – traffic safety assessment and energy reduction assessment. The safety assessment is the concern of this thesis, and the energy reduction assessment will be performed by my colleague in his master thesis. The main purpose of the results, which will be delivered by the assessments, is to validate the system from these two points of view, show possible advantages or disadvantages and to suggest whether the system should be either further implemented also to other parts of the city or whether it should undergo further development in order to achieve required performance and in that case, possible improvements will be suggested in this work.

1.1 Motivation

First main objective of this new approach to lighting system is decreasing energy consumption, which is connected with increasing the overall system efficiency, decreasing operation cost and also with reducing CO_2 emissions, as even these days most of the electrical energy is being produced by fossil fuel power plants. These prospects are firstly appealing because it is matter of prestige to create an efficient system. Secondly they are also desirable because they are compliant with the future initiatives that were set by the European Union, most importantly Europe 2020 A European strategy for smart, sustainable and inclusive growth. In this paper EU suggests five measurable targets for the year 2020 that provide a strategy to help the EU come out stronger from the economic crisis and turn it into a smart, sustainable and inclusive economy, which delivers high levels of employment, productivity and social cohesion. These five targets are: for employment, for research and development, for climate change and energy, for education and for combating poverty. This system is compliant with two of these targets and these are the target for research and development, because it is an innovative approach, and also the target for climate change and energy. This target is sometimes called "20/20/20" because its requirements are

following: "Reduce greenhouse gas emission by at least 20% compared to 1990 levels (with right conditions 30%); increase the share of renewable energy sources in the final energy consumption to 20%; and a 20% increase in energy efficiency." [1] The energy consumption reduction is achieved firstly by using the LED lamps themselves and secondly by the decreased luminance level when the traffic flow is low. Furthermore energy reduction is also required by national strategies like for example ITS action plan Austria, one of which targets is to help overcome social challenges such as climate change and resource scarcity by conserving natural resources. One of other concerns of the ITS action plan Austria are also safety issues, which are connected with personal mobility. [2] This means, obviously, that adaptive lighting systems can't compromise safety of any road users.

Moreover, the next reason for choosing this system over the traditional high pressure sodium lamps is the angle of the beam, which is narrower in this case. This means that the light is more concentrated in the direction toward the street, rather than to all directions, as the classical lamps tend to do. Apart from achieving even greater energy efficiency, this will also reduce the light pollution in a given area.

Furthermore the network of communicating nodes (lamps) can be also used for other applications than only for light control. This network can also serve as a wireless sensor network, which can collect data such as traffic flow parameters, air quality, noise levels, humidity or temperature. It could also be used for example as an access point to a city WIFI.

Another interesting application is to use this system for maintenance purposes. The lamp itself can report malfunction and thus there will be no need for vehicles patrolling for lamps, which are out of order, as it is done today, which can contribute to minimizing the maintenance costs.

Finally the light spectrum provided by LED lamp is very different from the light produced by a high pressure sodium lamps, which have been used till now. LED light is brighter, because different light wavelengths are represented more equally, which results in rather pure white color, unlike the light from high pressure sodium lamp, which tends to be yellow or grey. Therefore the idea is that LED light could provide more contrast, which would be beneficial for safety of all road users.

2 Lighting performance indicators

A human eye can adapt to a broad range of lighting levels, from faint to very strong ones. There are two types of photoreceptors, which are responsible for this adaptation – firstly, there are sensitive rods, which are useful for lower luminance and secondly, there are cones, which are less sensitive and are useful for higher luminance values.

The luminance range is divided into three regions according to which types of photoreceptors are working. In the photopic region of light adaption only cones are working. This mode is turned on during the daylight conditions, with luminance more than 1.0 cd/m². The eye is able to see detailed colors in this region. With decreasing luminosity, the cones become less effective and are assisted by the more sensitive rods. Usage of both photoreceptors results in less brightly colored overall impression since the rods can only process black and white images. This range of light adaption is called mesopic. With further reduction of luminance, the scotopic region of light adaption, which adapts to the dark, is reached. It adapts to dark conditions at luminance levels below 0.1cd/m². In this region only rods are working, which means that the perceived picture is black and white and mostly we are just able to recognize contours of objects. Visibility is a complex system that depends on many different factors and the performance can be described by parameters such as luminance, contrast, glare or uniformity which are described below.

Luminous flux, luminous intensity, illuminance and luminance

In order to characterize a light source basic indicators are defined. The luminous flux describes the quantity of light which is emitted by a light source. The unit of luminous flux is lumen (lm). Luminous intensity is a measure of power emitted by a light source of specific wavelength in a particular direction per unit angle. The unit of luminous intensity is candela (cd). Illuminance is the total luminous flux going through a surface. It is a measure of how much incident light illuminates a surface. The unit of illuminance is either lux (lx) or lumen per square meter (lm/m^2). Luminance describes the amount of light that passes through or is emitted from a particular area, and falls within a given solid angle. It indicates how much luminous power will be detected by an eye looking at the surface from a particular point of view and is essentially dependent on reflectance of a surface. The unit of luminance is candela per square meter (cd/m^2). These four parameters are schematically shown on figure 1. [27]
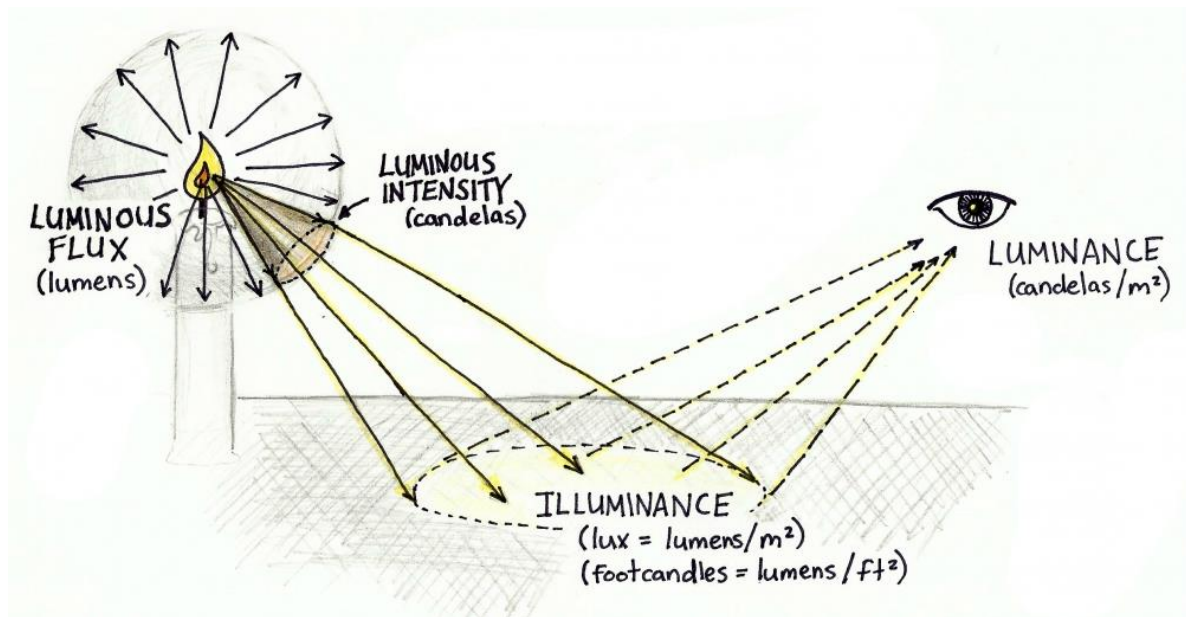
Figure 1 – Basic lighting indicators [28]

Glare

A phenomenon where visual perception is limited or even nonfunctional due to difficulties in seeing caused by bright light is called glare. It can be divided into three categories. Firstly, the discomfort glare occurs when light sources in the field of view cause disturbing effects and discomfort in vision without reducing the visual performance. Secondly, the disability glare is perceived when one or more glare sources form a light veil in the whole field of vision reduce contrast and visibility of a target. Thirdly, the dazzle or blinding glare appears when intensity of a light source rises over upper limit of the sensitivity area of the human eye.

Contrast

The contrast C between a relatively small object with sharp contours and its background is defined as follows:

$$C = \frac{L_0 - L_b}{L_b + L_{seq}}$$

Where:

L_0 is luminance of the object

L_b is luminance of the background

L_{seq} is disability glare which reduces contrast of an object.

Contrast is an important determining factor for the visibility of objects. Greater differences in luminance levels result in higher contrast and visibility. If the target luminance is close to the background luminance, regardless of the brightness level, the visibility is very low.

Color rendering

For visual performance and the feeling of comfort it is important that colors in an environment are reproduced naturally. Color rendering describes the effect of a light source on a perceived color of objects. To provide an unambiguous indication of the color rendering properties of a light source, the general color rendering index R has been introduced. It measures the ability of a light source to reproduce colors of objects in comparison with an ideal or natural light source (daylight). The maximum value of R is 100 and it decreases with decreasing color rendering quality. For example safety colors should always be easily recognizable and therefore light sources must have color rendering indicators greater than 20. (ISO 8995, 2006).

Uniformity

Adequate uniformity is necessary for visual comfort of road users and for overall visual performance. It is defined by the IEC 845-09-58 as the ratio of minimum luminance to average luminance on a road section under certain conditions. The higher the value of uniformity the closer the gap between maximum and minimum luminance and the higher is the visual performance. Uniform lighting allows perceiving the environment continuously and without sudden breaks caused by lighting level drops. Low uniformity ratios, frequent changes of contrasting high and low lit road segments cause enormous eye discomfort, as eyes change between the usage of rods and cones, leading to stress and tiredness which may often have a negative impact on road safety.

Correlated color temperature

The color temperature is a measure to quantify the color of a light source. Color appearance describes the ambience that a lamp provides - how "warm" or "cool" the light feels. The correlated color temperature was introduced by the CIE in 1987 and is defined by the temperature of a black body radiator having the same color appearance as the light source. The unit of the color temperature is expressed in Kelvin. The colors reach from red/orange white via yellow white and to blue white. Correlated color temperature gives us a good indication of the lamp's general appearance, but does not give information on its specific spectral power distribution. Therefore, two lamps may appear to be the same color, but their effects on object colors can be quite different. [29]

3 Road lighting technologies

There are several different ways, how streets can be lit. In this short overview these will be discussed from two different points of view – lamp technology and lighting control systems.

3.1 Lamps

One of the oldest lamp types is the classical bulb, which produces light simply by heating a wire with electric current because of impedance of the wire. This way of producing light is very ineffective – only about 5% of the energy is actually converted into visible light. That is mostly the reason, why they are not used for road lighting anymore. Nowadays the most common types of lamps are the so called high intensive discharge lamps. They are based on the principle of light being generated from an excitation of atoms of certain metals. The atoms excitation is achieved by an electrical discharge between two electrodes through inert gases such as neon, argon or xenon. Once electric current goes through the gas, more and more electrons get excited, which decreases the power consumption, while providing the same lighting intensity, because the produced plasma has a less electrical resistance. This state is usually achieved after several seconds after turning the device on. Although this effect is very preferable regarding the energy consumption, its time delay is also one of the main reasons for not using high intensive discharge lamps in adaptive road lighting systems, because these require to change lighting intensities more rapidly. The most recent, and because it is based on a different physical principle also most innovative way to produce light, is by using LED lamps.

3.1.1 Mercury vapor lamps

High pressure mercury vapor lamps were among the first high intensive discharge lamps and were often used to light outdoors and roads since the 1930s. Production of this lamp was rather cheap and it had a life span of around three years. The main disadvantages were the energy inefficiency, the color of produced light and also the usage of toxic mercury itself. New EU regulations, starting in 2015, prohibit the use of mercury vapor lamps. (Commission Regulation EC No 245/2009)

3.1.2 High pressure sodium lamps

High pressure sodium lamps were introduced in the 1960s. These lamps use a combination of sodium and mercury in a discharge through xenon gas at high pressures. Sodium alone would bring a deep orange light. Thanks to the influence of mercury and xenon the resulting light color has more tint of white. Unlike the mercury vapor lamps, which have a relatively constant voltage demand during their lifetime, the voltage input for sodium lamps

increases significantly during the operational time, in order to maintain constant luminance output values. Sodium lamps are commonly used on the streets also these days.

3.1.3 Metal halide lamps

Metal halide lamps were introduced almost simultaneously with the sodium lamps in the 1960s. The typical lamp is similar to mercury vapor lamps, however, the major difference is that the tube contains various metal halides in addition to mercury. These lamps are capable of producing light in a variety of colors depending on the used metal. For road lighting white light is obviously preferred. The main advantage of metal halide lamps over mercury or sodium lamps is the better spectral power distribution.

3.1.4 Light emitting diode lamps

Light emitting diode lamps are semiconductor devices, which emit light, when electrons pass through a PN transition and are therefore based on a completely different physical principle than the lamps mentioned before. Due to this principle the size and power of these lamps is limited and therefore such lamps usually consist of several modules, which are an assembly of one or more discrete LED lamps, in order to produce light, which can be suitable for road lighting. At present time, commercially available LED lamps can produce light of certain specific colors, nevertheless the white lamp type is the most efficient one. It uses light of a blue LED lamp together with yellow phosphor, which converts a part of the blue light into yellow light. The result is a bright white light. Depending on the ratio between blue and yellow light, the color temperatures can vary from 2,700K to 11,000K. Furthermore, LED lamps produce light in a way that can be more effectively controlled. Another big advantage of LED lamps is the turn on/off and dimming characteristic. It is possible to dim an LED lamp from 0-100% and there is no starting phase (heat up) needed. Compared to other commonly used lamp types, the different operation principle of LED lamps brings a broader spectral power distribution (shown on figure 2). We can note high content of blue light in LED lamps, which is believed to increase peripheral vision performance. [22]
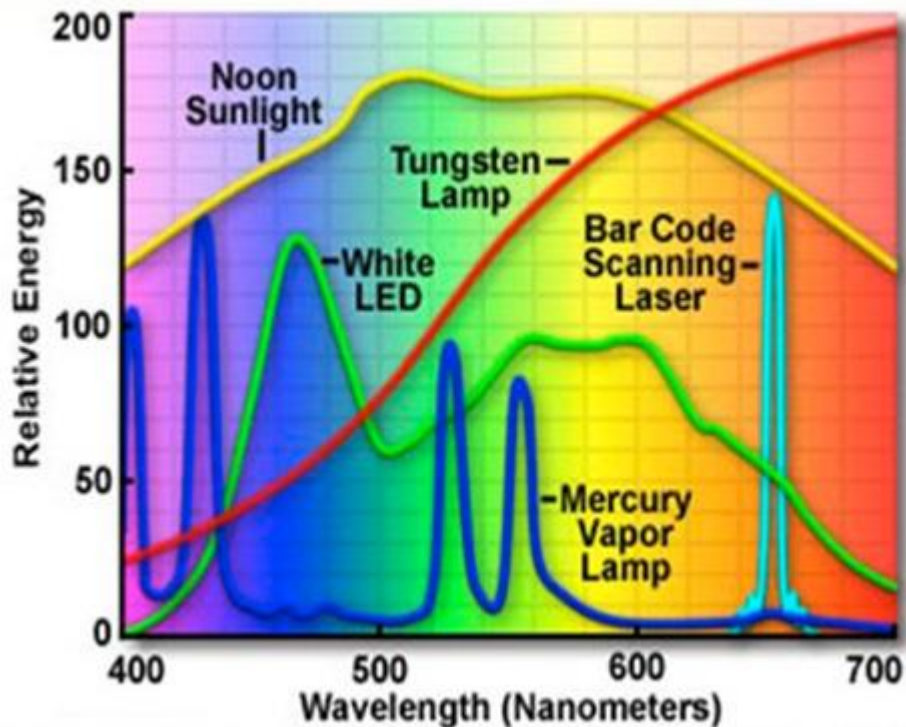
Figure 2 - Spectral power distribution of common light sources [23]

3.2 Control systems

At the early age of street lighting, lamps were usually turned on manually. Later with electric light sources automated techniques were introduced. Time controlling relays were used to turn lamps on and off at appropriate times. In principle such systems are still used nowadays. The following subchapters describe most common ways of lighting control systems, which are currently used.

3.2.1 Self-control

A self-controlled system can be triggered by time counters or by light-sensitive sensors. Time controlled systems have a preset time for turning them on and off, on the other hand, photosensitive control systems use photo resistors or photodiodes to provide a switching signal for every lamp node, when the luminance gets above or beneath some threshold level. It is also possible to control the whole city with just one light sensor. For example Vienna uses one light sensor placed at the energy service provider Wien Energie. When the illuminance level decreases below 50 lx for at least 5 minutes the turn on signal is triggered. Depending on the electrical load distribution of the electricity network, the public street lighting segments are turned on. The advantages of such control systems are the simple architecture and relatively low costs of equipment, installation and maintenance. Nevertheless preset turn on and off time has a poor capability to adapt to environmental

luminance changes or changes in driving conditions. The other disadvantage of photosensitive control is its vulnerability to dust, rain and snow, which can make the control inconsistent and inflexible and thus not useful for adaptive street lighting systems.

3.2.2 Remote control and monitor systems

All lamps in this type of system are controlled by a lighting control center with a centralized communication architecture. There are several different ways how this center can communicate with individual lamps.

Power line communication (PLC)

Since every lamp is connected to the power supply network, obviously a cost efficient way to connect the existing street lighting system would be via these power lines. Special power line protocols with very low overhead costs have been developed by several manufacturers in the recent years. Each lamp possesses a unique address, which enables a remote control of each individual lamp with a PC application. On the other hand, this will also make the network rather complex and possibly even slow. The range of communication using a power line depends on several factors like branches which divide the power of the signal, attenuation, switching power supplies and devices that consume power from the power line. The architecture of this solution is shown on figure 3. [25]

Figure 3 – Power line communication topology [25]
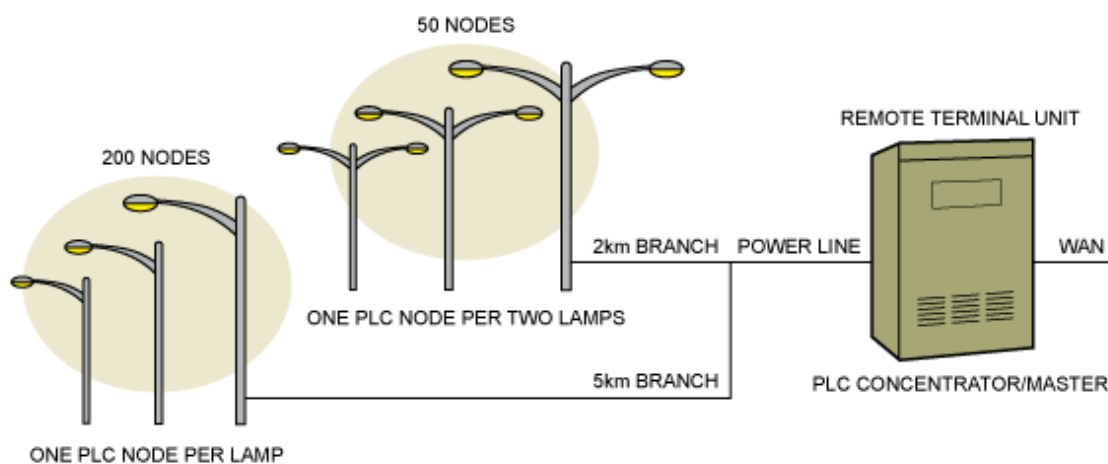
Wireless communication

This system can use wireless technologies to communicate with local control systems, which can bundle up to a few thousand lamps over a few kilometers to one control point. This control point avoids addressing of every single lamp individually and thus keeps the whole system fast. The list of possible wireless technologies to communicate with the

lamps ranges from WIFI, Zigbee or Bluetooth to GPRS/EDGE/HSPA/LTE. Due to a short range of some of the wireless communication systems the messages can be hopping from one lamp to the next one, which makes it possible to send information for long distances using low cost radio technology. Furthermore, wirelessly connected lamp posts equipped with different sensors are able to provide information about traffic situation or about environment (as well as PLC). The connection to the data center looks similar to the PLC - one local controller or gateway connects a few hundreds lamps. The system topology is shown on figure 4. [24]
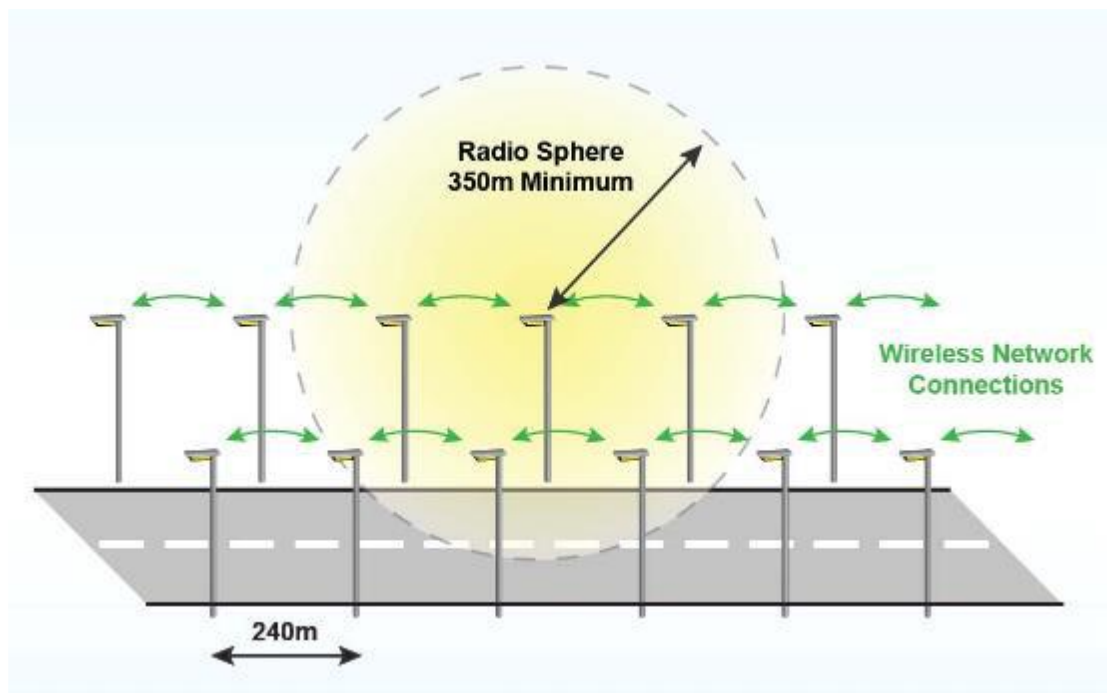
Figure 4 – Topology of wireless lighting control systems [24]

3.2.3 Adaptive street lighting

In case of adaptive street lighting, the lighting levels of road sections are set by applying different criteria such as road classification (arterial, local or collector), traffic volume, weather conditions or pedestrian activity, respectively conflict level. The most common design in urban areas is to use the highest pedestrian conflict level to calculate the required minimum lighting level for the considered road segment. As the awareness of environmental issues (energy consumption, lighting pollution…) has lately increased, trials of adaptive road lighting have been conducted. First attempts experimented with turning off a fraction of lamps in a lighting network - for example every second or third lamp has been turned off. Although this approach saves some energy, the uneven light distribution has a negative influence on traffic safety. Therefore more advanced systems have been developed. The proper adaptive, dynamic or intelligent street lighting optimizes the

luminance level and adapts to changing conditions and current needs. These systems are designed to take advantage of situations where it is possible to dim street lamps without affecting safety of those in that area. The setting of lamp luminance changes adaptively according to time of night, season, weather conditions or actual traffic flow. The main advantages of adaptive road lighting systems are the high control accuracy, individual lamp monitoring (failure, real time status and historical performance data), high scalability, compatibility with new technologies and possible energy savings. Disadvantages are high initial investment in equipment for centralized control center and also since it is a new technology much experience with long term operation hasn't been collected yet. System architecture is shown on figure 5. From a technical perspective adaptive street lighting systems consist of three parts:

Lighting controller

A lighting controller is located on each of the lamp poles, it consists of a lamp and ballast for the dimming functionality. It is responsible for switching and dimming of the lamp and for communication. Further functions are measurement of operational data, monitoring of the lamp, maintenance or possibly can also be used as an active communication repeater.

Segment controller

The lighting controllers are aggregated into segments, each of which has a central segment control unit. This basic infrastructure consists of a controller that handles various functions like scheduling, control, data logging or alarm handling. According to used communication technology it serves as a gateway to a wireless network or as a switch between wireless and power line communication. Segment controller exchanges important information between the lighting controller and the central management unit.

Central management system

Central management system controls all segments and merges data coming from the road side equipment with external traffic information. It consists of an online interface, which enables a lighting operator to control the complex network with many segments at different locations, from different service providers and communication systems from one or more places. Other components include luminance level control and traffic sensors, so that the system can adapt to current needs of the road users in real time. [26]
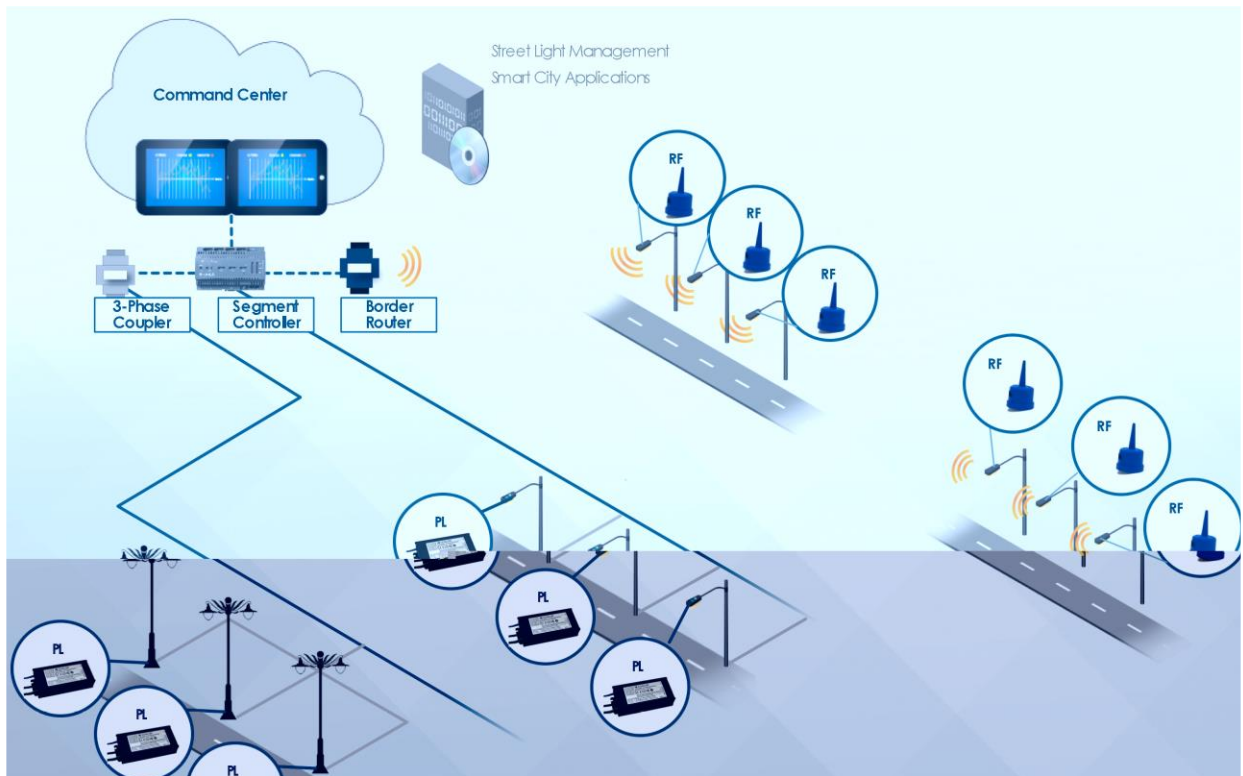
Figure 5 – System architecture of an adaptive street lighting system [26]

4 Existing adaptive road lighting projects

4.1 E-street light project

The main objective of this European project is to expand the market for energy efficient street lighting, as the partners within the consortium are all convinced about its significant energy saving potential, environmental and economic benefits and the increased level of traffic safety for the public. The project wants to test new financial instruments within street lighting such as energy performance contracting and third party financing. The core element for intelligent street lighting is fluent dimming of the lamps depending on the situation (weather conditions, traffic density and the complexity of the street). In addition the system may include energy measuring, two-way communication on the existing power supply and administrative toolkit for utilizing the operational tasks. Partners, who are participating in this project and who are testing this system in their environment at their pilot sites, are:

- Hafslund Nett AS, Norway
- Agęncia Municipal de Energia de Almada, Portugal
- Black Sea Regional Energy Centre, Bulgaria
- City of Göteborg, Traffic and Public Authority, Sweden
- Javna Razsvetljava d.d, Slovenia
- Investitionsbank Schleswig-Holstein, Germany
- Philips Lys A/S, Denmark Eltodo EG, Czech Republic
- Krajowa Agencja Poszanowania Energii S.A, Poland
- Selc Eireann Teorante/Selc Ireland Limited, Ireland
- Echelon BV, The Netherlands
- City of Oslo, Norway
- SITO, Finland [8]

Each of these partners is using his own unique solution, which has to be compliant with the European standards. In the end of the testing period it will be then possible to evaluate suitability of the different systems for different environments. I'm not going to describe all the different systems among the countries, instead I will only describe the demo project in Oslo to give an example.

The Oslo adaptive lighting project was created as a partnership between the street lighting operator Hafslund ASA and the Oslo municipality. In this system each individual light can be monitored and controlled independently, which means that the lighting conditions can be set differently for different situations or places such as business, public parks or roadways, which will also open the possibility to implement future use-charging or taxing programs based on street light energy consumption. Oslo's intelligent street lighting consists of several component, which are able to communicate with each other as illustrated on figure 6. These components are:

- Dimmable network of streetlights with electronic ballasts (power regulators)
- Segment controllers that send commands to the ballasts.
- A central management system that processes information from traffic sensors, weather sensors, and from the segment controllers.
- Traffic sensors, which communicate with the central management system to indicate traffic conditions.
- Weather sensors, which communicate with the central management system.
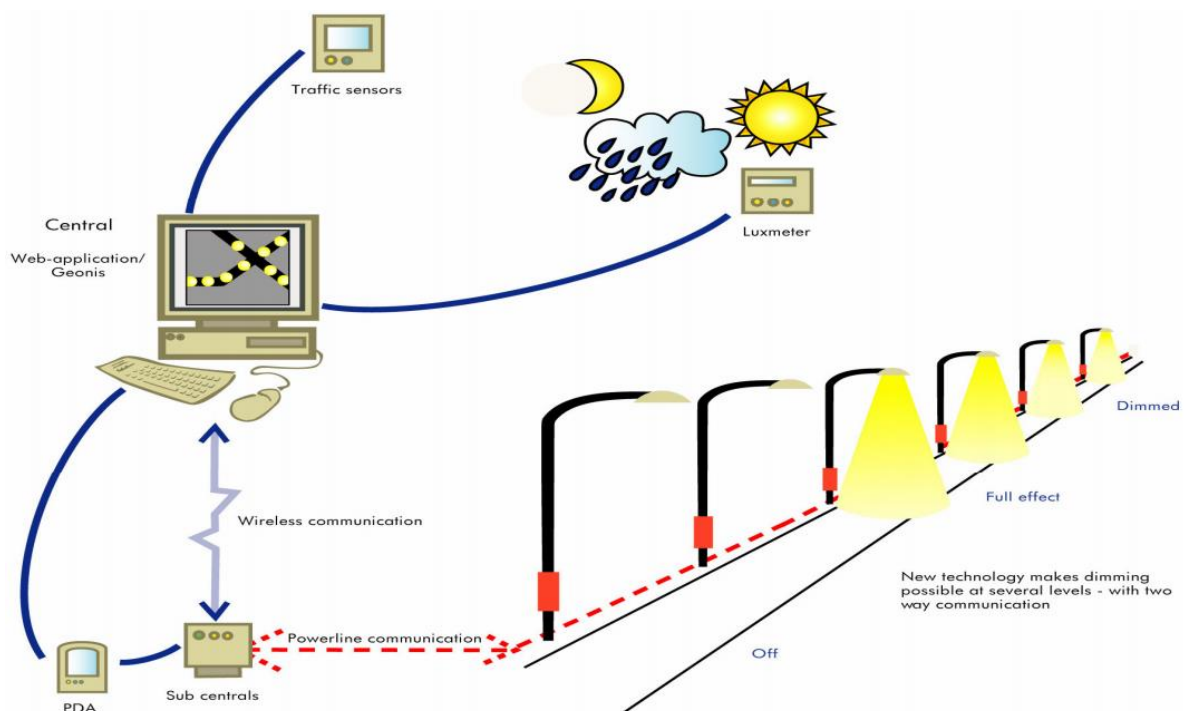
Figure 6: Design of intelligent street lighting in Oslo, Norway [9]

The individual streetlights communicate with their segment controller via existing 230V power line cables using LonWorks power line communications protocol. The Oslo segment controllers are Echelon *i.*LON 100 Internet servers, which use the cell phone data networks (GPRS) to receive data from traffic and weather sensors and to communicate with the city's central monitoring server as shown on figure 7. The *i.*LON 100 servers keep a track of the energy consumption and the operational time for future analysis. Furthermore the servers also send commands to individual lights over power line cables. In addition to real-time traffic and weather data, the segment controllers use an internal astronomical clock to determine natural light availability and automatically dim lights when it is appropriate. Oslo will eventually have 1000 segment controllers with 55000 streetlights in their network.
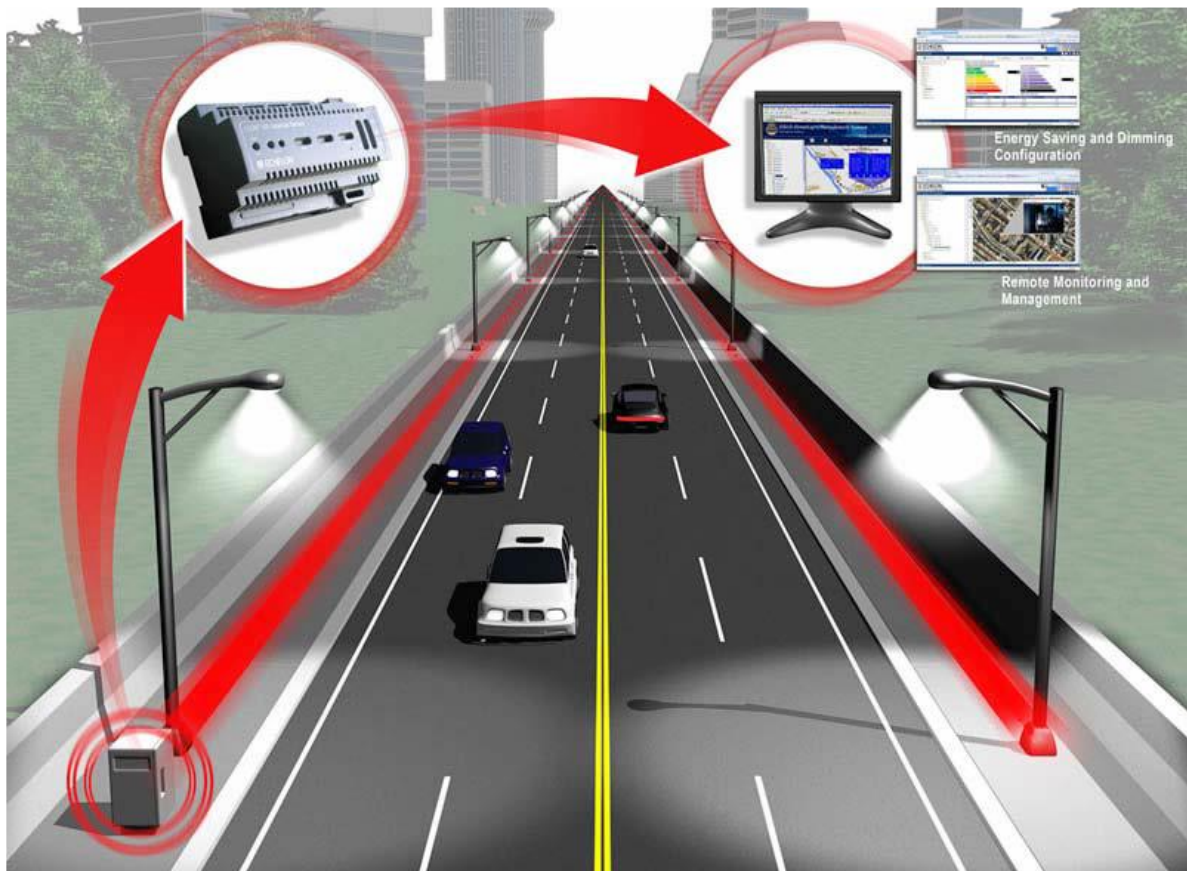
Figure 7: Echelon i.LON 100 segments controllers communicate with individual streetlights directly through existing power lines and with a central server wirelessly through GPRS. [9]

Monitoring software provided by the companies DotVision and Philips enables the city employees to control lighting networks remotely and they can also analyse the lighting performance, need for maintenance etc… Each individual light is incorporated in a GIS database, which allows the city employees to map all city lamps that are nearing the end of their lifespan and coordinate maintenance to replace aging lights. This is a major increase in efficiency when compared with the old methods of light maintenance, which included waiting for residents to report a burned out light or paying for maintenance trucks, which would cruise around the city and look for malfunctioning lights. [9]

This adaptive street lighting system has been tested over the last 12 years and unfortunately it is still too early to make an evaluation of all possibilities and benefits gained by using the system. Until now we can see, that the average energy consumption per burning hour is reduced about 37% of full energy consumption of a non-dimming high pressure sodium lamps. The energy consumption difference of course increases during winter. The estimation is that the decrease will grow up to 45-50% of full energy consumption per burning hour (calculated as an average value over one year). This is a prototype construction and the investment costs for each installed lamp are therefore high. The cost for each lamp is

almost twice as much when compared to a conventional street lighting installation. The payback time of the investment, in this early stage and with energy prices as today, is now somewhere in between 8 to 12 years. However, this is due to the small volumes and high development costs. In an industrial stage, with high quantities, the payback time of the investments will occur sooner. [30]

4.2 LITES (Intelligent street lighting for energy saving)

Project LITES delivers intelligent street lighting with solid states LED lamps with the main goal of decreasing energy consumption, as the name of the project already suggests. It aims to be installed in secondary streets, access roads, pedestrian and bike paths, as it is compliant with the general lighting requirements according to given standards. There will be four piloted sites implemented with street lighting using LED lamps, which will be optimizing all efficiency factors to generate a significant energy savings. The efficient energy saving solution will be tested in real life and validated during one year. During the project each one of the four pilots will be equipped with a network of around 50 lighting points. The four pilot sites for implementation of LITES project are:

- Municipality of Bordeaux (France),
- Municipality of Piaseczno (Poland),
- Riga Technical University campus, (Latvia)
- The Universidade de Aveiro (Portugal).

The main idea is to dim lamp power supply according to the situation, which will be evaluated by a set of embedded sensors, which will measure ambient light, temperature, electric current and motions of objects. The communication between the sensors and the individual lamps will be based on PLC technology. The project proposes to use a lamp unit DATALED52 with embedded intelligence and communication system. This lamp can operate under different voltage inputs (80-265) V. The dimming control will be done with using time profiles, so start and stop thresholds times will be set (start of the night with normal flow then reduced flow from 10pm and finally normal flow after 4:30am). Furthermore the controller is capable of twilight switch and temperature control. Each lamp can be equipped with a radio head, thanks to which the lamp becomes part of the network. This network will be used for sending commands to the lamps and for receiving data from lamp sensors such as the consumption or lighting duration. The lamp itself consists of a matrix of LED lamps, power supply, sensors, PLC interface and power supply control device. Data about luminance, motion, temperature, and about electrical current are sent from the sensors to the smart control device, there the data is processed by the embedded control software, and then a dimming signal is sent to the power supply in order to regulate luminance providing thus the gradation of the light emitted by the LED lamps. PLC provides the connection of the lamp to the electric cabinet and then to the Internet allowing the remote management of the pilot project. In addition the system includes energy measurements, two-way communication on

the existing power supply wires and administrative toolkit for processing the operational tasks. [7]

5 Project introduction

As already mentioned the pilot project of the adaptive LED lighting system developed by Swarco and Philips is currently being deployed in Angyalföldstraße in the city of Vienna. This street is located in north-west Vienna and connects its 20th and 21st district. The length of the street is about 1.5km. The average annual daily traffic is approximately 6000 vehicles according to an automatic vehicle counter in Angyalföldstraße (data from year 2010). [3] The night volumes are typically below 50 vehicles per hour.
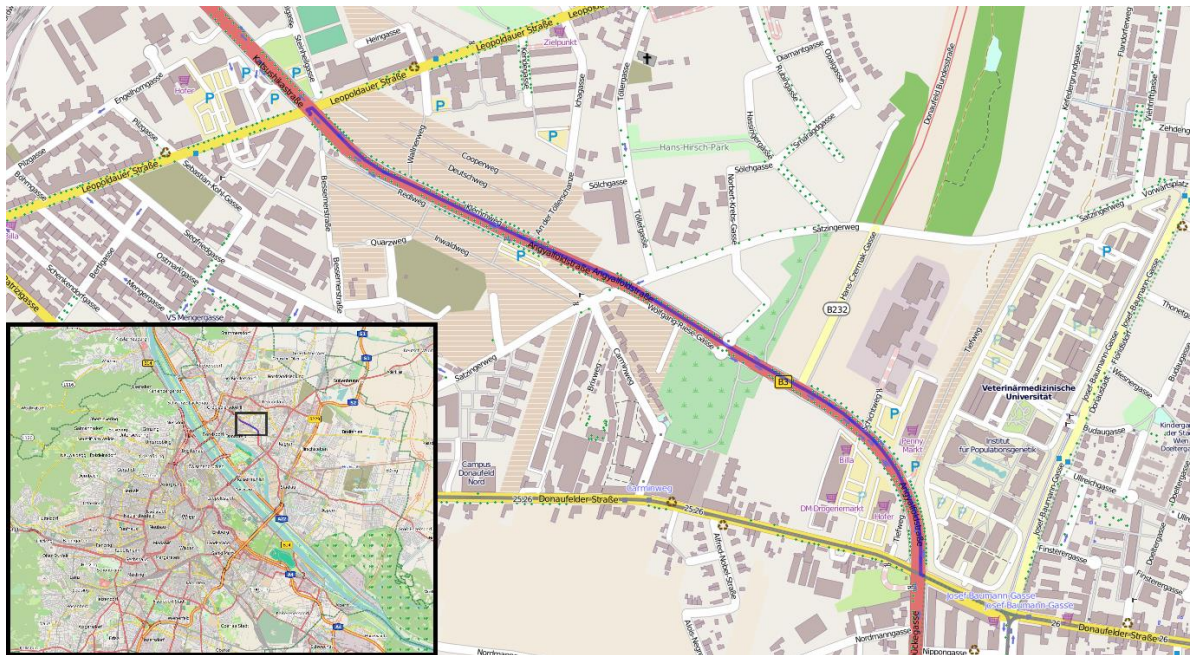
Figure 8 – Angyalföldstraße zoom-in and its location in Vienna (source: www.openstreetmaps.org)

5.1 Street description

Now I would like to describe the street in more detail and I will do so starting from its intersection with Donaufelder Strasse in south-east toward intersection with Leopoldauer Strasse in north-west describing sections between intersections:

1) Segment between Donaufelder Strasse and intersection with commercial area (Billa, Hofer, Penny, Bipa, NKD…) – There is one lane for vehicles for each direction and also separated lanes for bicycles and further also a pavement for pedestrians, which is separated by a noise barrier. The lighting for the pedestrians and cyclists is different from the assessed adaptive road LED lighting. Traffic signal control is present at initial intersection with Donaufelder Strasse, unlike at the intersection with the commercial area.

Figure 9 - Beginning of Angyalföldstraße at the intersection with Donaufelder Strasse

2) Segment between the intersection with the commercial area and intersection with Hans-Czermak-Gasse, which is equipped with traffic signaling, continues here also with one lane for each direction and with the bicycle lane still separated.

Figure 10 - Intersection of Angyalföldstraße and commercial areas to the left and right

3) Segment between the intersection with Hans-Czermak-Gasse and intersection with Satzingerweg, where it is only possible to join the Angyalföldstraße for vehicle approaching from Satzingerweg with no traffic signaling. There is still one lane in each direction. Both the pedestrian path and bicycle lane are now separated by a noise barrier with their own separated lighting.

Figure 11 - Intersection of Angyalföldstraße and Satzingerweg

4) Segment between the intersection with Satzingerweg and intersection with Leopoldauer Strasse has still one lane for each direction with no separation. Pedestrians and cyclist are separated by a noise barrier walls and with their own lighting on both sides of the street. In this section there are two pedestrian crossings, which are both equipped with traffic signal control. Traffic signaling is also present at the final intersection with Leopoldauer Strasse.

Figure 12 - Second pedestrian crossing in the section between Satzingerweg and Leopoldauer Strasse

There are several reasons, why this street was chosen for adaptive LED lighting pilot project in the city of Vienna. Probably the most important reason is that the lighting at this street is dedicated for individual transport mode users, which is ensured by spatial separation of the paths for different transport modes. This means that different lighting sources illuminate pedestrian path, bike path and the road itself. The adaptive lighting system will be deployed only for the road users. Dedicated lighting for different users is a nice feature, because it makes the project assessment more straight forward, because the lighting will only have direct influence on road users (Pedestrians or cyclists crossing the road at pedestrian crossing at intersections are not taken into account, because the lighting luminance will not be decreased at conflict zones, as intersections are, and thus they can be taken out from the assessment.) Next reason that lead to choosing this street over others is its low traffic volume during night. This is partly because there are many shops, which are closed during night hours, and partly because it is a suburban road. The low night traffic flow is desirable, because then the reduction in energy consumption will be more apparent, which is a desirable feature for a pilot project. Furthermore the cost for deploying this system are lower in such a street in comparison with other streets closer to the city center. The cost would be higher, because it is necessary to install induction loops in the street and also to change the light source in the lamps and during both these operations the street capacity will be temporarily decreased (taking into account external costs created by traffic congestions). Moreover the advantage of this street is, that there is only one lane in each direction, which again makes the assessment easier and more demonstrative, because we

don't need to take into account cars influencing each other with lateral movements, which are believed to play a significant role in road safety. The above mentioned induction loops are located at each of the intersections and will provide following traffic parameters:

- Traffic flow
- Speed
- Car classification

5.2 Lighting

There are 55 lights for road users in the street in total. All these light will be replaced with LED lamps – specifically Philips MileWide2 LED (Type: BRP432 ECO99-2S/740). The idea is to apply the variable luminance control according to traffic flow only on the lighting, which is not located at conflict zone (intersection, pedestrian crossing…). The lights, which are at conflict zones will also get a new LED lamp but their luminance output will be fixed at 100% during the whole night, so that safety will not be compromised at conflict zones. There are 28 lights, which are not located at conflict zones (variable luminance) and 27 lights, which are located at conflict zones (constant luminance). The distances between poles, the height of the lamp and the angle of the lamp will not be changed.

In the first phase of this adaptive street LED lighting project the lighting luminance will be time triggered. At the moment there are only two time frames – from 11pm to 5am the lighting luminance will be set to 70% of the maximum output, the rest of the night the lighting will be providing 100% of luminance output to road users. These two time slots were chosen according to historical traffic flow data and are compliant with Austrian and European norms for adaptive street lighting. The fully adaptive system is planned in the next project stage, then the lighting luminance will be set according to real time traffic parameters and weather conditions.

5.3 System structure

The lighting system consists of two subsystems:
- **City touch** - Management system for streetlights provided by Philips
- **Omnia** - Traffic management system provided by SWARCO

As shown on figure 13, the Omnia system monitors traffic data on a specific road stretch. The Omnia system dynamically assigns a predicted FRC (Functional Road Classes) to the monitored road stretch for the next time period, as the assessment of the traffic data from sensors is located within Omnia subsystem. The City touch system uses the FRC information (not the raw data) generated by the Omnia system to actuate specific luminance profiles (lighting class) over given road stretch. [Swarco]
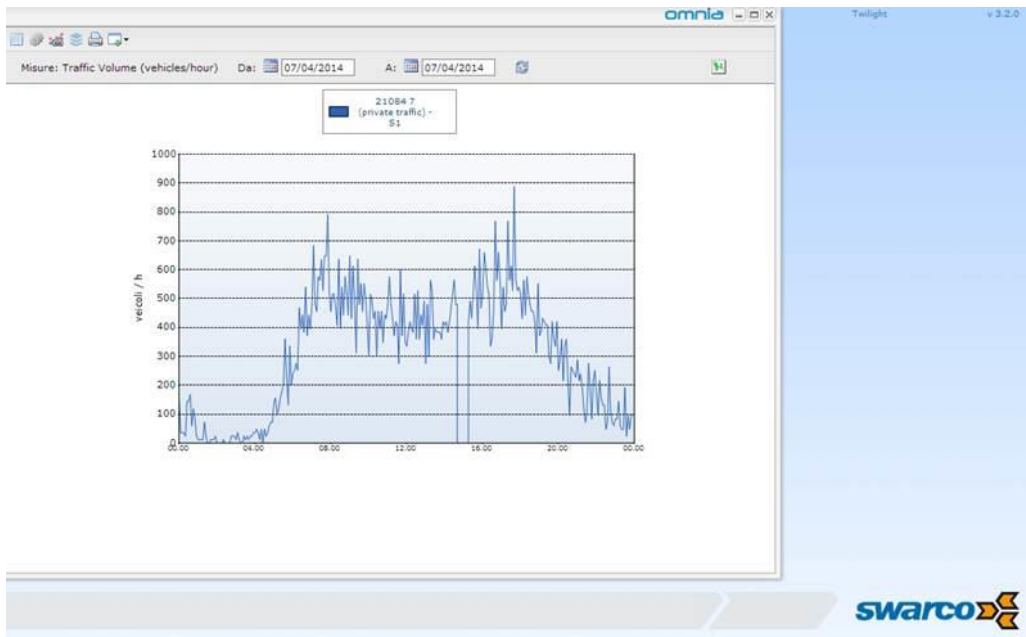
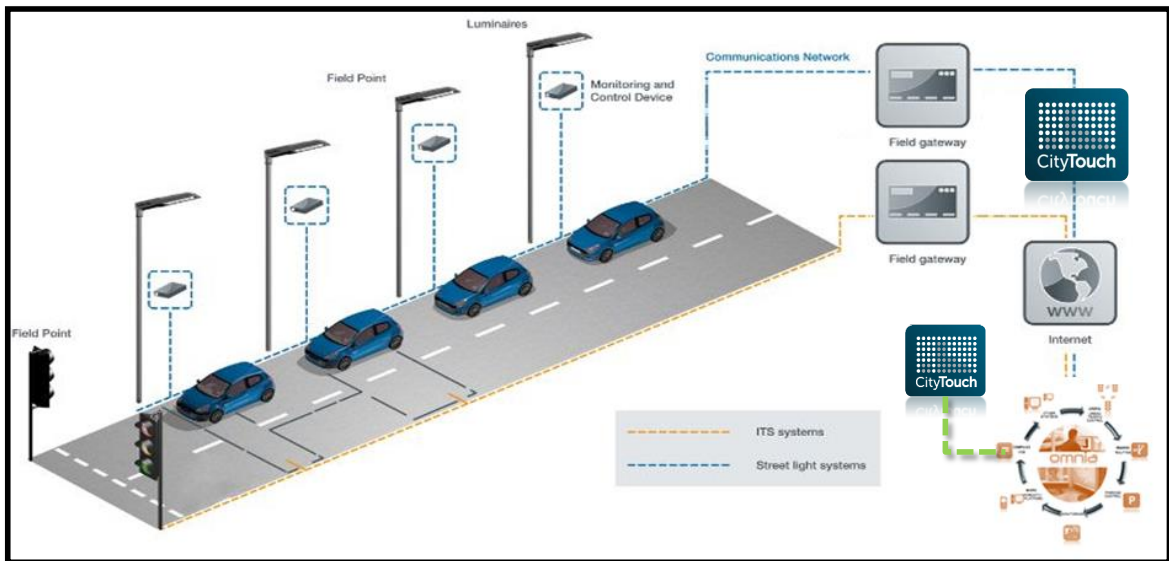Figure 13 – Screenshot from Omnia subsystem – example of traffic flow data visualisation [Swarco]

Figure 14 – General system design [Swarco]

6 Traffic safety Assessment design

The safety assessment is very challenging, because till now no robust standardized methodology, which would be accepted by academic public or industry, has been yet developed for given circumstances of this project. And that's why it is necessary to invent new technique to assess safety with different lighting intensities. To assess the road safety after adaptive lighting implementation, the idea is to use safety related traffic parameters from Angyalföldstraße. These will be statistically processed and compared for the situation with classical high pressure sodium lamps with fixed luminance output and for the situation with adaptive LED lighting. Several possible ways of how a road safety assessment in general can be performed will now be introduced, and finally an appropriate one will be chosen for the case of road safety assessment for given road with adaptive LED lighting.

6.1 Road traffic safety measures

According to ECMT (European Conference of Ministers of Transport), there are two kinds of safety indicators - direct and indirect safety measures. Number of accidents, number of people killed or injured in road traffic is regarded as a direct safety measure as it possess a sufficient degree of validity, reliability and availability to describe the local, national or international safety situation.

A number of indirect safety measures are also regarded as an indication of the safety situation, but they do not provide a complete picture. They don't provide a direct connection to road traffic safety. Indirect traffic safety measures include: the number of near-accidents, levels of exposure to road traffic, various behavioural measures, measures related to roadway and vehicle standards, measures of enforcement and related traffic legislation, other systematic traffic measurements and the awareness of safety problems among the general public.

Direct safety measures are of course preferable to assess road safety, because, as the name suggest, they provide a direct connection between themselves and road traffic safety. Some of the direct safety measures are actually mentioned in a definition of safety, which is: "The condition of being safe from undergoing or causing hurt, injury, or loss". Unfortunately only indirect traffic measures will be used for purposes of this safety assessment. The reason behind this is, that the time periods, from which the data for comparison of safety related traffic parameters for the situations before and after adaptive LED lighting implementation, will be too short to produce any statistically significant data for a comparison based on direct safety measures.

In the next subchapters the three most important and accepted approaches of assessing road traffic safety will be introduced.

6.1.1 Use of historical accident data

Traffic safety is preferably measured by direct safety measures, for example by the number of traffic accidents or the consequences/severity of these accidents. This approach is usually based on historical accident data. It is regarded as a reactive approach, which implies, that a significant number of accidents must be recorded, which can be often problematic, and so it also is in case of this adaptive LED lighting project. A further drawback connected with the previous issue is the long-time period of data collection needed to obtain sufficiently large accident data sets, which is required to statistically validate the result of implementation of a traffic safety influencing measure. This is caused by the random and sparse nature of traffic accidents (figure 15). Since accident occurrence is often a result of a complex and dynamic chain of events, it is difficult to perform safety analyses according only to statistical counts. [16]

6.1.2 Proximal safety indicators

Another approach for safety assessment involves the use of proximal safety indicators. These represent a temporal and spatial proximity characteristics of unsafe interactions between vehicles and near accidents. These indicators belong in the category of indirect safety measures. The main advantage of proximal safety indicators, or indirect safety measures in general, is that the parameters that they use, occur more frequently than accidents (direct measures) and require relatively short periods of observation in order to establish statistically reliable results. Proximal safety indicators are particularly useful for before and after studies where there is an emphasis on the assessment and comparison of safety influencing measures at specific traffic facilities as for example the new lighting system is. The result of traffic safety analysis based on proximal indicators is influenced by site specific elements related to roadway design (road width, steepness, curve radius…) and the dynamic and complex relationships among different traffic variables such as average speeds, traffic flows or vehicles composition. However, there have been a number of questions about the validity of proximal safety indicators as a measure of safety, originating from the underlying theories on which they are grounded. Because of that, the use of proximal indicators as an accepted measures of safety, has been limited in transportation science throughout the world. The possible distrust in proximal safety indicators is believed to stem, apart from other reasons, from the long established use of historical accident data as a traditional measure of traffic safety. This has made accident data the accepted measure of traffic safety. However, the need for validation of the proximal safety indicators may be exaggerated, or even unnecessary. They can be very useful in situations where proximal safety indicators serve as a useful evaluative tool and the safety analysis concerns safety prevention rather than accident prediction. [17] Criteria for proximal safety indicators were established by Svensson in 1998, stating that they must:

1. Complement accident data and be more frequent than accidents
2. Have a statistical and causal relationship to accident
3. Have a characteristic of near-accidents in terms of traffic safety continuum

The first criterion is rather obvious and is compliant with all existing safety indicators concepts. The second and third criteria are related to the validity of the relationship between proximal safety indicator and number of accidents and imply that proximal safety indicators exist before as a cause to the occurrence of an accident. According to these criteria we can now list an example of existing and well used proximal safety indicators:

- **Time to collision** was defined by J. Ch. Hayward as "the time required for two vehicles to collide if they continue at their present speed and on the same path". It is the most common proximal safety indicator and is calculated at the instance, when braking is initiated. Time to collision is usually measured using video analysis, as that is the easiest way to obtain required data for the computation for large numbers of vehicles. Time to collision calculations proceeds as follows :

$$TTC_i = \frac{x_{i-1}(t) - x_i(t) - l_i}{\dot{x}_i(t) - \dot{x}_{i-1}(t)}, \forall \dot{x}_i(t) > \dot{x}_{i-1}(t)$$

Where:

$\dot{x}_i$ is speed

x is position

l is vehicle length

There are three more indicators which are derived from the Time to collision and these are Exposed time to collision, Integrated time to collision and Post encroachment time

- **Time to zebra** was developed in order to evaluate the safety of pedestrians. It is used to assess the frequency and severity of encounters between pedestrians and vehicles at pedestrian crossings.

- **Potential index for collision with urgent deceleration** is an index to evaluate the possibility that two consecutive vehicles might collide assuming that the leading vehicle applies its emergency brake. It is defined as the distance between two vehicles when they completely stop.

- **Individual/platoon braking time risk** represents the likelihood of a rear end crash if the leading vehicle stops. It calculates with the speeds of the vehicles, the gap between them, deceleration capabilities, and surface adhesion.[18]

6.1.3 Safety-influencing factors

The last approach to assess traffic safety, that I intend to mention, also belongs to the category of indirect safety measures and it uses the so called safety-influencing factors. These are known or assumed to have an influence on traffic safety. These factors do not belong to the category of proximal indicators, because they do not satisfy the definitions and criteria listed earlier. Many of them are standard measures of traffic performance and are used in various fields of traffic analysis. As far as the road safety is concerned, they often have well established relationships with accident rates or severity of the accidents. These safety-influencing factors include:

- Speed
- Speed variance
- Gap acceptance in yielding situations
- Gaps or headways between vehicles in traffic stream
- Traffic flow rates (volume to capacity ratio, density)
- Frequency of red light violations
- Relative frequencies of turning manoeuvres

6.2 Road traffic safety assessment after adaptive LED lighting system implementation

For traffic safety assessment of this project, as for any other road safety assessment, it would be preferable to use the direct traffic measures and for example compare the number of accidents before and after the installation of adaptive lighting system, because the amount of accidents could provide a direct and unambiguous measure for the safety assessment. On the other hand the drawback of this solution is the necessity for long term observation of accident data. This data is accessible for the situation with the current lighting, as the accidents have been recorded by police for the past years. But taking into account the long time period of observation, it would also be needed to consider the overall improvements in traffic safety and the current trend of decreasing the amount of accidents. However it is not possible to get such long-term accident data from the situation after deployment of proposed adaptive lighting system, because the system is being deployed simultaneously as this master thesis is being written. Comparing accident rates obtained from years of observation from the original situation with the accident data from the upcoming situation with adaptive lighting with the accident rates only from a time period of several weeks or months, would

be statistically incorrect and insignificant, because accidents are a rather rare event on the road, and the probability that a traffic accident will occur there during this short time period is quite low, and even if an accident(s) occurred it would be statistically insignificant for this comparison as mentioned above. The phenomenon of low accidents rates is explained on the picture below, which shows the relation between the dangerousness of a traffic event and frequency of this event. [10]
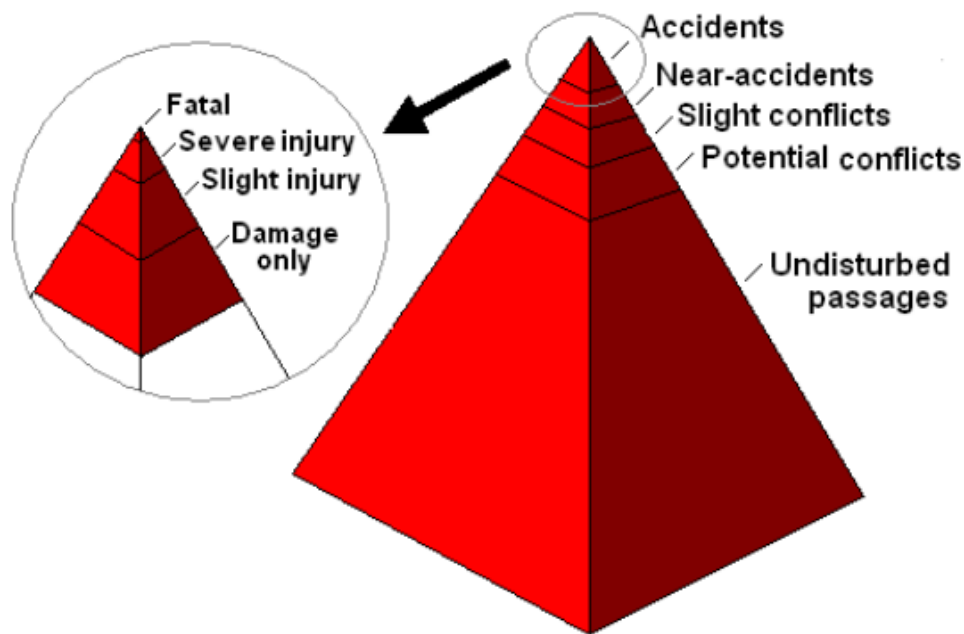
Figure 15 - Traffic safety continuum [10]

In the previous paragraph it is explained why a direct traffic safety assessment with the number of traffic accidents is not possible. Unfortunately the use of proximal indicators is also not possible, mostly because the second and third requirement – That they have to have a causal relationship to the accident, and that they have a characteristic of near accidents. These two conditions are not fulfilled, because the data available for the assessment originates in induction loops, which can offer data in a form of classical traffic parameters such as traffic flow or speed, and these parameters are not sufficient to identify, whether an event or action has a causal relationship to an accident, or whether it is a near accident. For the safety assessment with proximal indicators it is necessary to have access to video detection data from a given street, which would provide sufficient amount of information.

For these reasons a different approach for traffic safety assessment is proposed and thus with the use of safety influencing factors. The idea of this thesis is to analyze traffic data available from the induction loops, which are believed to influence traffic safety. In this case

road safety will be assessed as a change in driver's behavior, which will be seen as a change in the traffic parameters, which will be obtained from detectors (induction loops) in the street. The parameters that will be analyzed are (they are safety influencing factors):

- Mean speed
- Speed variance

Although a better way to do this would be to have one aggregated parameter from the measured traffic parameters, which would represent safety (not taking into account the accident rates as a measure). But constructing such a parameter exceeds framework of this thesis and it was recommended to focus on this topic in future studies. Instead of an aggregated parameter, the assessment will consist of comparison of above listed traffic parameters separately. The data will be analyzed by statistical methods such as hypothesis testing. This methodology will be applied on data, which are collected before adaptive lighting system implementation and also on data from period after implementation in a form of before and after study, so that the statistical comparison will be possible.

The data comparison will be carried out in several steps for each of the parameters separately. These steps are following:

- Hypothesis formulation
- Computation of appropriate test statistics
- Comparing statistics with corresponding critical values table
- Accepting/rejecting hypothesis

Furthermore it is necessary to know what the connection between these traffic parameters (safety influencing factors) and road safety is. The following subchapters will describe the relationships between chosen safety influencing factors and traffic safety.

6.2.1 Relationship between vehicle speed and traffic safety

Speed will be the most important input parameter for this assessment as it is the only safety influencing parameter that will be available from the Omnia subsystem. Fortunately speed is believed to have a major importance for road traffic safety. Speed data will be exported from Omnia and then, it will be used to create two characteristics – mean speed and speed variance.

It is often stated that speed is related to traffic safety in two particular ways. Firstly, higher speed gives all road users less time to react to the situation on the road. Secondly, because of the relationship between speed and kinetic energy, the risk of fatality and seriousness of an injury increases with higher speeds. The risk of a death for a pedestrian that is hit by a vehicle at 30 km/h is approximately 6-16 %, however if the speed of the vehicle

rises to 50 km/h, the risk of fatality increases to 40-85%. [14] It is suggested as a rule of thumb, that each 1 km/h of speed reduction results in a reduction in the number of accidents involving injury by up to 3%. [15]

Relationship between mean speed and road traffic safety

The relationship between changes in mean speed of traffic and changes in road safety has been handled by many studies. The model for this relationship has been evolving throughout the time and therefore many different estimates and proposals of the relationship have been established. The relationship between mean speed of traffic and road safety was for a long time modelled by power model. Power model describes the relationship between changes in speed and changes in the number of accidents or the number of accidents victims in terms of six power functions, all of which have the following form:

$$\frac{Accidents\ before}{Accidents\ after} = (\frac{Speed\ after}{Speed\ before})^{exponent}$$

The relative change in the number of accidents is estimated by rising the relative change in speed to an exponent. The value of the exponent varies according to severity of accidents.The power model output is increasing monotonic function, which means that the higher the speed, the greater the number of acidents. The function is shown on figure 16. The model has been updated several times to be more acurate at describing this relationship. [11]
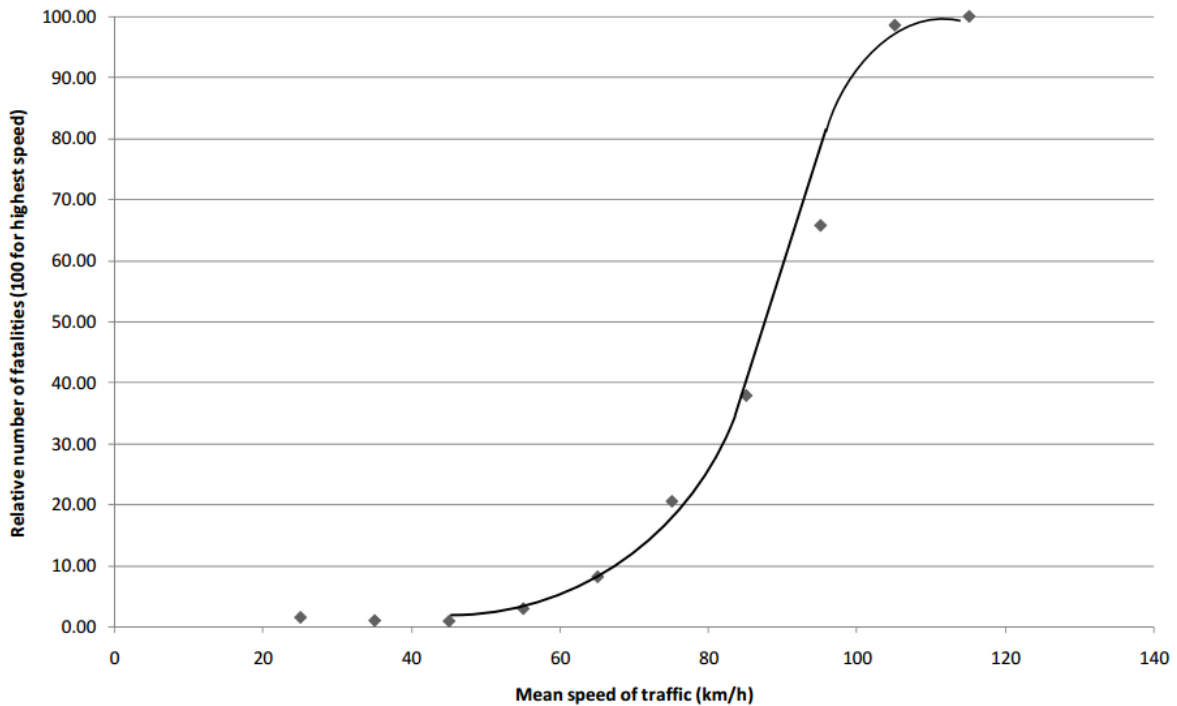
Figure 16 – Relationship between relative number of accidents and mean speed of traffic according to power model [11]

More recently, an exponential model has been proposed to describe the relationship between the mean speed of traffic and road safety. Exponential model is better suited for cases, when only certain share of vehicles change their speed. Both these models are based on extensive data analysis. The models can therefore be applied to predict the effects of changes in mean speed on the number of accidents and on the number of killed or injured road users. The conclusion is that the higher the speed, the greater the number of acidents. But we should also take into account that this relationship is influenced by the traffic flow for a given situation. The affect is, that the higher the traffic flow, the steeper is the function, which describes the relationship. This phenomenon is shown on figure 17. In case of Angyalföldstraße the traffic flow definitely can be marked as low, because the observed time period takes place during night, so the change in the number of accidents according to speed is expected to be low, if not none. [11]
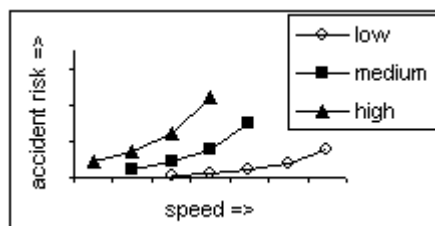
Figure 17 – Change in the relationship between speed and traffic safety for three different traffic flow states (low, medium and high) [11]

Relationship between speed variance and road traffic safety

It has been long believed that speed variance is also related to traffic safety. In past years the results had been not yet entirely conclusive. In the recent years, however, the data from loop detectors has made it possible to study the effects of speed variance in a much more rigorous way than before. With this data it is possible to determine what the value of speed variance was when an accident occurred and thus attempt to define the relationship between these two variables. As for the previous relationship, extensive data analysis is involved here. It has been found that increased speed variance increases the risk of accidents. [12] The first one to discover this relationship was David Solomon, who proposed the so called U-shaped Solomon curve, which can be seen on figure 18. On the other hand the variation in speeds of traffic is a crash factor only when vehicles are travelling closely enough to each other for the interaction to occur. [14]

A newer research [13] attempts to investigate this relation further. The road that was chosen for this assessment was located outside London with AADT=10000, heavy vehicle ratio was less than 12.5%. From observed data, they created a model of accident frequency according to several different values of the coefficient of variations in speed. On figure 19 we can see the output of this model. The result is compliant with the original proposal from Solomon, because the accident rate respectively involvement rate in accidents increases with increasing coefficient of variations in speed respectively variation from average speed.
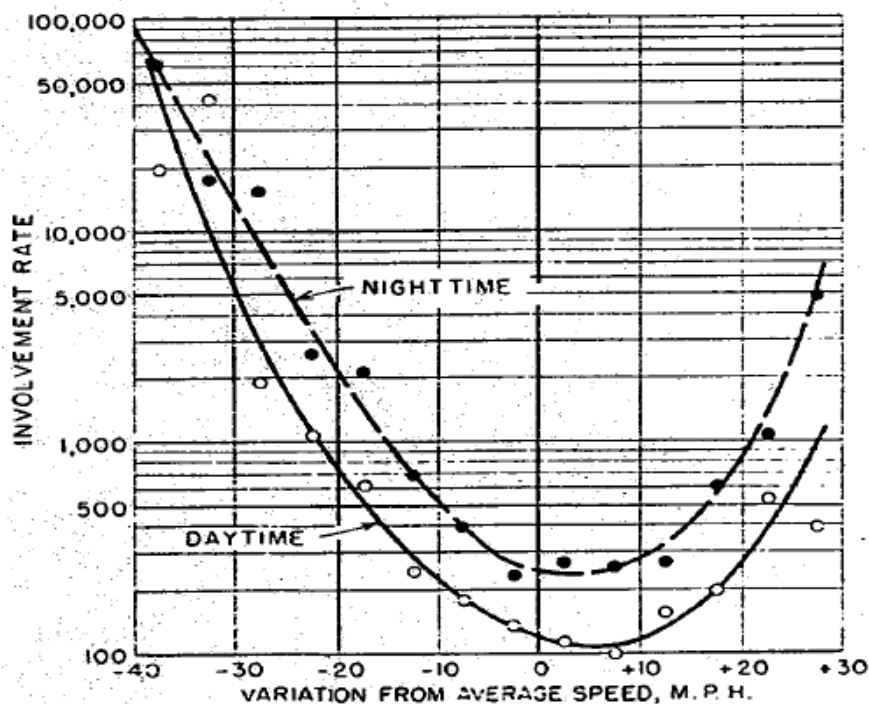
Figure 18 – Relationship between variations in vehicle speeds and their involvement in accidents [14]
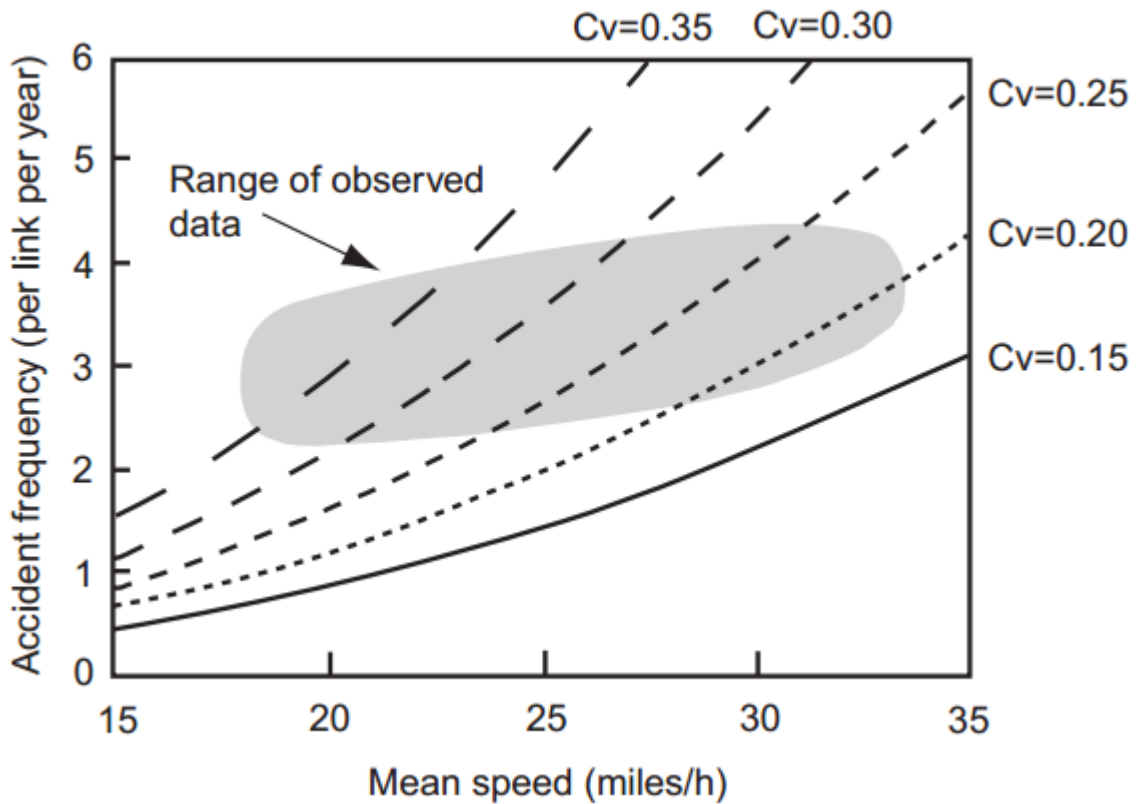
Figure 19 – Model of relationship between accident frequency and mean intensity for five different values of the coefficient in variations of speed [13]

From the above listed studies and researches, we can see, that they all agree on the relationships between road traffic safety and speed, and speed variance respectively. In the case of speed, the conclusion is that the relative number of accidents increases with increasing mean speed. Relative number of accidents is considered to be an indicator of safety. Therefore we can state that the greater the mean vehicular speed is, the worse will be the road safety.

For speed variance we can conclude that the accident frequency increases with increasing speed variance. Now we can make a similar statement as for mean speed: The greater the speed variance, the worse the traffic safety will be.

6.3 Statistical evaluation

The statistical comparison of speed data from situations with dimmed LED lighting and with original lighting, will be carried out in a form of classical hypothesis testing. Hypothesis testing usually consists of following four steps:

1. Stating null and alternative hypotheses

The first step of hypothesis testing is to convert the research question into null and alterative hypotheses. Null Hypothesis is a statement about the value of a population parameter and it usually expresses the expected result. Alternate hypothesis is a statement, which is accepted, if there is enough evidence to prove that the null hypothesis is false.

2. Selection of an appropriate test statistic

When testing a hypothesis about means of two data sets, we have the following choices:

- Two sample z-test
- Two sample pooled t-test with equal variances
- Two sample unpooled t-test with unequal variances
- Paired t-test

We choose an appropriate test according to the following conditions:

It is preferable to use two sample z-test, when:
- Data sets are independent from each other
- Number of samples $n > 30$.
- The distributions are normal
- The variances of the samples don't need to be equal
- All data must be selected at random from the population
- All data must have equal chance of being selected
- Sample sizes are as equal as possible

Two sample pooled t-test with equal variances is preferable when:
- Data sets are independent from each other
- Number of samples $n < 30$
- The distributions are normal
- The variances of the samples are equal (F-test)
- All data must be selected at random from the population
- All data must have equal chance of being selected
- Sample sizes are as equal as possible

Two sample unpooled t-test with unequal variances is preferable when:
- Data sets are independent from each other
- Number of samples $n < 30$
- The distributions are normal
- The variances of the samples don't need to be equal
- All data must be selected at random from the population

- All data must have equal chance of being selected
- Sample sizes are as equal as possible

Paired t-test is preferable when:
- Data sets are not independent to each other
- Number of samples $n < 30$
- The distributions are normal
- The variances of the samples don't need to be equal
- All data must be selected from matched pairs
- Sample sizes must be equal

When testing a hypothesis about variances of two data sets, we will use
- F-test
- Paired t-test for mean values of averages

3. Computation of the appropriate test statistic

For two sample z-statistics, we use the following formula:

$$z = \frac{\overline{x_1} - \overline{x_2}}{\frac{\sigma_1}{\sqrt{n_1}} + \frac{\sigma_2}{\sqrt{n_2}}}$$

For two sample pooled t-statistic with equal variances, we use the following formula:

$$t = \frac{\overline{x_1} - \overline{x_2}}{S_{pooled}(\frac{1}{\sqrt{n_1}} + \frac{1}{\sqrt{n_2}})}$$

$$S_{pooled} = \sqrt{\frac{s_1^2(n_1 - 1) + s_2^2(n_2 - 1)}{n_1 + n_2 - 2}}$$

For two sample unpooled t-statistics with unequal variances we use the following formula:

$$t = \frac{\overline{x_1} - \overline{x_2}}{\frac{s_1}{\sqrt{n_1}} + \frac{s_2}{\sqrt{n_2}}}$$

For paired t-statistics we use the following formula:

$$t = \frac{\overline{D}}{\frac{s_d}{\sqrt{n}}}$$

$$s_d = \sqrt{\frac{\sum(D_i - \overline{D})^2}{n - 1}}$$

Where:

$\overline{x_1}$ is the mean of the first data set

$\overline{x_2}$ is the mean of the second data set

n_1 is the number of measurements in the first data set

n_2 is the number of measurements in the second data set

s_1 is the standard deviation of the first data set

s_2 is the standard deviation of the second data set

$\overline{D}$ is the mean difference between matched pairs

D_i is the difference between individual matched values

s_d is the standard deviation of matched pairs

n is the number of pairs

An F-test will be used to test whether the variances of average speed from the two data sets are equal. Furthermore F-test will be also used to assess differences in the speed variances. This test can be a two-tailed test or a one-tailed test. The two-tailed version tests, whether the two variances are equal. The one-tailed version only tests in one direction - is the variance from the first data set either greater or less than the second data set variance. For the evaluation it uses the ratio of the two variances $\frac{\sigma_1^2}{\sigma_2^2}$, which is to be compared to a critical F-test value. The F-test has following requirements on the input datasets:

- Data sets are independent from each other
- The distributions are normal

4. Comparing statistics with table of critical values

Once test statistic is computed we use it to calculate the p-value. The p-value is an estimated probability of obtaining a test statistic result at least as extreme as the one that was actually observed, assuming that the null hypothesis is true. This p-value must then be compared with a critical value, which is read from z-score table, t-test critical value table or F-test critical value table. The tables are constructed according to different levels of confidence (an appropriate one needs to be chosen) and the size of compared datasets. The size of datasets is expressed in terms of degrees of freedom. An example of this table is shown on figure 20. If the computed test statistics value is located within the interval of acceptance, the null hypothesis is accepted, otherwise, the null hypothesis is rejected.

Degrees of Freedom	Confidence Level %			
	50	90	95	98
1	1.000	6.314	12.706	31.821
2	0.816	2.920	4.303	6.965
3	0.756	2.353	3.182	4.541
4	0.741	2.132	2.776	3.747
5	0.727	2.015	2.571	3.365
6	0.718	1.943	2.447	3.143
7	0.711	1.895	2.365	2.998
8	0.706	1.860	2.306	2.896
9	0.703	1.833	2.262	2.821
10	0.700	1.812	2.228	2.764
15	0.691	1.753	2.131	2.602
20	0.687	1.725	2.086	2.528
25	0.684	1.708	2.060	2.485
30	0.683	1.697	2.042	2.457
40	0.681	1.684	2.021	2.423
60	0.679	1.671	2.000	2.390
120	0.677	1.658	1.980	2.358
∞	0.674	1.645	1.960	2.326

Figure 20 – An example of a t-test table of critical values

6.4 Obtaining data

As already mentioned, traffic data was supposed to be obtained from Swarco's traffic management system Omnia. Unfortunately Swarco was not able to provide any speed data, which would be relevant to the assessed street. Swarco's detectors in Angyalföldstraße have been able to produce only traffic flow data (also at the time of finishing this thesis). Luckily, my colleague (Thomas Epp, whom I am thankful indeed) was kind enough to contact his colleague (Johann Kickinger, whom I would also like to thank) from ITS Vienna region and asked him for availability of the essential data. ITS Vienna region has access to detectors (induction loops) in Angyalföldstraße, which, unlike the Swarco's detectors, are able to collect speed data about passing vehicles. So in the end, these speed data from ITS Vienna region will be used to assess road traffic safety in Angyalföldstraße. ITS Vienna region has two detectors in the assessed street. These are located in the same location – each collects data from one direction. Unfortunately the data from second direction contained too many implausible values, because of frequent detector failures. Also the traffic flow for the second direction is about 40% greater than in the first direction. Under these circumstances it was decided to use only data from the first direction for the purposes of this road safety assessment. The obtained .csv file consists of raw speed data (speed of each vehicle is

recorded individually) from 25.06.2014 12:48:27 to 30.09.2014 23:59:51. Since the new lighting system was operational since September, this month will be used to obtain speed data from the situation after new lighting implementation. The speed data from the situation with the older lighting will be taken from the month July. The speed data will be selected within time periods from 11pm to 5am, since this is the time interval, when the lighting is turned on during the whole year – both in summer, when the sun goes down later and also rises earlier, and also in winter. Unfortunately because of the short time period of the assessment, it was not possible to compare speed data from the same time periods (e.g. July 2013 and July 2014), which means, that the conditions will not be necessarily the same. On the other hand it would be difficult to achieve the same conditions even with same time periods, because the traffic flow can change and also the weather doesn't need to be same in the same month in different years. In order to reach comparability of the two data sets, the length of both time periods – before and after implementation of the adaptive LED lighting system, were chosen to be equally long.

7 Road traffic safety assessment – Comparison of safety influencing factors

7.1 Previous studies regarding the relationship between road traffic safety and the level of luminance

The first study that I will introduce originates in United States, Florida. The data was collected between years 2000 and 2005. The assessed road was approximately 50 km long. This study was concerned with pedestrian safety and thus takes into account only crashes, where there were pedestrians involved. 105 pedestrian crashes out of the total 199 pedestrian crashes during the six year period occurred at night. Also, only 18 of these 105 crashes occurred at locations without streetlights, and the remaining 87 crashes occurred at locations where streetlights were present. Therefore, the lighting conditions at the crash site locations were analyzed. The results of this study are summarized in a column diagram, which shows the resulting relationship between lighting level and number of pedestrian accidents during night (see figure 21).The exact numbers are not of our interest here, but we can notice a general trend – the lower the lighting level, the greater amount of pedestrian accidents. [19]
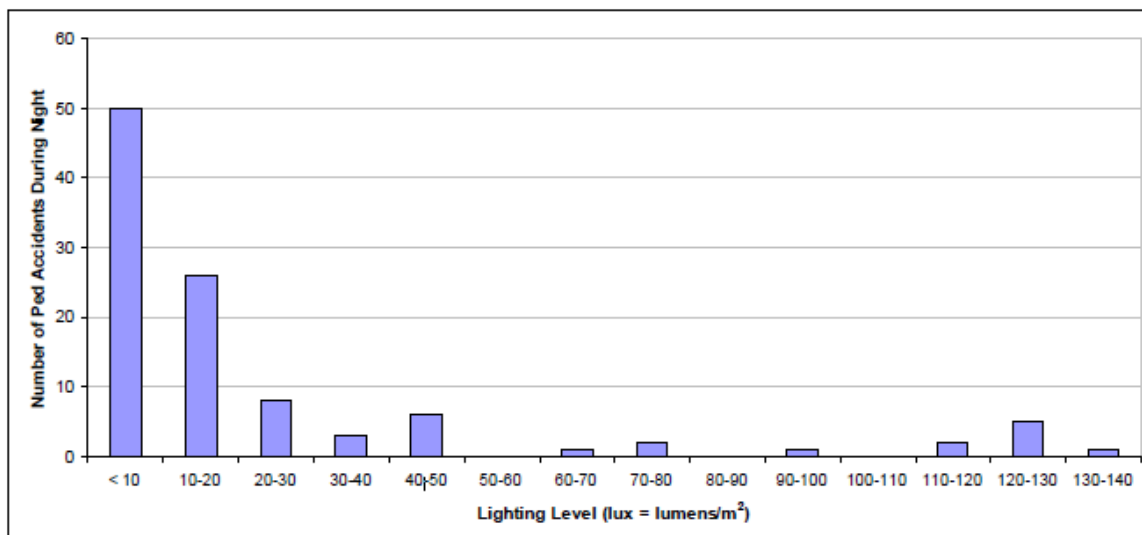
Figure 21 - Number of Pedestrian Accidents at Night for Different Lighting Conditions [19]

Next I will present findings of a study, which was performed in New Zealand. This study looked at a sample of street lighting installations spread over the urban areas of nine territorial local authorities. Standard street lighting parameters were measured in the field using a variety of instruments including luminance meter and a calibrated digital camera.

Field measurements were related to the ratio of night time to day time crashes (from the CAS database) as a measure of night time safety compared with daytime safety. This index makes use of the fact that road lighting only influences night time crashes. The regression models identified average luminance as the most important lighting variable with regard to road safety so the data was then grouped into bands with width of 0.25 cd/m^2 for more detailed analysis. The following general tendencies were found:

- A strong relationship was found between the average luminance of the road lighting and the night to day crash ratio.
- The response was similar in three groups of roads classified by traffic flow (under 9000, from 9000 to 12000 and from 12000 to 30000 vehicles per day
- The response was positive for both dry and wet road surfaces suggesting that road lighting continues to be effective even when the surface is wet and thus more reflective.
- Both major (traffic signal or roundabout controlled) and minor (all other) intersections showed a response to average luminance.

The result of this study is summarized in a diagram, which shows the relationship between average luminance and average night to day crash ratio for all reported crashes in examined time period. This diagram is shown on figure 22. As in the case of the first study, we will extract a trend, which is here as follows: the lower the lighting level, the greater amount of night to day crash ratio. [4]
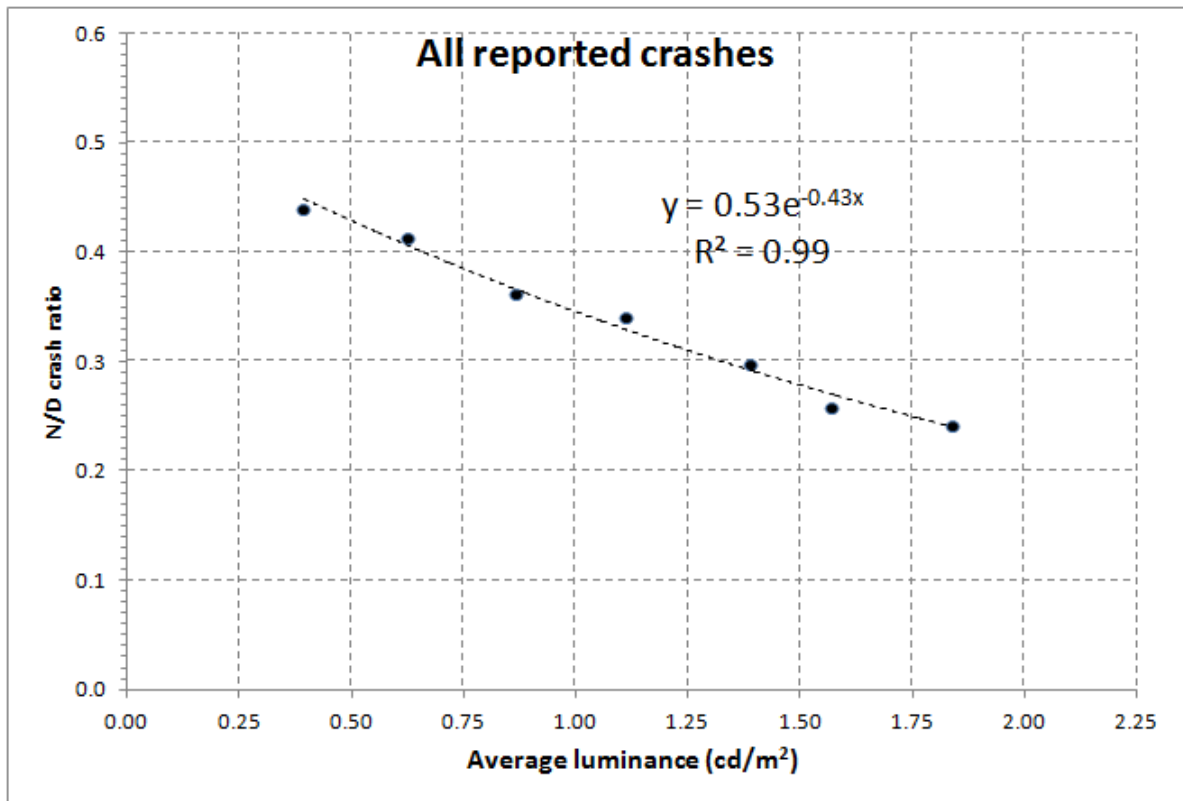
Figure 22 *The relationship between average luminance and the night to day crash ratio for all reported crashes. The downward slope of the line indicates a reduction in night crashes with an increase in average luminance. [4]*

Next study concerned with this topic comes from Brazil and France. This paper presents experimentation with observers, who were asked to assess the visibility of targets on the road surface under different levels of luminance. The experimentation has taken place at the University of Sao Paulo Campus in Brazil and in a private site in France. In both places, a luminous flux reduction system was installed. These experimentations intended to show how luminous flux reductions influence people behavior and to approximate minimum visibility levels for a safety and comfort purpose. A visibility level of 4 was achieved, which is considered sufficient to have a good recognition of objects (visibility) in suburban roads with small traffic and good weather. Unlike the previous studies, the resulting trend in relationship between road traffic safety and luminance is that reduced road lighting doesn't change person's ability to recognize objects on the road. [20]

The last study, that I'm going to mention, originates in Sweden and is concerned with pedestrian visibility on the road under different luminance. The visibility was quantified by the detection distance of a pedestrian who is about to cross a street. Six subjects, sitting as passengers in a vehicle, were used to set the detection distances. Two pedestrians were standing on the pavement along a street and the subjects' only task was to push a button when they could detect a pedestrian. The test site was located in an industrial area with no

or little traffic, and consequently, the measurements could be accomplished without any disturbance from oncoming vehicles. The results are summarized as follows:

- The detection distance of a pedestrian standing on pavement increases with increasing average luminance of the road surface if the luminance uniformity is constant.
- The detection distance of a pedestrian standing on the pavement increases with increasing luminance uniformity if the average luminance is constant.
- Road lighting with good uniformity and an average luminance of at least 0.5 cd/m^2 leads to more than 50 % rise in detection distance compared to no stationary lighting at all.

The conclusion in case of this study is, that the greater the luminance, the longer the distance to detect a pedestrian is. [21]

7.2 Null and alternative hypotheses

As a first step on the way to assess the changes in road traffic safety, I will formulate a null hypothesis about the relationship between traffic safety and level of luminance. The null hypothesis will be based on findings and result from previous studies and papers, which were discussed in previous chapter. Of course the results of studies regarding traffic safety depend on some site specific parameters, such as road geometry, volume, number of lanes, number and kind of intersections, pedestrian crossings, ratio of heavy vehicles and so on. This means that the exact results from various places around the world will of course differ in the exact form of the resulting relationship, but it should be possible to extract a general trend, which should be the same for most studies and this trend will be used as the null hypothesis.

As can be seen in the previous chapter, the studies usually try to establish an empiric relationship between road traffic safety and level of luminance. In terms of formulating the null hypothesis, the exact parameters are not important. Instead a common general trend is visible for majority of the studies – Traffic safety will get worse, if we decrease the luminance intensity, which will be our starting point - the null hypothesis, which I will try to accept or reject according to results from comparing the safety influencing parameters. Thus null hypothesis H_0 and alternative hypothesis H_1 are as follows:

H_0:"Traffic safety will get worse, after the luminance intensity is decreased."
H_1:"Traffic safety will stay the same or it will improve, after the luminance intensity is decreased."

Furthermore this hypothesis needs to be modified for each of the used safety influencing factors, which will be the key parameters for the assessment. This will be based

on findings of the previous studies on the topic of relationships between traffic safety and the safety influencing factors:

1. Null hypothesis H_0 and alternative hypothesis H_1 for mean vehicular speed:
   H_0:"The mean vehicular speed will increase, after luminance intensity is decreased"
   H_0: $\mu_1 < \mu_2$

   H_1:"The mean vehicular speed will stay the same or it will decrease, after luminance intensity is increased"
   H_1: $\mu_1 \geq \mu_2$

2. Null hypothesis H_0 and alternative hypothesis H_1 for speed variance:
   H_0:"The vehicular speed variance will increase, after luminance intensity is decreased"
   H_0: $\sigma_1 < \sigma_2$

   H_1:"The vehicular speed variance will stay the same or it will increase, after luminance intensity is decreased"
   H_1: $\sigma_1 \geq \sigma_2$

   Where:
   μ_1 is mean vehicular speed with classical street lighting
   μ_2 is mean vehicular speed with adaptive LED lighting
   σ_1 is vehicular speed variance with classical lighting
   σ_2 is vehicular speed variance with adaptive LED lighting

7.3 Selection of an appropriate test statistics

7.3.1 Mean vehicular speed

The goal of this subchapter is to choose the most suitable test statistics for the case of comparing two means of vehicular speeds – from situation with classical lighting and with adaptive LED lighting. The requirements for different test statistics, as described in chapter 6.3 Statistical evaluation, will be now discussed for the case of adaptive lighting safety assessment.

There are certainly going to be more than 30 samples in each of the datasets (It is expected to have speed measurements for both the time intervals from at least a month – with average nightly volume of 4.76* veh/hour, for 30 days, each day for 6 hours, this gives us approximately 1000 speed samples for each data set). With such big amount of data, we will expect, that vehicle speeds will be distributed normally, following the bell curve. This

expectation is based on the central limit theorem, which states, that "given a sufficiently large sample size from a population with a finite level of variance, the mean of all samples from the same population will be approximately equal to the mean of the population. Furthermore, all of the samples will follow an approximate normal distribution pattern, with all variances being approximately equal to the variance of the population divided by each sample's size." [31]

Furthermore the equality between speed variances from the two time periods should be evaluated. For this evaluation we will use the F-test for comparing variances of two datasets. As already mentioned before, the F-test uses a ratio of variances (F_{calc}) and compares that with critical value from a table (F_{tab}). The larger variance always needs to be in denominator. The zero hypothesis is, that the variances are equal: H_0: $\sigma_1 = \sigma_2$. Alternative hypothesis is then, that the variances are not equal: H_1: $\sigma_1 \neq \sigma_2$. In this case we are not interested, which variance is larger, only the equality or inequality is in our interest. This means, that a two-tailed F-test will be performed. Now follows the calculation.

$$F_{calc} = \frac{\sigma_1^2}{\sigma_2^2} = \frac{97.595}{89.751} = 1.087$$

We will work with the confidence level of 90% (We will cut of 5% of the t-distribution both on left and right side, as this is a two tailed test). To find the correct value in a table of critical values, we need to know the degrees of freedom for both datasets, respectively for nominator and denominator of F_{calc}. The degrees of freedom are given by $n_1 - 1$ and $n_2 - 1$ respectively, where n_1 and n_2 are the numbers of samples in both datasets.

$$n_1 - 1 = 8393$$
$$n_2 - 1 = 7219$$
$$F_{tab} = 1.038$$
$$F_{calc} > F_{tab}$$

Since the calculated value of F-test is greater than the critical table value, we reject the null hypothesis, and with 90% confidence we can say, that the variances of the two datasets are not equal: $\sigma_1 \neq \sigma_2$.

The last test requirement is that the sizes of samples are as equal as possible. Although it is impossible to guarantee that the same amount of vehicles will pass through the examined street during the same time interval with classical lighting as during the time interval with adaptive LED lighting. But as the daily flow usually follow very similar characteristics, it can be expected, that the amount of samples will be very similar for both time intervals, because their length will be equal. The flow characteristics from 1.9.2014 to 7.9.2014 and from 7.7.2014 to 13.7.2014 (Always Monday-Friday) can be seen on figure 23.

* The average value of traffic flow was obtained from Omnia traffic management system. The average is based on traffic flow data from 1.9.2014 to 8.9.2014. The hourly traffic flow values, which were used for computation of this average value, were selected only from the time interval, when the lighting system was dimmed – from 11pm to 5am.
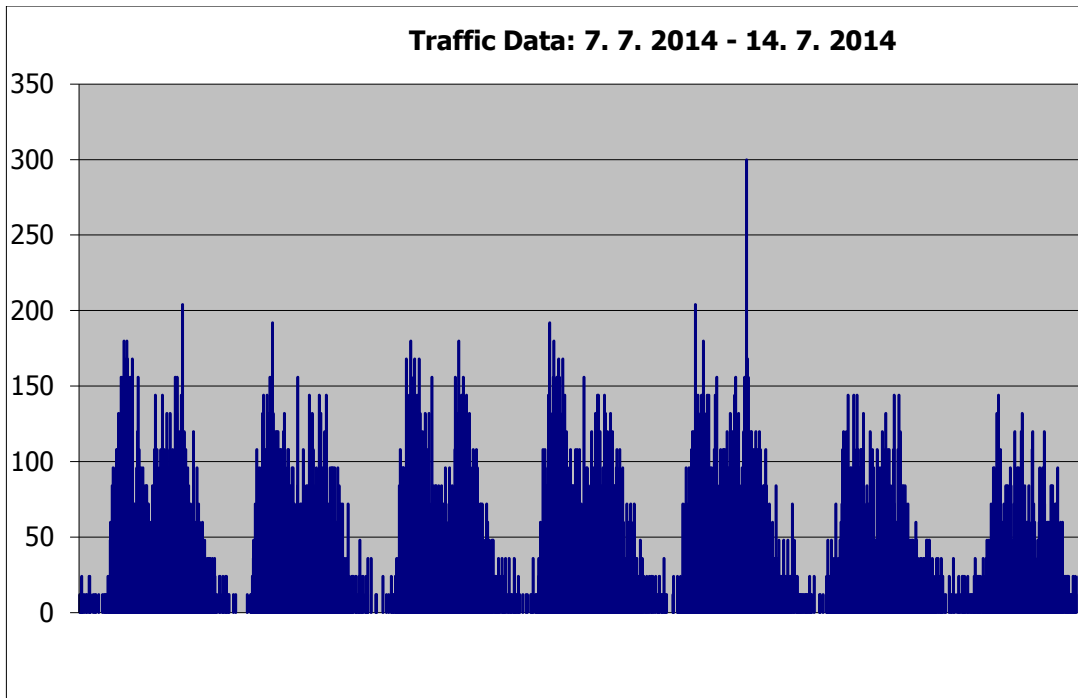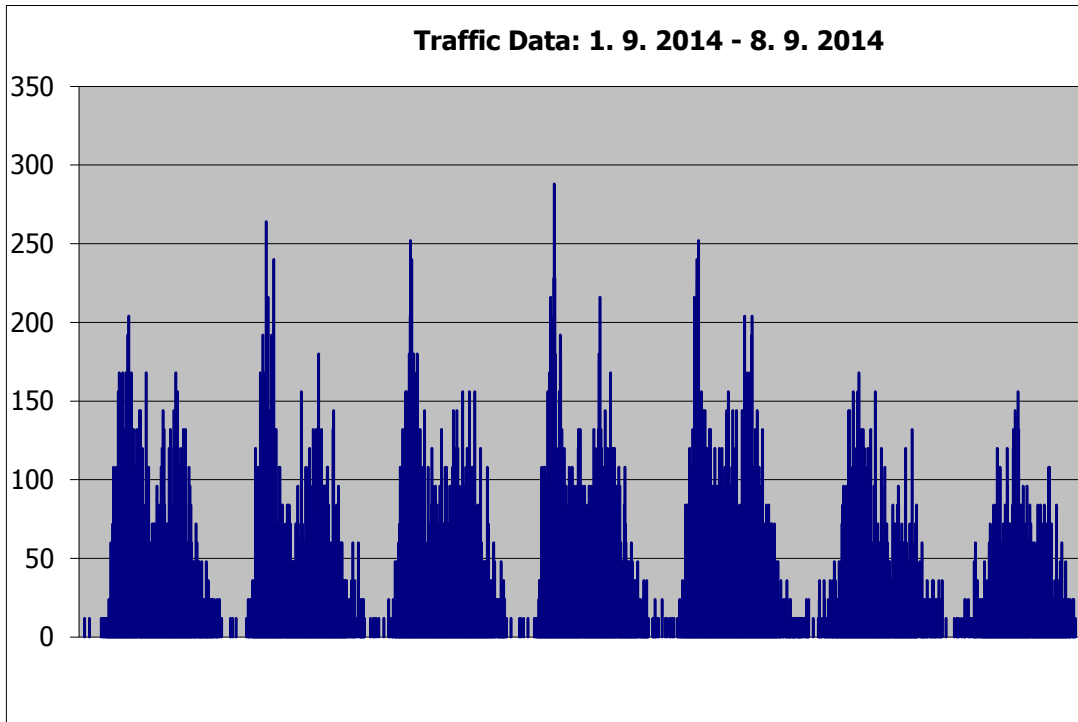
Figure 23 – Traffic flow characteristics from 1.9.2014 (Monday) to 7.9.2014 (Sunday) and below from 7.7.2014 (Monday) to 14.7.2014 (Sunday) [source - Omnia]

Next question that needs to be answered is, whether the datasets consist of pairs, which can be matched with each other. Unfortunately it is impossible to match individual vehicle from one time period with the same vehicle passing through in the second time period. The best way how to accomplish this matching would be by the using license plate matching, but for that we would need systems for automatic license plate recognition, which is not available in the testing street. Other possibility would in our case to create pairs of speed data from certain hours and days. Average vehicular speed values will be calculated for each day of the week (Monday-Sunday) individually for each of the 6 hours at night, during which the lighting is dimmed. By this approach we will obtain 42 matched pairs of vehicular speed data. Finally we can say, that the data sets from both time periods can be matched into pairs, depending on the data organization and rearrangements.

Finally it is necessary to know whether the two data sets are either independent or dependent. The definition says that "Two samples are independent if the sample selected from one population is not related to the sample selected from the second population. The two samples are dependent if each member of one sample corresponds to a member of the other sample. Dependent samples are also called paired samples or matched samples." [32] Thus according to definition our two data sets of vehicular speed are dependent to each other. In general comparative studies, which attempt to compare some quality before and after some condition has changed, are believed to have depend data sets. [33]

According to this short review about characteristics of the two data sets of vehicular speeds, we can conclude its characteristics:

- Both datasets follow normal distribution and have more than 30 samples
- Variances of the two datasets are not equal
- Sample sizes are as equal as possible
- Data sets can be matched into pairs, depending on the data organization and rearrangement
- Data sets are dependent

From the listed data set characteristics, we can conclude, that the most suitable option to test difference in means of vehicular speed before and after installation of adaptive LED lighting system is the **paired t-test**, and thus it will also be used to assess road safety in this thesis.

Also now that we have realized, that the two data sets are dependent on each other, we should recalculate the F-test for equality of variances, because F-test is valid only if performed on independent data sets, thus the F-test for equality of variances calculated above, is not valid. It is now not important for us to know, whether the variances are equal or not, because since the datasets are dependent, we have already chosen paired t-test for the hypotheses testing. The correct way how to compare the variance would be to create

groups, as for comparing vehicular means (see chapter 7.4), and then use paired t-test, which is compatible with dependent datasets. Although the result of this test is no longer of our interest in this chapter, I will provide at least the brief overview and the key variables of the paired t-test correct calculation for equality of variances (H_0 and H_1 stay the same):

$$\overline{D} = 11.856$$
$$S_d = 34.74$$
$$n = 42$$
$$t = 2.119$$
$$p = 0.0326$$
$$\alpha = 0.1$$
$$0.0326 < 0.1 \rightarrow p < \alpha$$

Where:

$\overline{D}$ is the mean difference between matched pairs of mean variance

S_d is the standard deviation of matched pairs of mean variance

n is the number of pairs of mean variance

t is the t-value for a given test, degrees of freedom and level of significance

$\propto$ is the chosen level of significance

p is the corresponding p-value to calculated

Calculated p-value is less than selected level of significance, thus we reject the null hypothesis, that the variances are equal. (Same result as for the original incorrect F-test)

7.3.2 Vehicular speed variance

The original idea of using the F-test has to be rejected for testing the differences in variances now with the knowledge about dependency of the datasets, and replaced by another test statistic, which would be also suitable for testing differences in variances between dependent datasets. Also for this comparison of variances, I will use paired t-test, as for the corrected testing of variance equality in previous chapter. It is also the same way of testing like for the vehicular mean speed. In the same fashion, we will also create 42 groups consisting of 7 days a week and 6 hours of operational adaptive LED lighting. (see chapter 7.4)

7.4 Data processing

Raw speed data obtained from ITS Vienna region need to be processed in order to be usable for intended road safety assessment. Received .csv file had a following layout (example of one record):

1190; 1; 25.06.2014 12:48:27; 25.06.2014 12:50:56; 4; 41

The data separated by semicolons has the following meaning (from left to right):
Node number; lane; timestamp of measurement; timestamp of data save; vehicle type; speed

     The first step was to create two separate files out of this raw data – one file for July and one for September, as each of the files will be used separately as an input to my program (described later). This was achieved manually. Furthermore it was necessary to classify the data. As mentioned earlier, I will use paired t-test for comparing vehicular mean speed and also for comparing the vehicular speed variance. This test requires, that the compared datasets are in a form of matched pairs. These pairs will be created for all week days and for all hours, during which the lighting luminance is decreased, individually. So the data classification needs to be done according to day and hour of timestamp of measurement. Using this logic, we get 42 groups (7 days and 6 hours in each day). A mean value of vehicular speed and also vehicular speed variance will be computed from data for each group separately. These mean values and variances will be computed for both of the assessed situations (July and September). Then they will be used as input values for paired t-test. To perform this data processing, I wrote a program in Microsoft Visual Basic 2008 Express Edition. Source code to this program is enclosed in appendix 2. Apart from only data classification, the program also attempts to avoid using implausible speed values for the calculation of means and variances. It is necessary to rule out implausible speed values, because I am working with raw speed data, which have not been processed before, and it is possible that the data contain values, which are not true and were caused by a faulty detector setting, error etc. This is achieved simply by taking into account only values, which were located inside the interval (10; 100) km/h. The output of the program is in a form of 2*42 matched pairs of vehicular average speeds and vehicular speed variances (all for July and September). Now that the data is classified and has an appropriate structure, we may proceed to the next step, which is computing the test statistics.

7.5 Computation of test statistics

     All statistical tests in this section were performed in Microsoft excel. All computations were done manually using basic arithmetical operations, except for computing p values out from t values, because software can deliver p values in higher precision, when compared with looking up the values in t table.

7.5.1 Mean vehicular speed

     I will use paired t-test to compare vehicular mean speeds (and vehicular speed variances) in the months July (with old lighting) and September (with new lighting system

with dimming). For both months vehicular speed data is organized into 42 groups, each of which corresponds to a certain hour in a certain day, as discussed earlier. Of course the number of samples, which were used to calculate the means within each group, is not the same for all groups. The smallest amount of samples for a group from July is 58, and 62 for a group from September. The largest amount of samples for a group from July is 468, and 458 for a group from September. The absolute value of the average of percentage difference between matched pairs (values from July are taken as 100%) is equal to 20.25%, the maximal value of this percentage difference is 49.59%, and the minimal percentage difference is 1.13%. The amount of samples for corresponding groups from July and September is rather similar, and in any case, the amounts are quite large, thus the differences in the amount of samples should not be of any significance for the comparison of means (or variances), so this issue will not be addressed anymore. Table with amount of grouped samples of matched pairs can be seen in table 1 in appendix 1.

Now to the actual calculation of paired t-test statistics. We will use formulas for t-test statistic and for standard deviation of matched pairs S_d listed in chapter 6.3. These formulas indicate that t-test is based on the differences between matched pairs. Actually two sample paired t-test is equal to a one sample t-test, which takes the differences between matched pairs as its input. In order to obtain positive value of average difference between matched pairs, the subtraction was done in a following way: $D_{i, September} - D_{i, July}$, as can be seen in table 2 in appendix 1.

$$t = \frac{\overline{D}}{\frac{S_d}{\sqrt{n}}}$$

$$S_d = \sqrt{\frac{\sum(D_i - \overline{D})^2}{n - 1}}$$

Where:
$\overline{D}$ is the mean difference between matched pairs of mean speed
D_i is the difference between individual matched values of mean speed
S_d is the standard deviation of matched pairs of mean speed
n is the number of matched pairs of mean speed

Standard deviation of matched pairs is equal to:

$$S_d = \sqrt{\frac{66.245}{41}} = \underline{1.271}$$

The t-statistic value is then:

$$t = \frac{0.830}{\frac{1.271}{\sqrt{42}}} = \underline{4.231}$$

Here it is worth noticing, that the average difference between the speed values of matched pairs is equal to $\bar{D} = 0.830$ km/h (table 2 in appendix 1). This means, that the average speed values for month September (with the new lighting system) were greater by 0.830 km/h than in the month July. However, it is not sufficient to simply compare two means like that, at least in terms of statistical testing. In the simple comparison, we don't take into account variance or number of samples within each dataset. That is the reason, why statistical test are used, because they include these variables into the comparison of means. Now that we know that, that one mean is greater than the other, we would like to know, whether the difference between means is significant on a chosen level of significance. In other words, if the difference is significant, we will accept null hypothesis, that the mean vehicular speed from September is greater than from July, and if the difference is not significant, we will reject it, giving possibilities to some of the alternative hypotheses, that the mean from September is less or equal to the mean from July.

Now it is important to say, that I am performing a one tailed paired t-test. The test is one tailed because the null hypothesis for means intends to test an inequality of the means: $H_0: \mu_1 < \mu_2$. If the null hypothesis was to test an equality of means: $H_0: \mu_1 = \mu_2$, the test would be two tailed, but that is not the case. The level of significance for this test is chosen to be $\alpha=0.05$, which is the most common level of significance used in statistical testing. If the determination of p-value was done using tables, and if this test was a two tailed test, we would need to look up a critical t-value in a p-table in a column for level of significance of $\alpha=0.025$, in order to select the appropriate value of a corresponding p-value to our above calculated t-value. That is apart from other reasons, why it is important to be aware of which kind of testing we are doing (one or two tailed). But in our case we will compute the p-value using function t-Test: Paired Two Sample for Means in Microsoft Excel Analysis Pak, because like so, we can obtain a p-value with higher precision, than by using a critical p table, by which we would only obtain an interval, where our p-value would belong. P-value is a measure of strength of evidence against the null hypothesis. In general it is valid, that the smaller the p-value the greater the evidence against the null hypothesis. In our case, for a one tailed t-test with 41 degrees of freedom (n-1) and with level of significance $\alpha=0.05$, I have obtained a p-value:

$$\mathrm{p} = \underline{0.0000637}$$

Next step after obtaining the p-value is to compare it to our chosen level of significance α. If the p-value is greater than level of significance, we accept the null hypothesis. On the other hand, if the p-value is less than the level of significance, we reject the null hypothesis. We can see, that in our case the p-value is much less than level of significance:

$$0.0000637 < 0.05 \rightarrow \mathrm{p} < \alpha$$

Since the p-value is less than level of significance, we reject null hypothesis H_0. **There is enough evidence to suggest that the average vehicular speed was not increased after the adaptive LED lighting implementation**. This means that although the average difference between speed values of matched pairs was greater than 0 ($\bar{D} = 0.830$ km/h), we

still proclaim, that the average vehicular speed was not increased, because according to paired t-test, this increase in vehicular average speed is not considered to be significant.

Furthermore we can create a 95% confidence interval for the change in mean vehicular speed. The value of t_α was looked up in a t-table in a column with level of significance α=0.05 and in a row for 41 degrees of freedom:

$$\overline{D} \pm t_\alpha \cdot SE(\overline{D})$$

$$SE(\overline{D}) = \frac{S_d}{\sqrt{n}} = \frac{1.271}{\sqrt{42}} = \underline{0.196}$$

$$t_\alpha \cdot SE(\overline{D}) = 2.020 \cdot 0.196 = 0.396$$

$$\overline{D} = 0.830$$

$$\mathbf{0.830 \pm 0.396}$$

Where:

$\overline{D}$ is the mean difference between matched pairs of vehicular mean speed

t_α is the t-value for a given test, degrees of freedom and level of significance

$SE(\overline{D})$ is the standard error of the mean difference between matched pairs of vehicular mean speed

The mean difference in mean vehicular speed was greater after the adaptive LED lighting implementation than with original road lighting. Now we can conclude that we are 95% confident, that the mean difference in mean vehicular speed lies between:

$$(\mathbf{0.434; 1.226})\ \textbf{km/h}$$

7.5.2 Vehicular speed variance

Unlike to the original concept, we will now also use paired t-test for comparing the vehicular speed variances between datasets from July and September, because of the realization of dependency of assessed datasets. As for the case with mean vehicular speed, we have 42 values of vehicular speed variance for each work day and for each 6 hours of the operation of adaptive street LED lighting. These values were always calculated as variance of all plausible speed samples in the given group, in the same way, as it was done for vehicular mean speed. We can also skip the discussion about comparability of datasets and the number of samples in compared groups, because this was already done in the previous chapter 7.5.1. The differences in variance between matched pairs will be also done in a following fashion (in order to obtain positive value of the mean difference between matched vehicular speed variances):

$D_{i,\ September}$ - $D_{i,\ July}$, this can be seen in table 3 in appendix 1.

Now we will proceed to the calculation of the paired t-test statistics:

Standard deviation of matched pairs is equal to:

$$S_d = \sqrt{\frac{49472.83}{41}} = 34.74$$

The t-statistic value is then:

$$t = \frac{11.86}{\frac{34.74}{\sqrt{42}}} = \underline{2.212}$$

Now let's discuss the value of average difference between matched pairs of average variance. This value is equal to $\bar{D} = 11.856$ km/h (table 3 in appendix 1). This means, that the average vehicular variances for September (with the new lighting system) was greater by 11.856 km/h than in the month July. Next step is again to test, whether this difference is significant and whether we will accept or reject the null hypothesis: H_0: $\sigma_1 < \sigma_2$. As for the comparison of vehicular mean speed, we will use level of significance α=0.05, and again we have 42 matched pairs of variance, which then leads to 41 degrees of freedom. This test is also one tailed, because the null hypothesis is about inequality of speed variance. With the above listed values Microsoft Excel Analysis Pak delivered a following p-value:

$$p = \underline{0.0163}$$

Now the p-value needs to be compared to our chosen level of significance, and on the basis of this comparison, we will be able to decide, whether to accept or reject the null hypothesis:

$$0.0163 < 0.05 \rightarrow p < \alpha$$

Because the p-value is less than level of significance, we reject null hypothesis H_0. **There is enough evidence to suggest that the vehicular speed variance was not increased after the adaptive LED lighting implementation**. This means that although the average difference between vehicular speed variance values of matched pairs was greater than 0 ($\bar{D} = 11.856$), we still proclaim, that vehicular speed variance was not increased, because according to paired t-test, this increase in vehicular speed variance is not considered to be significant.

Now we can create a 95% confidence interval for the change in mean value of vehicular speed variance. The value of t_α was looked up in a t-table in a column with level of significance α=0.05 and in a row for 41 degrees of freedom:

$$SE(\bar{D}) = \frac{34.736}{\sqrt{42}} = \underline{5.360}$$

$$t_\alpha \cdot \text{SE}(\overline{\text{D}}) = 2.020 \cdot 5.360 = 10.877$$

$$\overline{\text{D}} = 11.856$$

$$\mathbf{11.856 \pm 10.877}$$

Where:

$\overline{D}$ is the mean difference between matched pairs of vehicular speed variance

t_α is the t-value for a given test, degrees of freedom and level of significance

$SE(\overline{D})$ is the standard error of the mean difference between matched pairs of vehicular speed variance

The mean difference in vehicular speed variance was larger after the adaptive LED lighting implementation than original road lighting. Now we can conclude that we are 95% confident, that the mean difference in speed variance lies between:

$$(\mathbf{0.979; 22.733})$$

7.6 Evaluation of tests

We could see that null hypotheses for both our safety influencing factors about increasing mean vehicular speed and about increasing vehicular speed variance were rejected.

Mean vehicular speed was greater in September with the adaptive LED lighting, than in July with the classical lighting. With 95% confidence, we can say, that the increment in mean speed lies in the interval (0.434; 1.226) km/h. By the means of paired t-test, we reached a conclusion that this difference in mean speed is not significant, and thus we concluded, that mean vehicular speed did not increase after adaptive LED lighting implementation. This decision was based on the comparison of the p-value, which we obtained as a test result, with chosen level of significance. In this case the p-value (p=0.0000637) was much less than the level of significance (α=0.05).

Vehicular speed variance was also greater in September than in July. With 95% confidence, we can say, that the increment in speed variance lies in the interval (0.979; 22.733). Using paired t-test, we realized, that this difference is not significant, and we concluded, that vehicular speed variance did not increase after adaptive LED lighting implementation. The decision was reached by comparing the p-value with the level of significance. Also in this case the p-value (p=0.0163) was less than the level of significance (α=0.05).

We can notice, that there is a rather great difference between the p-values for mean speed and for speed variance. As already mentioned earlier, p-value is a measure of strength of evidence *against* the null hypothesis. In general it is true, that the smaller the p-

value the greater the evidence against the null hypothesis. Therefore, we can say that the null hypothesis about mean speed was rejected "more" than the null hypothesis about speed variance. However, this does not influence or change the conclusions, which were made earlier.

8 Conclusion

Now let's discuss, what do the conclusions reached in previous chapter mean for road traffic safety. The relationships between safety, speed and speed variance are described in chapter 6.2.1. The conclusion was that the higher the speed or speed variance, the worse the resulting road traffic safety was (in terms of involvement in accident). The studies regarding this topic in chapter 6.2.1 showed some different approaches for modelling these relationships. The models are dependent on site specific parameter like traffic flow, ratio of heavy vehicles or the road geometry, its width on so on. If there was proven to be any significant change in the values of safety influencing factors before and after adaptive LED lighting implementation, and if we calibrated the presented models properly, we would be able to estimate the change in the resulting road traffic safety in terms of forecasted change in accident frequency (over some time period). But this is not the case. Using the two sample paired t-test to test the null hypotheses about inequality between means of speed (H_0: $\mu_1 < \mu_2$) and between speed variances (H_0: $\sigma_1 < \sigma_2$) from the situations before and after adaptive lighting implementation, we found out that the observed differences both in mean speed and speed variances are not significant, so the null hypotheses was rejected. This is despite the fact, that the calculated mean value of the differences between matched pairs both for speed and speed variance were nonzero. For both safety influencing factors the mean value was greater for September (the situation with adaptive LED lights) than for July (the situation with original road lighting). With a 95% confidence interval the mean value of the differences between matched pairs of mean speed lies inside following interval: (0.434; 1.226) km/h. With a 95% confidence interval the mean value of the differences between matched pairs of speed variance lies inside following interval: (0.979; 22.733). We can see that both the intervals also include values rather close to zero. This corresponds with the fact that the mean value of the differences between matched pairs for both safety influencing parameters was found to be insignificant by paired t-test. But let's get back to the actual safety assessment. There is enough evidence to suggest that both the mean vehicular speed and vehicular speed variance were not increased after the adaptive LED lighting implementation. Together with the findings from chapter 6.2.1 we can disprove our original null hypothesis about road traffic safety: H_0:"Traffic safety will get worse, after the luminance intensity is decreased." Since in our case safety is represented in terms of safety influencing factors (speed and speed variance), we will reject this null hypothesis too. Therefore we can conclude, **that road traffic safety does not get worse**, after the luminance intensity from the adaptive LED lighting in Angyalföldstraße is decreased for fixed time intervals (11pm – 5am) with low traffic flow.

Further improvements in this road safety assessment could be done in several different directions. Firstly it would be interesting to use longer time periods for the data collection. For example take values from one year with the classical lighting and also from one year with the operational adaptive LED lighting. It would probably be necessary to

classify the data for paired t-test in more detail, perhaps also according to individual months. This was impossible to be achieved in framework of this thesis, because the adaptive LED lighting has been only operational since September 2014, so the time interval for data collection could not have been longer. It was difficult to gain access to the data from September, because it is still a very recent period by the time of writing this work. Other possibility how to get larger datasets would be to use data from more inputs. For example it would be possible to use data from more detectors (which are already installed in the assessed street) or we could also use data from FCD. Another improvement would be to use some direct safety measures. For example the usage of accident data would be very useful. Unfortunately this approach requires very long periods of data collection, so it was impossible to be used here. The parameters used for this safety assessment belong to the category of indirect safety measures. Safety assessment with direct safety measures would provide a more accepted result, because for example safety assessment done by comparing numbers of accident is generally known.

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Appendix 1

Table 1 - Comparison of number of samples between July and September

	July	September		
Mon	**number of samples**	**number of samples**	**sample difference**	**absolute_percent_difference**
23-24	223	264	-41	18.39
00-01	230	154	76	33.04
01-02	107	96	11	10.28
02-03	69	63	6	8.70
03-04	58	67	-9	15.52
04-05	173	214	-41	23.70
Tue				
23-24	352	287	65	18.47
00-01	193	139	54	27.98
01-02	130	108	22	16.92
02-03	79	70	9	11.39
03-04	88	71	17	19.32
04-05	222	213	9	4.05
Wed				
23-24	388	251	137	35.31
00-01	240	130	110	45.83
01-02	140	90	50	35.71
02-03	99	63	36	36.36
03-04	90	72	18	20.00
04-05	232	181	51	21.98
Thu				
23-24	454	284	170	37.44
00-01	203	129	74	36.45
01-02	169	99	70	41.42
02-03	123	62	61	49.59
03-04	86	64	22	25.58
04-05	222	182	40	18.02
Fri				
23-24	401	424	-23	5.74

00-01	232	142	90	38.79
01-02	149	101	48	32.21
02-03	100	74	26	26.00
03-04	104	100	4	3.85
04-05	219	212	7	3.20
Sat				
23-24	467	458	10	2.14
00-01	302	276	26	8.61
01-02	189	222	-33	17.46
02-03	179	167	12	6.70
03-04	126	145	-29	25.00
04-05	153	165	-12	7.84
Sun				
23-24	268	204	64	23.88
00-01	355	359	-4	1.13
01-02	278	265	13	4.68
02-03	190	201	-11	5.79
03-04	158	169	-11	6.96
04-05	153	182	-29	18.95
sum	8393	7219	**average**	20.25
min	58	62	**max**	49.59
max	468	458	**min**	1.13

Table 2 – Input data for calculation of paired t-test for vehicular mean speed

	July	September		
Mon	**Average speed**	**Average speed**	**Difference D_i**	**$(D_i-D)^2$**
23-24	52.75	53.79	1.04	0.05
00-01	53.24	55.34	2.09	1.60
01-02	53.65	56.79	3.14	5.33
02-03	56.58	56.16	-0.42	1.56
03-04	55.83	55.33	-0.50	1.77
04-05	52.54	54.43	1.88	1.11
Tue				
23-24	52.38	54.27	1.90	1.14
00-01	54.13	54.04	-0.10	0.86
01-02	53.42	56.19	2.76	3.73
02-03	55.47	58.46	2.99	4.66
03-04	56.06	55.14	-0.92	3.05
04-05	53.11	52.45	-0.67	2.24
Wed				
23-24	53.33	53.35	0.03	0.64
00-01	54.24	53.52	-0.71	2.38
01-02	54.38	56.50	2.12	1.67
02-03	55.80	56.78	0.98	0.02
03-04	54.37	55.03	0.66	0.03
04-05	53.44	53.72	0.27	0.31
Thu				
23-24	52.87	53.42	0.55	0.08
00-01	55.38	55.16	-0.22	1.11
01-02	55.48	56.20	0.72	0.01
02-03	54.07	57.37	3.31	6.13
03-04	54.78	53.59	-1.19	4.06
04-05	54.10	53.87	-0.23	1.12
Fri				
23-24	52.03	53.68	1.65	0.68
00-01	54.09	56.21	2.12	1.66
01-02	56.18	57.40	1.21	0.15
02-03	55.14	53.99	-1.15	3.93
03-04	56.19	55.74	-0.45	1.64
04-05	53.39	54.32	0.93	0.01

Sat				
23-24	50.98	54.01	3.03	4.86
00-01	53.10	54.33	1.23	0.16
01-02	54.16	55.57	1.41	0.34
02-03	54.69	55.60	0.91	0.01
03-04	53.80	55.82	2.02	1.41
04-05	55.39	55.52	0.12	0.50
Sun				
23-24	53.65	52.82	-0.83	2.74
00-01	53.71	53.18	-0.53	1.86
01-02	55.03	54.90	-0.12	0.91
02-03	53.82	55.32	1.50	0.45
03-04	55.09	56.43	1.34	0.26
04-05	55.18	56.15	0.97	0.02
			average=0.83	**sum=66.24**

Table 3 - Input data for calculation of paired t-test for vehicular speed variance

	July	September		
Mon	**Speed variance**	**Speed variance**	**Difference D_i**	**$(D_i-D)^2$**
23-24	76.49	73.41	-3.07	222.90
00-01	89.54	138.91	49.37	1407.36
01-02	62.97	96.73	33.77	480.11
02-03	68.00	92.82	24.82	168.17
03-04	159.73	109.11	-50.62	3903.18
04-05	144.04	104.18	-39.86	2674.24
Tue				
23-24	95.44	102.68	7.24	21.32
00-01	90.48	95.31	4.83	49.29
01-02	104.36	60.83	-43.53	3067.06
02-03	63.17	223.53	160.36	22053.31
03-04	154.87	137.89	-16.97	831.18
04-05	100.73	75.27	-25.46	1392.55
Wed				
23-24	95.28	84.02	-11.25	533.92
00-01	69.93	89.72	19.79	62.98
01-02	76.39	84.91	8.52	11.10
02-03	73.61	89.35	15.74	15.12
03-04	130.75	146.24	15.50	13.27
04-05	98.70	133.33	34.63	518.79
Thu				
23-24	107.85	92.54	-15.31	737.95
00-01	70.37	71.44	1.08	116.19
01-02	85.28	93.54	8.26	12.92
02-03	89.35	109.61	20.26	70.63
03-04	86.63	95.25	8.62	10.46
04-05	98.11	86.55	-11.55	547.88
Fri				
23-24	77.10	83.41	6.31	30.77
00-01	59.78	114.57	54.79	1843.10
01-02	64.75	75.11	10.36	2.22
02-03	94.08	108.01	13.93	4.31
03-04	111.94	145.05	33.11	451.92
04-05	78.83	113.79	34.96	533.82

Sat			
23-24	85.00	86.73	1.73	102.61
00-01	92.65	71.09	-21.56	1116.61
01-02	101.09	69.08	-32.01	1924.49
02-03	92.27	152.79	60.52	2367.90
03-04	107.10	131.16	24.06	149.05
04-05	84.28	97.46	13.18	1.75
Sun			
23-24	75.06	90.50	15.44	12.88
00-01	98.76	89.63	-9.12	440.06
01-02	77.04	81.56	4.53	53.73
02-03	59.41	87.57	28.16	265.70
03-04	101.77	148.50	46.73	1216.48
04-05	88.01	105.65	17.64	33.51
			average=11.86	**sum=49472.83**

Appendix 2

Source code of my program for traffic data classification written in Microsoft Visual Basic 2008 Express Edition:

```vb
Imports System.IO

Module Module1

    Sub Main()

        Dim strfilename As String
        Dim num_rows As Long
        Dim num_cols As Long
        Dim x As Integer
        Dim y As Integer
        Dim a, b As Integer
        Dim strarray(1, 1) As String

        Dim eleven As Integer = 0
        Dim zero As Integer = 0
        Dim one As Integer = 0
        Dim two As Integer = 0
        Dim three As Integer = 0
        Dim four As Integer = 0
        Dim dateTemp As Date
        Dim timetemp As Date

        Dim mo1, tu1, we1, th1, fr1, sa1, su1 As Integer
        Dim mo2, tu2, we2, th2, fr2, sa2, su2 As Integer
        Dim mo3, tu3, we3, th3, fr3, sa3, su3 As Integer
        Dim mo4, tu4, we4, th4, fr4, sa4, su4 As Integer
        Dim mo11, tu11, we11, th11, fr11, sa11, su11 As Integer
        Dim mo0, tu0, we0, th0, fr0, sa0, su0 As Integer

        Dim sum1, sum2, sum3, sum4, sum11, sum0 As Integer
        Dim avg1, avg2, avg3, avg4, avg11, avg0 As Double
```

```vbnet
    My.Computer.FileSystem.WriteAllText("D:\!Data\Dropbox\Adaptive
lighting\Thesis\calculation\output\Monday.csv", "", False)
    My.Computer.FileSystem.WriteAllText("D:\!Data\Dropbox\Adaptive
lighting\Thesis\calculation\output\Tuesday.csv", "", False)
    My.Computer.FileSystem.WriteAllText("D:\!Data\Dropbox\Adaptive
lighting\Thesis\calculation\output\Wednesday.csv", "", False)
    My.Computer.FileSystem.WriteAllText("D:\!Data\Dropbox\Adaptive
lighting\Thesis\calculation\output\Thursday.csv", "", False)
    My.Computer.FileSystem.WriteAllText("D:\!Data\Dropbox\Adaptive
lighting\Thesis\calculation\output\Friday.csv", "", False)
    My.Computer.FileSystem.WriteAllText("D:\!Data\Dropbox\Adaptive
lighting\Thesis\calculation\output\Saturday.csv", "", False)
    My.Computer.FileSystem.WriteAllText("D:\!Data\Dropbox\Adaptive
lighting\Thesis\calculation\output\Sunday.csv", "", False)


    strfilename="D:\!Data\Dropbox\Adaptive
lighting\Thesis\calculation\real_data\September.csv"

    If File.Exists(strfilename) Then
    Dim tmpstream As StreamReader = File.OpenText(strfilename)
    Dim strlines() As String
    Dim strline() As String

    strlines = tmpstream.ReadToEnd().Split(Environment.NewLine)

        num_rows = UBound(strlines)
    strline = strlines(0).Split(";")
    num_cols = UBound(strline)
    ReDim strarray(num_rows, num_cols)

    For x = 0 To num_rows - 1
       strline = strlines(x).Split(";")
       For y = 0 To num_cols
          strarray(x, y) = strline(y)
       Next
    Next

    End If
```

```vb
Dim Mon(5, num_rows) As String
Dim Tue(5, num_rows) As String
Dim Wed(5, num_rows) As String
Dim Thu(5, num_rows) As String
Dim Fri(5, num_rows) As String
Dim Sat(5, num_rows) As String
Dim Sun(5, num_rows) As String


For x = 1 To num_rows

    If strarray(x, 0) <> "" Then

        dateTemp = CDate(strarray(x, 0))
        strarray(x, 0) = dateTemp

        timetemp = CDate(strarray(x, 1))
        strarray(x, 1) = timetemp


        If strarray(x, 7) <> "" Then
            If Weekday(strarray(x, 0)) = 5 Then

                If CInt(Left(strarray(x, 1), 2)) = 23 And strarray(x, 7) > 10 And strarray(x, 7)
< 100 Then
                    Thu(0, th11) = strarray(x, 7)
                    th11 += 1
                End If

                If CInt(Left(strarray(x, 1), 2)) = 0 And strarray(x, 7) > 10 And strarray(x, 7) <
100 Then
                    Thu(1, th0) = strarray(x, 7)
                    th0 += 1
                End If

                If CInt(Left(strarray(x, 1), 2)) = 1 And strarray(x, 7) > 10 And strarray(x, 7) <
100 Then
                    Thu(2, th1) = strarray(x, 7)
                    th1 += 1
```

```
                End If

                If CInt(Left(strarray(x, 1), 2)) = 2 And strarray(x, 7) > 10 And strarray(x, 7) <
100 Then

                    Thu(3, th2) = strarray(x, 7)
                    th2 += 1
                End If

                If CInt(Left(strarray(x, 1), 2)) = 3 And strarray(x, 7) > 10 And strarray(x, 7) <
100 Then

                    Thu(4, th3) = strarray(x, 7)
                    th3 += 1
                End If

                If CInt(Left(strarray(x, 1), 2)) = 4 And strarray(x, 7) > 10 And strarray(x, 7) <
100 Then

                    Thu(5, th4) = strarray(x, 7)
                    th4 += 1
                End If

            End If


            If Weekday(strarray(x, 0)) = 6 Then

                If CInt(Left(strarray(x, 1), 2)) = 23 And strarray(x, 7) > 10 And strarray(x, 7)
< 100 Then

                    Fri(0, fr11) = strarray(x, 7)
                    fr11 += 1
                End If

                If CInt(Left(strarray(x, 1), 2)) = 0 And strarray(x, 7) > 10 And strarray(x, 7) <
100 Then

                    Fri(1, fr0) = strarray(x, 7)
                    fr0 += 1
                End If

                If CInt(Left(strarray(x, 1), 2)) = 1 And strarray(x, 7) > 10 And strarray(x, 7) <
100 Then
```

```vb
                Fri(2, fr1) = strarray(x, 7)
                fr1 += 1
            End If

            If CInt(Left(strarray(x, 1), 2)) = 2 And strarray(x, 7) > 10 And strarray(x, 7) <
100 Then

                Fri(3, fr2) = strarray(x, 7)
                fr2 += 1
            End If

            If CInt(Left(strarray(x, 1), 2)) = 3 And strarray(x, 7) > 10 And strarray(x, 7) <
100 Then

                Fri(4, fr3) = strarray(x, 7)
                fr3 += 1
            End If

            If CInt(Left(strarray(x, 1), 2)) = 4 And strarray(x, 7) > 10 And strarray(x, 7) <
100 Then

                Fri(5, fr4) = strarray(x, 7)
                fr4 += 1
            End If

        End If


        If Weekday(strarray(x, 0)) = 7 Then

        If CInt(Left(strarray(x, 1), 2)) = 23 And strarray(x, 7) > 10 And strarray(x, 7)
< 100 Then

                Sat(0, sa11) = strarray(x, 7)
                sa11 += 1
            End If

            If CInt(Left(strarray(x, 1), 2)) = 0 And strarray(x, 7) > 10 And strarray(x, 7) <
100 Then

                Sat(1, sa0) = strarray(x, 7)
                sa0 += 1
            End If
```

```
If CInt(Left(strarray(x, 1), 2)) = 1 And strarray(x, 7) > 10 And strarray(x, 7) <
100 Then
    Sat(2, sa1) = strarray(x, 7)
    sa1 += 1
End If

If CInt(Left(strarray(x, 1), 2)) = 2 And strarray(x, 7) > 10 And strarray(x, 7) <
100 Then
    Sat(3, sa2) = strarray(x, 7)
    sa2 += 1
End If

If CInt(Left(strarray(x, 1), 2)) = 3 And strarray(x, 7) > 10 And strarray(x, 7) <
100 Then
    Sat(4, sa3) = strarray(x, 7)
    sa3 += 1
End If

If CInt(Left(strarray(x, 1), 2)) = 4 And strarray(x, 7) > 10 And strarray(x, 7) <
100 Then
    Sat(5, sa4) = strarray(x, 7)
    sa4 += 1
End If

End If


If Weekday(strarray(x, 0)) = 1 Then

If CInt(Left(strarray(x, 1), 2)) = 23 And strarray(x, 7) > 10 And strarray(x, 7)
< 100 Then
    Sun(0, su11) = strarray(x, 7)
    su11 += 1
End If

If CInt(Left(strarray(x, 1), 2)) = 0 And strarray(x, 7) > 10 And strarray(x, 7) <
100 Then
    Sun(1, su0) = strarray(x, 7)
    su0 += 1
End If
```

```
            If CInt(Left(strarray(x, 1), 2)) = 1 And strarray(x, 7) > 10 And strarray(x, 7) <
100 Then

                Sun(2, su1) = strarray(x, 7)
                su1 += 1
            End If


            If CInt(Left(strarray(x, 1), 2)) = 2 And strarray(x, 7) > 10 And strarray(x, 7) <
100 Then

                Sun(3, su2) = strarray(x, 7)
                su2 += 1
            End If


            If CInt(Left(strarray(x, 1), 2)) = 3 And strarray(x, 7) > 10 And strarray(x, 7) <
100 Then

                Sun(4, su3) = strarray(x, 7)
                su3 += 1
            End If


            If CInt(Left(strarray(x, 1), 2)) = 4 And strarray(x, 7) > 10 And strarray(x, 7) <
100 Then

                Sun(5, su4) = strarray(x, 7)
                su4 += 1
            End If

        End If


        If Weekday(strarray(x, 0)) = 2 Then

        If CInt(Left(strarray(x, 1), 2)) = 23 And strarray(x, 7) > 10 And strarray(x, 7)
< 100 Then

                Mon(0, mo11) = strarray(x, 7)
                mo11 += 1
            End If


        If CInt(Left(strarray(x, 1), 2)) = 0 And strarray(x, 7) > 10 And strarray(x, 7) <
100 Then

                Mon(1, mo0) = strarray(x, 7)
                mo0 += 1
```

```
        End If

        If CInt(Left(strarray(x, 1), 2)) = 1 And strarray(x, 7) > 10 And strarray(x, 7) <
100 Then

            Mon(2, mo1) = strarray(x, 7)
            mo1 += 1
        End If

        If CInt(Left(strarray(x, 1), 2)) = 2 And strarray(x, 7) > 10 And strarray(x, 7) <
100 Then

            Mon(3, mo2) = strarray(x, 7)
            mo2 += 1
        End If

        If CInt(Left(strarray(x, 1), 2)) = 3 And strarray(x, 7) > 10 And strarray(x, 7) <
100 Then

            Mon(4, mo3) = strarray(x, 7)
            mo3 += 1
        End If

        If CInt(Left(strarray(x, 1), 2)) = 4 And strarray(x, 7) > 10 And strarray(x, 7) <
100 Then

            Mon(5, mo4) = strarray(x, 7)
            mo4 += 1
        End If

    End If


    If Weekday(strarray(x, 0)) = 3 Then

        If CInt(Left(strarray(x, 1), 2)) = 23 And strarray(x, 7) > 10 And strarray(x, 7)
< 100 Then

            Tue(0, tu11) = strarray(x, 7)
            tu11 += 1
        End If

        If CInt(Left(strarray(x, 1), 2)) = 0 And strarray(x, 7) > 10 And strarray(x, 7) <
100 Then

            Tue(1, tu0) = strarray(x, 7)
```

```
                tu0 += 1
            End If


            If CInt(Left(strarray(x, 1), 2)) = 1 And strarray(x, 7) > 10 And strarray(x, 7) <
100 Then

                Tue(2, tu1) = strarray(x, 7)
                tu1 += 1
            End If


            If CInt(Left(strarray(x, 1), 2)) = 2 And strarray(x, 7) > 10 And strarray(x, 7) <
100 Then

                Tue(3, tu2) = strarray(x, 7)
                tu2 += 1
            End If


            If CInt(Left(strarray(x, 1), 2)) = 3 And strarray(x, 7) > 10 And strarray(x, 7) <
100 Then

                Tue(4, tu3) = strarray(x, 7)
                tu3 += 1
            End If


            If CInt(Left(strarray(x, 1), 2)) = 4 And strarray(x, 7) > 10 And strarray(x, 7) <
100 Then

                Tue(5, tu4) = strarray(x, 7)
                tu4 += 1
            End If

        End If


        If Weekday(strarray(x, 0)) = 4 Then

            If CInt(Left(strarray(x, 1), 2)) = 23 And strarray(x, 7) > 10 And strarray(x, 7)
< 100 Then

                Wed(0, we11) = strarray(x, 7)
                we11 += 1
            End If


            If CInt(Left(strarray(x, 1), 2)) = 0 And strarray(x, 7) > 10 And strarray(x, 7) <
100 Then
```

```vb
            Wed(1, we0) = strarray(x, 7)
            we0 += 1
         End If

         If CInt(Left(strarray(x, 1), 2)) = 1 And strarray(x, 7) > 10 And strarray(x, 7) <
100 Then

            Wed(2, we1) = strarray(x, 7)
            we1 += 1
         End If

         If CInt(Left(strarray(x, 1), 2)) = 2 And strarray(x, 7) > 10 And strarray(x, 7) <
100 Then

            Wed(3, we2) = strarray(x, 7)
            we2 += 1
         End If

         If CInt(Left(strarray(x, 1), 2)) = 3 And strarray(x, 7) > 10 And strarray(x, 7) <
100 Then

            Wed(4, we3) = strarray(x, 7)
            we3 += 1
         End If

         If CInt(Left(strarray(x, 1), 2)) = 4 And strarray(x, 7) > 10 And strarray(x, 7) <
100 Then

            Wed(5, we4) = strarray(x, 7)
            we4 += 1
         End If

       End If
      End If
    End If
  Next




  For a = 0 To num_rows
    If Mon(0, a) > 10 And Mon(0, a) < 100 Then
      sum11 = sum11 + CInt(Mon(0, a))
    End If
```

```
Next

For a = 0 To num_rows
    If Mon(1, a) > 10 And Mon(1, a) < 100 Then
        sum0 = sum0 + CInt(Mon(1, a))
    End If
Next

For a = 0 To num_rows
    If Mon(2, a) > 10 And Mon(2, a) < 100 Then
        sum1 = sum1 + CInt(Mon(2, a))
    End If
Next

For a = 0 To num_rows
    If Mon(3, a) > 10 And Mon(3, a) < 100 Then
        sum2 = sum2 + CInt(Mon(3, a))
    End If
Next

For a = 0 To num_rows
    If Mon(4, a) > 10 And Mon(4, a) < 100 Then
        sum3 = sum3 + CInt(Mon(4, a))
    End If
Next

For a = 0 To num_rows
    If Mon(5, a) > 10 And Mon(5, a) < 100 Then
        sum4 = sum4 + CInt(Mon(5, a))
    End If
Next

avg1 = sum1 / (mo1)
avg2 = sum2 / (mo2)
avg3 = sum3 / (mo3)
avg4 = sum4 / (mo4)
avg0 = sum0 / (mo0)
avg11 = sum11 / (mo11)
```

```
        My.Computer.FileSystem.WriteAllText("D:\!Data\Dropbox\Adaptive
lighting\Thesis\calculation\output\Monday.csv", CStr(avg11) + vbCrLf + CStr(avg0) +
vbCrLf + CStr(avg1) + vbCrLf + CStr(avg2) + vbCrLf + CStr(avg3) + vbCrLf + CStr(avg4) +
vbCrLf + vbCrLf, True)



    sum1 = 0
    sum2 = 0
    sum3 = 0
    sum4 = 0
    sum11 = 0
    sum0 = 0



    For a = 0 To num_rows
       If Tue(0, a) > 10 And Tue(0, a) < 100 Then
          sum11 = sum11 + CInt(Tue(0, a))
       End If
    Next

    For a = 0 To num_rows
       If Tue(1, a) > 10 And Tue(1, a) < 100 Then
          sum0 = sum0 + CInt(Tue(1, a))
       End If
    Next

    For a = 0 To num_rows
       If Tue(2, a) > 10 And Tue(2, a) < 100 Then
          sum1 = sum1 + CInt(Tue(2, a))
       End If
    Next

    For a = 0 To num_rows
       If Tue(3, a) > 10 And Tue(3, a) < 100 Then
          sum2 = sum2 + CInt(Tue(3, a))
       End If
    Next

    For a = 0 To num_rows
       If Tue(4, a) > 10 And Tue(4, a) < 100 Then
```

```vbnet
            sum3 = sum3 + CInt(Tue(4, a))
        End If
    Next

    For a = 0 To num_rows
        If Tue(5, a) > 10 And Tue(5, a) < 100 Then
            sum4 = sum4 + CInt(Tue(5, a))
        End If
    Next

    avg1 = sum1 / (tu1)
    avg2 = sum2 / (tu2)
    avg3 = sum3 / (tu3)
    avg4 = sum4 / (tu4)
    avg0 = sum0 / (tu0)
    avg11 = sum11 / (tu11)

    My.Computer.FileSystem.WriteAllText("D:\!Data\Dropbox\Adaptive
lighting\Thesis\calculation\output\Tuesday.csv", CStr(avg11) + vbCrLf + CStr(avg0) +
vbCrLf + CStr(avg1) + vbCrLf + CStr(avg2) + vbCrLf + CStr(avg3) + vbCrLf + CStr(avg4) +
vbCrLf + vbCrLf, True)




    sum1 = 0
    sum2 = 0
    sum3 = 0
    sum4 = 0
    sum11 = 0
    sum0 = 0

    For a = 0 To num_rows
        If Wed(0, a) > 10 And Wed(0, a) < 100 Then
            sum11 = sum11 + CInt(Wed(0, a))
        End If
    Next

    For a = 0 To num_rows
        If Wed(1, a) > 10 And Wed(1, a) < 100 Then
```

```vbnet
        sum0 = sum0 + CInt(Wed(1, a))
      End If
   Next

   For a = 0 To num_rows
      If Wed(2, a) > 10 And Wed(2, a) < 100 Then
         sum1 = sum1 + CInt(Wed(2, a))
      End If
   Next

   For a = 0 To num_rows
      If Wed(3, a) > 10 And Wed(3, a) < 100 Then
         sum2 = sum2 + CInt(Wed(3, a))
      End If
   Next

   For a = 0 To num_rows
      If Wed(4, a) > 10 And Wed(4, a) < 100 Then
         sum3 = sum3 + CInt(Wed(4, a))
      End If
   Next

   For a = 0 To num_rows
      If Wed(5, a) > 10 And Wed(5, a) < 100 Then
         sum4 = sum4 + CInt(Wed(5, a))
      End If
   Next

   avg1 = sum1 / (we1)
   avg2 = sum2 / (we2)
   avg3 = sum3 / (we3)
   avg4 = sum4 / (we4)
   avg0 = sum0 / (we0)
   avg11 = sum11 / (we11)

   My.Computer.FileSystem.WriteAllText("D:\!Data\Dropbox\Adaptive
lighting\Thesis\calculation\output\Wednesday.csv", CStr(avg11) + vbCrLf + CStr(avg0) +
vbCrLf + CStr(avg1) + vbCrLf + CStr(avg2) + vbCrLf + CStr(avg3) + vbCrLf + CStr(avg4) +
vbCrLf + vbCrLf, True)
```

```
sum1 = 0
sum2 = 0
sum3 = 0
sum4 = 0
sum11 = 0
sum0 = 0


For a = 0 To num_rows
    If Thu(0, a) > 10 And Thu(0, a) < 100 Then
        sum11 = sum11 + CInt(Thu(0, a))
    End If
Next


For a = 0 To num_rows
    If Thu(1, a) > 10 And Thu(1, a) < 100 Then
        sum0 = sum0 + CInt(Thu(1, a))
    End If
Next


For a = 0 To num_rows
    If Thu(2, a) > 10 And Thu(2, a) < 100 Then
        sum1 = sum1 + CInt(Thu(2, a))
    End If
Next


For a = 0 To num_rows
    If Thu(3, a) > 10 And Thu(3, a) < 100 Then
        sum2 = sum2 + CInt(Thu(3, a))
    End If
Next


For a = 0 To num_rows
    If Thu(4, a) > 10 And Thu(4, a) < 100 Then
        sum3 = sum3 + CInt(Thu(4, a))
    End If
Next


For a = 0 To num_rows
    If Thu(5, a) > 10 And Thu(5, a) < 100 Then
        sum4 = sum4 + CInt(Thu(5, a))
```

```vb
      End If
   Next

   avg1 = sum1 / (th1)
   avg2 = sum2 / (th2)
   avg3 = sum3 / (th3)
   avg4 = sum4 / (th4)
   avg0 = sum0 / (th0)
   avg11 = sum11 / (th11)

   My.Computer.FileSystem.WriteAllText("D:\!Data\Dropbox\Adaptive
lighting\Thesis\calculation\output\Thursday.csv", CStr(avg11) + vbCrLf + CStr(avg0) +
vbCrLf + CStr(avg1) + vbCrLf + CStr(avg2) + vbCrLf + CStr(avg3) + vbCrLf + CStr(avg4) +
vbCrLf + vbCrLf, True)



   sum1 = 0
   sum2 = 0
   sum3 = 0
   sum4 = 0
   sum11 = 0
   sum0 = 0

   For a = 0 To num_rows
      If Fri(0, a) > 10 And Fri(0, a) < 100 Then
         sum11 = sum11 + CInt(Fri(0, a))
      End If
   Next

   For a = 0 To num_rows
      If Fri(1, a) > 10 And Fri(1, a) < 100 Then
         sum0 = sum0 + CInt(Fri(1, a))
      End If
   Next

   For a = 0 To num_rows
      If Fri(2, a) > 10 And Fri(2, a) < 100 Then
         sum1 = sum1 + CInt(Fri(2, a))
```

```
        End If
    Next

    For a = 0 To num_rows
        If Fri(3, a) > 10 And Fri(3, a) < 100 Then
            sum2 = sum2 + CInt(Fri(3, a))
        End If
    Next

    For a = 0 To num_rows
        If Fri(4, a) > 10 And Fri(4, a) < 100 Then
            sum3 = sum3 + CInt(Fri(4, a))
        End If
    Next

    For a = 0 To num_rows
        If Fri(5, a) > 10 And Fri(5, a) < 100 Then
            sum4 = sum4 + CInt(Fri(5, a))
        End If
    Next

    avg1 = sum1 / (fr1)
    avg2 = sum2 / (fr2)
    avg3 = sum3 / (fr3)
    avg4 = sum4 / (fr4)
    avg0 = sum0 / (fr0)
    avg11 = sum11 / (fr11)

    My.Computer.FileSystem.WriteAllText("D:\!Data\Dropbox\Adaptive
lighting\Thesis\calculation\output\Friday.csv", CStr(avg11) + vbCrLf + CStr(avg0) + vbCrLf
+ CStr(avg1) + vbCrLf + CStr(avg2) + vbCrLf + CStr(avg3) + vbCrLf + CStr(avg4) + vbCrLf
+ vbCrLf, True)




    sum1 = 0
    sum2 = 0
    sum3 = 0
    sum4 = 0
```

```
sum11 = 0
sum0 = 0

For a = 0 To num_rows
   If Sat(0, a) > 10 And Sat(0, a) < 100 Then
      sum11 = sum11 + CInt(Sat(0, a))
   End If
Next

For a = 0 To num_rows
   If Sat(1, a) > 10 And Sat(1, a) < 100 Then
      sum0 = sum0 + CInt(Sat(1, a))
   End If
Next

For a = 0 To num_rows
   If Sat(2, a) > 10 And Sat(2, a) < 100 Then
      sum1 = sum1 + CInt(Sat(2, a))
   End If
Next

For a = 0 To num_rows
   If Sat(3, a) > 10 And Sat(3, a) < 100 Then
      sum2 = sum2 + CInt(Sat(3, a))
   End If
Next

For a = 0 To num_rows
   If Sat(4, a) > 10 And Sat(4, a) < 100 Then
      sum3 = sum3 + CInt(Sat(4, a))
   End If
Next

For a = 0 To num_rows
   If Sat(5, a) > 10 And Sat(5, a) < 100 Then
      sum4 = sum4 + CInt(Sat(5, a))
   End If
Next

avg1 = sum1 / (sa1)
```

```
avg2 = sum2 / (sa2)
avg3 = sum3 / (sa3)
avg4 = sum4 / (sa4)
avg0 = sum0 / (sa0)
avg11 = sum11 / (sa11)

My.Computer.FileSystem.WriteAllText("D:\!Data\Dropbox\Adaptive
lighting\Thesis\calculation\output\Saturday.csv", CStr(avg11) + vbCrLf + CStr(avg0) +
vbCrLf + CStr(avg1) + vbCrLf + CStr(avg2) + vbCrLf + CStr(avg3) + vbCrLf + CStr(avg4) +
vbCrLf + vbCrLf, True)


sum1 = 0
sum2 = 0
sum3 = 0
sum4 = 0
sum11 = 0
sum0 = 0

For a = 0 To num_rows
    If Sun(0, a) > 10 And Sun(0, a) < 100 Then
        sum11 = sum11 + CInt(Sun(0, a))
    End If
Next

For a = 0 To num_rows
    If Sun(1, a) > 10 And Sun(1, a) < 100 Then
        sum0 = sum0 + CInt(Sun(1, a))
    End If
Next

For a = 0 To num_rows
    If Sun(2, a) > 10 And Sun(2, a) < 100 Then
        sum1 = sum1 + CInt(Sun(2, a))
    End If
Next

For a = 0 To num_rows
    If Sun(3, a) > 10 And Sun(3, a) < 100 Then
```

```vbnet
            sum2 = sum2 + CInt(Sun(3, a))
        End If
    Next


    For a = 0 To num_rows
        If Sun(4, a) > 10 And Sun(4, a) < 100 Then
            sum3 = sum3 + CInt(Sun(4, a))
        End If
    Next


    For a = 0 To num_rows
        If Sun(5, a) > 10 And Sun(5, a) < 100 Then
            sum4 = sum4 + CInt(Sun(5, a))
        End If
    Next


    avg1 = sum1 / (su1)
    avg2 = sum2 / (su2)
    avg3 = sum3 / (su3)
    avg4 = sum4 / (su4)
    avg0 = sum0 / (su0)
    avg11 = sum11 / (su11)


    My.Computer.FileSystem.WriteAllText("D:\!Data\Dropbox\Adaptive
lighting\Thesis\calculation\output\Sunday.csv", CStr(avg11) + vbCrLf + CStr(avg0) +
vbCrLf + CStr(avg1) + vbCrLf + CStr(avg2) + vbCrLf + CStr(avg3) + vbCrLf + CStr(avg4) +
vbCrLf + vbCrLf, True)




    For a = 0 To 5
        For b = 0 To num_rows


            If Mon(a, b) <> "" And Mon(a, b) > 10 And Mon(a, b) < 100 Then
                My.Computer.FileSystem.WriteAllText("D:\!Data\Dropbox\Adaptive
lighting\Thesis\calculation\output\Monday.csv", Mon(a, b) + ";", True)
            End If
```

```
        If Tue(a, b) <> "" And Tue(a, b) > 10 And Tue(a, b) < 100 Then
            My.Computer.FileSystem.WriteAllText("D:\!Data\Dropbox\Adaptive
lighting\Thesis\calculation\output\Tuesday.csv", Tue(a, b) + ";", True)
        End If


        If Wed(a, b) <> "" And Wed(a, b) > 10 And Wed(a, b) < 100 Then
            My.Computer.FileSystem.WriteAllText("D:\!Data\Dropbox\Adaptive
lighting\Thesis\calculation\output\Wednesday.csv", Wed(a, b) + ";", True)
        End If


        If Thu(a, b) <> "" And Thu(a, b) > 10 And Thu(a, b) < 100 Then
            My.Computer.FileSystem.WriteAllText("D:\!Data\Dropbox\Adaptive
lighting\Thesis\calculation\output\Thursday.csv", Thu(a, b) + ";", True)
        End If


        If Fri(a, b) <> "" And Fri(a, b) > 10 And Fri(a, b) < 100 Then
            My.Computer.FileSystem.WriteAllText("D:\!Data\Dropbox\Adaptive
lighting\Thesis\calculation\output\Friday.csv", Fri(a, b) + ";", True)
        End If


        If Sat(a, b) <> "" And Sat(a, b) > 10 And Sat(a, b) < 100 Then
            My.Computer.FileSystem.WriteAllText("D:\!Data\Dropbox\Adaptive
lighting\Thesis\calculation\output\Saturday.csv", Sat(a, b) + ";", True)
        End If


        If Sun(a, b) <> "" And Sun(a, b) > 10 And Sun(a, b) < 100 Then
            My.Computer.FileSystem.WriteAllText("D:\!Data\Dropbox\Adaptive
lighting\Thesis\calculation\output\Sunday.csv", Sun(a, b) + ";", True)
        End If

    Next

    My.Computer.FileSystem.WriteAllText("D:\!Data\Dropbox\Adaptive
lighting\Thesis\calculation\output\Monday.csv", vbCrLf, True)
    My.Computer.FileSystem.WriteAllText("D:\!Data\Dropbox\Adaptive
lighting\Thesis\calculation\output\Tuesday.csv", vbCrLf, True)
    My.Computer.FileSystem.WriteAllText("D:\!Data\Dropbox\Adaptive
lighting\Thesis\calculation\output\Wednesday.csv", vbCrLf, True)
    My.Computer.FileSystem.WriteAllText("D:\!Data\Dropbox\Adaptive
lighting\Thesis\calculation\output\Thursday.csv", vbCrLf, True)
```

```
        My.Computer.FileSystem.WriteAllText("D:\!Data\Dropbox\Adaptive
lighting\Thesis\calculation\output\Friday.csv", vbCrLf, True)
        My.Computer.FileSystem.WriteAllText("D:\!Data\Dropbox\Adaptive
lighting\Thesis\calculation\output\Saturday.csv", vbCrLf, True)
        My.Computer.FileSystem.WriteAllText("D:\!Data\Dropbox\Adaptive
lighting\Thesis\calculation\output\Sunday.csv", vbCrLf, True)

    Next

  End Sub

End Module
```

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List of abbreviations

EU	European Union
CO_2	Carbon dioxide
LED	Light Emitting Diode
ITS	Intelligent Transport Systems
LITES	Intelligent street lighting for energy saving
PLC	Power Line Communication
AADT	Annual Average Daily Traffic
ECMT	European Conference of Ministers of Transport
CIE	International commission on illumination
WIFI	Wireless Fidelity
FRC	Functional Road Class
CAS	Crash Analysis System
CEN	European Committee for Standardization
FCD	Floating Car Data
GPRS	General Packet Radio Service
HSPA	High Speed Packet Access
EDGE	Enhanced Data rates for GSM Evolution
LTE	Long Term Evolution