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Intelligent control system for street lighting

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Abstract

Street lighting is an important aspect of infrastructure in terms of both safety and comfort, but it also consumes a lot of energy. Unutilized light causes a waste of energy, and without any form of control for the street lighting, this problem will continue to increase along with the expansion of road networks. The aim of this master thesis has been to propose an intelligent control system for street lighting that can adapt to the velocity of individual road users, to investigate if this could provide ways to improve the efficiency of street lighting. Previous control approaches include systems based on ambient light intensity or presence of road users, but no studies were found in which illumination adapts to the velocity of road users. The project involved three main steps, including a literature study, a system implementation and an evaluation. In the proposed system, street lights cooperate to detect road users and calculate their velocities in order to adapt the illumination and make it follow their movement. It can be concluded from the evaluation results that the velocity readings help further optimize the illumination control in comparison with systems that do not consider velocity. The velocity readings make it possible to only illuminate the roadway in the direction of travel, while also adapting the distance of illumination to the recorded speed. The proposed control scheme is considered a viable solution for reducing the amount of unutilized light, consequently reducing the energy consumption of street lighting.

Keywords: Intelligent street lighting, energy conservation, adaptive control.
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1 Introduction

This chapter provides an introduction to this master thesis project. Section 1.1 presents relevant background information to motivate the investigated problem. Section 1.2 describes the overall aim of the project, and section 1.3 presents the scope set for the project. Section 1.4 states the research questions considered during the course of the project. Section 1.5 presents the outline of the report, and section 1.6 describes the company at which this project was carried out, along with another thesis performed in parallel.

1.1 Background and problem motivation

Street lighting is an important aspect of infrastructure in terms of both safety and comfort. With the continuous growth of society, cities are expanding and more and more people reside outside the immediate city centers. As cities grow larger, more street lighting is required to cover the extended networks of roads and walkways. Street lighting also consumes a lot of energy. While illumination technology is continuously being developed to become more and more energy efficient, street lighting altogether is an expense that cannot be overlooked. Previous studies have shown that general street lighting accounts for nearly 40% of the total consumption of electrical energy of a modern city [1].

On country roads and other more remote roads, there is usually very low traffic density during nighttime. Without any form of control, roads are illuminated for hours each night while there is only activity during a fraction of the time. This means that a lot of energy is wasted, which is a problem that will continue to increase along with the expansion of cities and road networks. A solution for this problem will be important for reaching a sustainable development of infrastructure in the future.

Previous research and development within the field of intelligent street lighting has shown the feasibility of reducing the energy consumption by introducing some form of intelligent control for the illumination. This approach benefits both the environmental impact and the operating costs of street lighting. Of the reviewed systems, some take the ambient light intensity into consideration [1], [2], [3], whereas others adapt to the presence of road users, i.e., vehicles or pedestrians [4], [5], [6], [7], [8], in order to utilize the street lighting more efficiently.
Within systems based on detection of road users, recurring approaches are to either illuminate predefined static sections upon detection [4], [5], or activate individual light sources to make the light follow the movement of road users more closely [6], [7], [8].

No previous studies have been found in which control systems for street lighting adapts the illumination to the velocity of road users. However, it is believed that the velocity could be an important factor in further optimizing the control of street lighting, in terms of being able to determine in which direction and for how long of a distance from a road user the illumination should be active.

This master thesis project will therefore consider the implementation and evaluation of a control system that takes the velocity of individual road users into consideration. It will be investigated whether knowing the velocity of movement will provide any obvious benefits and ways to improve the efficiency of street lighting.

1.2 **Overall aim**

The aim of this thesis project is to propose an intelligent control system for street lighting. The system should be able to detect how road users move past street lights and calculate their velocities in order to adapt the illumination to the movement of each individual road user. The system should make the light follow the movement of a road user and be able to predict how far ahead the road should be illuminated in order to achieve the required visibility for a given velocity.

A system with this functionality is expected to further optimize the illumination adaption and provide an improved experience as compared to other systems that do not take the velocity of individual road users into consideration. In order to create a system of this type, it will be important to determine how the different nodes, i.e., street lights, should interact with each other in order to provide the desired functionality.
1.3 **Scope**

The project will focus on the functionality of the control system and the cooperation between nodes. An approach for determining the velocity of road users will also be examined. The implementation will be limited to developing a prototype system that can be used to test and evaluate the functionality of the proposed control scheme on a small scale. An implementation with actual street lights will not be considered during the course of this project.

The system will mainly be designed considering roads with low traffic density, where control of individual street lights is believed to offer greater advantages. Hence, handling situations where several road users occupy the same space at the same time will not be prioritized.

1.4 **Detailed problem statement**

The objective of the project will be to implement and evaluate an intelligent control system for street lighting that can adapt to the movement of individual road users. More specifically, the following questions will be examined and answered during the course of the project:

- How should nodes interact with each other to provide the intended functionality?
- What data and calculations are required in order to make the system functional?
- Will the system be able to provide a lower energy consumption as compared to other systems?
- Will the system be responsive and reliable enough not to cause any distractions or uneven performance?
- How can road users be detected properly by the system in a real-world environment?

1.5 **Outline**

The report consists of a total of six chapters. Following this introductory chapter is a summary of the reviewed theoretical information in chapter 2. Chapter 3 presents the methodology used in the different stages of the thesis project. Chapter 4 gives a description of the implemented system functionality. Chapter 5 presents the evaluation of different aspects of the system, and chapter 6 presents the conclusions of the entire thesis.
Furthermore, there is a list of the references used throughout the project, followed by two appendices containing measurement results obtained during parts of the system evaluation.

1.6 Contributions

This master thesis project is performed in collaboration with Syntronic, at their head office located in Gävle, Sweden. Syntronic is a company specializing in technical solutions involving electronics, electromechanics and software [9]. Syntronic offers services within research and development, product introduction, production and aftermarket support in order to help customers create finished products from their ideas [10]. Founded in Sweden in 1983, Syntronic is now represented in six countries and has a total of 500 employees around the world [9].

This project is also carried out in parallel with another master thesis. While this project concentrates mainly on the system functionality, in terms of node cooperation, calculations, road user detection and illumination control, the other project, titled “Distributed communication for streetlight systems”, focuses on the networking and communication of the system [11].
2 Theory

This chapter presents a summary of the theoretical information reviewed during the literature study of this master thesis. Section 2.1 presents a summary of the reviewed related work. Section 2.2 presents information regarding stopping sight distance calculations. Section 2.3 describes the Internet of Things concept and section 2.4 gives an introduction to the advantages of light emitting diodes.

Street lighting has been shown to help reduce the number of traffic accidents and increase the experienced level of safety and comfort [8]. These are apparent benefits that likely mean that street lighting in its current sense will remain in use for a long time to come. As street lighting in general accounts for almost 40% of the total consumption of electrical energy in modern cities [1] and the amount of street lights are believed to increase by more than 300% during the next ten years, growing issues of both financial and environmental character are expected [8].

For these reasons, it is believed important to consider optimizing the usage of street lighting. The general purpose of an intelligent control system for street lighting is to adapt to different situations and provide road users with the required illumination. The reason for implementing control is to reduce the energy consumption, and thereby the environmental impact of the street lighting, which can also help increase the life time of the light sources [12]. Another advantage of adaptive control is that it helps minimize light pollution, which is an issue that can be of concern to the wellbeing of both people and animals [13].

Conventional approaches to street light control are to either use a clock and calendar combination or use sensors to monitor the ambient light in order to determine when the street lights should switch on and off. This means that the street lights are active even if no road users are utilizing the light, causing unnecessary energy consumption. [8] A common approach in modern control systems for street lighting is situation-based control, where real-time data regarding the current traffic flow is used to determine the required illumination intensity [5], [12].
Some systems also consider dimming the lights in relation to the expected traffic density in order to conserve energy. This could however be considered to counteract the original purpose of the street lighting. Reducing the light intensity or switching the street lights off altogether during time intervals when low traffic density is expected decreases the visibility, making it more difficult to navigate the road and detect possible obstacles. This could instead lead to an increased number of accidents during these time intervals. [8]

2.1 Related work

As part of the preparation for this master thesis project, a number of scientific articles describing related work were reviewed. The following sections describe the reviewed articles and present some of the key components of the presented systems. Section 2.1.1 presents systems using light based control, whereas section 2.1.2 presents systems using detection based control. Section 2.1.3 presents a system selected for comparison with the system proposed in this master thesis, and section 2.1.4 gives a short analysis of the reviewed systems.

2.1.1 Light based control

Of the reviewed articles, some describe control systems in which the street lighting adapts to the intensity of the ambient light.

One of these articles describes a system which adjusts the intensity of the illumination in accordance with the measured ambient light in order to provide an even light intensity. The system is designed for use in a parking lot, and implements separate control for each street light, issued by a central device. The system does not incorporate any form of road user detection, but mentions a concept referred to as train of light as a consideration for future work. [1]

Another system is designed to switch every other light source off when the ambient light is considered bright enough. In this system, nodes are in charge of groups of several street lights. The nodes monitor the ambient light intensity, and when it is above a certain level every other street light is switched off in order to reduce the energy consumption. The same principle is applied during specific time intervals when low traffic density is expected. [2]
A third reviewed article describes a control system which adjusts the intensity of the street lights according to calculated sunrise and sunset times. The system utilizes a central control device which in turn is in control of a number of system nodes that each is responsible for its own group of street lights. [3]

2.1.2 Detection based control

Other reviewed articles present systems based on road user detection, which are described below.

One of these articles proposes a system where, upon detection of movement, predefined sections of the road are illuminated in order to provide proper visibility for the road users. If no movement is detected, the illumination is dimmed in order to reduce the energy consumption. The system is controlled by a central device that determines the behavior of all light sources. [4]

In another system, movement detection is used to always keep the street light closest to a moving road user switched on, while all of the remaining lights are switched off. Infrared (IR) sensors located in-between the street lights are used to detect when a road user moves from one light to another. When a road user is detected by a sensor, the two street lights on either side switch states, with the intention of always keeping the street light closest to the road user on. A central control device is used to process the sensor readouts and realize the control for several light sources. The article does however not describe what type of IR sensor that is used for detecting road users. [6]

A third reviewed system is also based on a central control device. Here, each street light is a system node equipped with sensors to collect relevant information, including a passive infrared (PIR) sensor, used to detect the presence of road users, and a phototransistor used to measure the ambient light intensity. When a node detects the presence of a road user, it switches its light source on if the measured ambient light is below a predefined threshold value. The light source then remains active until a preset time interval has passed. After this, the node resets and awaits the detection of another road user. [7]
Furthermore, another study presents a system which combines a PIR sensor and an electromagnetic Doppler effect sensor to detect vehicles. This study concludes that the examined PIR sensor was sensitive to changes in the ambient temperature and exposure to direct sunlight, causing issues with false detections. The Doppler effect sensor was however not affected by temperature changes or exposure to sunlight, and in turn produced less false detections. Therefore, the study proposes combining the two sensors in order to reduce the number of false detections to a minimum. [14]

2.1.3 Compared study

One of the reviewed studies has been selected for comparison with the system proposed in this project. The study presents a system designed to adapt the street lighting to the movement of individual road users. The system is decentralized and utilizes a short-range wireless network in order to make it possible for the nodes to cooperate and produce the required illumination. Each node in the system is uniquely identified and programmed with information of its location. [8]

The study does not consider the actual sensors to be used to detect road users, but assumes an approach that makes it possible to differentiate between pedestrians and vehicles in order to provide different illumination schemes. The system is designed to illuminate a segment of fixed length around each road user. For a pedestrian, the illuminated segment is 150 m in each direction, with a descending intensity further away from the point of detection, whereas the illuminated segment for a vehicle is 100 m in each direction, with full light intensity for the entire segment. The reason for illuminating the road in both directions from a road user is mentioned being that the system does not implement any means for detecting in which direction a road user is moving. [8]

The described system is designed for use with LED light sources. For the purpose of evaluation, it is assumed that each street light is equipped with a 25 W LED light source and that the street lights are located 30 m apart. The results of the evaluation indicate that the system consumes between 2 and 55% of the energy required by a comparable state-of-the-art system, and as little as 1 to 2% of the energy consumed by a conventional system where the street lights are kept on during all hours in which the system is active. [8] For this reason, this system has been selected for comparison in order to evaluate the system proposed in this master thesis.
2.1.4 Analysis

None of the reviewed articles mentions an approach that considers the velocity of individual road users when adapting the illumination. Whereas [8] considers the speed-limit of a road as a way to predict the required distance of illumination, it does not consider the direction of movement and has no way of adapting if a road user would be traveling above or below the given speed-limit [8]. A road user traveling at a lower speed might not require the same distance of illuminated road, whereas emergency vehicles could require travelling at higher speeds than other road users, hence requiring a longer distance of illumination.

Several of the reviewed studies describe systems that implement some form of centralized control [1], [3], [4], [6], [7]. For the purpose of this project, it is however considered to implement nodes that can make decisions on their own and cooperate to realize the control. By doing this, it is believed that less data will have to be sent through the network, and that separate parts of the system could work independently, without having to interfere with each other.

Of the reviewed studies, some also describe approaches for monitoring the health and operation of light sources [1], [3], [6], [7], [14], as well as strategies for dimming light sources [1], [3], [4], [8], which are areas not considered in this thesis project. Instead, as mentioned in chapter 1, this project will focus on the implementation and evaluation of a system that can adapt the street lighting to the movement and velocity of individual road users.

2.2 Stopping sight distance

To make it possible to adapt the distance of illuminated road to the velocity of a road user, it will be of importance to consider the required visible distance. This is of particular importance considering vehicles travelling at high speeds, as drivers should be able to detect any obstacles in the road in order to avoid potential collisions. The stopping sight distance is the sum of the reaction distance and the braking distance, which is the recommended minimum visible distance required to be able to detect a stationary obstacle and decelerate to a stop well in time before reaching the obstacle [15].
A study on the topic of determining stopping sight distances has been considered in relation to the intent of making it possible to adapt the illumination distance to the velocity of individual road users. The study recommends the mathematical model shown in Eq. (1) for calculating the stopping sight distance \( SSD \), where the two addends are the reaction distance and the braking distance. In this model, \( V \) is the initial speed of the road user in km/h, \( t \) is the reaction time in s, and \( a \) is the deceleration rate in m/s\(^2\) achieved when braking. [15]

\[
SSD = 0.278Vt + 0.039V^2/a
\]  

(1)

The report proposes the use of \( t = 2.5 \) s and \( a = 3.4 \) m/s\(^2\), as these values are well within reason for the majority of drivers and vehicles. It is also mentioned that the model is based on drivers, vehicles and road surfaces below average standards, meaning that the model would provide a substantial safety margin in most cases. [15]

The concept of stopping sight distance is generally used when designing and constructing roads [15]. However, for the purposes of this project, it is considered suitable for making it possible to determine the distance of illumination required by road users.

Although the reviewed study is nearly 20 years old, the results are still considered valid. What has to be taken into consideration is that there are a large number of older vehicles in use, meaning that any advantages presented by modern vehicular technology cannot be considered if the system should be made suitable for all road users.

2.3 Internet of Things

In general, Internet of Things (IoT) refers to the concept of incorporating the capability of computation and networking into ordinary objects in order to open up new ways of information exchange and interaction. By including these capabilities into devices not normally capable of decision making or communication, functionality otherwise not possible can be developed [16].
IoT systems for traffic monitoring and management are emerging as part of the smart city concept. The purpose of these systems is to improve traffic flow and reduce the environmental impact of transportation in general. By adapting the behavior of control systems to external events, such as changes in the surrounding environment or the actions of people, more optimized solutions can be offered. [16]

As IoT systems become a more natural part of people's everyday lives, there is also an increased concern for possible integrity violations. With systems that collect and utilize data regarding people's movement and behavior, there is an inevitable risk that an unauthorized party could gain access to the data. Issues of this type can partially be avoided by not collecting any type of personal data. However, it is important to keep in mind that seemingly harmless information could still be associated with specific persons or events if combined with data from other systems. [16]

2.4 LED technology

The development of the light emitting diode (LED) technology has resulted in LEDs being widely used in a variety of everyday applications and becoming more and more prominent within general illumination. White LEDs can produce light with an intensity and color temperature that closely resemble the properties of natural light, making them particularly suitable for the purpose of illumination. [13]

As LED light sources are more energy efficient and have a longer lifetime as compared to their conventional counterparts, they are considered an undeniable replacement for older technology in the course of time. Further advantages of LED light sources are that they offer fast switching times and easily can be dimmed, while also being less harmful to the environment regarding production. In general, LEDs come at a higher purchase cost than corresponding conventional light sources, but as they have a longer expected life time and consumes less energy, the overall cost of an LED light source is considered significantly lower. [13]
The above mentioned properties are considered to make LED light sources suitable candidates for the implementation of the proposed system for adaptive street lighting. It is believed that fast switching times will be of importance for being able to make a system of this type perform as intended. The fact that LED technology helps to reduce the energy consumption and operating costs as compared to other alternatives is also believed to be important for the overall efficiency of the proposed system.
3 Methodology

This chapter presents the methodology applied during the course of this master thesis. Section 3.1 presents the approach for the initial literature study and section 3.2 describes the system implementation. Section 3.3 presents the procedure of evaluating the implemented system.

3.1 Literature study

A literature study was conducted in order to gain insight into some existing systems for intelligent street lighting. In order to make a scientific contribution and aid further development within the field, it was important to consider previous research and development. A number of scientific articles were reviewed in order to determine what has been investigated previously and what areas remain unexamined.

Furthermore, some concepts related to the intended system were also reviewed. This helped gain additional knowledge considered important to the project as a whole. The information was obtained from scientific articles, technical reports and books. All of the information gathered during the literature study is summarized in chapter 2.

When reviewing literature it is important to have a critical approach towards available sources. The literature study strived to only include what is considered reliable and relevant references in order to obtain correct and useful information.

3.2 System implementation

When implementing the system functionality, the first step was to specify a set of requirements for the system. These requirements include the responsibilities of the system nodes, how nodes should be able to interact with each other and how the intended system should function as a whole. The requirement specification is presented in section 4.1.
As mentioned in section 2.1, it has not been considered to investigate functionality that has already been implemented and tested in a variety of other studies. Instead, the main focus has been put towards investigating a new approach for adopting street lighting to individual road users. This functionality could in turn potentially be added to other systems or extended with more functionality.

The actual implementation was carried out in small steps, implementing one new feature at a time and continuously performing tests along the way. The reason for this was to facilitate troubleshooting and quickly discover potential problems. In some instances, this approach could be considered somewhat time consuming, but it is also believed to help reducing the risk for any issues being left unnoticed.

As mentioned in section 1.6, this master thesis was performed in parallel with another thesis project. Potential problems could occur if the two separate implementations would not be compatible, meaning that extra caution had to be taken along the way of the implementation. The implementation of this project was carried out with the contents of the other project in mind, in order to facilitate the process of combining the two implementations before testing and evaluating the complete system.

### 3.3 Evaluation procedure

When the implementation had been completed, the entire system was evaluated in order to verify that it was functioning as intended and to examine its performance.

The first step of the evaluation procedure was to perform a number of fundamental tests of the system functionality. This was done using the prototype system described in section 4.2. The purpose of these tests was to verify that nodes could detect the presence of objects and send out messages containing the corresponding data, and that the data could be received by other nodes in order to make the system behave as expected when an object was moved past system nodes. These tests are described further, along with the obtained results, in section 5.1.
Another part of the evaluation procedure was to investigate the energy efficiency of the proposed system. This was done by comparing the proposed system to the system described in [8], which as mentioned in section 2.1.3 is shown to consume less energy than other control systems for street lighting. Comparisons were performed both in regard to the static behavior of the other system, and based on the assumption that the other system would be able to adapt to different velocities. The comparison, which is further described in section 5.2, was then used to determine whether the system proposed in this master thesis theoretically would consume less energy.

Furthermore, it was examined if the two different node configurations, described in section 4.4, would have a noticeable impact on the system performance in terms of measuring the time interval between two detections. In order to find out if communication delays or other time costs within the created program would affect the time measurements, time intervals of a predetermined length captured using the two configurations were compared. Rather large sets of measurements were performed in order to obtain a more reliable result, since the nodes had to be manually manipulated in order to start and stop the capture of each time interval. This test is described more in detail in section 5.3.

The final test of the evaluation procedure involved road user detection in a real-world environment. It was investigated how well a system node could detect passing road users utilizing a selected sensor, described in section 4.4. The test involved detection of road users in the form of vehicles, pedestrians and cyclists, and it was investigated how well these road users could be detected and if erroneous detections would occur. A possible weakness of this test is that only a limited amount of detections were performed, hence these results consist of rather small sets of data. This test is described further in section 5.4.
4 Implementation

This chapter describes the implementation of the street lighting control system. Section 4.1 presents the requirements stated for the system, and section 4.2 gives an overview of the system structure and functionality. Section 4.3 provides a more detailed description on how system nodes cooperate in order to realize the control. Section 4.4 describes the different approaches for detecting road users, and section 4.5 presents the calculations performed by the system nodes.

4.1 Requirement specification

In order to aid the process of creating the control system, a number of requirements were established prior to the actual implementation.

- Each system node should be able to detect when a road user moves past it, to make it possible to determine the position and velocity of the road user. Nodes should then cooperate in order to adapt the illumination to a moving road user in order to offer a more optimized control as compared to previously proposed solutions.

- The system should be able to adapt the distance of illumination to the velocity of a road user. In relation to the required stopping sight distance described in section 2.2, the visible distance required in order to avoid a potential collision is dependent on the velocity. The system should also include the possibility to utilize a fixed distance of illumination.

- The system should be completely freestanding and independent, as to not require any external input from other systems, such as mobile phones or positioning systems.

- The system should not depend on a central control device. Instead, all system nodes should be equivalent in terms of their decisive power, meaning that no node should be superior or inferior to another. Each individual node should utilize the information made available by other nodes in order to determine its required actions.
In order to achieve a system of this type, it is also required that the nodes are able to form a network that makes it possible to communicate and exchange necessary information. The communication should be as fast as possible, to not considerably affect the calculations to be performed by the system. This means that detections of road users should be reported to other system nodes with as short delays as possible, as the velocity calculations will be directly dependent on the recorded time. The networking and communication of the system is not covered in this thesis project, but is described in detail in [11].

4.2 System overview

In the proposed system, each street light constitutes a separate node that is responsible for detecting passing road users, sharing information, and controlling its own light source. The control is performed in cooperation with the neighboring nodes in order to determine when a road user is present and what actions are required.

The system prototype includes five nodes which each consist of a Zolertia RE-Mote and the sensors used for detecting road users, as described more in detail in section 4.4. The Zolertia RE-Mote is a development platform based on a 32 MHz ARM Cortex-M3 processor. The platform includes 512 kB of flash memory and 32 kB of RAM and has three integrated 12-bit ADCs. It also includes two RF transceivers, one for 2.4 GHz and one for 863-950 MHz communication. [17]

The general idea of the control system is based on creating dynamic groups of nodes that carry the generated information of detected road users. From here on, these groups of nodes are referred to as road user sections. A road user section is created whenever a system node detects a road user and transmits a message to its neighboring nodes. The road user section then follows the movement of the road user by being relocated every time a new node detects the road user, and the available information is used by each included node in order to determine the required actions.
A road user section is not explicitly tied to a specific set of nodes, but is merely a result of the fact that messages are distributed to a finite number of nodes surrounding a road user. The road user section includes the node that detects the road user, as well as a predefined number of nodes in each direction from this node. Within each road user section, a number of nodes will switch their light sources on in order to provide the road user with proper illumination. The number of active light sources is determined by the illumination distance.

The illumination distance can either be a fixed number of nodes or a dynamic number based on the velocity of the road user. The velocity is also used to determine in which direction the illuminated distance is required. If the direction of movement is known, the road will only be illuminated in the same direction, whereas an unknown velocity will result in the road being illuminated in each direction from the road user.

Nodes are given unique identification (ID) numbers that are used to tell them apart and to know how they are located in relation to each other along a road. The velocity of a detected road user is represented as positive in the direction of increasing ID numbers and negative in the direction of decreasing ID numbers.

Figure 1 visualizes how the road user section and the illuminated distance change as a road user moves. This example shows a road user section with a length of three nodes in each direction from the detecting node and a fixed illumination distance of two nodes. The road user section is indicated by the red dotted line, whereas the filled-in squares represent active street lights.

In Figure 1 a), a road user is detected at node five, but its velocity has not been established. This means the road will be illuminated in both directions from the point of detection. The generated road user section includes nodes two to eight.

In Figure 1 b), the road user has moved from node five to node six, and as a result of a detection at node six, the road user’s velocity is now known. Upon detection, the road user section is relocated to include nodes three to nine, and the light sources in the opposite direction of the recorded velocity are switched off.
Figure 1 c) shows a possible scenario where the road user has changed direction after detection at node six, and been detected again moving in the opposite direction. The road user section still includes the same nodes as in case b), while the illumination is instead active in the opposite direction as the velocity has changed from positive to negative.

Figure 1: Visualization of the road user section and illuminated distance in different scenarios: a) detection at node five, unknown velocity, b) detection at node six, positive velocity, c) detection at node six, negative velocity. Each square represents a street light node, where the filled-in ones are active.

### 4.3 Node cooperation

The system nodes cooperate in order to provide control based on the location and velocity of a road user. When a node detects a road user, the nodes within the specified road user section are provided with the required information to be able to determine their respective actions. This information includes the ID of the detecting node, the ID of the node the message was forwarded from, the velocity of the road user and the corresponding illumination distance.

When a node receives a message, it will first evaluate if it is within the required illumination distance. If not, it is immediately established that the received message should not influence the current state of the node, and the message is not further acted upon. If the node is within the required illumination distance, it proceeds to evaluate the velocity specified in the message in order to determine its further actions.

The message either contains a known velocity or has the velocity set to zero, indicating that it has not been calculated and is still unknown. In the case the message does not contain a known velocity, the node will switch its light source on as it is unable to determine if the detected road user is moving toward it or not. Furthermore, it is determined if the received message was sent from a neighbor with a lower or a higher ID number than the node in question, as this is used to indicate where the road user was detected.
If the received message originates from one of the neighboring nodes, the node will also start to measure the time it takes the road user to travel from the neighboring node to the current node. This time is then used to calculate the velocity of the road user once it moves past the node, which is described further in section 4.5. The above described procedure, executed when receiving a message containing an unknown velocity, is also depicted in the flowchart of Figure 2.

![Flowchart of the procedure executed after receiving a message containing an unknown velocity.](image)

**Figure 2**: Flowchart of the procedure executed after receiving a message containing an unknown velocity.

If a received message instead contains a known velocity, the node knows whether or not its light source should be switched on. Provided the node is within the required illumination distance, as mentioned above, it will first be determined whether the received message was sent from the neighbor with a higher or lower ID than the current node.
It will then be evaluated if the road user is moving toward the node or not. As mentioned in section 4.2, the velocity is specified in relation to the ID numbers of the system nodes. For instance, this means that a road user detected at a node with a lower ID having a positive velocity is moving toward the node in question, whereas a negative velocity instead means the road user is moving away from the node.

If the road user is moving toward the node, an indication of an approaching road user being detected at a neighboring node will be set. If the message also originates from one of the neighboring nodes, the node will start measuring the time it takes the road user to reach it, to be able to calculate the velocity. If the road user on the other hand is moving away from the node, the indications of an approaching road user will be reset, awaiting a new message. This procedure, executed after receiving a message with a known velocity, is also shown below in the flowchart of Figure 3.

When a message is received, the current time is also captured to be able to generate a timeout if no new messages are received within a certain time interval. The purpose of this is to make sure no nodes keep their light sources switched on when a road user leaves the system. When this timer is active and the set interval has passed, the node resets any ongoing measurements and indications of detected road users.

A node’s light source is controlled using three bits that indicate if a road user has been detected at the current node or a node with either a higher or lower ID. Whenever any one of these bits is high, the light source is switched on and remains in this state until either a new message is received or the above described timeout is triggered.
4.4 Road user detection

The capability of detecting passing road users is essential to the functionality of the proposed system. In order to make this possible with the prototype, IR distance sensors of the model Sharp GP2Y0A21YK0F have been used. This type of sensor consists of an IR diode and a position sensitive detector, and utilizes triangulation in order to determine the distance to an object within its detection range. Objects can be detected within a range of 10 to 80 cm, and the output is an analog voltage corresponding to the measured distance. [18]
Furthermore, a Sharp GP2Y0A710K0F IR distance sensor has also been considered for the purpose of evaluating detection of road users in a real-world environment, which is described in section 5.4. This sensor is very similar to the above mentioned GP2Y0A21YK0F, as it uses the same detection technique. The major difference between the two models is that the GP2Y0A710K0F has a significantly longer range of detection, covering a distance of 100 to 550 cm. [19]

The sensors are used to monitor sections perpendicular to the road in front of each system node in order to determine when a road user passes by. This is depicted in Figure 4, where the red dotted lines show the sections monitored by each system node. For this particular application, the actual distance measurements have not been considered. The sensors are merely used as a means of detecting whether or not a road user is present in front of a node, and the placement from side to side on the road surface does not affect the system behavior.

![Figure 4: Sections monitored by each system node.](image)

In the program created for the system nodes, the actual detection has been addressed by comparing the sensor output to a threshold value, to determine when an object is present in front of the sensor. This threshold value is slightly higher than the value expected when no object is present within the detection range of the sensor. Rising and falling edges in the state of a sensor reading are distinguished by comparing the current state of the sensor to its previous state.

Two different approaches for road user detection have been considered when implementing the prototype, where nodes include either one or two IR sensors. The functionality of these two configurations is described below in section 4.4.1 and 4.4.2 respectively.
4.4.1 One sensor per node

With the configuration using one sensor per node, a node monitors the state of its connected sensor in order to determine whether or not an object is present. Once a rising edge occurs, indicating that an object has just been detected, the node reviews its current operational state, which is based on information previously received from neighboring nodes.

There are two possible outcomes of this situation. If the node is not currently capturing the time for a road user approaching from a neighboring node, this means that the detected road user has just entered the system. When using one sensor per node, the node itself cannot determine the velocity of the road user. In this case, the velocity is set to zero, indicating that it is unknown.

If the node is instead capturing the time interval of a road user that is approaching from a neighboring node, it will record the time passed and use this to calculate the velocity of the road user, which is described further in section 4.5. The functionality for detection using one sensor is also depicted in the flowchart of Figure 5.

![Flowchart of the functionality for detection using one sensor.](image-url)
After detecting a road user and performing the required actions, two bits are set high, where one is used to indicate a successful detection and the other to indicate that a road user is present at the current node.

4.4.2 Two sensors per node

If instead using two sensors per node, the process of detecting a road user is slightly more involved. When a rising edge is detected in the state of one of the two sensors and no detection has already been initiated by the same sensor, it is evaluated if the opposite sensor has already started detecting a road user. If this is the case, the node will record the time passed between the detections. This time interval is then used in order to calculate the velocity of the road user. Two bits are also set to indicate a successful detection and the presence of a road user at the current node.

If no detection has been started by the opposite sensor, the node will capture the current time as the start of the detection and set a bit that indicates an ongoing detection initiated by the sensor in question. In the case that the node is also capturing the time for an approaching road user, this is where the time interval is recorded in order to calculate the velocity over the distance between two nodes. The above described functionality for detecting road users using two sensors is also shown below in the flowchart of Figure 6.

When a falling edge is detected in the state of a sensor, meaning that a road user has left the region visible to the sensor, a bit is set high in order to indicate that a detection has ended. When these bits are high for both of the sensors, any indications of an ongoing detection is reset in order to make sure a new detection can be started.

The above mentioned procedure is the same for both of the two sensors, with the exception that the velocity is represented as positive in the direction of increasing node ID numbers and negative in the other, as previously described in section 4.2. Whether a node uses one or two sensors, a detection of a road user always results in the generation of a new message to be transmitted to the corresponding road user section.
Figure 6: Flowchart of the functionality for detection using two sensors.

4.5 Calculations

As mentioned previously, the system measures the time it takes a road user to travel between nodes. A node captures the time from the point when receiving a message indicating that a neighboring node has detected a road user, to the point when the node in question detects the road user. The velocity is then calculated based on the captured time interval and a predefined value for the distance between the nodes.

A node using two sensors also calculates the velocity of a road user at the moment of detection using the same principle. When a road user is detected at one of the two sensors, a new time interval is started. Once the road user is detected by the opposite sensor, the time interval is captured. The velocity is then calculated based on a predefined value for the spacing in-between the sensors and the captured time interval.

Once a successful detection has been performed and the velocity of the road user calculated, the node will assemble the message to be sent out within the road user section. If the system has been configured to use a dynamic illumination distance, this step also includes determining the illumination distance corresponding to the road user velocity.
The minimum required illumination distance is calculated using Eq. (1), shown in section 2.2. If the minimum required distance would be less than the distance between two nodes, it is increased to include one more street light in order to not only switch on the light the road user is currently passing.

The required distance is then divided by the node distance in order to get the illumination distance expressed in the corresponding number of nodes. If there is a remainder of the division, the number of nodes for the illumination distance is increased by one in order to make sure the entire required distance is illuminated.

Before assembling the message, a final adjustment is performed. If the calculated illumination distance would be greater than or equal to the set length of the road user section, the illumination distance is set to one node less than the road user section. The reason for this is that nodes otherwise potentially could be left out of the road user section if a road user changes direction, meaning that it will not receive a new message and be left on until a timeout is generated.

After transmitting the generated message to the neighboring nodes, the timeout timer mentioned in section 4.3 is also reset in order to make sure the node will switch its light source off if the road user would leave the system and no new messages are received within a certain time.
5 Results

This chapter presents the results obtained when testing and evaluating the implemented control system. Section 5.1 describes the initial tests performed in order to verify the system functionality. Section 5.2 presents a comparison between the proposed system and another compared system, in terms of the expected energy consumption for different road user velocities. Section 5.3 presents a comparison between the two implemented node configurations in order to investigate possible time delays within the system, and section 5.4 describes the results obtained when detecting road users in a real-world environment.

5.1 Initial system tests

Prior to evaluating its performance, the implemented control system was tested in order to verify that it was functioning as intended. A number of fundamental tests were performed using the five prototype system nodes described in section 4.2. The implementation of this thesis project was combined with the implementation described in [11] to create a complete system.

The first test involved to investigate that a node could detect an object and in turn generate the expected message to be sent out and received by the neighboring nodes. This was verified to work as intended, where a node using only one sensor would generate a message containing an unknown velocity sent to its two nearest neighbors, whereas a node using two sensors could calculate the velocity of the passing object and include this in the message.

The second test included to examine that the neighboring nodes could use the received information and that the next node in line could start measuring the time interval required for the object to reach it and then capture the time interval and calculate the corresponding velocity. This was also verified to work as intended, and the next node in the direction of travel would successfully capture the time passed in-between the detections and calculate the corresponding velocity.
Finally, it was also established that the road user section and illumination distance would reposition as intended and follow the movement of the object. In order to perform this test using the five nodes, the road user section was set to a length of three nodes, while the illuminated distance was set to a fixed value of two nodes.

As mentioned above, using one sensor per node will result in an unknown velocity for the initial detection of an object. In this case, nodes within the illumination distance in both directions from the point of detection will switch their light sources on. Once a second detection is performed, the system knows in which direction the object is moving, and hence the light sources in the opposite direction are switched off. In the case of using two sensors per node, the velocity is determined immediately, and the light sources in the opposite direction will not be switched on. Both of these cases were verified to work as intended for an object being moved past the system nodes.

5.2 Energy consumption

In order to evaluate the efficiency of the proposed control system, estimations of the expected energy consumption were performed. The system described in [8] was selected for comparison since it, as mentioned in section 2.1.3, is shown to consume less energy than both conventional control systems and another comparable state-of-the-art control scheme. From here on, the control system presented in [8] is referred to as the compared system.

For the evaluation of the compared system, it is assumed that street lights are spaced 30 m apart, and that a road user traveling in a vehicle at a velocity of 50 km/h will require an illumination distance of 100 m [8]. In order to make the evaluation of the system proposed in this thesis project comparable, the same street light spacing and road user velocity are considered.

In the compared system, an illumination distance of 100 m corresponds to a total of seven active street lights, including the detecting street light and three additional street lights in each direction [8]. This is depicted in Figure 7 a) where node five detects a road user, resulting in an illuminated segment from node two to node eight.
For the proposed system, Eq. (1) gives a recommended minimum illumination distance of 63 m for a velocity of 50 km/h. According to the calculations described in section 4.5, using a distance of 30 m between the street lights, this corresponds to a total of four active street lights, including the detecting node and three additional nodes in the direction the road user is traveling. This illumination distance is shown in Figure 7 b), where nodes five to eight are active.

Comparing the above two cases, it is evident that the proposed system reduces the number of active street lights while still maintaining the same illuminated distance in front of the road user as the compared system. If utilizing the same number of street lights as in the case of the compared system, six street lights in front of the detecting street light could be illuminated by the proposed system. This would in turn correspond to road user velocities of between 88 and 99 km/h. This approach is shown in Figure 7 c).

As [8] does not mention how the illumination distance would change for other velocities than the fixed value of 50 km/h, it is assumed for the purpose of this evaluation that the compared system would adopt the same scheme as the system proposed in this thesis.

Based on this assumption, the graph of Figure 8 shows the theoretical number of active street lights required by the compared system (represented by the blue line) and the proposed system (represented by the red line), for velocities of between 0 and 150 km/h. As can be seen from the graph, the proposed system utilizes fewer street lights for every velocity. The difference in the amount of active street lights increases with increased velocity, as the compared system adds two new street lights for each step, whereas the proposed system adds one.
Figure 8: Graph showing the theoretical number of active street lights expected by the compared system (blue line) and the proposed system (red line) for road users traveling at different velocities.

5.3 Node configuration comparison

Another test was carried out in order to evaluate the performance of the two different node configurations described in chapter 4.4, where nodes include either one or two sensors. The test was performed in order to determine whether communication delays or other time costs within the created program would have a noticeable impact on the recorded time intervals. This was done by comparing the time intervals captured by two nodes equipped with one sensor each to the time intervals captured by a single node equipped with two sensors.

Time intervals of approximately two seconds were generated by manually manipulating the states of the sensors. Sets of 100 measurements were performed for each of the two node configurations. The obtained results are shown in Appendix A, where Table A.1 contains the time intervals recorded using two separate nodes equipped with one sensor each, and Table A.2 contains the time intervals recorded using one node equipped with two sensors. The mean values of each set of 100 measurements are 1989.1 and 1988.6 ms for the respective node configurations, which results in a difference of 0.5 ms.
5.4 Road user detection in a real-world environment

A number of test detections were performed in order to evaluate the performance of an IR sensor that could potentially be used in a real-world environment. The sensor in question is the Sharp GP2Y0A710K0F, which is described more in detail in section 4.4.

Detections were performed on road users in the form of vehicles, pedestrians and cyclists. All detections were performed with road users passing at a distance of approximately three meters from the sensor, moving perpendicularly to the direction of the sensor. The results of the detections are shown in Appendix B.

Table B.1 presents the results obtained when using the IR sensor to detect passing vehicles. Two sets of detections were performed, each including 20 vehicles, which are numbered in the first column. For the first set of detections, shown in the second column, the sensor was held at a height \((h)\) of approximately 80 cm. For the second set of detections, shown in the third column, the sensor was instead mounted to a fixed surface of the same height.

As can be seen from the values of Table B.1, the first set of detections contains several instances of vehicles generating multiple detections. For the set of 20 vehicles, six resulted two or more detections, corresponding to an error rate of 30%. For the second set of measurements, where the sensor was mounted to a fixed surface, the number of erroneous detections was reduced to one out of the 20 vehicles, or 5%.

The results obtained when detecting passing pedestrians are shown in Table B.2. For this test, two sets of detections were performed including 20 pedestrians each, with the sensor mounted to fixed surfaces of two different heights.

For the first set of detections, shown in the second column of Table B.2, the sensor was mounted at a height of 80 cm. As can be seen from this set, none of the pedestrians were detected more than once. For the second set of detections, the sensor was relocated to a height of 100 cm. The results of this set are shown in the third column, where it can be seen that two of the 20 detected pedestrians resulted in two detections each, giving an error rate of 10%.
Table B.3 shows the results obtained when detecting cyclists. Three sets of detections were performed, each including 20 cyclists. The sensor was mounted at heights of 70, 80 and 120 cm for the three different sets of detections. The resulting sets contain a large number of erroneous detections, where 10, 14 and 12 cyclists out of the three sets of 20 were detected multiple times. This corresponds to error rates of 50, 70 and 60% respectively.

During the course of performing the road user detections, no false detections were experienced when the sensor was mounted to a static object. However, if moving the sensor during measurement, several false detections were registered even if no objects were present within a distance well over the sensing range. Prior to performing the first set of detections, the sensor was tested at different distances in order to verify the specified range. A walking pedestrian could be detected at a distance of about 6.5 m, which is further than the specified range of 5.5 m.
6 Conclusions

This chapter presents the conclusions of this master thesis project. Section 6.1 gives some general conclusions of the project, followed by a short discussion of the evaluation results in section 6.2, and some suggestions for future development in section 6.3.

6.1 General conclusions

The primary aim of this master thesis is considered fulfilled, as the project has resulted in a control scheme with the basic functionality for making street lighting adapt to the movement of individual road users. The system is able to detect the presence of road users and calculate their velocities in order to make the light follow their movement. The system can either utilize a fixed illumination distance or base the illumination distance on the calculated speed of movement.

It is believed that a system in which the control is based on the velocity of road users will make it possible to provide more efficient control than systems only based on location detection, which is also indicated by the obtained evaluation results. The study has shown that this approach is viable, and it is considered a further step within the field of intelligent street lighting. The proposed approach is considered a way to reduce the problem of energy being wasted on unutilized illumination. This is believed to be important for reaching a sustainable development of infrastructure.

Apart from making the street lighting more energy efficient, a system of this type is also believed to provide an advantage regarding the safety and comfort experienced by road users. As the illumination follows the movement of individual road users, it is possible to see when other road users are approaching. Therefore, the proposed system is considered to provide road users with a visual aid that is not possible in conventional control schemes.
As mentioned in section 1.3, the proposed system is intended mainly for roads with relatively low traffic density. The main reason for this is that a control system of this type is believed to provide greater advantages in these areas, where most of the available light would not be utilized if the illumination would be kept on continuously. This type of control might not be suitable for roads with high traffic density, as street lights switching on and off very frequently could instead cause a disturbing effect for both road users and residents. For this reason, it is believed that another approach would have to be considered for these areas.

During the design and implementation of the proposed control system, it has been important to consider related ethical aspects. A system of this type, intended to be considered for future development of street lighting, can have an impact on public safety and comfort. Therefore, it is important that the proposed solution is able to provide the intended functionality without counteracting the original purpose of the street lighting. For this reason, any shortcomings with the system have been clarified and possible solutions discussed in section 6.3.

Integrity is another important aspect that was considered when designing the system as it is intended to be part of peoples’ everyday lives. As the system functionality is based on tracking the movement of road users, the system has been made completely freestanding to avoid collecting information from other systems, such as mobile phones, that could be directly associated with specific persons.

Presented below are the conclusions related to each of the five research questions stated in section 1.4:

- **How should nodes interact with each other to provide the intended functionality?**

In the proposed system, the nodes interact and cooperate by sharing information of detected road users. There is only interaction between nodes within each separate road user section, meaning that the entire system will not have to be aware of every detected road user. Instead, nodes are only given information regarding nearby road users that could influence their respective behavior. All system nodes are equal, meaning that no node can decide what another node should do. The actions of individual nodes are only based on the available information of nearby road users.
• What data and calculations are required in order to make the system functional?
The data required to make the proposed system functional includes the location and velocity of detected road users. The velocity makes it possible to know in which direction a road user is traveling, and the required illumination distance is calculated from the speed of movement. In combination with the location of the road user, each system node can determine its required actions. By measuring the time it takes a road user to travel a known distance, its velocity is calculated.

• Will the system be able to provide a lower energy consumption as compared to other systems?
As indicated by the evaluation results, the proposed control system is able to reduce the expected energy consumption from that of the compared system. The reason for this is that the added functionality of measuring the velocity of road users makes it possible to adapt the illumination to each specific case. This is discussed further in section 6.2.

• Will the system be responsive and reliable enough not to cause any distractions or uneven performance?
During the system evaluation, it was established that the system is responsive in terms of not introducing any noticeable delays as messages are passed along from node to node. It is also considered reliable, as no unexpected behavior was noticed. However, some issues arise due to the fact that the system is unable to distinguish road users from each other, which is further discussed in section 6.3.

• How can road users be detected properly by the system in a real-world environment?
The investigated approach of using IR distance sensors to realize point detection in front of the system nodes has proven satisfactory for detecting passing road users in order to calculate their velocities. However, an important part of future development is to further investigate if this approach would be suitable in a real-world implementation, or if possible complements or a completely different strategy would be preferred, as is discussed more in section 6.3.
6.2 Evaluation discussion

An important point of interest was to investigate whether knowing the velocity of a road user would provide any significant benefits regarding the energy efficiency of the street lighting. The obtained results conform to the initial expectations that the velocity readings would in fact help to further optimize the illumination control in comparison with systems that do not consider the velocity of road users. As can be concluded from the evaluation results, it is possible to reduce the expected energy consumption by adapting the illumination to the velocity of individual road users.

Both the direction and speed of movement are considered important for adapting the illumination to the movement of individual road users. By knowing the direction of movement, it is possible to only illuminate the roadway in the same direction, in essence reducing the energy consumption to almost half of what would otherwise be required. From knowing the speed of movement, the system is able to further adapt and only provide the required illumination distance.

It can be concluded that knowing the direction of movement has the largest impact on the expected energy consumption, whereas the calculated speed offers a way to further reduce the energy consumption when road users travel at different speeds. Instead of having a fixed illumination distance, the system can adapt to each specific case.

As mentioned in section 2.1.3, the compared system presented in [8] is expected to consume between 2 and 55% of the energy required by a comparable state-of-the-art system. Based on the results shown in section 5.2, the system proposed in this thesis is considered able to reduce the energy consumption to near half of the compared system. However, this comparison only gives an indication of the expected energy consumption. In order to get a more accurate view of the system efficiency, it would either have to be simulated or tested in a real-world setting.

By comparing time intervals captured using the two implemented node configurations, it was also evaluated if any time costs within the implemented control program would affect the velocity calculations. As indicated by the results of this evaluation step, there is no apparent difference between the two sets of captured time intervals, suggesting that no significant delays are introduced by the system functionality.
While evaluating the performance of the IR sensor for detecting passing road users in a real-world environment, it was found that both vehicles and pedestrians could be detected in a satisfactory manner. When on the other hand detecting cyclists, the results were consistently erroneous and are not considered adequate for the purpose of detection.

Due to the limited number of detections performed, it is difficult to draw any objective conclusions regarding the sensor’s performance in a real-world environment. A larger set of measurements would have been preferred to get a more representative view, but was not possible due to time constraints.

### 6.3 Future development

An apparent limitation of the proposed system is that it cannot distinguish between individual road users upon detection. This means the system could have an unwanted behavior in situations where several road users are moving in close proximity to each other. The main issue with this is that the system potentially could switch light sources off too early.

If two or more road users are traveling in close proximity, between two system nodes, the system cannot know how many road users to expect before switching off the light source behind a detected road user. In its current state, the system will simply switch the previous light source off after detecting one of the road users at the next node.

The same problem will also occur if a new road user enters the system in front of an already detected road user. In this case, the system will interpret this situation as if the previously detected road user has reached the next street light, when it in fact is another road user. This will cause the node behind it, where the previously detected road user might still be located, to switch its light source off.
During the implementation of the proposed system, it was considered adding counters to keep track of the number of road users approaching from each direction. This could potentially help solve the problem of missing any road users that have already been detected by waiting for the corresponding number of road users to pass a node before allowing a light source to be switched off. However, as road users can both enter and leave the system at any point in time, part of the problem would still remain. For this reason, it would be recommended spending more time solving this issue as part of any future development of the system.

The chosen sensing strategy gives the advantage of being able to detect when a road user moves past a certain section of road directly in front of each street light. This means it is easy to calculate the velocity of a road user by capturing the time it takes to travel a known distance, which is important for the functionality of the proposed system. However, this approach poses other issues, including the fact that it is not possible to know if a road user is present in the proximity of a street light.

This essentially means the system will not be able to provide any illumination before a road user has passed at least one of the system nodes. It is also not possible to determine whether a road user that stops being detected has left the system, or if it simply has stopped in-between two street lights. By further investigating solutions for these issues, it is believed that the system performance could be enhanced, providing a more comfortable experience for road users.

A possible solution to these problems could be to include PIR sensors in the system nodes. Whereas the currently included IR distance sensors are used to detect road users at specific points to calculate their velocities, the PIR sensors would instead be able to detect the presence of road users within a certain range from each system node. This could make it possible to determine whether a road user is nearby, to make sure light sources are not switched off unintentionally.

It will be important to further investigate if the approach of adding PIR sensors would be suitable in a real-world implementation. If this complement would not help eliminating the above described issues, another approach might have to be considered for the actual road user detections.
Another important consideration for future development is to evaluate the proposed control scheme in a real-world scenario. As it is difficult to estimate in advance how road users would experience the control, it is important to test the system in order to evaluate its feasibility. This could help determine if the implemented scheme would be suitable, or if some changes would have to be made in order to provide a more comfortable experience for road users.

In relation to road user comfort, it might also be of interest to further elaborate the illumination scheme. As of now the system is able to illuminate either a static or a dynamic distance in front of a road user. However, in order to increase the experienced comfort, it could also be considered to change the illumination scheme in relation to the recorded speed.

Vehicles moving at high speeds likely would not gain anything from having the road illuminated behind them. On the other hand, pedestrians or vehicles moving at low speeds are considered more likely to change direction and could therefore want to have some illumination behind them as well. Although this approach is not optimal from the perspective of energy conservation, it is also a question of the safety and comfort experienced by the road users.
References

The following list contains the references used during the course of this master thesis project:


[18] GP2Y0A21YK0F Distance Measuring Sensor Unit (datasheet), Sharp Corporation, Dec. 2006
[19]  *GP2Y0A710K0F Distance Measuring Sensor Unit (datasheet)*, Sharp Corporation, Dec. 2006
Appendix A: Node configuration comparison results

Table A.1 and A.2 contain the time intervals recorded when comparing the two implemented node configurations. Time intervals of approximately two seconds were generated by manually manipulating the states of the IR sensors, in order to determine whether communication delays or other time costs within the created program would affect the recorded time noticeably. These results are described further in section 5.3.

**Table A.1:** Time intervals recorded using two nodes equipped with one sensor each.

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<td>1912</td>
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<td>1988</td>
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Table A.2: Time intervals recorded using one node equipped with two sensors.

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<th>Recorded time intervals (ms)</th>
<th>1992</th>
<th>1980</th>
<th>1994</th>
<th>1910</th>
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Appendix B: Road user detection results

Tables B.1, B.2 and B.3 show the results obtained when performing test detections of passing road users in the form of vehicles, pedestrians and cyclists respectively. All detections were performed with road users passing at a distance of approximately three meters from the sensor, moving perpendicularly to the direction of the sensor. These results are described further in section 5.4.

Table B.1: Results obtained when detecting passing vehicles.

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</table>

h ≈ 80 cm, hand-held sensor  h ≈ 80 cm, fixed sensor
Table B.2: Results obtained when detecting passing pedestrians.

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h ≈ 80 cm  h ≈ 100 cm
### Table B.3: Results obtained when detecting passing cyclists.

<table>
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