Bachelor Thesis

Erhebungstechnologien in Mobilitätsbereich

Exploring Survey Methods for Acquisition of Mobility Data

Sviatoslav Pavlov

Datum: 12.10.2020

Abstract

Traffic data is fundamental for assessing current and past performance and supporting decision-making, as it provides the ground for understanding the movement of motorized and non-motorized traffic flows and serves as a starting point for engineers and government officials to intelligently plan for the future. Recent advancements of traffic data, due to the latest technological advances, enabled to automatically collect the data on highways, sidewalks, and pedestrian crossings that are needed to power smart traffic systems and improve the road safety.

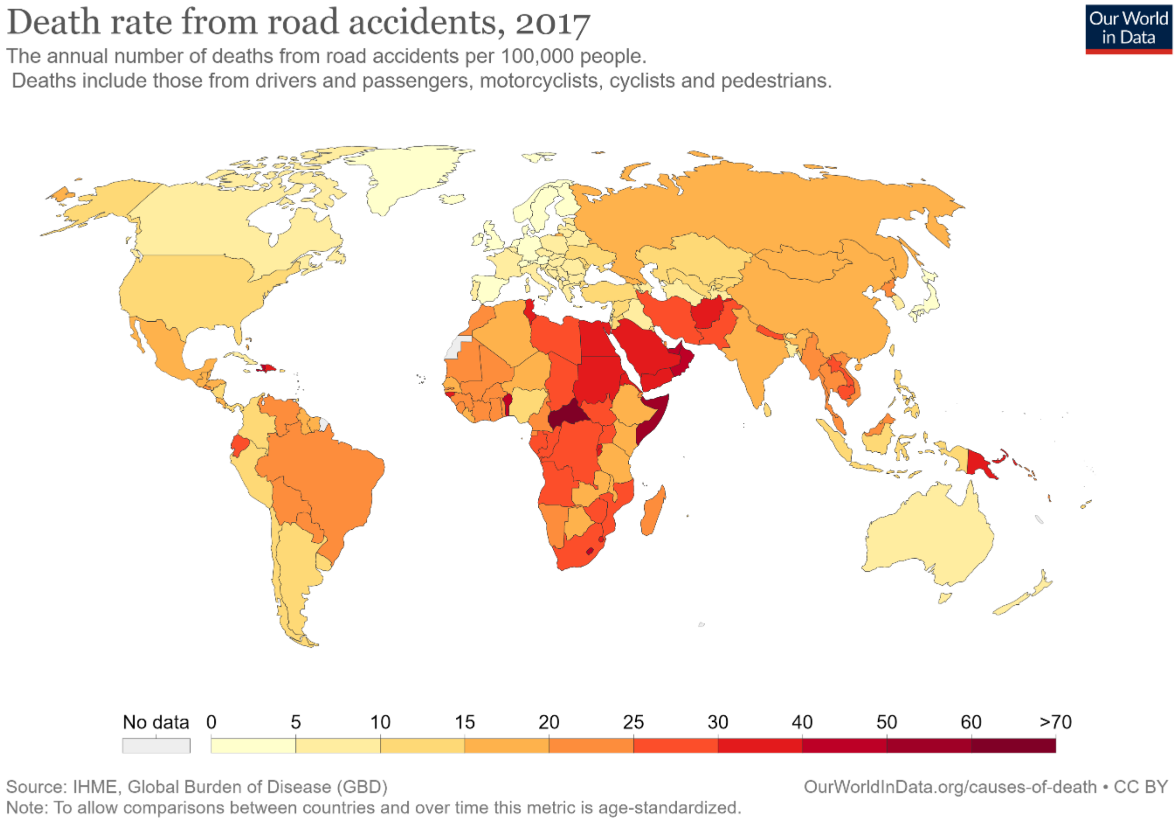
This bachelor thesis presents an overview of current as well as new and emerging technologies and procedures for traffic monitoring. Specifically, will be discussed and examined the advantages and limitations of every approach. Furthermore, will be provided practical case studies of implementing the latest technologies for collecting traffic data and developing traffic monitoring programs.

1 Introduction

Mobility data can be described as a process of movement of people and goods. No matter whether you commuting by foot, bicycle, E-scooter or car, all these interactions add up to statistical data. Growing population, over the past 100 years the population of Earth had more than quadrupled, and globalization increases the number of interactions, which boosts the significance of mobility data, both on local and international scale, as more stress is being put on traffic facilities and infrastructure.

Mobility data is a great tool in identifying major trends and is vital for planning and building „smart" cities. For example, the acquisition of such data can help the governors in keeping high standards of living by reducing travel time, ensuring smooth functioning of system and improving connectivity as well as proving better transport facilities for citizens by analysing public routes and transits. There are numerous case studies that demonstrate how smart management system help implement bike-friendly infrastructure in the city of Chicago, reduce traffic congestion along Shoreline Boulevard in the City of Mountain View [Ross (2018)]. Hence, a well-designed traffic monitoring system provides fundamental data to effectively manage transportation system as well as intelligently plan for the future.

Furthermore, high traffic volumes and increased interactions between people also impacts the safety of the transportation network in terms of number of crashes, injuries and other road accidents. More economically developed countries are utilizing various monitoring technologies to gather information on travel speed, state of infrastructure and seatbelt wearing rates. As a result, the **Figure 1** demonstrates that as of 2017, all European countries have road mortality rate below 10 (per 100,000 population), whilst in most African countries the mortality rate is well above 25 [IHME (2017)].



Source: IHME, Global Burden of Disease (GBD)
OurWorldInData.org/causes-of-death • CC BY
Note: To allow comparisons between countries and over time this metric is age-standardized.

Fig.1 Death rate from road accidents, 2017 [IHME (2017)]

The first-time people recognized the importance of analysing pedestrian and vehicle flows, researches were using written questionaries, telephone interviews and web-based surveys. One of the first traffic counting unit was developed in 1937, which consisted out of a weatherproof road strip connected to a six-volt storage battery [Popular Mechanics (1937)]. As one can imagine, such techniques are very time-consuming, money ineffective, not to mention possible inaccuracies due to human error. Nowadays, due to ever-growing population and recent advances in technology, these traditional survey methods are becoming outdated and are being less and less executed. As a result, new techniques have emerged and proven to be more cost-effective and be able to track multimodal personal behaviour. Furthermore, as these advanced methods are being done with a help of radars, lasers, floating cellular data and GPS, this allows constant data processing and ongoing monitoring.

The scope of my bachelor thesis covers the assessment of existing and new collection methods of mobility data of motorized and nonmotorized traffic intended for urban planning, in other words to say, the focus will be made on local interactions. At first, will be mentioned and discussed all latest survey methods in order to get an overview of recent advances and afterwards will be analysed in depth two different approaches, floating data and real-time monitoring, used for data analysis.

2 Exploring differences between motorized and nonmotorized traffic flows

Although basic technologies to count pedestrians, cyclists and vehicles are similar, however, due to the latest technological advances separate equipment and a different configuration of sensors are being implemented for monitoring nonmotorized traffic.

Therefore, before exploring various counting techniques for motorized and nonmotorized traffic it is vital to recognize key differences between movement of pedestrians/ cyclists and vehicles since it has a direct link to counting data collection procedures and survey methods.

At first one should take into account that monitoring techniques for counting pedestrians and cyclists are still evolving and hence error rates that are linked with various procedures are still to be discovered. It is important to point out that transportation planning and management evolved just in 1950s and 1960s in the USA and England due to ever-growing usage of motor vehicles [Hamilton et al (2014)]. Followed by integration of bicycle and pedestrian pathways into standard transportation planning that happened many years later. Although all methods for data acquisition both for motorized and nonmotorized traffic have and only to a certain extent can be used to estimate actual traffic flows, in comparison to nonmotorized traffic, possible sources of errors and outliers for motorized traffic are well understood and documented [U.S. Department of Transportation (2016)].

Secondly, the unpredictability of the movement of nonmotorized traffic is a crucial factor when it comes to choosing the sensor or technique intended for surveying purposes. Since pedestrians have a free range of movement and tend to take shortcuts, jaywalk and travel in groups, at the same time cyclists can as well travel outside the designated bikeways, such actions make it difficult to place, calibrate and aim the equipment. **Figure 2** demonstrates the findings of the study that examined the frequency of violation of traffic rules by pedestrians and motorists at different intersections [Cinnamon (2011)]. The map indicates the total combined violations as a proportion of total volume, for pedestrians and vehicles. As one can clearly see, at all observed locations pedestrians tend to commit road-rule violations more frequently than motorists.

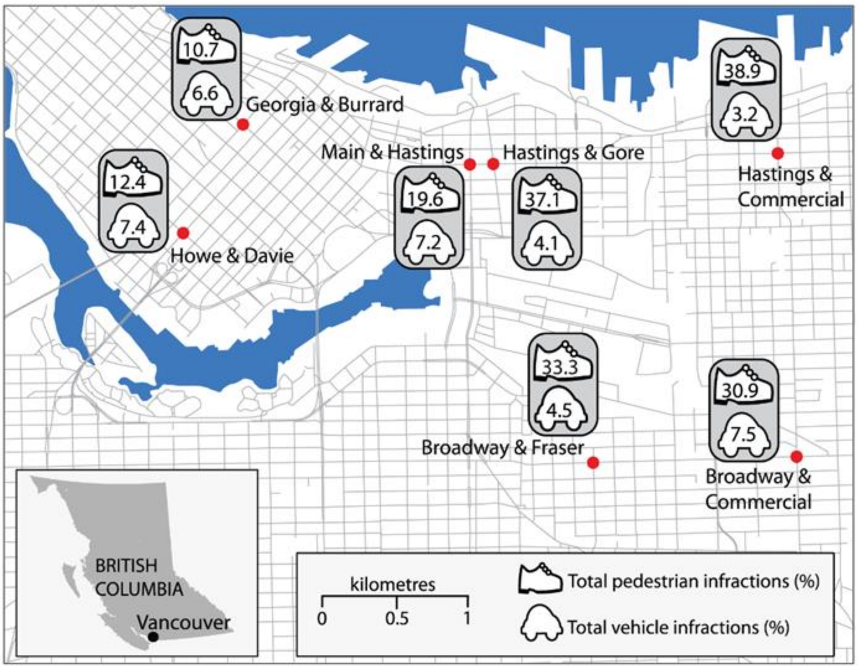


Fig.2 Total pedestrian and motorist violations observed at intersection in the city of Vancouver [Cinnamon (2011)]

The third key difference is the tendency to use short-duration counts over long duration counts when counting nonmotorized flows since often it is part of the research to chronicle physical attributes such as age, gender, use of the helmet as well as to track origin-destination movement [Griffin et al (2014)]. By combining short-duration counts with long-duration counts can be established a statistical data of hourly, monthly and annual patterns.

Fourthly, monitoring techniques for nonmotorized and motorized traffic can be distinguished by the scale of data collection. Because nonmotorized flows are usually studied in smaller environments, for example, intersections or tourist sites, than motorized flows, such limited locations may not very accurately represent the general area of interest. Most of the time, sites for conducting surveys are chosen based upon high traffic rates or as an urban plan for facility improvement. As a result, one should keep in mind that the collected data represents a biased estimate of overall usage.

Fifthly, pedestrian and bicycle volumes tend to be more variable than motor vehicle volumes, depending on the time of travel, day or night, or weather conditions. In particular on a sunny day, counting pedestrians can be a very challenging task for automated systems, due to occlusions, as there are no relatively sizable gaps needed to differentiate between the individuals [U.S. Department of Transportation (2016)].

3 Overview of techniques

Many of the techniques and methods for counting vehicles have been adopted by agencies and urban planners to count cyclists and pedestrians. Most transportation agencies have standard procedures for collecting vehicular counts and have historical data available for assessing daily, seasonal and annual trends. In the meantime, the initial lack of nonmotorized volume data posed obstacles for agencies in their efforts to plan and improve facilities for pedestrians and cyclists. Currently, traffic monitoring technology is evolving quickly due to two factors: firstly, more modern, low cost computing and communication technology becomes available and secondly the growth is driven by the need for more accurate and efficient information.

3.1 Use of smartphones: Bluetooth, Wi-Fi Signal and/or GPS

Cell phones can actively be used in transmitting “here I am” note via Bluetooth and/or Wi-Fi signal. Included in these messages is a unique code (Media Access Control, short MAC, address) associated with the device’s Bluetooth or Wi-Fi transmitter. Hence, by comparing the locations and times with different MAC addresses, a possible route and travel time can be estimated. An increased use of GPS equipped devices provides a low-cost way of obtaining location and time specific information ready for traffic analysis [Vitale, Astarita, Guido (2013)]. When using this method, it is nearly impossible to differentiate between different modes of travel: by car, by bike, by foot. As a result, so far, such studies were isolated by nonmotorized environments such as city centers, subway stations, and recreational zones. However, estimating total flow volumes from these data samples can be problematic since adjacent factors as the percentage of users with Bluetooth and Wi-Fi enabled devices and percentage of users with multiple Bluetooth devices, such as tablets, phones, earpiece, have to be taken into account.

Furthermore, surveys can as well be conducted using standalone GPS devices or smartphone applications that make use of a phone’s GPS functionality to collect nonmotorized trip data. This approach can be very helpful in evaluating route choices, origin-destination patterns as well as the assessment of demand at different locations. However, once again the sample bias still exists since the user has to own a smartphone and remember to use the app on every trip [Rojas et al (2016)].

3.2 Manual counting

Manual counting can be done on site or from the video. Manual counting on site is performed by human data collector in the field and this is the most common data acquisition method amongst all [Nkaro et al (2014)]. Although automated technologies have improved significantly in recent years, manual counts are still being implemented by companies due to lack of finances, personnel or legal permission for installation of automated detectors in public areas.

Additionally, manual counts are still being used whenever there is interest in documentation of additional characteristics such as type of car, number of passengers in case of motorized traffic and age, gender, helmet use in case of nonmotorized traffic [Ryus et al (2014)]. Also, manual counting can be used for validation of automated counting equipment.

Manual counting conducted using paper sheets, smartphone apps, count boards or “clicker” counts. Manual counts last for a few hours in certain time intervals. The advantages of this method lay in surveyors’ ability to capture turning movements or additional information about the users. The filled-in data sheets should then be collected and manually entered into database or spreadsheet. On the downside, manual counts are subjected to data collector’s behaviour, fatigue and motivation, experience and training as well as only short-term counts are possible [Diogenes et al (2007)].

Manual counts from video are done by reviewing a video footage of a permanently or temporarily installed camera. Methodology is similar to conducting manual counting on site, however the video recording makes it possible for an observer to slow down or speed up the video in accordance with traffic volume. Furthermore, video can be reviewed multiple times by several data collectors, which is linked directly with data accuracy [Ryus et al (2014)]. Additionally, data collectors don’t have to be present in the field for several hours, which makes it possible to collect the data even during bad weather conditions and night time.

3.3 Automated counting

Automated counting system are based upon either pre-installed cameras and visual sensors or additionally fixed equipment. Then, computer algorithms use the data from the video recording or point cloud to identify pedestrians, cyclists, and vehicles passing through the observed area or section. Automated counts can capture both intersection counts by labeling and tracking users turning left and right, as well as perform screen line counts, by recording motorized and nonmotorized traffic crossing an imaginary line. **Figure 3** demonstrates an example of computer vision embedded to camera, enabling recognition of each physical shapes such as cars, pedestrians and traffic signs.

Minimal human interaction, low installation and maintenance costs, amongst others, some of the advantages of such approach. Furthermore, the immunity of lidars to low lighting conditions provides accurate capture data and reduces the complexity of traffic sensor infrastructure [Ryus et al (2014)].

The limitations of automated counts are due to the necessity of installation of multiple sensors, as cameras especially are subjected to environmental conditions, such as direct sunlight, glare from passing by cars and nearby streetlight, and susceptible to obscure issues, for example a truck can stop in front of a sensor and block the entire field of view. However, due to less intense human work, these systems are extensively being developed and tested.

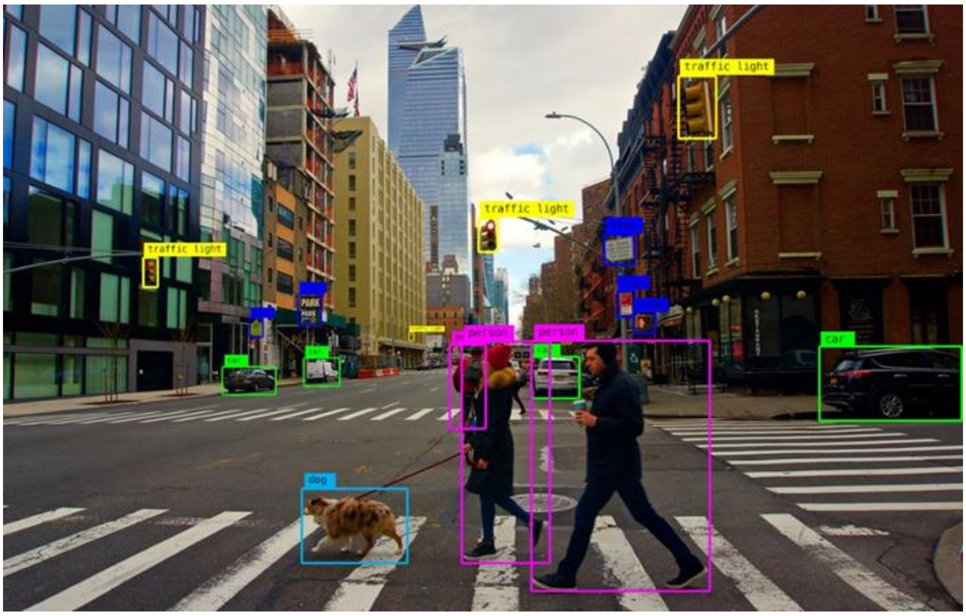


Fig.3 Object Detection and Classification with Machine Learning [AlwaysIA (2020)]

3.4 Rubber tubes

Another way of counting traffic flow is by stretching one or more pneumatic tubes across the roadway and as a bicycle or vehicle passes over this tube, a pulse of air passes through a tube to a detector, which then registers a count. Multiple tubes can be used to determine the speed and direction of traffic. Furthermore, this technology is very frequently used for short duration counts, vehicle classification by axle count, planning as well as research studies [Mimbela et al (2007)]. One of the useful features of this technique is that the data can be analyzed in real-time as well as post-processed by professionals using recorded data.

Additionally, these pneumatic tubes can be used in places with mixed traffic, for example, cars, bicycles, and busses, since the pulses coming from a heavy bus would have a higher amplitude, one can easily distinguish between various means of transportation just by observing the differences in air pulses [Ryus et al (2014)]. On the other side, such approach is not guaranteeing in delivering accurate results in cold conditions and rubber tubes are not durable since they tend to deteriorate fast under high-traffic conditions and last for only a month.

3.5 Piezoelectric sensor

The piezoelectric sensor emits an electric signal when it is physically deformed. In general, two strips are being placed on the pavement and the data logger registers an electric signal sent by the sensor, as a result, the order in which the signals were sent gives the direction of movement and the time interval between the signals provides the speed.

Piezoelectric strips are used for counting cyclists at permanent count sites, both multi-use paths and cycle tracks as well as these sensors are utilized for classifying vehicles by axle count and measure travel speeds and vehicle weight [Mimbela et al (2007)]. Therefore weighing-in-motion devices often used together with piezoelectric sensors.

3.6 Microwave radar

Most commercially available microwave radar sensors used for detection and measurement purposes of traffic at intersections transmit electromagnetic energy at the X-band frequency of 10.525 GHz [Klein et al (2006)]. At the same time, sensors at higher frequencies illuminate smaller ground areas and hence are capable of higher spatial resolution.

One can distinguish between microwave radar sensors and Doppler sensors. The microwave radar sensor detects an object by emitting electromagnetic energy from an antenna towards the monitored area. As a vehicle passed by the sensor, a portion of transmitted energy gets reflected back towards the antenna. The pulses are then recorded by the data logger and traffic flow data metrics such as speed, volume, and occupation are calculated [Mimbela et al (2006)].

Doppler principle allows monitoring vehicle speed using a constant frequency signal. The idea behind is simple, the frequency of the received signal is increasing as the vehicle approaches the radar and decreasing as the vehicle moves away from it [U.S. Department of Transportation (2016)].

Whilst both types of sensors remain unaffected by bad weather conditions and can monitor up to 8 road lanes simultaneously, the key difference between these two approaches is that microwave radar can detect stopped and slow-moving vehicles and Doppler radar cannot detect those.

3.7 Inductive loop detector

Inductive loop detectors (ILD) can be installed either on top or below the pavement and are usually intended for counting motorized and nonmotorized traffic flows at permanent count locations. Through wires runs an electric current that forms a magnetic field, as a result, the sensor detects the changes in the magnetic field that occur when metal parts of a bicycle or vehicles pass over the loops.

When using loop detectors researchers have to account for electromagnetic interference which could lead to errors in raw data as well as for non-standard bicycles, for example, tandem bicycles, which could lead to inaccuracies in data. Furthermore, ILD are susceptible to street utility vehicles and penetration of water [Ryus et al (2014)].

3.8 Infrared sensor

Passive infrared (IR) sensors are used to detect pedestrians and cyclists by measuring the infrared energy radiation emitted by humans and comparing the temperature change afterward. Infrared devices are typically installed as permanent installations and are best to be installed at one-user type location since these sensors cannot differentiate between pedestrians and cyclists. Active infrared sensors are capable of detecting vehicle presence at traffic lights, speed and queue measurement and length assessment [Mimbela, Klein (2007)]. **Figure 4** presents an overview of functionality of infrared beacon installed atop roadway. When it is necessary to quantify nonmotorized traffic flows, researches usually combine IR devices together with loop detectors or pneumatic tubes. Inaccuracies in raw data may arise due to occlusions, as a big group of people or cyclists passes by a sensor. Also, the sensor's performance can be affected by extreme weather conditions.

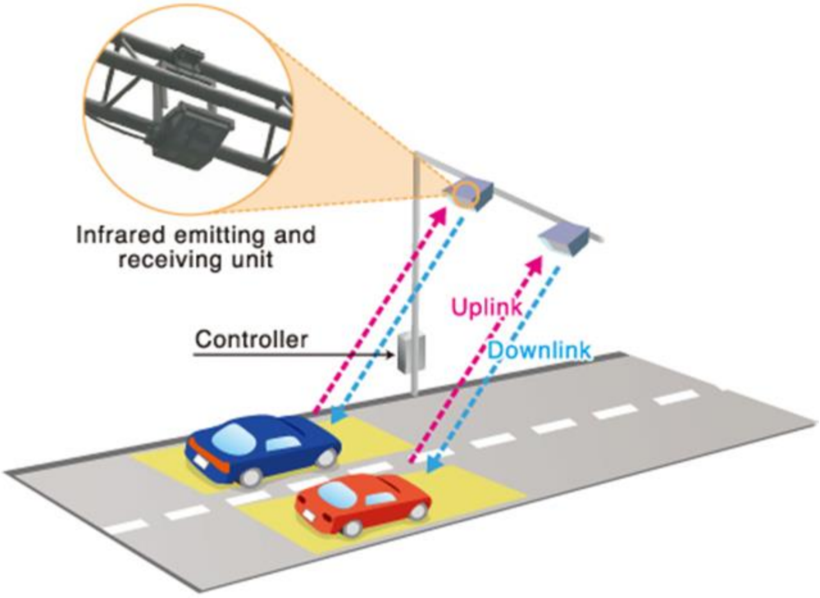


Fig.4 Infrared Vehicle Detector [Klein et al (2006)]

In comparison to passive infrared sensors, active infrared sensors are placed on opposite sides of a traveled way, in such set-up, one sensor acts as an emitter of the infrared beam and another as a receiver. As an object crosses the pathway, the beam is broken for a certain period of time and a person is detected. Just as passive infrared sensors, active infrared sensors cannot distinguish between cyclists and pedestrians. Furthermore, although active infrared sensors are very mobile and very easy to install, these devices are not designed for permanent pathway monitoring, since different objects like animals, insects, and even leaves can lead to errors in results [Ryus et al (2014)].

3.9 Pressure and acoustic pads

Pressure and acoustics pads are usually installed under the ground and function by detecting change in force, in case of pressure pads, or passage of energy, in case of an acoustic pad, caused by car or bicycle wheels or feet. The software in pads can successfully distinguish between various means of transportation and such technology can be put into action on paved and unpaved roads [U.S. Department of Transportation (2016)]. When installing pads, one should consider that pedestrians, cyclists and vehicles should pass right above the pads, thus these pads should be placed where traffic flow happens as a single file [Ryus et al (2014)].

3.10 Magnetic sensor

At small detection location, magnetic sensors or magnetometers can be used to count motorized and nonmotorized traffic flows. By either being buried under the pathway or hidden in box on the side of the travelled way, the datalogger detects any activity through changes in the normal magnetic field as metal parts pass by the sensor. Magnetometers are usually used as a part of the vehicle detection system in order to detect presence and any movement of vehicles or other traffic.

However, on the downside, most magnetic sensors are not capable of detecting stopped cars or bicycle due to the fact that they require a constant flow of traffic with respect to time. Therefore, these sensors must be placed carefully, at sites where it is not possible for commuters to come to a standstill [Mimbela, Klein (2007)].

3.11 Ultrasonic sensor

Ultrasonic sensors function by transmitting pressure waves of sound energy at a frequency between 25 and 50 kHz, which is above the human audible range [U.S. Department of Transportation (2016)]. Most ultrasonic sensors operate with pulse waveforms that predefine a distance to the road surface by detecting the portion of the transmitted energy that is reflected towards the sensor. Once a distance, other than to a road surface, is measured, the sensor defines this as a presence of a vehicle. Ultrasonic sensors can provide vehicle count, presence and occupancy information by recording the time at which the car crosses each beam [Soobin et al (2014)].

The performance of these sensors can be influenced by environmental conditions such as temperature changes and extreme air turbulence. Additionally, ultrasonic sensors cannot recognize stopped vehicles [Klein et al (2006)].

3.12 Traffic counting techniques and procedures

This section provides a comprehensive overview of the current state of traffic monitoring technologies based in findings from the research, a summary is presented in **Table 1.**

Since technologies are evolving continuously at unprecedented rate, future innovations can lead to influx of new technologies that can substantially improve traffic data collection and processing methods.

Tab. 1 Overview of traffic monitoring technologies

Technology	Typical application	Accuracy	Limitations	Cost
Use of smartphones: Bluetooth, Wi-Fi signa and/or GPS	Real-time traffic flow and road monitoring, movement is captured with a network of smart sensors.	A recent study by the University of Calabria revealed that measures obtained from smartphones accurately reflect traffic attributes with a 95% confidence interval.	This technology is bounded by maximum signal range of Bluetooth and Wi-Fi signals, around 100 meters. Also, the user has to have a gadget at his disposal that emits those signals.	Low, since personal devices can accurately provide position and speed of movement, cost for stationary ranges between 100€ and 500€.
Manual counting	Applicable to all site types to count pedestrians, cyclists and vehicles.	Depends on data collector's behaviour and experience. Undercount rates ranging between 8% and 25% for 15-minute intervals [Diogenes et al (2007)].	Quality of collected data is subjected to collector's fatigue and undercount. Only short-term counts are possible.	Moderate, since start-up costs can exceed 40€ per hour including training, labour and management.
Automated counting	Can be installed at bicycle lanes and	Classification accuracy of 88% for	May require multiple	High, cost for a software and

	intersections to monitor turning movement and crosswalk counts.	bicycles and pedestrians, which was lower than vehicle classification accuracy	cameras in order to collect the data of the entire intersection. Only short-duration counts are possible due to limited data storage.	hardware package (video image processing) ranges between 2500€ and 20000€.
Rubber tubes	Rubber tubes has proven to be very effective in collecting bicycle data for days up to several weeks.	Multiple researches indicate that the tubes usually undercount. The average percentage deviation, representing the overall divergence from the perfect accuracy, was -17,9%.	Require routine maintenance, especially at sites with high traffic volumes, as tubes can wear out and tear. Furthermore, additional permissions might be required for installation.	High, the average equipment cost range between 1,000€ and 3,000€, excluding maintenance cost.
Piezoelectric sensor	Can be placed at multi-use paths or cycle tracks for counting bicyclists.	According to studies, the divergence from perfect accuracy across all data is -11,4%.	Piezoelectric sensor can't be used in mixed-flow traffic and requires specialized installation process.	Although equipment cost is medium relative to other technologies, these costs are spread over a long period of time. One lane (equipment and installation) 900€-1200€.
Microwave radar	Typically microwave radars are used for long-duration counts of vehicles, without tearing up the roadway	According to the Detector Evaluation and Testing Team (DETT) of the California Department of Transportation microwave radars can deliver better than 95% overall vehicle count accuracy at 30-secodns and 5-minute intervals.	Maintenance, proper position and calibration are crucial for qualitative traffic data.	Low, sensor purchase cost lays between 600€ and 1700€.
Inductive loop detector	Loop detectors are usually used for	A study by DETT indicated that the	At sites, where it is not	Sensor purchase cost is

	permanent traffic counts and typically installed on paved facilities.	inductive loops on the freeway undercounted by 0.1%, while the high-occupancy vehicle lane loops undercounted by 0.9%.	possible to cover the entire area with loops, the undercount may occur as bicyclists and vehicles ride outside of the area covered by the loop.	low, but installation cost is high, due to the need of pavement saw cuts and traffic controls.
Infrared sensor	Electronic toll collection, traffic data studies, flow measurement, traffic monitoring.	Vehicle Speed Accuracy: +/-10% Vehicle Detection Accuracy >99.9% (one vehicle in field-of-view)	Infrared sensor can't distinguish between pedestrians and cyclists, as well as high inaccuracies may arise due to high traffic volumes (i.e. pedestrians travelling in groups)	Moderate, active infrared sensors cost between 2,500€ and 5000€, whilst the price for passive infrared sensors ranges between 600€ and 1000€.
Pressure and acoustic pads	Usually pressure and acoustic pads are installed in the ground and are used to count pedestrians and cyclists on unpaved roads.	Movement detection accuracy of pressure sensors is +/-0.05%.	Limited field of detection, since users have to pass directly above the sensor. Also, not feasible for locations with severe weather conditions, where the ground freezes.	Although these pads are inexpensive compared to other technologies, high installation costs still apply.
Magnetic sensor	Most frequently, magnetometers are used to count bicyclists and due to a limited detection range they are usually installed at site where users travel as a single file	Research by the University of Bielsko-Biala and the University of Silesia, revealed that the magnetometers are able to provide accurate detection only for vehicles. The detection accuracy is that case is was above 80%, while the accuracy of pedestrian detection is close to 50%	Magnetic sensors account for a relatively small detection area.	Since installation requires excavation of an unpaved are, followed by replacement, the start-up costs are relatively high compared to other technologies

Ultrasonic sensor	Advanced traffic signal control, freeway monitoring	The vehicle detection accuracy of ultrasonic sensor is approximately 99.5% (overhead mount, one lane in the field of view)	Environmental conditions may alter the performance of the sensor. Ultrasonic sensors can't detect halted vehicles	Moderate, sensor purchase cost ranges between 500€ and 1500€

4 Case studies

Since traditional monitoring systems such as manual observations, inductive loop and pneumatic tubes are mature methods that are well documented and examined, this section of bachelor thesis is devoted to new and emerging technologies due to latest technological advances, these includes automated laser and radar traffic detection systems and on-board traffic tracking devices.

4.1 Case study 1: Hawkeye Radar developed by Rhythm Engineering

Hawkeye radar is a vehicle detection system that utilizes a Frequency Modulated Continuous Wave (FMCW) to accurately detect vehicle's presence, occupancy, speed, classification, queue length, traffic incidents as well as wrong-way travel.

To begin with, vehicles can be detected using two types of microwave radar sensors: continuous wave (CW) Doppler Radar and a FMCW radar. In comparison to FMCW radar, CW Doppler radar is not capable of detecting a stopped vehicle without the need for a supplementary sensor. The FMCW radar makes up for this limitation and this makes it more favorable for detection purposes. In this type of radar, the wavelength frequency varies constantly with respect to time. Vehicle speed is estimated by taking a traveled pathway and dividing it into areas known as "zone" that all have a defined length. The distance between leading edges of adjacent zones is divided by the time between the vehicle's arrival at those leading edges in order to determine its speed.

The FMCW radar used in a Hawkeye sensor is a third-generation vehicle detector radar and is known as 3D-UHD. This detector delivers more accurate results than forerunning radars since it separates vehicles by the angle of travel, range, and speed. 3D-UHD utilizes a high-speed modulation and adds an adaptive beam formation to enhance the accuracy of detection.

Hawkeye's antenna contains a matrix of receivers, besides a 3D-UHD transmitter, that both intercepts an analyze the reflected waves. The beams formed 24 or more at the time, track movement in three dimensions, and comprise a simultaneous Digital Beam Formation (DBF) that is forward-firing and is accurate to and beyond a range of 300 meters [Rhythm Engineering (2020)]. Once Hawkeye detects a vehicle in its field of vision, it assigns a unique identification. Recognizing the importance of nonmotorized traffic, this radar can as well be used to detect and track pedestrians and cyclists.

The advantage of using this technology is that radar does not need visible light to operate and there is no decrease in Hawkeye's performance from day to night time. Furthermore, the sensor's performance remains unaffected by the change in weather conditions. To put it into perspective, magnetometers lose their battery life in cold weather and video detection cameras are subject to fog, rain, and ambient light. The range accuracy of the sensor is <±0.25 meters, therefore it can serve as a helping hand for professionals in managing traffic signals efficiently and proactively.

The data is then can be visually presented in the Hawkeye Automated Signal Performance Measures (ASPM) module. It provides an array of metrics such as arrivals, volume, delay, average speed, and live traffic events.

4.2 Case study 2: Leddar T16 by LeddarTech

The Leddar T16 traffic sensor is a 2D solid-state lidar is specifically designed for traffic management systems. A solid state lidar consist out of silicon chip and MEMS mirrors that direct the laser beam, no moving parts are involved in a system as it is the case with mechanical lidars. Leddar digital signal processing technology can detect and identify all types of traffic, including pedestrians, cyclists, and vehicles, hence the scope of use of T16 ranges from city roads to highways. The Leddar T16 measures both the distance and angular positioning for each detected target. The collected raw data enables functionalities such as vehicle identification, measurement of speed, and additional traffic data collection owning to an integrated video sensor with a Pan&Tilt actuator.

T16 is a sensing technology based on the LED illumination (infrared spectrum) and the tine-of-flight of light principle. The LED sources illuminate the area of interest, whilst the multi-segment sensor receiver collects the backscattered light and measures the time taken for signals to return to the sensor. The return signals are digitalized and can be processed with a software development kit, the Leddar Enabler SDK, which provides a user-friendly application programming interface (API) with C libraries and code examples for Windows.

Furthermore, due to a resistant and waterproof case (IP67 ingress protection), the Leddar T16 traffic sensor provides high reliability even under the most challenging environmental conditions such as rain, snow, and fog. Also, with its above-ground installation, the Leddar T16 sensor can precisely, the sensor's accuracy is ±5 cm, detect moving objects up to 5 meters [LeddarTech (2020)].

Additionally, Leddar T16 sensor has a fixed high data rate of 200 Hz which meets the stringent requirements for high-speed open road tolling (ORT) applications and is effective for vehicle classification at speeds that exceed 180 km/h. Also, high measurement rates allow for better form definition, improved detection of black cars and small objects.

In comparison to mechanical lidars that captures a single vertical line of data points as a laser source rotates, a Flash Solid State Lidar (FSSL) is similar in principle to a photography flash on a regular camera that sends over 100,000 light pulses per second and instead of generating a point cloud, it produces a 3D profile of the vehicle's surface.

4.3 Case study 3: Bitcarrier developed by Worldsensing

Bitcarrier is a real-time traffic and road monitoring system, on one hand, it allows drivers to obtain instant updates about journey times and incidents and on the other hand, helps city agencies wirelessly collect raw data and manage traffic flows.

The functionality of the Bitcarrier can be outlined in three steps: a collection of data, processing of information, and lastly data visualization. The software uses a 2,4 GHz frequency band to scan for Bluetooth and Wi-Fi signals emitted by mobile phones and GPS-navigators. Bitcarrier can simultaneously detect Bluetooth and Wi-Fi devices and capture up to 500 unique gadgets per minute that travel at speeds ranging between 5km/h and 160 km/h [WorldSensing (2020)].

Bitcarrier can output key traffic metrics as traffic intensity, congestion level, travel times, vehicle speed, output historical and real-time traffic data statistics, and keeps track of accidents, roadblocks, and demonstrations. All aforementioned features are necessary for improving mobility strategy, managing and optimizing traffic in real-time and help manage congestion and reduce pollution.

The software package consists of two individual tools for analysis and activation of data in real-time: the Bitcarrier Configuration Tool (BCT) and the Bitcarrier Visualisation Tool (BVT). The BCT helps users to easily configure their installations and allows setting up all Bitcarrier sensors, whilst BVT is an online map demonstrating results in real-time.

Furthermore, algorithms developed by Worldsensing ensure that all Bluetooth and Wi-Fi identifiers audited by the sensors are anonymized using a hash algorithm so that the physical address of a device is not traceable. Also, the communication between the client and the server is done using a proprietary protocol resulting in a very low GPRS (General Packet Radio Service) data consumption.

Bitcarrier sensor itself is a piece of equipment with an ultra-low-power processor specifically designed for outdoor installations, has an IP67 degree of protection, and is resistant to all weather conditions.

A few years ago, Worldsensing helped develop in Bogota one of the most complete and advanced mobility management solutions in the world. Before the partnership, Colombian capital was suffering from significant congestion problems and with the traffic management system, they were able to improve mobility, security, and service and unify several systems in one central control center responsible for vehicle counting, incidents monitoring, and traffic flow management.

4.4 Case study 4: TrafficSense developed by Cellint Traffic Solutions

The latest technological advances in smartphones make it possible to build a comprehensive picture of traffic in a city, just by floating cellular data. Such approach is considered to be the most cost-efficient since it has low start-up costs as no extra infrastructure or hardware needed in cars or along the roads and does not require any ongoing maintenance.

TrafficSense enables to monitor all means of transport by aggregating data points generated by the cellular network and then assigning GPS coordinates to each point in real-time. The system can distinguish between pedestrian pathways, bicycle tracks, highways, and lanes which are separated by some type of terrain. Once an algorithm assigns a path to a phone, the system can measure the position of the accurately.

Just by using cellular data, TrafficSense can deliver real-time speed, travel time, congestion detection as well as origin-destination pattern analysis of motorized and nonmotorized traffic.

One of the most apparent drawbacks of this technology is that in order for the system to work, there has to a constant cell phone connection present. Additionally, it can only track users that have installed the apps with localization tracker turned on and this limits the scope of the survey since there are still present a lot of devices that do not transmit any information. Therefore, such data represents only a fraction of all real-time traffic flows.

In 2006 the Kansas Department of Transportation compared road traffic data provided by TrafficSense to the existing traffic monitoring SCOUT system that uses inductive loops. As a result, an independent evaluation for the Kansas Department of Transportation showed that the average difference between the system's speed measurement over the sensors was less than 5 miles per hour and the average latency in detecting slowdowns by TrafficSense in comparison to inductive loops at the site was about 4 minutes [Telvent Farradyne (2007)]. Hence, it was reported that the TrafficSense data was clearly reflecting traffic conditions in addition to the fact that the system was deployed in just 2 months and did not require any road works.

4.5 General comparison of Case Studies

In this section will be compared four aforementioned traffic data collection methods according to the following criteria: application field, accuracy, limitations, and cost. Collected data is presented in Table 2.

4.5.1 Breakdown of Hawkeye Radar

As noted earlier, Hawkeye Radar can be used for vehicle classification, continuous vehicle tracking as well as intersection live view. Due to a third-generation UMRR radar, Hawkeye is one of the most advanced multi-lanes, multi-object tracking radar technology. The maximum detection range of the radar is 340 meters, whilst the minimum range is 1.5 meters. Furthermore, according to the datasheets, the range accuracy of the sensor is less than +/-0.25 meters and detection speed accuracy is less than +/-0.28 meters.

Although Hawkeye has not been yet tested rigorously by independent parties, one can still think of the following disadvantages of using radar technologies: first of all, the detection accuracy is affected by occlusions, hence more radars might be needed to cover the entire area. Secondly, multiple studies have shown that radar sensors have decreased detection accuracy for slow-moving traffic.

Hawkeye offers the following traffic monitoring solutions: Hawkeye Detection for Intersections, this package costs 25,000$ and includes four radar detectors, a Hawkeye processor, and a cabinet cabling. An automated signal performance measures and data visualization included with the purchase.

4.5.2 Breakdown of Leddar T16

The Leddar T16 offers a precise and cost-efficient sensor for various transportation applications, such as electronic tolling, traffic monitoring, and traffic law enforcement. Inside the sensor is a digital signal processing technology, capable of distinguishing between vehicles, pedestrians, and cyclists. According to specification of Leddar T16, the sensor’s detection range is up to 50 meters, whilst detection accuracy is +/- 5 centimetres.

Since Leddar T16 is a 2D solid-state lidar, the following drawbacks are associated with it: limited field of view, as the sensor only scans in the direction it faces as well as lower resolution when comparing to mechanical or digital scanning lidars.

LeddarTech offers two types of T16 sensors, one is for tolling application and one is for traffic solutions. The price ranges between 3,300€ and 4,000€.

4.5.3 Breakdown of Bitcarrier

Bitcarrier is capable of delivering real-time traffic maps and key traffic metrics. Furthermore, the system has an incident alert system to inform about accidents, roadblocks and demonstrations. Although the system hasn’t been tested yet by any third parties, some real-life example show that Bitcarrier is capable of improving mobility strategy, decrease costs through easy maintenance, and provide citizens and drivers with valuable updates.

Typically, the following issue is associated with traffic devices that rely on the data provided by GPS or a network provider: inaccuracy in path estimations. With increasing of the distance between two consecutive locations, map-matching becomes more challenging since there are more possible trajectories that the user can undertake to reach the destination point.

4.5.4 Breakdown of TrafficSense

Cellular probe data has proven to be just as effective as traditional data collection methods in monitoring traffic flows. TrafficSense system from Cellint uses cellular probes to measure and report real-time traffic information.

A research conducted by the Kansas Department of Transportation used the data collected by the Scout loop detectors as a baseline against which the Cellint speeds were compared. Three analyses were performed: an analysis of slowdown events, a category analysis, and a least square analysis. The slowdown analysis examined the system’s latency with respect to the beginning of slowdown events. The other two analyses were general measures of fit between the two data sets, and were used to identify the latency value that provided the best overall match. The average latency for slowdowns was between 5 and 7 minutes. Furthermore, the study found out that the Cellint seemed to deliver bias data toward 70 mph when traffic volumes were extremely low, such as during night-time hours.

Tab.2 An overview of TrafficSense, Bitcarrier, Leddar T16 and Hawkeye Radar

Technology	Typical Application	Accuracy	Limitations	Cost
Hawkeye Radar	System is capable of detecting and tracking vehicles, cyclists and pedestrians at intersections	Range accuracy: <+/-0,25m Speed accuracy: <+/-0,28m/sec	Detection accuracy affected by occlusions, decreased detection accuracy of slow-moving traffic.	15,000$-25,000$
Bitcarrier	Urban and inter-urban environments; highways; railroads; event venues	Bitcarrier sensors capture up to 500 unique devices per minute which travel at speeds ranging from 5 km/h to 160 Km/h	Inaccuracy of position and path estimation	No information
Leddar T16	Electronic tolling, traffic monitoring and traffic law enforcement	+/- 5 cm	Low resolution, limited field of view	3,300€-4,000€
TrafficSense	Real-time traffic monitoring of all transportation modes via mobile network	Average latency for slowdowns is between 5 and 7 minutes.	The Cellint system seemed to bias data toward 70 mph when traffic volumes were extremely low, such as during night-time hours.	1,000$/km road monitored per year

5 Conclusion

Traffic is an overarching topic, every one of us contributes to traffic data daily by driving home from work, doing shopping, or cycling through a city. Without adequate traffic data, agencies and engineers can't design a transportation network that would ensure the safety and utility of every transportation mode. Currently, there are no established standard procedures for consistently collecting urban traffic data and as a result, the quality of these data is often poor or unknown.

There are many different types of monitoring systems on the market. This paper evaluates the usefulness and accuracy of state-of-art approaches for vehicle, pedestrian, and bicycle detection system applications. Yet, no sensor, considered in this study, can very precisely and accurately detect and track pedestrians, cyclists, or vehicles. Meaning that the detection accuracy can only be significantly improved by fusing the data from multiple sensors. Judging by the rate of technological advances, we will be seeing more effective and efficient ways to collect, process, and store traffic data as industries and researches will be making the use of new resources, know-how, and equipment.

There is still plenty of specific challenges that could be addressed in further researches, amongst others for example establishing certain control standards and quality assurance for urban count data and understanding travel patterns of non-motorized traffic.

6 References

[1] Ryus P., Ferguson E., Laustsen K.M.- *Guidebook on Pedestrian and Bicycle Volume Data Collection,* 2014. Available: https://www.nap.edu/read/22223/chapter/1

[2] U.S. Department of Transportation- *Traffic Monitoring Guide*, 2016. Available: https://www.fhwa.dot.gov/policyinformation/tmguide/tmg_fhwa_pl_17_003.pdf

[3] Soobin J., Eil K., Inbum J.-*Traffic Measurement on Multiple Drive Lanes with Wireless Ultrasonic Sensors*, 2014. Available: https://www.researchgate.net/publication/269181462_Traffic_Measurement_on_Multiple_Drive_Lanes_with_Wireless_Ultrasonic_Sensors

[4] Minge E.- *Evaluation of Non-Intrusive Technologies for Traffic Detection*, 2010.

[5] Vitale A., Astarita V., Guido G.- *Using Smartphones As a Tool To Capture Road Traffic Attributes*, 2013. Available: https://www.researchgate.net/publication/266672987_Using_Smartphones_As_a_Tool_To_Capture_Road_Traffic_Attributes

[6] U.S. Department of Transportation- *Exploring Pedestrian Counting Procedures*, 2016. Available: https://www.fhwa.dot.gov/policyinformation/travel_monitoring/pubs/hpl16026/hpl16026.pdf

[7] Middleton D., Longmire R., Shawn T.- *State of the Art Evaluation of Traffic Detection and Monitoring Systems*, 2007. Available: http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.117.8214&rep=rep1&type=pdf

[8] Bernas M., Placzek B., Korski W., Loska P., Smyla J., Szymala P.- *A Survey and Comparison of Low-Cost Sensing Technologies for Road Traffic Monitoring*, 2018. Available: https://www.mdpi.com/1424-8220/18/10/3243

[9] Mimbela E., Klein L.-A *Summary of Vehicle Detection and Surveillance Technologies Used in Intelligent Transportation Systems*, 2007. Available: https://www.fhwa.dot.gov/policyinformation/pubs/vdstits2007/vdstits2007.pdf

[10] Diogenes M., Ragland D., Greene-Roesel R.- *Pedestrian Counting Methods at Intersection: A Comparative Study*, 2007. Available: https://www.researchgate.net/publication/46439516_Pedestrian_Counting_Methods_at_Intersections_A_Comparative_Study

[11] Klein L., Gibson D., Mills M.- *Traffic Detector Handbook: Third Edition-Volume I*, 2006. Available: https://www.fhwa.dot.gov/publications/research/operations/its/06108/06108.pdf

[12] LeddarTech- *Leddar T16 Specification Sheet*, 2020. Available: https://leddartech.com/download/specsheet-leddar-t16-traffic-sensor/

[13] WorldSensing- *Bitcarrier Technical Brochure*, 2020. Available: https://www.worldsensing.com/wp-content/uploads/2016/09/Bitcarrier-TDS.pdf

[14] Rhythm Engineering- *Hawkeye User Guide*, 2020.

[15] Telvent Farradyne- *Kansas City Scout Traffic Management Center Special Report*, 2007

[16] Global Burden of Disease Collaborative Network- *Death Rate from Road Accidents*, 2017. Available: https://ourworldindata.org/grapher/death-rates-road-incidents?time=1990..2017

[17] Cinnamon J., Hameed S., Schuurman N.- *Pedestrian Injury and Human Behaviour: Observing Road-Rule Violations at High-Incident Intersection*, 2011. Available: https://www.researchgate.net/publication/51243235_Pedestrian_Injury_and_Human_Behaviour_Observing_Road-Rule_Violations_at_High-Incident_Intersections

[18] Ross S.- *Valley Transportation Authority* ,11/05/2018. Available: https://www.vta.org/blog/multimodal-improvement-plans-pass-mountain-view-and-santa-clara

[19] IHME, Global Burden of Disease Study 2017 (GBD 2017) Results- *Our World in Data* ,2017. Available: https://ourworldindata.org/grapher/death-rates-road-incidents?time=2017

[20] Popular Mechanics- *Strip Across Road Counts Cars and Registers Hourly Total*, 1937. Page 416. Available: https://books.google.at/books?id=rNoDAAAAMBAJ&printsec=frontcover&source=gbs_ge_summary_r&cad=0#v=onepage&q&f=false

[21] Griffin G., Nordback K., Götschi T., Stolz E.- *Monitoring Bicyclist and Pedestrian Travel and Behaviour*, 2014. Available: http://onlinepubs.trb.org/onlinepubs/circulars/ec183.pdf

[22] Nkaro A., Sharma B., Tshaakane L., Matu., Sarma D., Norku F.- *Traffic Data Collection and Analysis*, 2004. Available: https://www.vegvesen.no/_attachment/336339/binary/585485

[23] AlwaysAI- *Object Detection in Computer Vision*, 2020. Available: https://learn.alwaysai.co/object-detection

[24] Hamilton A., Waterson B., Cherrett T.- *The evolution of urban traffic control: changing policy and technology*, 2013. Available: https://www.researchgate.net/publication/259646971_The_evolution_of_urban_traffic_control_changing_policy_and_technology

[25] Rojas M., Sadeghvaziri E., Jin X.- Comprehensive Review of Travel Behavior and Mobility Pattern Studies That Used Mobile Phone Data, 2016. Available:

https://www.researchgate.net/publication/309694986_Comprehensive_Review_of_Travel_Behavior_and_Mobility_Pattern_Studies_That_Used_Mobile_Phone_Data